STUDY ON COMPACTION MOISTURE RANGE SPECIFICATIONS OF NORTH DAKOTA STATE AND DEVELOPMENT OF EMPIRICAL EQUATIONS FOR PREDICTING COMPACTION CHARACTERISTICS

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

Stability of soil plays an important role in the construction of engineering structures like pavements, buildings, embankments, dams, etc. Compaction is the process where proper stability of soil is ensured with required specifications. In this study, efforts have been made to develop empirical equations for Proctor test methods which help in predicting compaction parameters in relation with Atterberg limits for a soil type. The use of empirical equations will help in economy of the project by saving the time involved in performing laboratory activities and associated costs. Results indicate that Plastic limits holds a good correlation and can be utilized in compaction prediction parameters for Modified Proctor. This study also aimed to analyze the current compaction moisture range specifications of North Dakota State to provide recommendations on their current standards. A saturation peak concept is proposed that will aid in determining the limiting moisture range as the compaction density increases.

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DEDICATION

A teacher always guides a student in a right direction to make their beautiful tomorrow. I dedicate this work to my mother, Mrs. Sarojini Tanajirao Kadam, a teacher by profession and my inspiration in life.

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CHAPTER 1: INTRODUCTION

One of the most important aspects of ensuring engineering stability of buildings, pavements, slopes and other structures is the soil underneath and its properties. For design considerations, it is essential for a geotechnical engineer to investigate the soil properties and strength contributing parameters which are determined by in-situ and laboratory tests. Soil tests are classified as Index properties and strength properties based upon the requirements. Determination of Index properties like moisture content, specific gravity, Atterberg limits, grain size distribution, in -situ density, and relative density are required for soil class classification. Strength properties like shear strength, permeability, compressibility characteristics, compaction characteristics and swell potential are required for engineering designs. One of the most essential for geotechnical engineers are the compaction characteristics.

Compaction is the process of application of mechanical energy to reduce air voids. Compaction results in decrease in settlement of soil and permeability with increase in shear strength and bearing capacity. Proper compaction is required when working on civil engineering works like pavements, placing fills, improvement on properties of existing soil, earth dams and embankments. Failure in achieving desired compaction may result in frost heave susceptibility, pavement failure, settlement, uneven surfaces on pavements, and higher costs. Soils are broadly classified as cohesive and non-cohesive soils depending upon the frictional and cohesive forces and so the compaction process can be termed as compaction of cohesive soils and compaction of non-cohesive soils (Hilf, 1991). In the field of engineering soil classification is an important aspect where the engineers can classify and relate the soil to the engineering designs based upon their properties. In United States two major soil classification systems are used where Table 1 gives general description of soils based upon Unified Soil Classification System and Table 2 gives soil classification based upon AASHTO specifications. The North Dakota Department of Transportation (NDDOT) classifies the soils based upon AASHTO classification system.

Table 1: General Soil Classification (Astm & International, 2006)

	Group Symbol and Name
Coarse grained soils (≥ 50% retained on N0. 200 sieve)	GW (Well graded gravel)
	GP (Poorly graded gravel)
	GM (Silty gravel)
	GC (Clayey gravel)
	SW (Well graded sand)
	SP (Poorly graded sand)
	SM (Silty Sand)
	SC (Clayey Sand)
Fine grained soils 50% or passing No. 200 sieve	CL (Lean Clay)
	ML (Silt)
	OL (Organic Clay/SIlt)
	CH (Fat Clay)
	MH (Elastic silt)
	OH (Organic Clay/ Silt)
	PT (Peat)

Table 2: AASHTO Classification for Silt and Clayey Soils (Aashto, 2009)

General Classification	Silt-Clay materials (>35% passing the 0.075 mm sieve)				
Group Classification	A-4	A-5	A-6	A-7	
				A-7-5	A-7-6
Sieve Analysis, % passing No. 200					
	36 min.	36 min.	36 min	36 min.	
Liquid Limit	40 max.	41 min.	40 max.	41 min.	
Plasticity Index	10 max.	10 max.	11 min.	11 min.	
Material Type	Silty Soils		Clayey Soils		

1.1. Factors Affecting Compaction

Compaction of soil is governed by various factors, including:

- Water Content of the Soil
- Type of soil
- Compaction Energy
- Methods of Compaction

1.1.1. Effect of Water Content

The soil is usually stiff at lower water contents and at increasing water contents the soil becomes workable. Dry density of soil increases with increase in water content till optimum water content is reached. When optimum moisture content is reached, it retards the expulsion of air voids with no further reduction of air voids in soil thus achieving the dry unit weight of soils. When the compaction curve approaches zero air void line giving the maximum dry density with optimum moisture content. When this state approaches further increase in moisture content results in reduction of dry unit weight.

1.1.2. Type of Soil

Generally, the compaction parameters vary with the type of soil. The coarse-grained soils have higher dry densities than fine grained soils. Gradation of soil is an important parameter for achieving the required compaction characteristics. Addition of small fines to a coarse-grained material can increase the dry density of soil. However, the amount of fines should be kept to a minimum as more fines will decrease the dry density. The amount of voids are high in cohesive soil than cohesionless soil. Cohesive soils such as clays have very high optimum moisture content and less dry density. In general, proper gradation of soil is necessary as a well graded soil will have higher density than poorly graded. The maximum dry density of clayey soil may be as low as 60 lb/ft^3 where as a well graded sand may have a maximum dry density will be about 130 lb/ft^3 (Johnson & Sallberg, 1960). Figure 1 and Figure 2 illustrates the variation of Dry density and moisture content for Fat Clay and Silty Sand illustrating the variation of compaction characteristics with soil type.

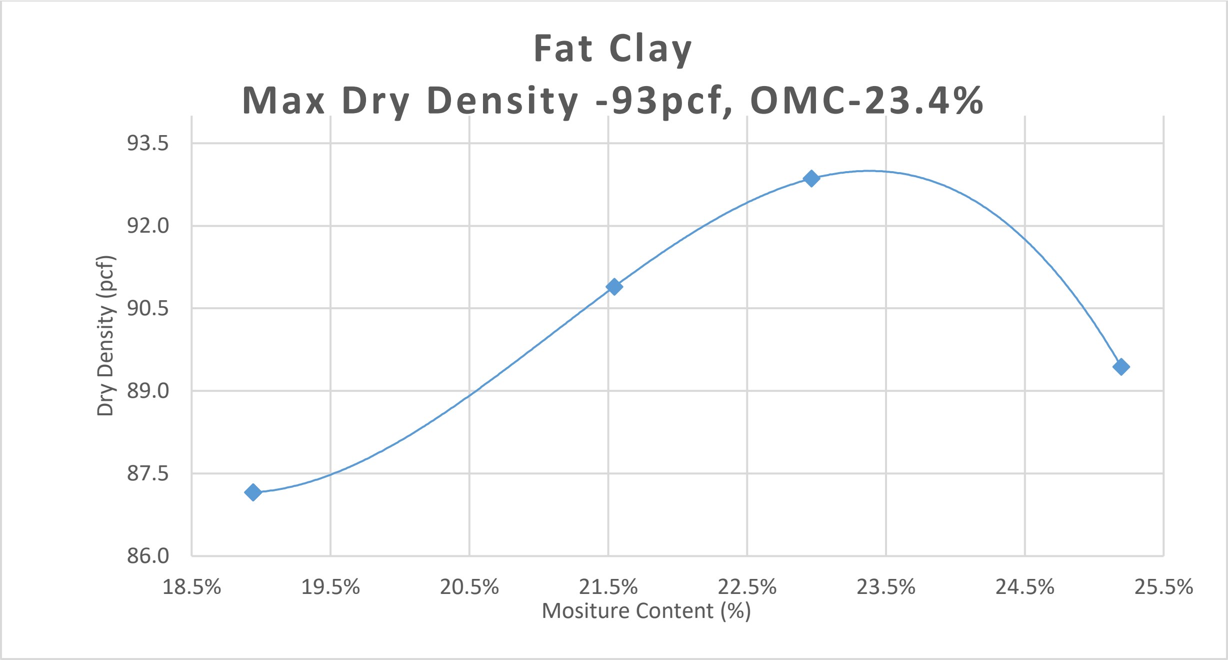

Figure 1: Moisture Density Curve for Fat Clay

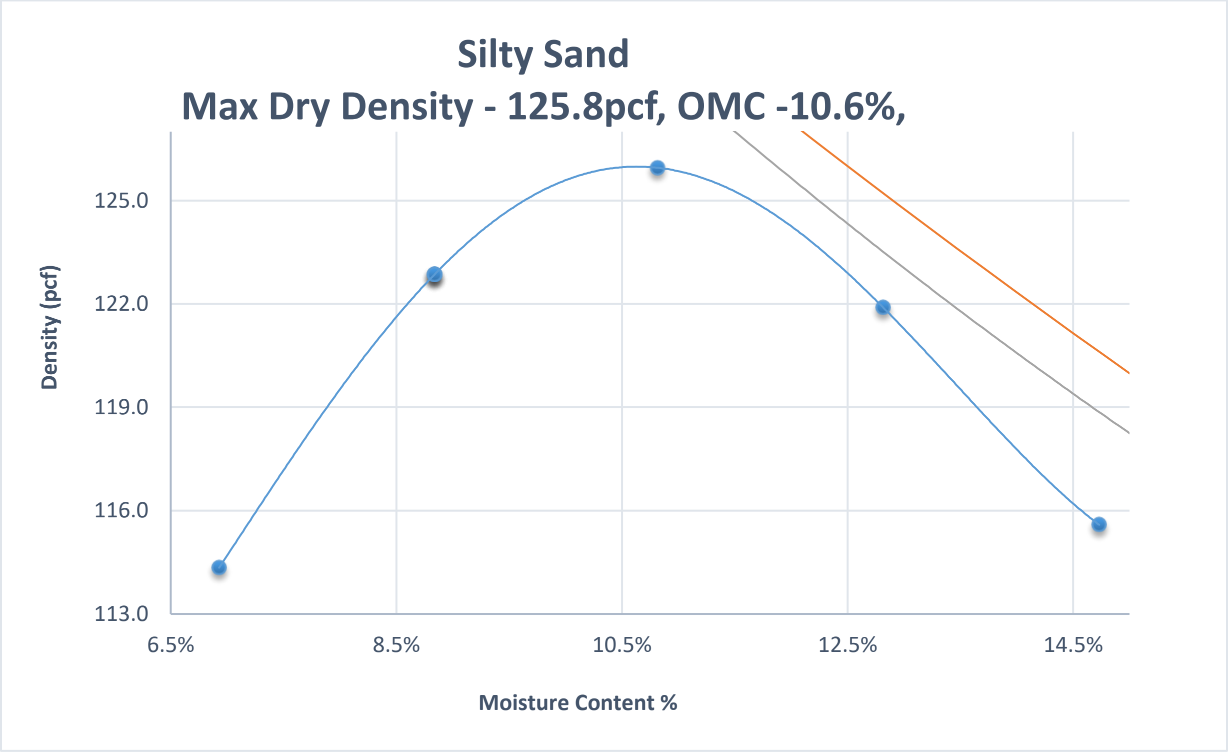

Figure 2: Moisture Density Curve for Silty Sand

1.1.3. Compaction Energy

Compaction energy is a prominent factor which affects the engineering properties of soil. The amount of compaction energy defines the degree of compaction required for engineering considerations. At higher moisture contents greater than the optimum, the use of higher compaction energy will have small or no effect on dry unit weights. Control of moisture content is necessary in governing the dry unit weight. Studies have been carried to determine the effect of compactive energy on soil properties.

The degree of compaction required on field varies with its purpose of compaction. When compacting for an Airfield construction, 100% of relative compaction is required based on standard AASHTO maximum dry unit weight. The degree of compaction for pavement construction varies from 90% to 95% (Basma, 1993). Attom (Attom, 1997) studied the effect of compactive energy on shear strength, permeability and swelling pressure of compacted cohesive soil. In his study, ten different compaction energies were applied for standard and modified proctor by varying the number of blows for each layer. Unconfined compression test, permeability and swell test were conducted to determine the effect of increasing compactive energy. Following were the test results on compactive energy

1. When the soil is compacted with increasing energies on the dry side of optimum there is significant increase on unconfined shear strength. With the increasing compaction energy on wet side of optimum there is there is low or no effect on unconfined shear strength.
2. There is decrease in permeability when the soil is compacted at any compaction level on the dry side of optimum and then increases on the wet side of optimum. It is found that permeability is lowest at optimum moisture content.

3. There is increase in swelling pressure with increasing compactive energy when the water content is below the optimum and remains unaffected when the water content is above optimum.

1.1.4. Methods of Compaction

Soil Compaction is a process of densification of soil, thereby increasing the bearing capacity and the expulsion of air voids. The mode and method of compaction in field greatly depends on the soil type and the degree of compaction to be achieved based on laboratory tests.

1.1.5. Laboratory Methods for Compaction

To determine the compaction characteristics of soil, two test methods are being practiced depending upon the compaction energy, type of soil and the compaction requirements necessary in the field. The test methods are commonly referenced as Standard Proctor and Modified Proctor Test. Table 3 gives the specifications for the above two tests described.

Table 3: Standard and Modified Proctor Test Method *(ASTM, 2007)(ASTM D1557, 2012)*

	Standard Proctor ASTM D 698, AASHTO T-99	Modified Proctor ASTM D 1557, AASHTO T-180
Diameter of mold (inches)	4	4
Height of mold (inches)	4.584	4.584
Volume of mold (ft^3)	0.033	0.033
Compaction Layers	3	5
Weight of Hammer (lb)	5.5	10
Height of Drop (inches)	12	18
Number of blows per layer	25	25
Compaction Energy (ft-lb/ft^3)	12,400	56,000

Table 4: ASTM Specifications for Determining the Size of Proctor Mold

ASTM Method	Mold Size (inches)	Sieve Size	Number of blows per layer	Specification
A	4	-No.4	25	≤ 5% by mass retained
B	4	-3/8 in.	25	≤ 5% by mass retained
C	6	-3/4 in.	56	≤ 30% by mass retained

Table 5: AASHTO Specification for Determining Size of Proctor Mold

AASHTO Method	Mold Size (inches)	Sieve Size	Number of blows per layer	Specification
A	4	-No.4	25	≤ 5% by mass retained
D	6	-3/4 in.	56	≤ 30% by mass retained

The suitability of compaction depends upon the desired engineering purpose and recommendation by engineers for using either Standard or Modified Proctor method. For use of any of the Proctor methods Table 4 and Table 5 gives general guidelines for determining the size of Proctor depending upon the soil composition.

1.1.6. Field Compaction Methods

Compaction of soil depends upon the compaction characteristic results determined in laboratory using standard or modified Proctor. During field compaction, the contractor/engineer decides the type of equipment required for compaction depending upon the lift thickness, compaction energy, soil type, required dry unit weight and moisture content, job site conditions and the ground water table.

Commonly used Compaction methods are Vibration, Impact, Kneading and pressure. Each method is carried out by either static or vibratory compaction machinery. Kneading and pressure is achieved by static forces which relies on the weight of the machine. Vibratory force makes use of mechanically driven force in addition to the machine weight for compaction. Vibratory force methods (Vibration and Impact) helps achieve compaction to the deeper layers as well. Some commonly used compaction machinery are described below.

1.1.6.1. Smooth Drum Rollers

They compact the soil by a method of static compaction. They consist of cylindrical drum of smooth surface which are propelled by one, two, or three drums. Factors like width and diameter of drum, axle load, and rolling speed help achieve the soil compaction (Caterpillar, 2000). These rollers fail to achieve desired compaction if the soil is too wet or the lift thickness of soil is high.

Figure 3: Smooth Drum Roller ("Smooth Drum Roller," n.d.)

1.1.6.2. Pneumatic Tired Rollers

They compact the soil in a manner of static and kneading action. The treads of the tire along with the tire pressure helps achieve compaction. Factors like tire pressure, surface area of wheel, and wheel load influence compaction. In a comparative study between pneumatic-tire rollers and sheepfoot roller, pneumatic tire rollers utilize less time and cost to compact the soil (Winterkorn & Fang, 1991).

Figure 4: Pneumatic Tired Roller

1.1.6.3. Sheepfoot, Padfoot, and Tamping Rollers

These rollers consist of a compacting foot that extend outwards from the drum and are either self-propelled or pulled by machinery equipment. The size of there is about 8 inches long with pad diameter from 3 to 5 inches (Caterpillar, 2000). These rollers achieve compaction by kneading action where the foots of the rollers will break the natural bonding of the particles achieves maximum density. With the number of passes, the roller feet initially will penetrate deep in the soil and with increasing passes the penetration decreases. High compaction is achieved with increasing number of passes and when the foot penetration is minimum. In a research study, these rollers produce uniform compaction with successive but also tends to produce some irregular surfaces from foot penetration with underlying layers of soil (Rodriguez & Sowers, 1988).

Tamping foot rollers consist of a dozer blade, four padded wheels and travel at high speeds compared to other rollers. They compact the soil by means of impact. pressure, vibration, and kneading. As these rollers compact the soil by all methods, they reduce the necessity requirement of the other rollers. However the utilization of these rollers will be based on size of the project, and economical considerations. If the soil is too wet, tamping foot roller are desired since they have less contact pressure due to smaller surface area of feet (Parsons, 1992). For compaction on cohesive and fine grained soils sheepsfoot roller are well suited but also sheepsfoot roller travel at low which affects the compaction of soil(Parsons, 1992).

Figure 5: Padfoot Roller

1.1.6.4. Vibratory Rollers

These rollers compact the soil by method of compaction. These rollers are similar to smooth drum rollers but in addition with vibration capacity. They consist of mounted weights inside the drum and with oscillating process vibration compaction is achieved. They are designed with high speeds and greater compaction energy to achieve compaction with minimum number of passes. They are generally used in the areas of cohesionless soils.

Figure 6: Vibratory Roller (“Vibratory Roller,” n.d.)

1.2. Engineering Properties of Compacted Soil

As discussed, compaction of soil decreases the number of air voids thus increasing the engineering properties like shear strength, shrinkage and swell potential, and permeability. It is observed that shear strength of soil is higher when compacted on dry side of optimum moisture content (Seed, Mitchell, & Chan, 1961). CBR value which is used to determine the load bearing capacity of soils yields and lower value with increasing moisture content (Yoder & Witczak, 1975). Clayey soil is most prone to swelling when it is compacted to wet side of optimum. Swelling of soil causes upward pressure and may lead to deterioration of structures.

Permeability of soil factor is of important concern to study the settlement of foundation or other structures. It is a measure of rate of flow of water through soil particles due to porosity. Gravel particles possess high permeability than clay particles which settle over time. However, the latter case is more dangerous in terms of settlement. For a silty clay, compaction on wet side of optimum will reduce the permeability than on dry side where it may be more porous (Lambe, 1958). Permeability coefficients depends upon the scope and purpose of the work/ structure the soil is being compacted for. It varies depending upon the work for which it is performed like dams, landfill liners, canal liners, site reclamation, foundations, and on subgrades. Some of the important factors affecting permeability are particle size, void ratio, degree of saturation, and structure of soil mass.

Frost is another characteristic of compacted soils and their compaction should be well attended which involve freezing temperatures. Frost susceptible soils can lead to swelling due to presence of ice termed as heaving and settlement of soil during thawing conditions. Both these conditions can lead to distortion in structures. Clayey soils hold more moisture and has better insulation than silt and sands and hence silty soils are more prone to frost susceptibility. To avoid the frost action, it is required to compact the soil at higher energies or to avoid the frost susceptible soils (Monahan, 1986).

1.3. Study on Compaction Curve and Types

Soils will have different physical properties depending upon the geology, geography and nature of origin and with application of compaction will cause the soil properties to react differently. The change in soil properties during compaction results in differing compaction curves. Many researchers have presented their ideas about compaction curves and their types. Ohio family of curves was set up for determination of Proctor characteristics through one-point proctor method. Ohio Family of curves was well suited and followed a specific pattern of curves with increasing compaction energy as the soil in that region has a similar geologic origin. (Hun Li et al., n.d.) during their study on family of compaction curves considered two types of curves, Type A and Type B. Type A being the curve that shifts towards left side on the plot of dry density and moisture content and Type B is the curve that moves upward and left with increasing compaction energy. They formulated equations for the family of compaction curves with varying energies of compaction which will ease in determination of one-point Proctor. In all scenarios, the knowledge of compaction curve was important which paved way for researchers to study more on the shape of the proctor curve and the factors controlling its shape. (Hilf, 1991) (Howell, Shackelford, Amer, & Stern, 1997) presented their ideas about curve fitting which utilized polynomial equations of second, third and fourth order. These curve fitting equations had some shortcomings as the regression parameters uses pure fitting curves, those equations are best suited for over a limited value of moisture content range. In some situations it happens that the predicted values may cross the zero air void curve. With the above short comings (Hun Li et al., n.d.) developed equations to determine compaction parameters for fine grained soils which can predict family of compaction curves. Their study described important parameters of the compaction curve which are explained in below. They considered the dry and wet conditions for defining the curve parameters.

1. Different regions of Compaction Curve

   The curve has been divided into three regions as dry region, transition region, and wet region. Compaction boundaries.

2. Boundary Conditions

   An important condition is the degree of Saturation (Sm) which is on the wet side of the curve and the maximum degree of saturation (Sm) is almost constant for fine grained soils (Hun Li et al., n.d.). Maximum degree of saturation is found on the wet side of the curve which runs parallel to the zero sir void curve (Hausmann, 1990). Degree of saturation is an important factor considered in this study for determination of moisture range specifications.

3. Compaction Curve Shape

   Generally, the shape of compaction curve is bell shaped and the shape is based on the physical properties and the type of compaction method used (Hausmann, 1990) . Poorly graded soil yield a flat curve and the well graded soils will generate a bell-shaped curve. Mathematical application on the shape of curve or expression to define the shape are still yet to proposed. The width between dry and wet region of the curve is the actual compactible moisture range.

Lee and Suedkamp (Lee & Suedkamp, 1972) studied the characteristics of irregularly shaped compaction curves of soils used for engineering practices must have a well-defined curve. Any irregularities in Proctor curves will result in incorrect maximum dry densities and optimum moisture content. They studied macroscopic and microscopic characteristics and behavior that causes irregularity in curves. Study of irregularity of curves was important aspect in this study as they contribute towards correlation of compaction curve shape and their index properties. It is found that soil mostly consists of silicate minerals which includes kaolinite, montmorillonite, illite, quartz, and feldspar (Horn & Deere, 1962). Lee and Suedkamp in their study of irregularity in shapes of curves did investigation on 35 different soil samples which they revealed the types of different peaks in the curve depending upon the mineral composition. They presented four types of compaction curves which were observed in our research on the soil samples tested. Type A (single peak-Figure 7), Type B (1-1/2 peak curve-Figure 8), Type C(double peak-Figure 9), Type D (oddly shaped-Figure 10). There results indicate that soils having liquid limit between 30 and 70 will yield Type A curve and soil below liquid limit 30 and above 70 showed irregularities in curve shape. The primary reason for irregularity in shape of the curves is based on the mineral composition. Montmorillonite (three layered silicate) with major composition of sand may yield 1-1/2 peak curve and kaolinite (two layered silicate) with sand yield double peak curves. When working on compaction of cohesive soils it is important to allow a clay prep or wetting period after adding moisture as cohesive soils absorb moisture over time. A wetting period of twelve (12) hours is recommended by as per ASTM procedures. Wetting period allows water to distribute evenly over the sample which will yield a proper compaction curve.

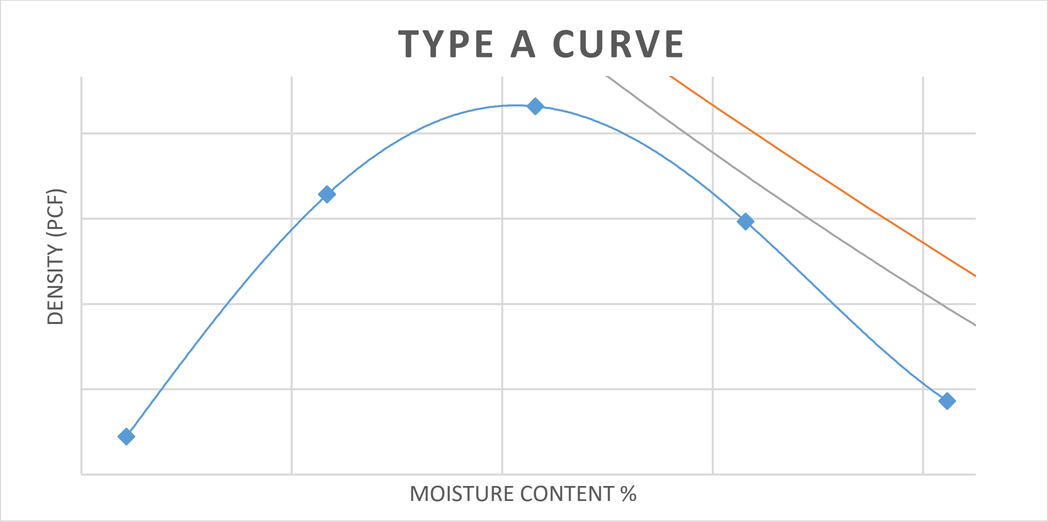

Figure 7: Single Peak Curve Type A

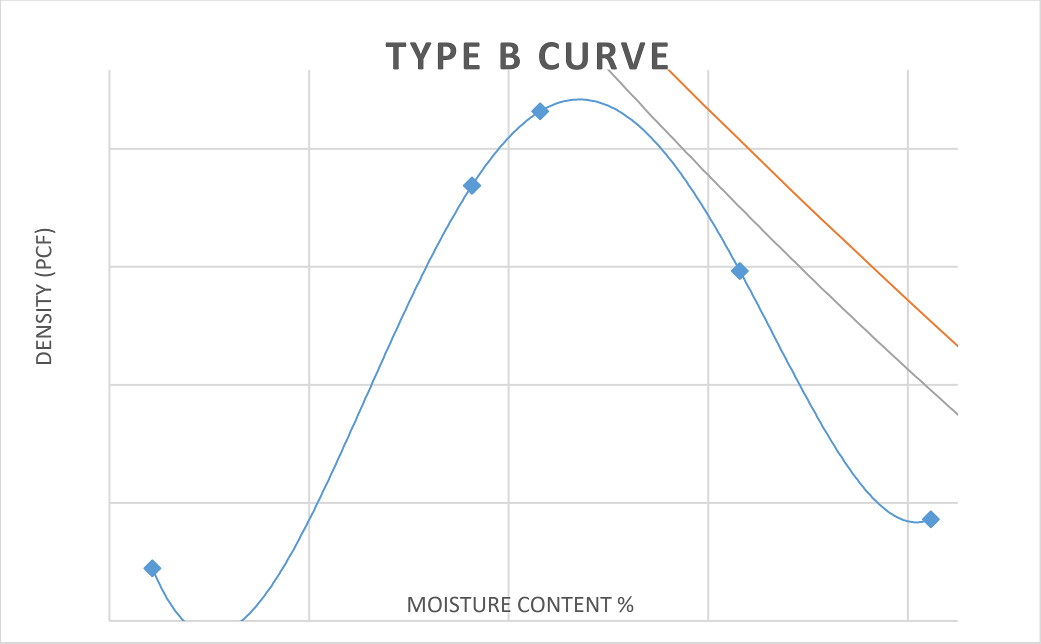

Figure 8: One and Half Peak Curve Type B

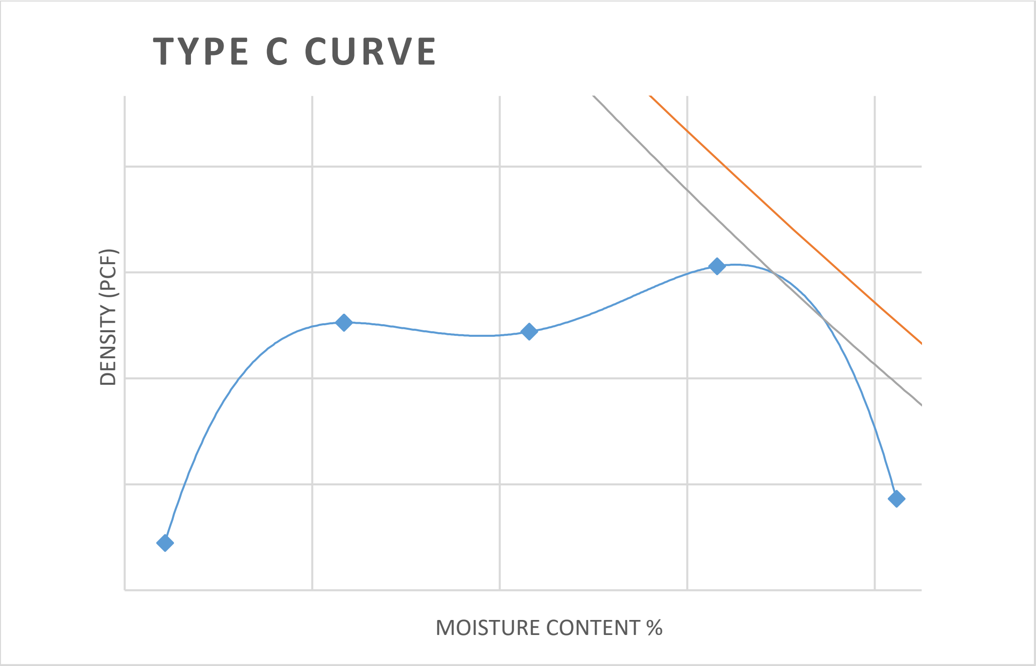

Figure 9: Double Peak Curve Type C

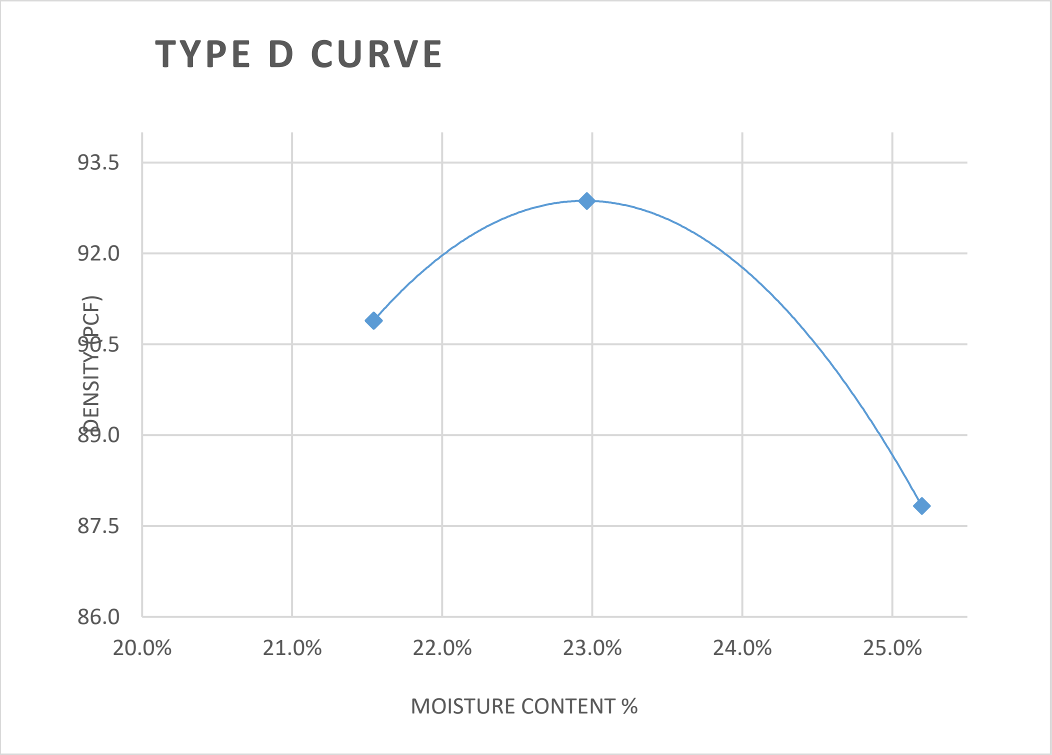

Figure 10: Oddly Shaped Curve Type D

1.4. Research Organization and Objectives

Research studies makes one think critical about a subject and to predict outcomes with validation theory for its implementation in respective sector. Research studies are always focused in a way of contributing knowledge in the world of knowledgeable. With a sense of possible outcomes to make an ease in engineering application particularly geotechnical engineering, my research study focused on imparting knowledge in the field of geotechnical engineering. This research study/thesis contained multiple aspects which included development of empirical models for prediction of compaction parameters, and to check the specification for compaction moisture range set by NDDOT to provide with recommendations on their specification. This study was organized with the following tasks:

- **Task 1** – Background of soil compaction, its importance in the field of engineering
- **Task 2** – Study on factors affecting soil compaction, major engineering soil types, and laboratory test procedures for compaction.
- **Task 3** - Study on field compaction methods describing some of the general equipment's used during field compaction.
- **Task 4** – Study on compaction curve and shape.
- **Task 5** – Research Objectives, Literature review, and analysis of results
- **Task 6** - Conclusions

1.5. Research Objectives

1. To develop empirical equations between compaction parameters and index properties of soil to provide prediction parameters for maximum dry density, optimum moisture content, and maximum saturation line (Sm) for T-99 and T-180 Proctor types.

2. Study the specifications set by NDDOT on compaction moisture range with their respective test types T-99 and T-180 and perform analysis on the moisture range to provide recommendations on their current specifications.

3. Methods to determine the limiting moisture range when compacting with an increased density with saturation peak concept.

CHAPTER 2: PREDICTION OF COMPACTION PARAMETERS

2.1. Problem Statement

To develop empirical equations between compaction parameters and Atterberg limits for providing prediction parameters for maximum dry density and optimum moisture content for T-99 and T-180 Proctor types.

2.2. Literature Review

Determination of compaction characteristics of soil is very important to achieve the desired strength and suitability of material. For a civil engineer, it is necessary to know the compaction characteristics when compacting the soil in field. The civil engineer/contractor relies on the data provided from the lab report for compaction of soil in field. There are certain situations when the fill material to be compacted is from different borrow sources. In such scenarios, it becomes necessary to obtain compaction characteristics from lab tests for such type of soil. Since laboratory tests are time consuming process, it is desirable to make use of correlations with Atterberg limits in predicting compaction characteristics which may be used as a tool for preliminary assessment (Nagaraj, Reesha, Sravan, & Suresh, 2015)

Many studies have been carried out for to develop empirical relationship between maximum dry density and optimum moisture content with physical properties of soil. One of the first attempts was made by (Jumikis, 1958) where he developed a correlation between optimum moisture content with liquid limit and plastic limit.

(Di Matteo, Bigotti, & Ricco, 2009) Conducted a research study on prediction of compaction characteristics with physical and index properties of soil of fine-grained and clayey soils. Around 30 soil samples were collected from various parts of central Italy. Compaction characteristics were determined with standard proctor test and basic physical and index properties were determined. Multiple regression analysis were performed to determine the prediction of compaction parameters. Following were the equations of their study -

$$OMC_p = -0.86\,LL + 3.04(LL/G_S\,) + 2.2 \tag{1}$$

$$MDD_p = \left(\left(40.316.\,OMC_p^{-0.295}\right).\,PI^{0.032}\right) - 2.4 \tag{2}$$

But, the above equations were valid only under the following conditions

- $7 \leq OMC \leq 23\%$
- $15 \leq MDD \leq 22$ kN/m^3
- $18 \leq LL \leq 82\%$
- $1 \leq PI \leq 51\%$
- $2.47 \leq G_s \leq 3.09$

(Sridharan & Nagaraj, 2005) in their study on compaction characteristics of fine grained soils showed that plastic limit bears a good correlation with compaction characteristics. There methodology included collection of 10 soil samples and determination of their properties with standard test methods. There results show that plastic limit correlates well with optimum moisture content and maximum dry density depending upon the data set collected and the data from other literature review.

Following were there resulting equations –

$$OMC = 0.92w_p \tag{3}$$

$R^2 = 0.99$

$$\gamma_{dmax} = 0.23(93.3 - w_p) \tag{4}$$

$R^2=0.93$

A similar study by (Saikia, Baruah, Das, & Jyoti, 2017) on prediction of compaction characteristics was carried out by collecting 40 fine grained samples collected from different parts of Assam (India). Standard tests were carried out for determination of physical and index properties of soil sample. There results and analysis shows good correlation of compaction characteristics with liquid limit.

$$\gamma_{dmax} = 20.97 - 0.127LL \tag{5}$$

$R^2 = 0.90$

$$OMC = 0.42LL + 7.104 \tag{6}$$

$R^2 = 0.85$

As predicting compaction characteristics only on liquid or plastic limit might have some potential drawbacks, they also developed a regression model based on both the consistency limits. A multivariable linear regression tool was developed with the following equations.

$$\gamma_{dmax} = 21.07 - 0.119LL - 0.02PL \tag{7}$$

$R^2 = 0.90$

$$OMC = 0.35LL + 0.163PL + 6.26 \tag{8}$$

$R^2 = 0.86$

Their results convincingly showed good correlation but are valid only for standard proctor energy levels and for the range of consistency limits observed in their study. (Hammond, 1980) developed empirical relations between physical properties of soil with maximum dry density and optimum moisture content. He developed the relationship for soil types – clayey and sandy gravel, clayey silty sand where the plasticity index was above A line on classification chart, and silt clays prone to swelling. Below equations give empirical equations developed by Hammond for optimum moisture content.

$$OMC = 0.42\ PL + 5\ (Clayey\ and\ Sandy\ gravel) \tag{9}$$

$$OMC = 0.45\ PL + 3.58\ (clayey\ silty\ sand) \tag{10}$$

$$OMC = 0.96\ PL - 7.7\ (silty\ clay) \tag{11}$$

Another research carried out by (Benbouras, Kettab, Zedira, Petrisor, & Debiche, 2017) on relation of dry density with other geotechnical properties revealed that there were average or ineffective correlations between dry density and other geotechnical parameters. There sample size was around 700 of soil samples of Algerian clay. For prediction of compaction characteristics some of the researchers confined there study for the soils which have fractions less than 425 µm.(Gurtug & Sridharan, 2002) in there study made use of natural soils having fractions less than 425 µm with more than 98% by weight of soils and there were few studies that made use of natural soils having soil fractions of all sizes.

In addition to linear models for prediction factor, Hyperbolic models were also used in determining the dependent variable in relation with independent variable. Hyperbolic relationships were used to study the shear thinning behavior of the bentonite drilling mud in consideration with in presence and absence of polymer (Vipulanandan & Mohammed, 2014). Their study concluded that hyperbolic models were effective in defining relationships between bentonite and polymer than Herschel-Bulkley and Casson models by means of R squared and root mean square of error (RMSE). (Mohammed, 2017) aimed to focus there study in developing correlations between physical and mechanical properties of clays with high plasticity and Nonlinear correlation were developed between undrained shear strength (S_u) and compression index (C_c) and index properties of soil. Table 6 gives a summary of empirical equations studied as a background knowledge to perform analysis on current data.

Table 6: List of Empirical Equations for Predicting Maximum Dry Density and Optimum Moisture Content Developed by Previous Researchers

Soil Type	Empirical Equations
Fine grained and clayey soils	$OMC_p = -0.86\,LL + 3.04(LL/G_S\,) + 2.2$ $MDD_p = \left((40.316.\,OMC_p^{-0.295}).\,PI^{0.032}\right) - 2.4$
Fine grained	$OMC = 0.92w_p$ $\gamma_{dmax} = 0.23(93.3 - w_p)$
Fine grained	$\gamma_{dmax} = 20.97 - 0.127LL$ $OMC = 0.42LL + 7.104$
Fine grained	$\gamma_{dmax} = 21.07 - 0.119LL - 0.02PL$ $OMC = 0.35LL + 0.163PL + 6.26$
Clayey and Sandy gravel	$OMC = 0.42\,PL + 5$
Clay with Silt and Sand	$OMC = 0.45\,PL + 3.58$

2.3. Situation Where Above Problem Finds Application

As discussed, empirical equations for predicting maximum dry density and optimum moisture content can be utilized in situations where time and cost are important factors. Installation of pipes and culverts during roadway construction are specific scenarios where the empirical methodology can be applied. Pipes and culverts are installed to allow flow of water or discharge under the roadways or from other similar constructions. Their design and installation is based on the discharge capacity and the allowable discharge through them. Proper trenching, soil stability on which the pipes are resting, and the stability and compaction of soil at the point where the pipe length extends from the width of the roadway are some of the installation considerations for piping and culverts. Proper backfilling is done for the pipe length that extends from the roadway width. The process of backfilling involves placing of the borrow material (normally clay with rock gravel) across the extended length of discharge pipe in desired lifts on both sides and up to a height of required stability. When backfilling the pipe work, it is necessary to have the compaction characteristics of the soil sample being placed at the location for the crew working out there. Sometimes it so happens that the borrow material may be from different sources with no compaction characteristics available. In such situations delays in the work are expected where the compaction crew has to wait till the compaction characteristics of the materials available. Such situations were observed at the construction of Highway 1804 Phase II, Williston District, North Dakota as captured in Figure 11 and Figure 12. The empirical equations for predicting compaction characteristics can also be made use of for small works where economic considerations are considered.

Figure 11: Pipe Work at HWY 1804, North Dakota

Figure 12: Pipe Work and backfilling at HWY 1804, North Dakota

Various laboratory tests in geotechnical engineering require compaction parameters to get started with the tests. California Bearing Ratio is a test carried out to determine the mechanical strength of subgrade or base material to ensure proper load carrying capacity without failure. The test is dependent upon the maximum dry density and optimum moisture content of soil to check for penetration and CBR value.

Soil Cement stabilization is a technique carried on various sites to improve the subgrade load carrying capacity by site reclaiming procedure. In North Dakota most of the oil well pads after the process of hydraulic fracking and crud extraction perform soil cement stabilization on the sites. The process is carried by mixing the soil with percentage of cement content that yields highest psi with varying moisture contents.

Soil Resistivity test is carried out to check the electrical resistance of soil in areas where underground electrical utilities are being laid. Soil resistivity is measured is Ohms-meter or Ohms-centimeter. Higher the resistivity, lower the electrical conductivity and will cause no deterioration of pipes underground. Soil resistivity is measured in in-situ condition and in saturated condition by varying the moisture content of soil. The above are a few tests in geotechnical engineering where there is need of compaction parameters to determine the outcome of the results.

2.4. Methodology

Based on the previous research studies and literature review, an experimental study was set up to perform analysis in developing empirical equations for prediction of compaction characteristics for soils of North Dakota. For this study, a large data set pertaining to soil engineering properties and standard tests was collected from NDDOT Materials and Research Center, Bismarck, North Dakota. The data consisted of results of material testing carried on all the State and Highway projects of North Dakota. Data set consisted of various projects over years, soil type and classification as per AASHTO class, Atterberg test results, and laboratory compaction characteristics test results as shown in Table 7 and Table 8. For ease of interpretation, NDDOT has divided the State into eight (8) regions shown in Figure 13 so that each project can be named to the respective region. Current research Data set consisted of 45% of projects from region 3, 40% of projects from region 8 and remaining 15% of data consisted from various regions. However, the research aimed to concentrate on AASHTO class A-7-6 of soil type and its properties.

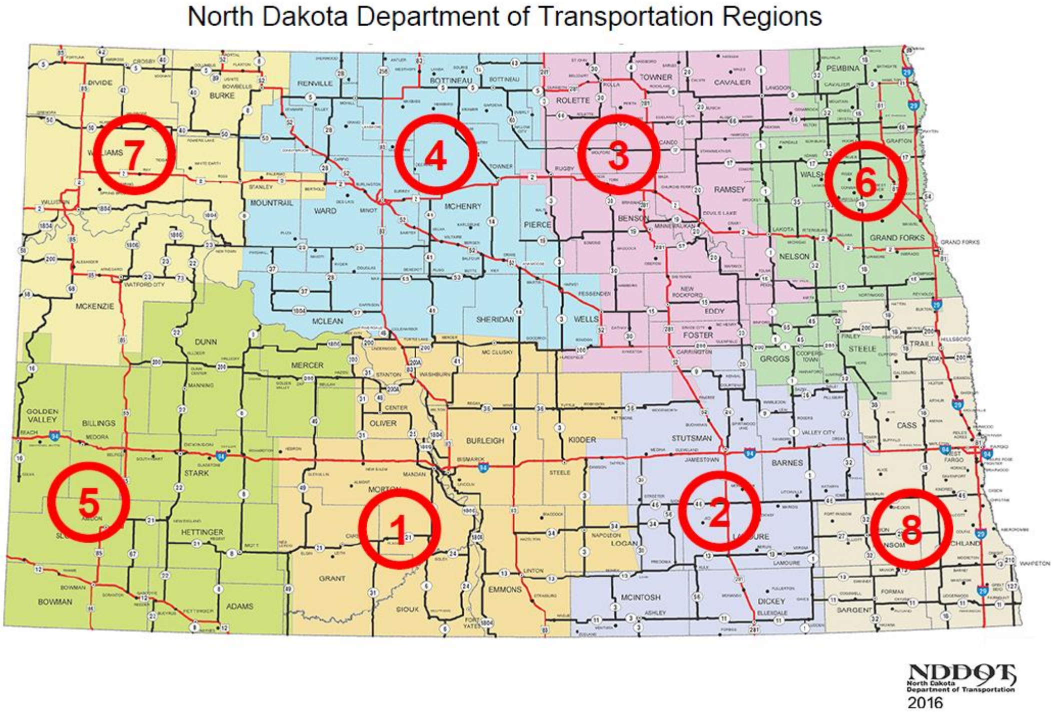

Figure 13: NDDOT State Regions

The next task involved filtering the data as per the needs of the objective of research. The data set was filtered depending upon the test and soil type. This study concentrated on soil type A-7-6 AASHTO classification. A-7-6 soil type are those where the liquid limit of soil is above 41% and plasticity index is above 11%. Most of the soil in North Dakota are of clay origin and also the soil type used for backfilling pipes are usually the borrow material of clay type soils. After sorting and selecting data for this study, the later task involved was to perform statistical analysis. R software was made use of to fit the second order polynomial and taking their first derivative to determine the Maximum Dry Density and Optimum Moisture Content. Statistical Analysis Software (SAS) was made use of to perform regression analysis in developing empirical relationships for predicting compaction characteristics with Atterberg limits for soils of North Dakota region. Simple Linear Regression was performed for each test type T-99 and T-

180 for predicting Maximum Dry Density and Optimum Moisture Content by having Atterberg limits as independent variables. The prediction compaction characteristics were each analyzed separately for each separate Atterberg Limit. Upon analyzing and studying, the predicted outcome was judged based on the regression R sq. values for each test and Atterberg type.

Table 7: Data Set

ProjectNo	LabNo	LL401	PI401	PlasLim1	TextClass1	AASHTO1	GroupNo1	OptMoist1	MaxDryDen1
NH-3-281(118)190	1471	31	9.1	22.1	CLY LM	A-4(5)	5	15.7	109.5
NH-3-281(118)190	1472	67	35.2	31.8	SLTY CLY LM	A-7-5(33)	33	18.8	103.4
NH-3-281(118)190	1478	39	8.6	30.7	SLTY LM	A-4(8)	8	16.6	108.5
SS-8-018(080)075	420	44	18.1	26.1	CLY	A-7-6(18)	18	21.3	97.9
SS-8-018(080)075	432	46	19.1	26.9	SLTY CLY	A-7-6(22)	22	22.6	97.4
NH-3-281(130)148	951	39	16.5	22.0	CLY LM	A-6(8)	8	13.2	114.9
NH-3-281(130)148	953	43	17.5	25.7	CLY LM	A-7-6(12)	12	15.5	109.9
NH-3-281(130)148	956	41	19.1	22.1	CLY LM	A-7-6(10)	10	13.5	116.6
NH-3-281(130)148	958	44	20.6	23.3	CLY LM	A-7-6(14)	14	15.5	112.4
NH-3-281(130)148	960	44	23.1	21.1	CLY	A-7-6(14)	14	15.2	110.8
NH-3-281(130)148	961	46	21.8	24.0	CLY	A-7-6(15)	15	15.8	112.5

Table 8: Data Set

ProjectNo	Dry Density 1	Dry Density 2	Dry Density 3	Dry Density 4	%Moisture 2	%Moisture 3	%Moisture 4	%Moisture 5	ND Test Type
NH-3-281(118)190	103	106.3	110.1	109.9	13.1	14.9	17	18.9	T-180
NH-3-281(118)190	96.7	100.1	102.4	104.4	14.8	17.5	19.4	22.2	T-180
NH-3-281(118)190	100.9	104.4	108.8	108.8	13.8	15.6	17.6	19.7	T-180
SS-8-018(080)075	92.4	94.4	96.8	98.2	17	18.9	20.5	24.5	T-99
SS-8-018(080)075	92.3	95.3	96.9	97.7	19.7	21.7	23.7	25.9	T-99
NH-3-281(130)148	107.9	112.2	114.8	114.6	10.7	12.7	14.7	17	T-180
NH-3-281(130)148	102.6	106.2	109.1	110.4	12.1	13.9	15.9	18.3	T-180
NH-3-281(130)148	110.7	114.7	116.5	116.1	11.5	13.4	15	17.2	T-180
NH-3-281(130)148	105.2	109.5	112	111.3	12.6	14.5	16.6	18.6	T-180
NH-3-281(130)148	105	108.6	110.3	110.6	12.2	14.2	16.2	18.3	T-180
NH-3-281(130)148	105.1	110.1	111.9	110.6	13.1	14.9	17.3	19.1	T-180

2.5. Results

Simple linear regression was performed on the data set using Statistical Analysis Software for predicting the Optimum Moisture Content and Maximum Dry Density. To better understand the variation with test types, the T-99 and T-180 test results were combined in one analysis for each single Atterberg parameters.

Figure 14 represents the regression model analysis for predicting optimum moisture content given the liquid limit for T-99 and T-180 Proctor test. The data set consisted of 70 observations for T-99 and 91 observations for T-180. Table 9 lists the output result for predicting Optimum Moisture Content with Liquid limit. As observed very little correlation was observed with coefficient of determination of 0.28 for T-99 and 0.24 for T-180.

Figure 15 represents comparison of regression models in predicting Optimum Moisture Content given the Plastic Limit. Parameter estimates for Optimum moisture content given the liquid limit are tabulated in Table 10. A better comparison is obtained with coefficient of determination of 0.33 for T-99 and 0.62 for T-180 Proctor types.

Figure 16 and Table 11 represents the variation of Optimum Moisture Content with Plasticity Index. Plasticity index shows very low correlation with optimum Moisture content and the observed R square values are 0.17 for T-99 and 0.05 for T-180.

Figure 17 and Table 12 shows the comparison of predicting Maximum Dry Density with Liquid limit. Liquid limit shows very little relation with Maximum Dry Density. The coefficient of determination observed was 0.22 for T-99 and 0.15 for T-180.

Figure 18 and Table 13 represents the SAS analysis of Maximum Dry Density with Plastic Limit. A good relation is observed with Plastic Limit with R square values of 0.16 for T-

99 and 0.69 for T-180 proctor Curves. On the other hand, no significance relation is observed between Maximum Dry Density and Plasticity Index.

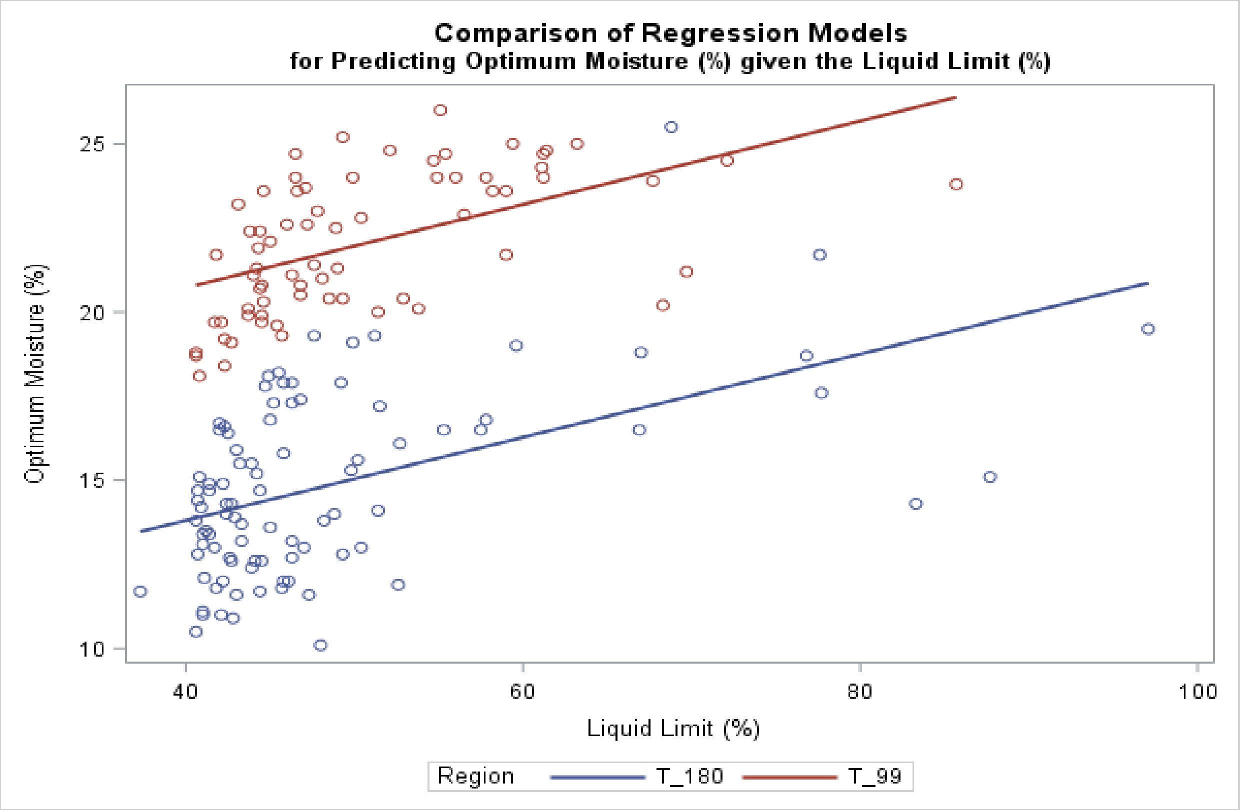

Figure 14: Comparison of Regression Models of OMC with Liquid Limit

Table 9: Parameter Estimates of Optimum Moisture with Liquid Limit

Test Type	T-99	T-180
No. Of Observations	70	91
R-Sq	0.28	0.24
Parameter Estimate	15.77 + 0.123LL	8.862+0.123LL

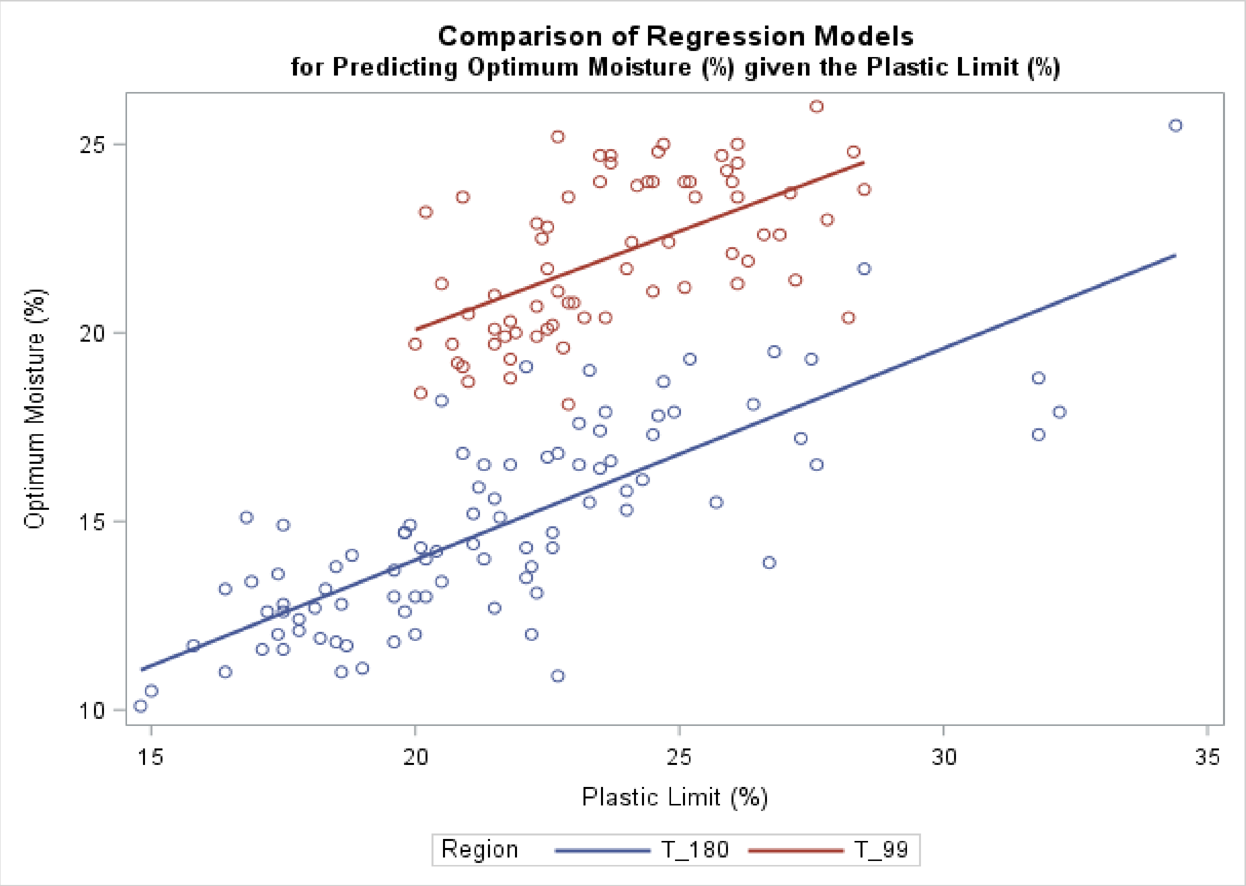

Figure 15: Comparison of Regression Models of OMC with Plastic Limit

Table 10: Parameter Estimates of Optimum Moisture with Plastic Limit

Test Type	T-99	T-180
No. Of Observations	70	91
R-Sq	0.33	0.62
Parameter Estimate	9.621 + 0.523PL	2.74 + 0.56 PL

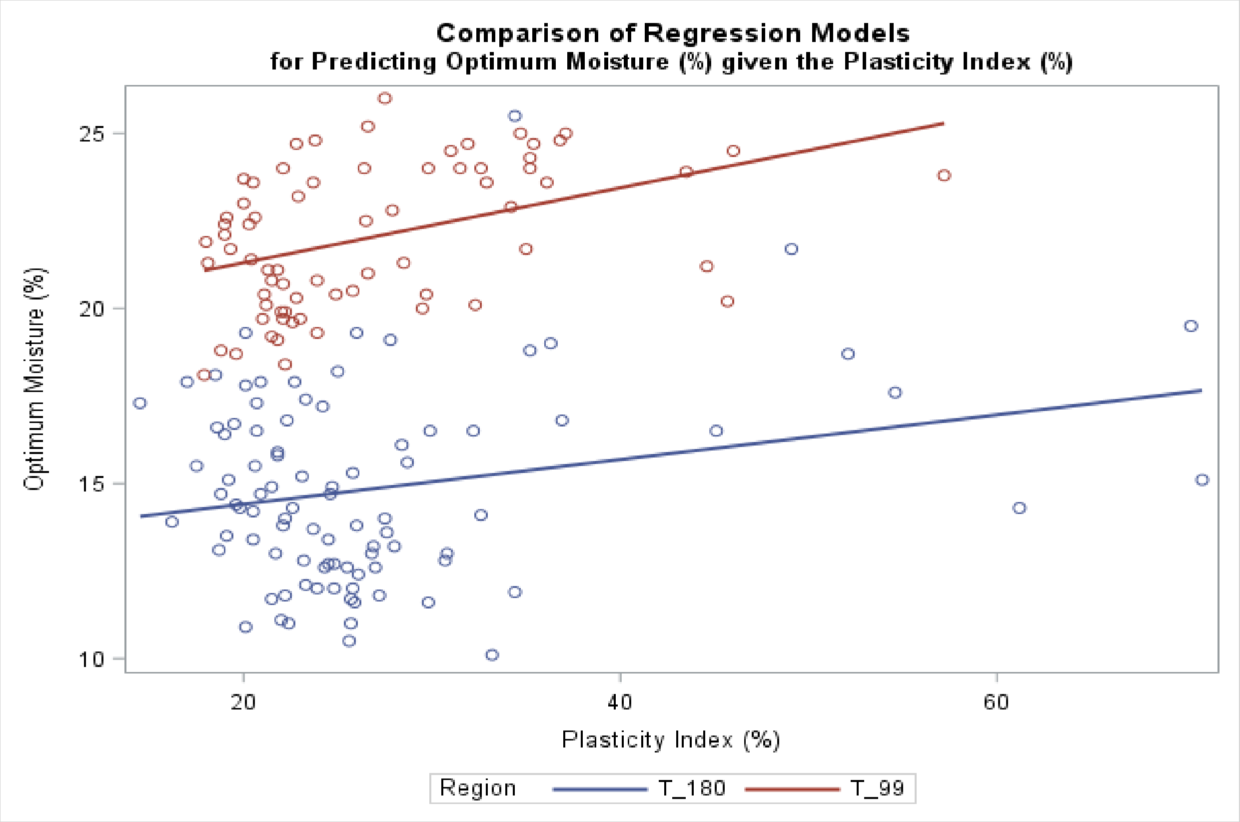

Figure 16: Comparison of Optimum Moisture with Plasticity Index

Table 11: Parameter Estimates of Optimum Moisture with Plasticity Index

Test Type	T-99	T-180
No. Of Observations	70	91
R-Sq	0.17	.05
Parameter Estimate	19.16 + 0.10PI	13.13 + 0.06 PI

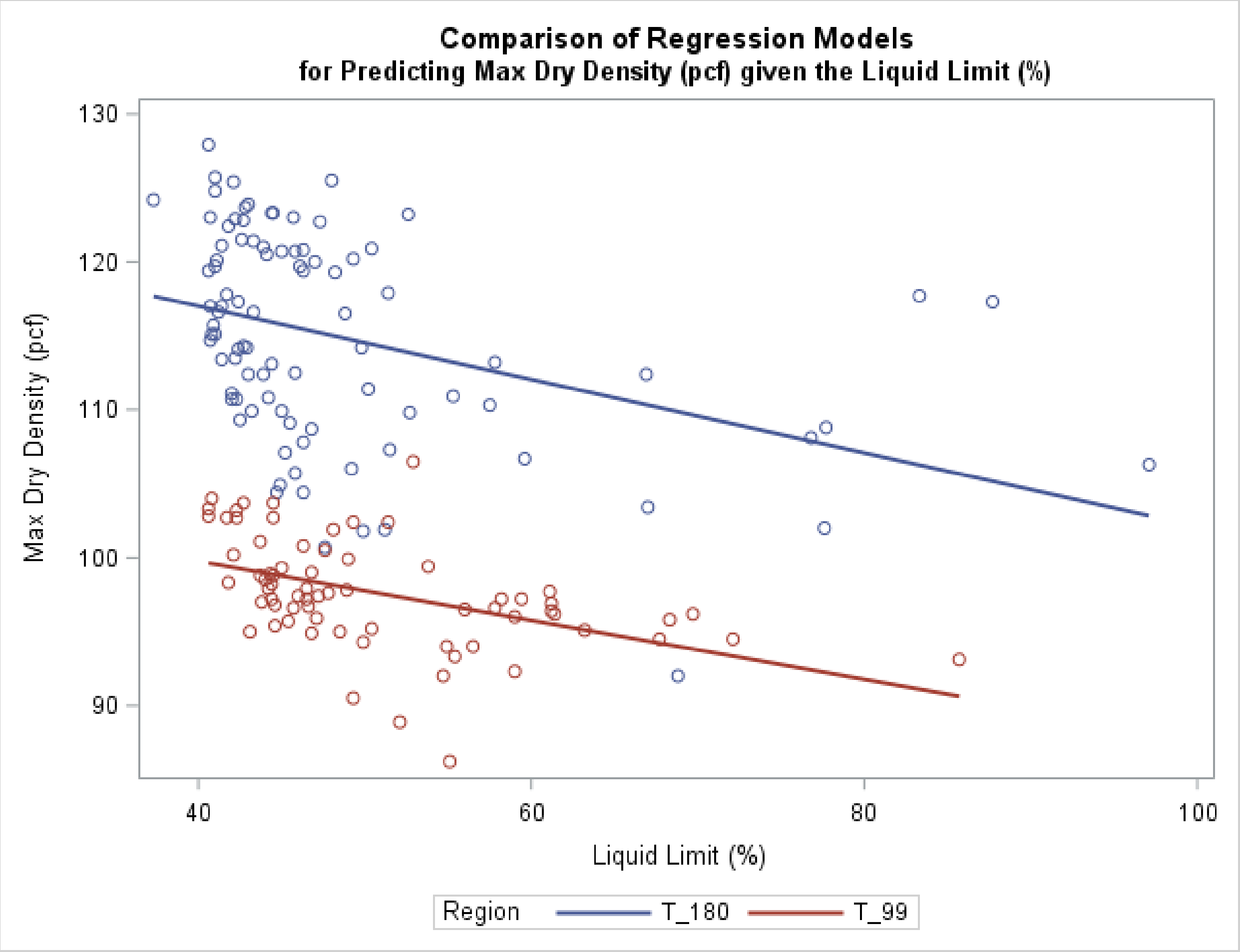

Figure 17: Comparison of Max Dry Density with Liquid Limit

Table 12: Parameter Estimates of Maximum Dry Density with Liquid Limit

Test Type	T-99	T-180
No. Of Observations	70	91
R-Sq	0.22	0.15
Parameter Estimate	107.73 – 0.199LL	126.93 – 0.24LL

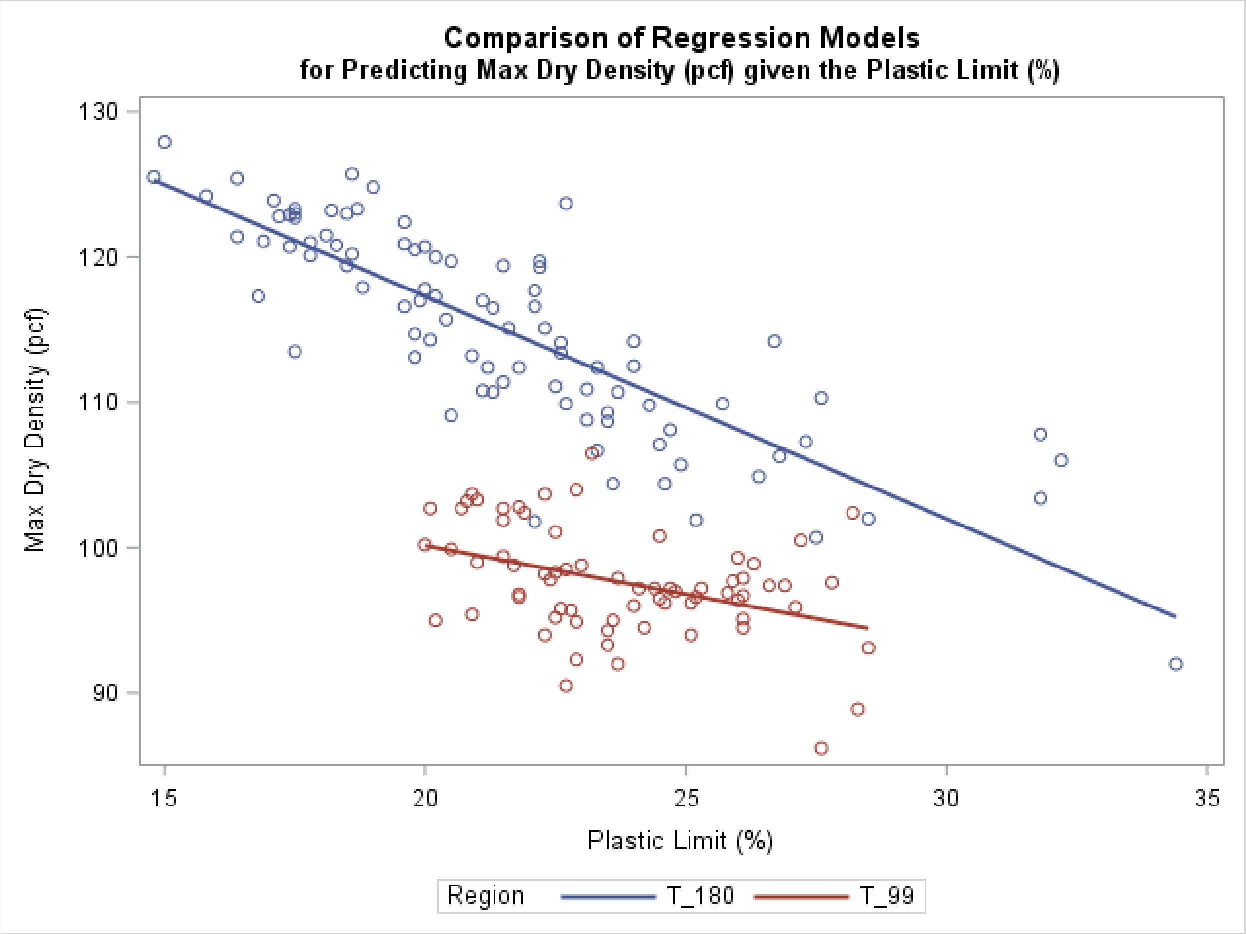

Figure 18: Comparison of Maximum Dry Density with Plastic Limit

Table 13: Parameter Estimates Of Maximum Dry Density with Plastic Limit

Test Type	T-99	T-180
No. Of Observations	70	91
R-Sq	0.16	0.69
Parameter Estimate	113.51 – 0.66 PL	147.95 – 1.53 PL

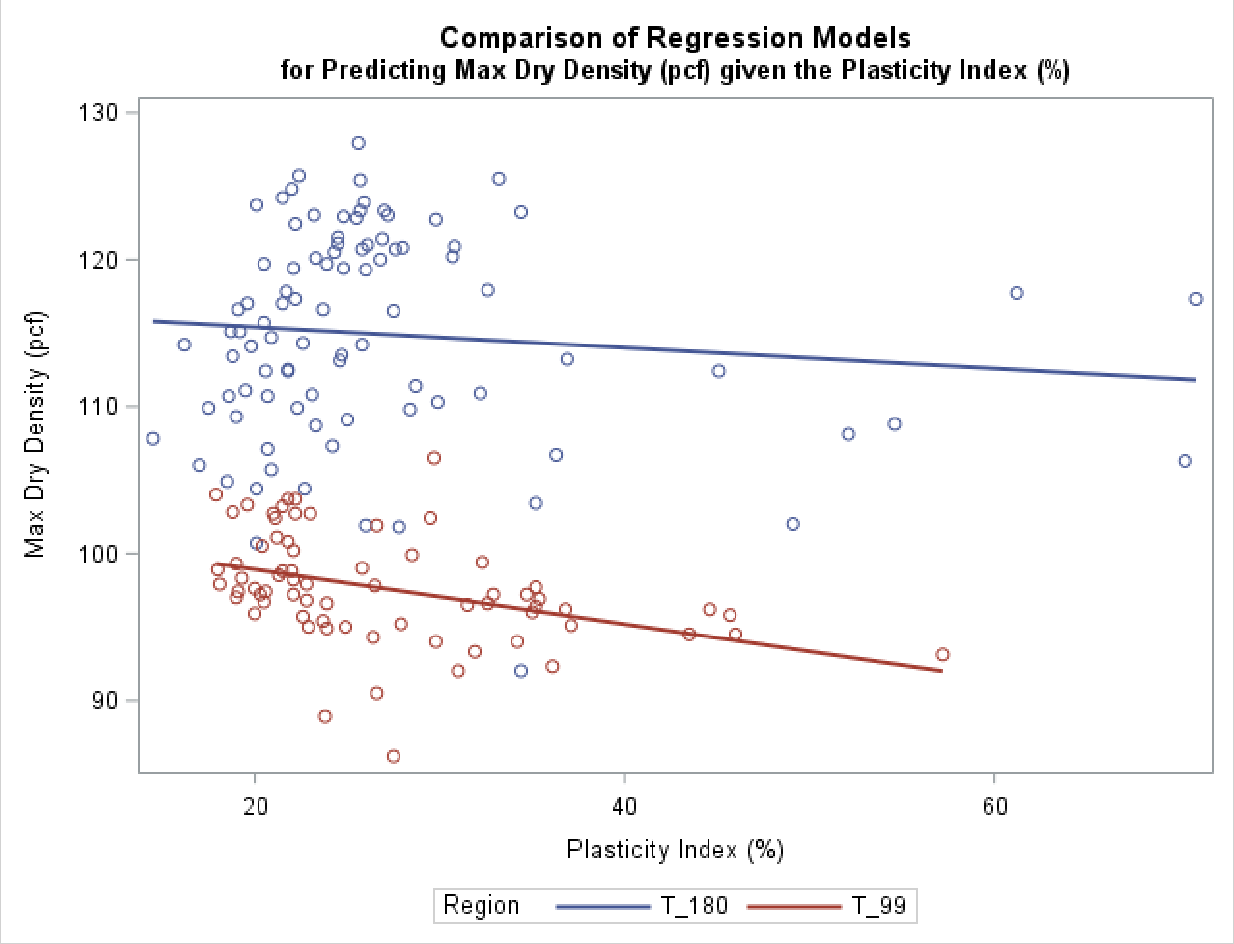

Figure 19: Comparison of Maximum Dry Density with Plasticity Index

Table 14: Parameter Estimates Of Max Dry Density with Plasticity Index

Test Type	T-99	T-180
No. Of Observations	70	91
R-Sq	0.16	0.01
Parameter Estimate	102.63 – 0.18PI	116.82– 0.07PI

2.6. Maximum Degree of Saturation (S_m) and Relation with Atterberg Properties

Compaction curve is governed by limiting boundary conditions having dry and wet side as there limiting region. Degree of Saturation is a parameter that defines the wet side of the compaction curve. When $S_m = 1$ it defines 100 % degree of saturation where the compaction curve gets in contact with zero Air void line which is practically impossible to have zero voids. With the change in S_m values the compaction curve shifts vertically and S_m values follow a similar range for a particular type of soil (Hua Li & Sego, 2000). Compaction in the field is done with a wide range of moisture specifications. But in reality, when targeting the moisture on wet side one can only compact until the soil reaches a maximum degree of saturation then by limiting the moisture range on wet side.

Li and Siego developed an approach to determine the degree and saturation with limiting boundary condition with different parameters like Saturation (S_m), shape factor (n) describing as n increases the curve becomes narrower and as the curve flattens as n decreases, width factor (p) that determines the upper width of the curve and called as compactible moisture range. Parameter (w_m) used to indicate dry condition of compaction curve. Figure 20, Figure 21, and Figure 22 were taken from Li's study on compaction curve and its approach to degree of saturation that is being utilized in this study to determine the limiting moisture range for specified. The degree of saturation equation is described later in this study.

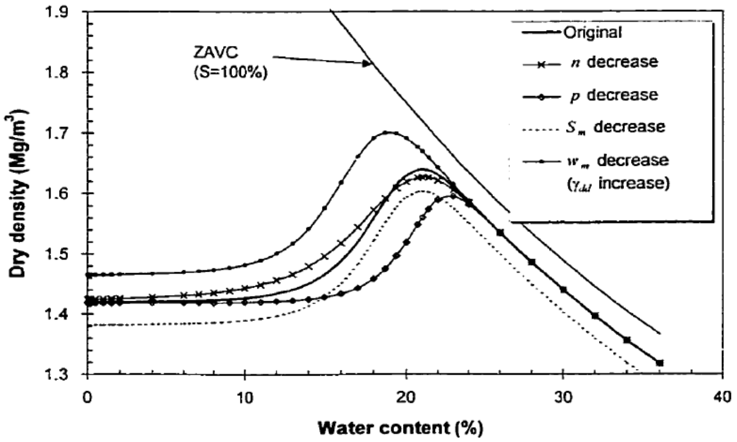

Figure 20: Parameter n, p, S_m, W_m on Compaction Curve (Hua Li & Sego, 2000)

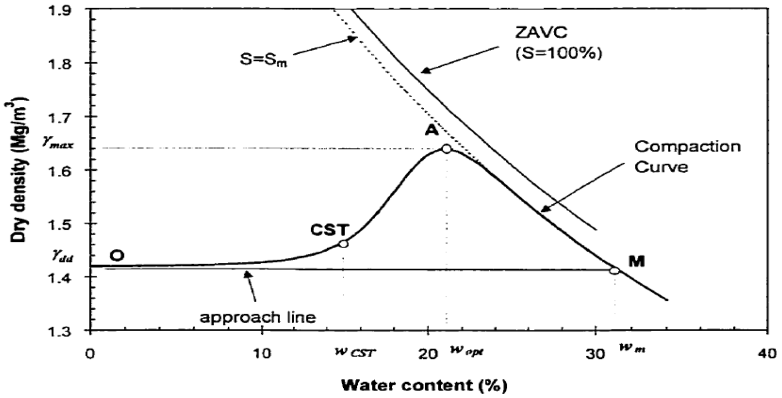

Figure 21: Complete Compaction Curve (Hua Li & Sego, 2000)

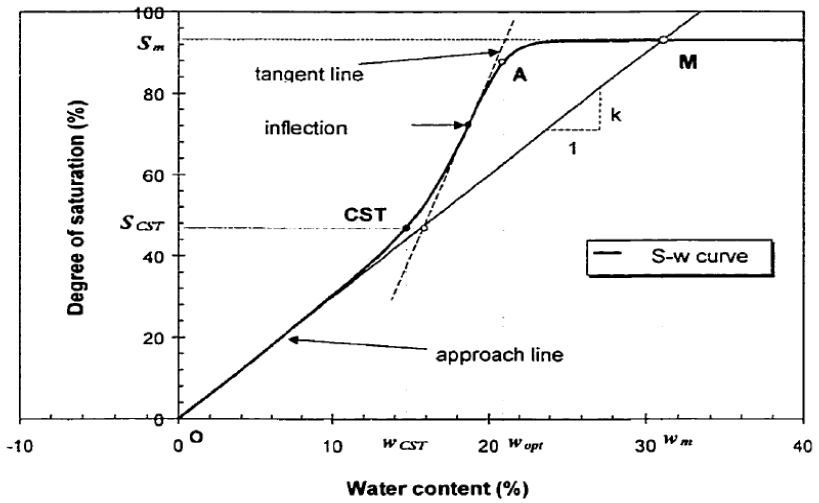

Figure 22: Degree of Saturation versus Water Content (Hua Li & Sego, 2000)

In Chapter 3 analysis have been made on current moisture specifications of NDDOT and their actual limiting moisture range by the concepts of Li in determining the S_m values. With the analyzed S_m values from Chapter 3 simple linear regression was performed on maximum degree of saturation with Atterberg Limits.

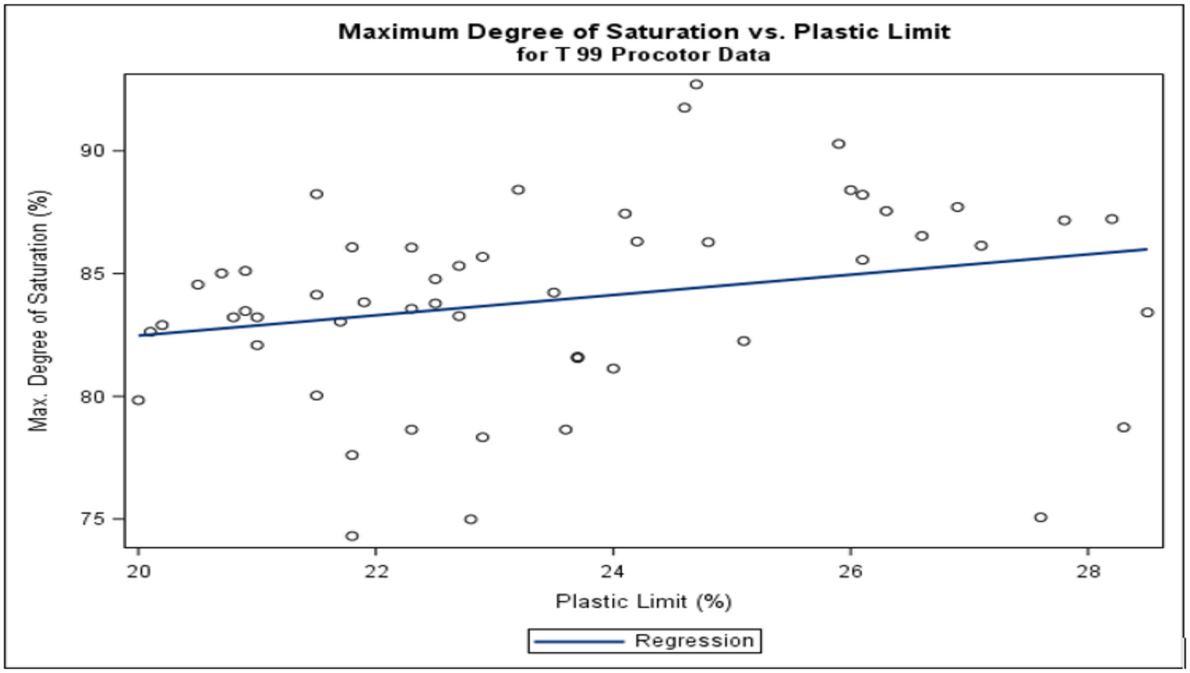

Figure 23: Relation of S_m with Plastic Limit for T 99 Proctor Data

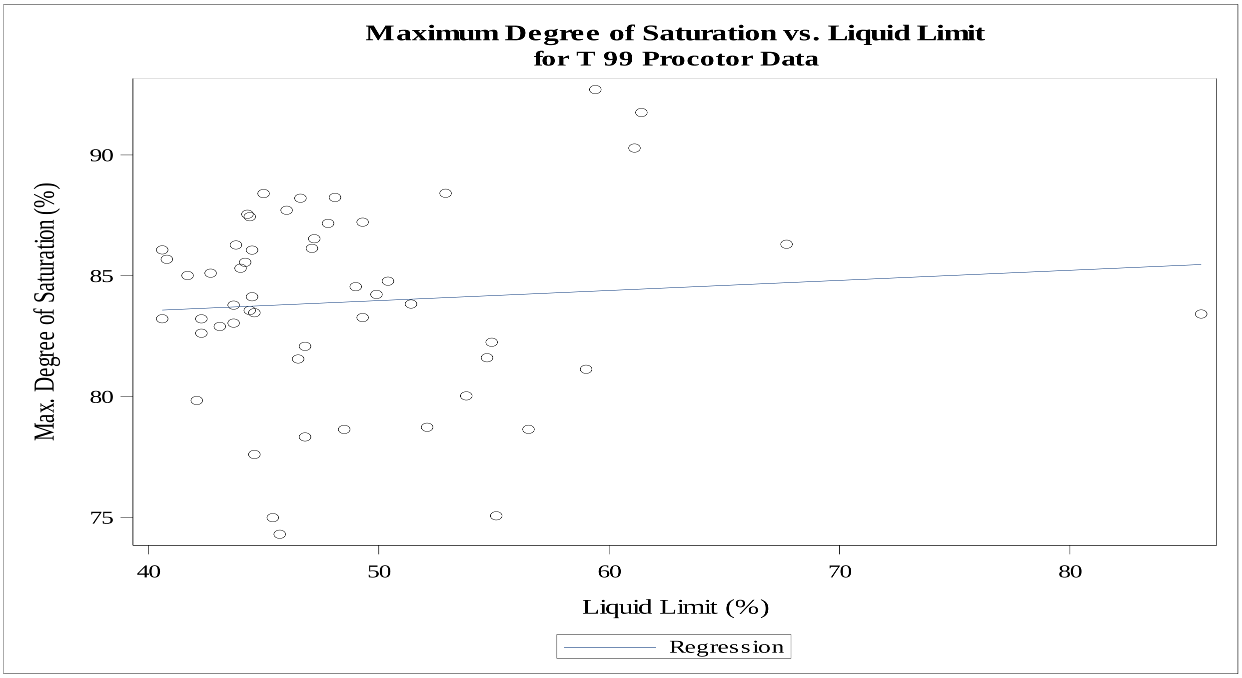

Figure 24: Relation of S_m with Liquid Limit for T99 Proctor

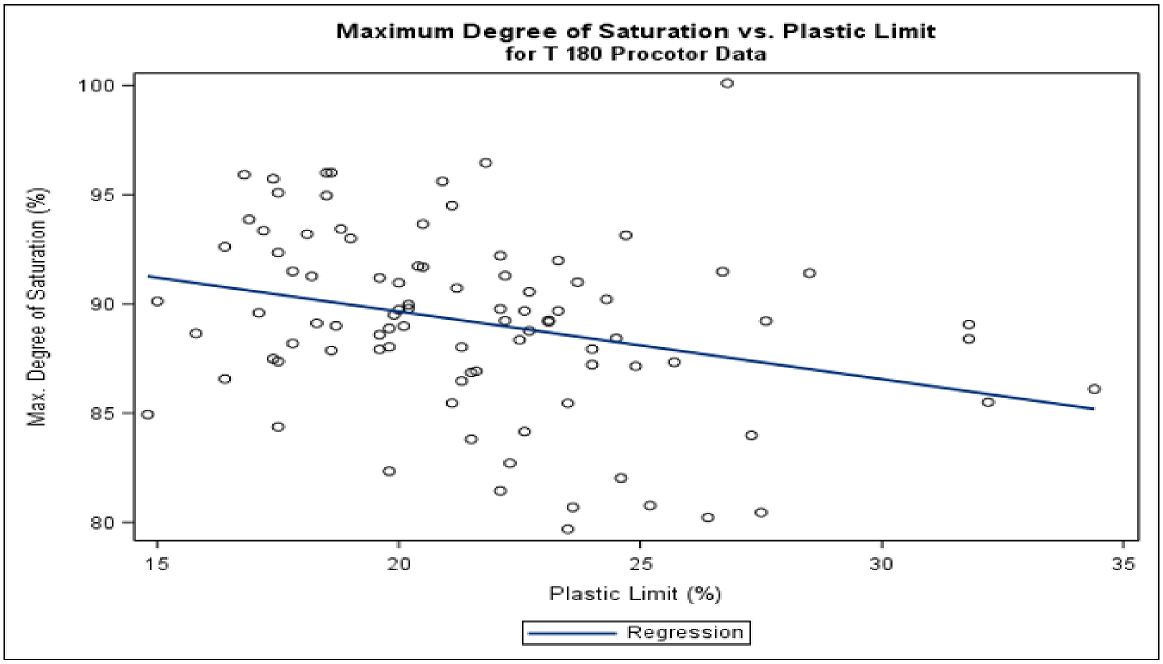

Figure 25: Relation of S_m with Plastic Limit for T180 Proctor

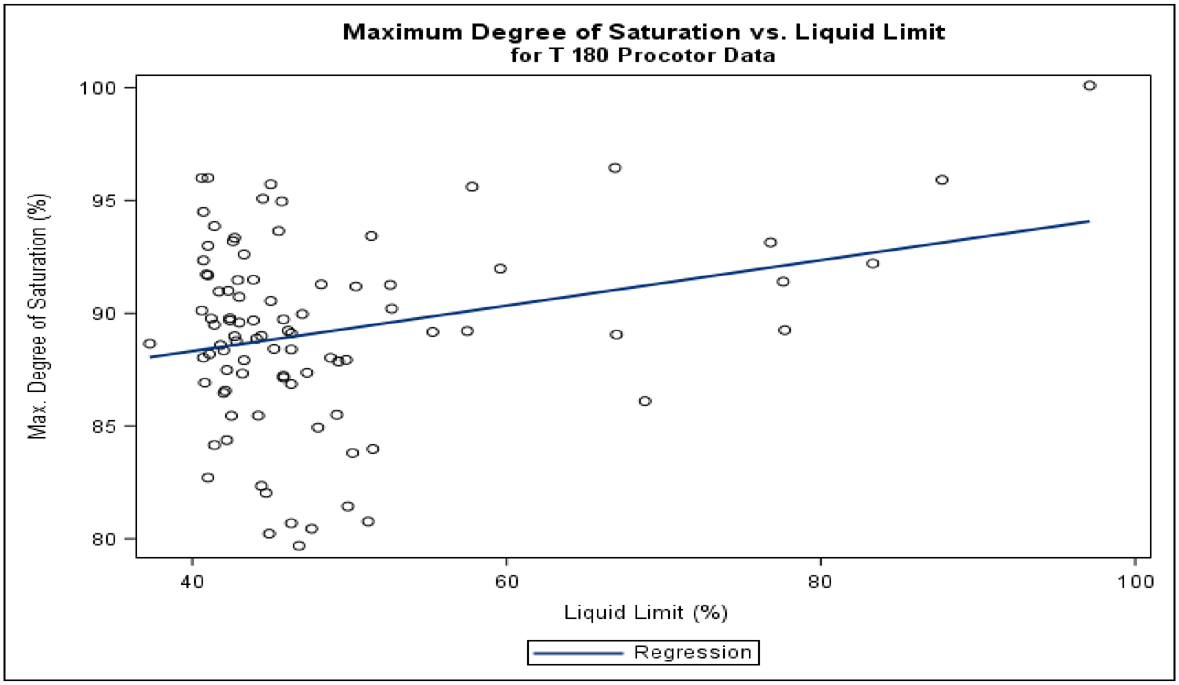

Figure 26: Relation of S_m with Liquid Limit for T180 Proctor

Table 15: Results Summary of Maximum Degree of Saturation with Atterberg Limits

	Parameter Estimate	R - sq
Relation of S_m with Plastic Limit for T 99 Proctor Data	0.4137PL + 74.196	0.0622
Relation of S_m with Liquid Limit for T 99 Proctor Data	0.0418x + 81.881	0.0069
Relation of S_m with Plastic Limit for T 180 Proctor Data	-0.3099x + 95.847	0.0857
Relation of S_m with Liquid Limit for T 180 Proctor Data	0.1008x + 84.287	0.0744

2.7. Conclusions

Maximum Dry Density and Optimum Moisture content are two important compaction characteristics of soil. These are the important two parameters controlling the strength and stability of soil and other overlying structures. The study aimed to investigate the prediction models for Maximum dry density and Optimum Moisture content with the index properties of soil using simple linear regression analysis. A comparative study was made for clayey soil of North Dakota having AASHTO classification A-7-6 for both T-99 and T-180 proctor types. From the results of the study, it was found that Plastic Limit correlates well with Optimum Moisture Content and Maximum Dry Density for T-180 Proctor method than other Atterberg properties. No good correlation was found in relation of index properties of T-99 Proctor data with Maximum dry density and optimum moisture content. With the comparative study performed for determining compaction parameters with Atterberg limits selecting the best following empirical equations are proposed to predict the compaction characteristics for T-180 Proctor method.

$$OMC = 2.74 + 0.56\,PL \tag{12}$$

$$MDD = 147.95 - 1.53\,PL \tag{13}$$

After performing simple linear regression on Maximum Degree of Saturation with Atterberg Limits showed no good coefficient of determination results that can be considered for relation and prediction factor. The above proposed equations can be made used to predict compaction characteristics of the soil when compacting in the field for T-180 Proctor method. These equations will be handy in situations for quickly assessing the compaction characteristics while eliminating the necessity of laboratory methods. Utilization of above equations contribute to the economy of the project by reducing time and cost implications. However, there are some limitations when using the above equations which are described below.

- The above equations are suitable only for T-180 Proctor types.
- The above equations developed were based upon soil type A-7-6 where the liquid limit of soils was ≥ 41% and the equations are limited to only these specifications and soil type.
- The equations are suitable for quickly assessing the engineering properties which may differ from realistic values and would encourage to use laboratory results depending on the need and purpose of work.

CHAPTER 3: MOISTURE RANGE SPECIFICATION ANALYSIS

3.1. Objective

To study the specifications set by NDDOT on compaction moisture range with their respective test types T-99 and T-180 and perform analysis on the moisture range to provide recommendations on their current specifications.

3.2. Background

As discussed in chapter 1, compaction is a process of decreasing the air voids to achieve a maximum dry density with corresponding optimum moisture content. Compaction results in decrease of settlements, permeability and increase of strength and bearing capacity in soils. The Department of Transportation in United States adopt different testing procedures for compaction and have different specifications for achieving the relative dry density in field over a given compaction range. The test methods and specifications adopted by the Department of Transportation for compaction process have been adopted depending upon the type of native soil and the material used as fill to achieve the desired compaction.

For state projects in North Dakota, the Department of Transportation specifications recommends compacting the soil for laboratory testing using AASHTO T180 test to achieve the maximum dry density and optimum moisture content and endorses to achieve a minimum of 90 % of maximum dry density over a range water content varying from OMC to +4 %. The concept of zero air void line and degree of saturation are two prominent factors when working with the above objective and the concepts are described below.

3.3. Zero Air void line

Concept of zero air void line plays an important role when plotting the proctor curves. It is never possible to expel entire air form the sample, but if it does then it signifies that the sample is completely saturated or has achieved 100 percent saturation. Conceptually this is not possible, as all the compacted curves lies on the left side of the zero-air void line. Engineers reject the test where they find a situation where a compacted proctor curve touches or crosses the zero-air void line. The reasons for rejecting a test sample which produced more that 100 percent saturation may be for quality control/quality assurance or for economic considerations. In situations where it happens that the test crosses the saturation line then it’s over to the contractor compacting the sample in field to vary his requirements on soil variability or compaction parameters. To reduce the compacting sample below the 100 percent saturation line the engineer may ask the contractor to produce a drier fill and by also maintaining the density requirements. The case might be challenging if the sample is too wet as it will involve more work for drying (Schmertmann, 1989)

3.4. Methodology

Following steps and methods were employed for the outcome of above objective –

1. Collection of data set for wide range of Proctor tests and filtering as per the required soil type. After the necessary data has been sorted, plots of the Proctor curves were made with their moisture range specifications in Microsoft Excel as shown in Figure 27 and Figure 28. A second order polynomial degree was used to model each Proctor curve for analysis.
2. To check for 100% degree of saturation and beyond plots of zero air void line were made for the respective Proctor types with assumed Specific Gravity of 2.75 for Clays, 2.70 for Clay Loam, and 2.65 for Sands. The equation for calculating Zero Air Void line is given below.

$$\gamma_{zav} = \frac{G_s \gamma_w}{1 + wG_s} \tag{14}$$

Where,

G_s = Specific Gravity of Soils (Assumed specific gravity is 2.65 for Clay, 2.70 for Clayey Loam, 2.75 for Sands)

γ_w = Unit weight of soils (62.4 lb/ft^3)

w = water content (%)

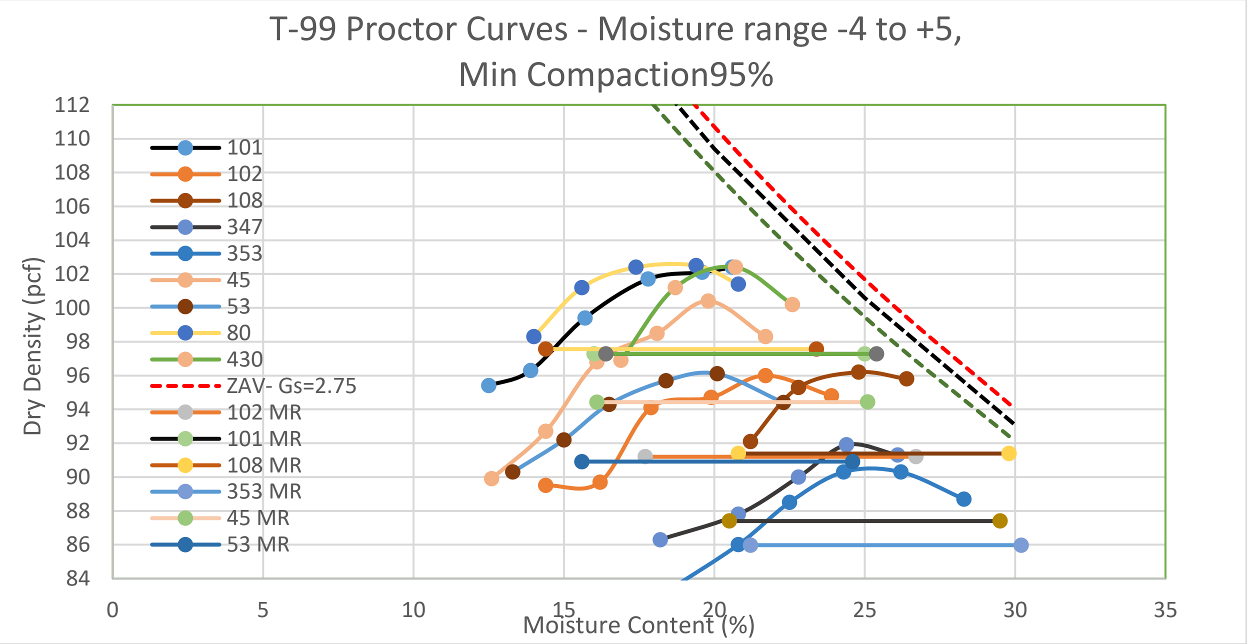

Figure 27: T99 Proctor Curves with NDDOT Specifications

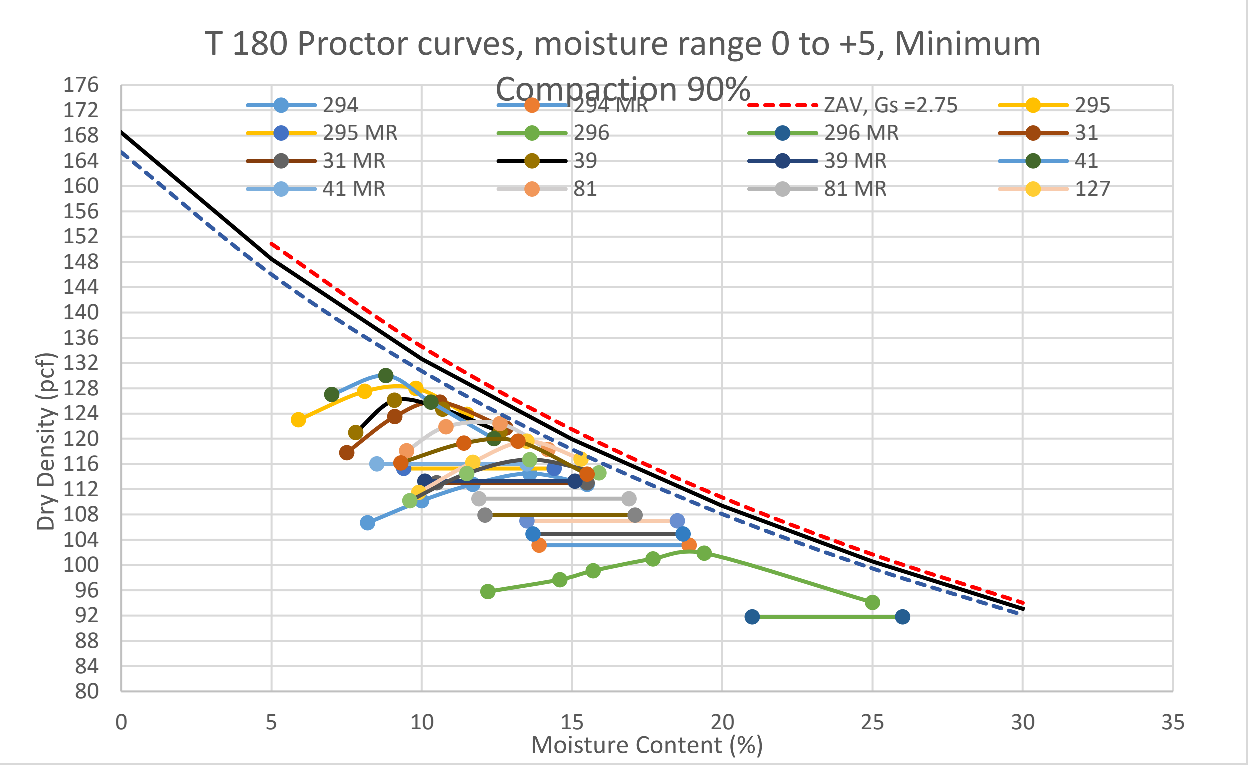

Figure 28: T180 Proctor Curves with NDDOT Specifications

3. After the plotting of zero air void line, the next step was to look at the specifications with maximum saturation value for each soil sample of proctor curve for the test types T-99 and T-180. The maximum degree of saturation was based upon the multiple degree of saturation values possessed by the Proctor curve. The following equation gives the value for degree of saturation.

$$S = \frac{G_s w}{\frac{G_s \gamma_w}{\gamma_d} - 1} \tag{15}$$

Where,

S = degree of saturation

G_s = specific gravity of soils

w= water content

γ_d = Maximum Dry Density

γ_w = Unit weight of soils (62.4 lb/ft^3)

The following example illustrates the process that was carried out to check the specifications for all proctor curves from the data set.

Lab No: 354, Report: 27, Soil Type : A-7-6(19), Test : T-99, Gs : 2.75

Table 16: Proctor Data Sheet for Lab: 71, Test Method T-99

	1	2	3	4	5
Dry Density (pcf)	91.6	94.1	94.8	94.8	92.3
% Moisture	18.5	20.7	22.4	24.2	25.9
Max. Dry Density (pcf)	95				
Opt. Moisture Content (%)	23.2				

Table 17: Degree of Saturation Proctor:71, Test method T-99

	S1	S2	S3	S4	S5
Degree of Saturation(%)	58.2518	69.11797	76.0375	82.14766	82.90123

4. After being calculated the maximum degree of saturation, plots of maximum saturation line were made similar to zero air void line which will help to determine the compaction moisture range on the wet side of optimum moisture content. Below equation gives the plot of maximum saturation line (Sm). Figure 29 shows the method employed to plot maximum degree of saturation by the using the below equation.

$$S_m = \frac{G_s \gamma_w}{1 + \frac{w G_s}{S}} \tag{16}$$

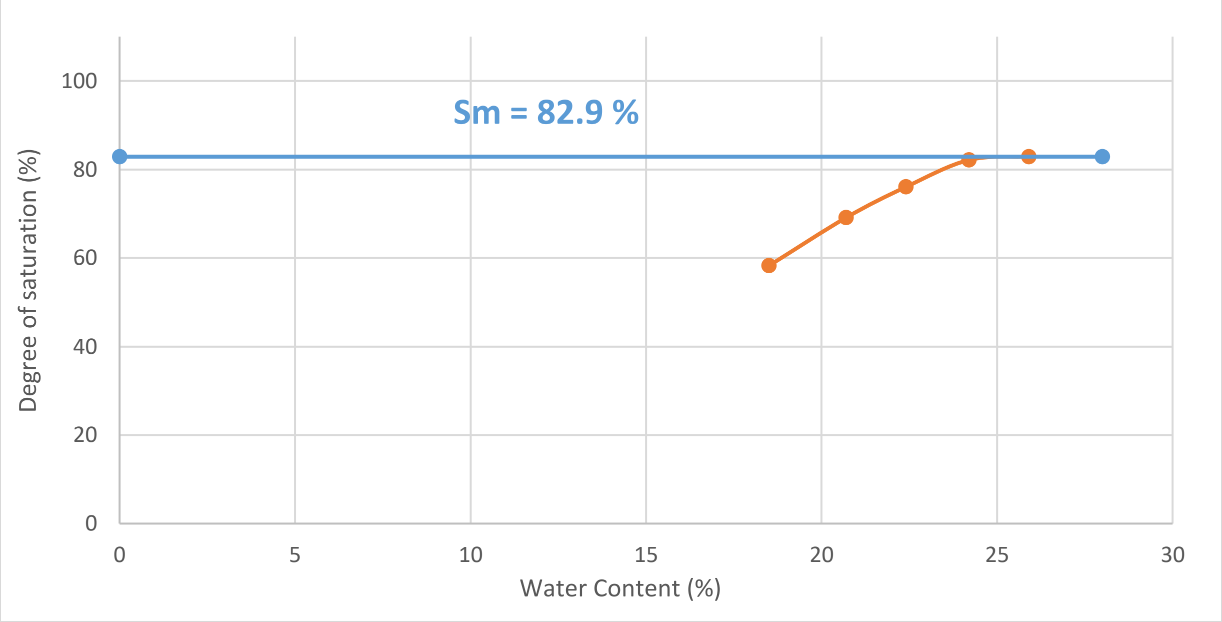

Figure 29: Plot of Maximum Degree of Saturation

5. The last step involved was in plotting the necessary plots and specifications of Proctor curves which includes the minimum allowable dry density, maximum saturation line, zero air void line, and moisture range specifications as shown in Figure 30 for T- 99 Proctor method. With all these plots, the actual workable moisture range was determined on the wet side of optimum moisture content and then tabulated with current specifications of NDDOT compactible moisture range.
6. Similar methodology was employed to determine workable moisture range for T-180 Proctor test type.

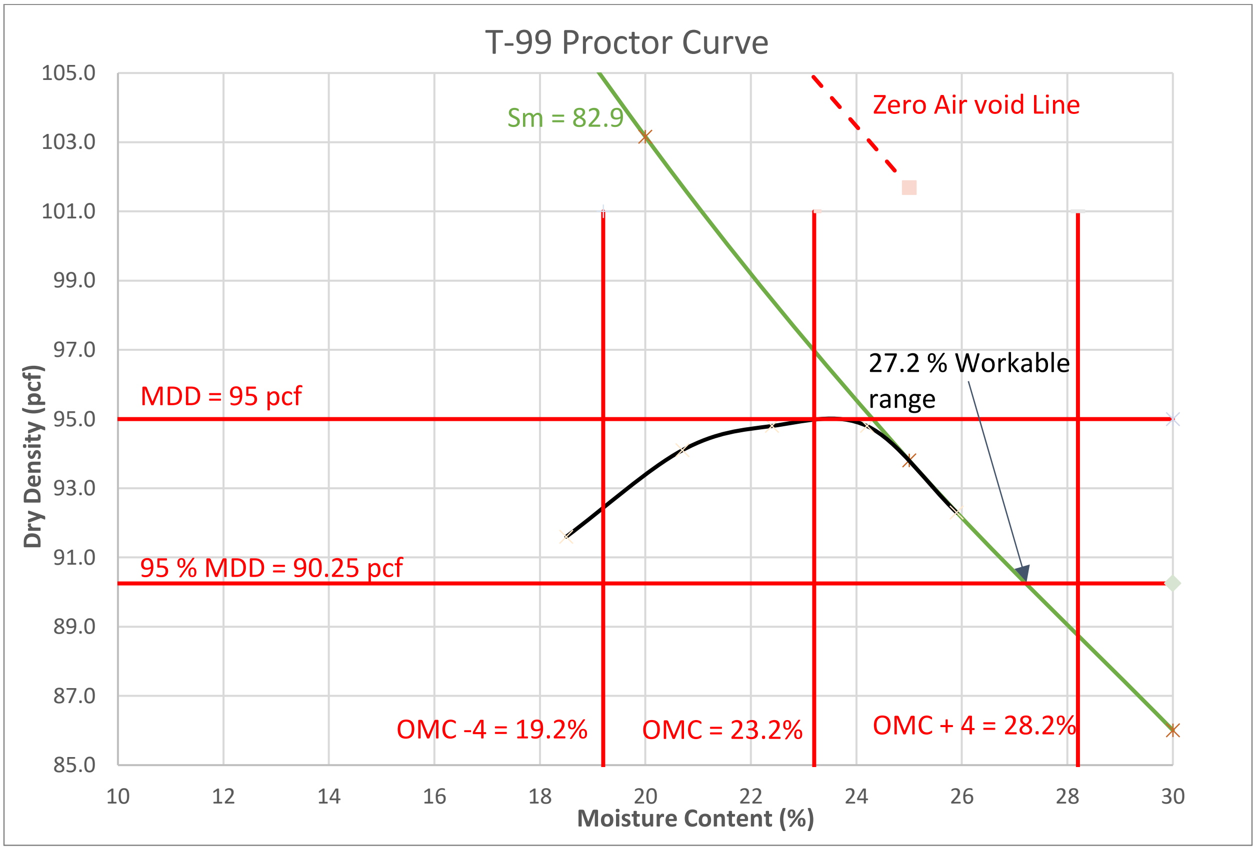

Figure 30: T-99 Proctor Curve with Workable Moisture Range Specifications

3.5. Results

The above described methodology was carried out for the T-99 and T-180 Proctors present in the data set for the soil type A-7-6 with assumed specific gravities of 2.65 for Clays, 2.70 for Clayey Loam, and 2.75 for Sands.

Table 18: Workable Range Specification for T-99 Proctors

Report No	Lab No	TextClass1	Specific Gravity (Gs)	AASHTO1	OptMoist1	MaxDryDen1	Moisture Content (RHS) with current specification	Workable range on wet side for Min Compaction
14	101	CLY	2.75	A-7-6(19)	20	102.4	25	25.8
14	102	CLY	2.75	A-7-6(31)	21.7	96	26.7	26
14	103	CLY	2.75	A-7-6(30)	24	94	29	27.8
14	105	CLY	2.75	A-7-6(18)	21	101.9	26	24.9
14	108	CLY	2.75	A-7-6(42)	24.8	96.2	29.8	29

Table 18: Workable Range Specification for T-99 Proctors (continued)

Report No	Lab No	TextClass1	Specific Gravity (Gs)	AASHTO1	OptMoist1	MaxDryDen1	Moisture Content (RHS) with current specification	Workable range on wet side for Min Compaction
14	109	CLY	2.75	A-7-6(40)	25	97.2	30	29
14	113	CLY	2.75	A-7-6(34)	24.3	97.7	29.3	28
27	345	CLY	2.75	A-7-6(30)	22.9	94	27.9	26.5
27	347	CLY	2.75	A-7-6(30)	24.5	92	29.5	28.5
27	353	CLY	2.75	A-7-6(26)	25.2	90.5	30.2	30
27	354	CLY	2.75	A-7-6(19)	23.2	95	28.2	27.2
27	355	CLY	2.75	A-7-6(22)	23.6	95.4	28.6	27.1
27	361	CLY	2.75	A-7-6(23)	21.3	99.9	26.3	24.9

Table 18: Workable Range Specification for T-99 Proctors (continued)

Report No	Lab No	TextClass1	Specific Gravity (Gs)	AASHTO1	OptMoist1	MaxDryDen1	Moisture Content (RHS) with current specification	Workable range on wet side for Min Compaction
12	49	SLTY CLY	2.75	A-7-6(18)	18.7	103.3	23.7	22.8
12	52	SLTY CLY	2.75	A-7-6(22)	20.7	98.2	25.7	25.5
12	53	SLTY CLY	2.75	A-7-6(22)	19.6	95.7	24.6	24.1
12	54	SLTY CLY	2.75	A-7-6(22)	19.9	98.8	24.9	25
12	55	SLTY CLY	2.75	A-7-6(22)	19.7	100.2	24.7	23.4
13	57	SLTY CLY	2.75	A-7-6(19)	21.1	98.5	26.1	26
13	58	SLTY CLY	2.75	A-7-6(21)	19.7	102.7	24.7	24.5
13	59	CLY	2.75	A-7-6(19)	19.1	103.7	24.1	23
13	60	SLTY CLY	2.75	A-7-6(21)	19.2	103.2	24.2	22.9
13	61	SLTY CLY	2.75	A-7-6(25)	20.5	99	25.5	24.8
13	62	CLY	2.75	A-7-6(19)	19.7	102.7	24.7	23.2
13	63	CLY	2.75	A-7-6(19)	24.7	97.9	29.7	25
13	64	CLY	2.75	A-7-6(25)	24	94.3	29	28
13	65	CLY	2.75	A-7-6(24)	24.8	88.9	29.8	29.8
13	66	CLY	2.75	A-7-6(30)	26	86.2	31	30
15	68	SLTY CLY	2.75	A-7-6(19)	22.4	97	27.4	27
15	69	SLTY CLY LM	2.7	A-7-6(16)	18.8	102.8	23.8	23
15	71	CLY LM	2.7	A-7-6(11)	18.1	104	23.1	22.4
15	80	SLTY CLY	2.75	A-7-6(21)	18.4	102.7	23.4	22.9
15	85	CLY	2.75	A-7-6(17)	20.1	101.1	25.1	24

Table 18: Workable Range Specification for T-99 Proctors (continued)

Report No	Lab No	TextClass1	Specific Gravity (Gs)	AASHTO1	OptMoist1	MaxDryDen1	Moisture Content (RHS) with current specification	Workable range on wet side for Min Compaction
15	87	SLTY CLY	2.75	A-7-6(23)	20.3	96.8	25.3	24.5
15	88	SLTY CLY	2.75	A-7-6(24)	19.3	96.6	24.3	23.5
15	89	SLTY CLY	2.75	A-7-6(24)	20.8	94.9	25.8	25.8
12	420	CLY	2.75	A-7-6(18)	21.3	97.9	26.3	26.4
12	422	CLY	2.75	A-7-6(23)	23.6	96.7	28.6	28
12	423	CLY	2.75	A-7-6(22)	22.4	97.2	27.4	27.4
12	424	CLY	2.75	A-7-6(23)	22.6	97.4	27.6	27
12	425	CLY	2.75	A-7-6(22)	23	97.6	28	27
12	427	CLY	2.75	A-7-6(19)	22.1	99.3	27.1	26.4
12	428	CLY	2.75	A-7-6(18)	21.9	98.9	26.9	26.2
12	429	CLY	2.75	A-7-6(18)	19.9	103.7	24.9	23.2
12	430	SLTY CLY	2.75	A-7-6(24)	20.4	102.4	25.4	24
12	432	SLTY CLY	2.75	A-7-6(22)	22.6	97.4	27.6	27.4
12	434	SLTY CLY	2.75	A-7-6(23)	23.7	95.9	28.7	27.8
34	779	CLY LM	2.7	A-7-6(19)	20.4	106.5	25.4	22
34	782	CLY	2.75	A-7-6(42)	23.9	94.5	28.9	28.8
34	786	CLY	2.75	A-7-6(63)	23.8	93.1	28.8	27.8

Table 19: Workable Range Specifications for T-180 Proctors

Report No	Lab No	TextClass 1	Specific Gravity (Gs)	AASHTO 1	OptMoist1	MaxDryDen 1	Moisture Content (RHS) with current specification	Workable range on wet side for Min Compaction
7	71	CLY	2.75	A-7-6(9)	17.8	104.4	22.8	24.8
7	72	CLY	2.75	A-7-6(5)	16.4	109.3	21.4	23
7	74	CLY	2.75	A-7-6(8)	14.7	113.1	19.7	20.5
7	79	CLY	2.75	A-7-6(9)	14.7	113.4	19.7	21
7	85	CLY LM	2.7	A-7-6(10)	18.1	104.9	23.1	24.4
7	89	CLY	2.75	A-7-6(11)	14	117.3	19	20.5
7	90	CLY	2.75	A-7-6(13)	17.9	105.7	22.9	25.5
7	91	CLY	2.75	A-7-6(14)	19.3	100.7	24.3	26
7	92	CLY LM	2.7	A-7-6(13)	12.6	122.8	17.6	18.2
7	93	CLY	2.75	A-7-6(15)	17.9	104.4	22.9	24
7	94	CLY	2.75	A-7-6(13)	17.4	108.7	22.4	22
7	95	CLY LM	2.7	A-7-6(13)	16.8	109.9	21.8	24.3
7	96	CLY	2.75	A-7-6(11)	14.9	117	19.9	20.5
7	97	CLY	2.75	A-7-6(10)	15.1	115.1	20.1	20.8
7	98	CLY	2.75	A-7-6(11)	16.7	111.1	21.7	23
7	99	CLY LM	2.7	A-7-6(11)	16.6	110.7	21.6	23.4
7	100	CLY LM	2.7	A-7-6(12)	17.3	107.1	22.3	24.3
7	101	CLY LM	2.7	A-7-6(13)	15.9	112.4	20.9	22.4
8	103	SNDY LM	2.65	A-7-6(3)	13.9	114.2	18.9	21
8	104	CLY LM	2.7	A-7-6(7)	14.4	117	19.4	21
8	128	CLY LM	2.7	A-7-6(9)	13.8	119.4	18.8	20.1
8	140	CLY LM	2.7	A-7-6(11)	16.5	110.7	21.5	22
9	144	CLY	2.75	A-7-6(17)	12.6	123.3	17.6	19
9	147	CLY	2.75	A-7-6(15)	13.4	121.1	18.4	19.8

Table 19: Workable Range Specifications for T-180 Proctors (continued)

Report No	Lab No	TextClass 1	Specific Gravity (Gs)	AASHTO 1	OptMoist1	MaxDryDen 1	Moisture Content (RHS) with current specification	Workable range on wet side for Min Compaction
9	149	CLY	2.75	A-7-6(15)	13.2	121.4	18.2	19
9	150	SNDY CLY	2.65	A-7-6(5)	11	125.7	16	16.9
9	151	CLY	2.75	A-7-5(37)	25.5	92	30.5	
9	152	CLY	2.75	A-7-6(60)	17.6	108.8	22.6	24.5
9	155	CLY	2.75	A-7-6(75)	19.5	106.3	24.5	29
9	158	CLY	2.75	A-7-6(63)	15.1	117.3	20.1	22
9	159	CLY	2.75	A-7-6(53)	21.7	102	26.7	28.9
9	161	CLY	2.75	A-7-6(13)	12.8	123	17.8	18.5
9	163	CLY	2.75	A-7-6(14)	12.7	121.5	17.7	19.4
9	166	SLTY CLY LM	2.7	A-7-6(24)	11.8	123	16.8	18.4
9	167	CLY	2.75	A-7-6(40)	19	106.7	24	26.5
9	169	CLY	2.75	A-7-6(27)	13.6	120.7	18.6	20.2
9	171	CLY	2.75	A-7-6(42)	16.8	113.2	21.8	24
9	172	CLY	2.75	A-7-6(70)	14.3	117.7	19.3	21
9	173	CLY	2.75	A-7-6(14)	11	125.4	16	16.5
9	174	CLY	2.75	A-7-6(34)	14.1	117.9	19.1	21
11	308	CLY	2.75	A-7-6(53)	18.7	108.1	23.7	26
11	317	CLY	2.75	A-7-6(26)	18.2	109.1	23.2	25.5
50	1418	CLY	2.75	A-7-6(16)	11.7	124.2	16.7	16.2
50	1425	CLY	2.75	A-7-6(13)	10.5	127.9	15.5	16
50	1432	CLY	2.75	A-7-6(17)	13.8	119.3	18.8	20
50	1436	CLY	2.75	A-7-6(19)	13.4	119.7	18.4	19.8
50	1437	CLY	2.75	A-7-6(12)	13.1	115.1	18.1	19.8

Table 19: Workable Range Specifications for T-180 Proctors (continued)

Report No	Lab No	TextClass 1	Specific Gravity (Gs)	AASHTO 1	OptMoist1	MaxDryDen 1	Moisture Content(RHS) with current specification	Workable range on wet side for Min Compaction
51	1473	SLTY CLY LM	2.7	A-7-5(17)	17.3	107.8	22.3	24
51	1474	SLTY CLY LM	2.7	A-7-5(17)	17.9	106	22.9	24.1
51	1483	CLY	2.75	A-7-6(12)	19.3	101.9	24.3	25.5
51	1487	CLY	2.75	A-7-6(14)	17.2	107.3	22.2	23.8
51	1488	CLY	2.75	A-7-6(15)	15.6	111.4	20.6	21.8
51	1490	CLY	2.75	A-7-6(17)	19.1	101.8	24.1	26
51	1491	CLY	2.75	A-7-6(13)	14.9	113.5	19.9	21
315	1989	CLY	2.75	A-7-6(15)	12.1	120.1	17.1	19
315	1990	CLY	2.75	A-7-6(16)	11.7	123.3	16.7	17.8
315	1991	CLY	2.75	A-7-6(17)	11.6	123.9	16.6	17.7
315	1992	CLY	2.75	A-7-6(19)	13	120	18	19.1
315	2004	CLY	2.75	A-7-6(23)	11.9	123.2	16.9	13.1
315	2007	CLY LM	2.7	A-7-6(7)	10.9	123.7	15.9	17
315	2009	CLY	2.75	A-7-6(9)	14.3	114.3	19.3	21.8
315	2014	CLY	2.75	A-7-6(51)	16.5	112.4	21.5	24.1
7	248	CLY	2.75	A-7-6(27)	11.6	122.7	16.6	17.9
7	249	CLY	2.75	A-7-6(25)	12.4	121	17.4	19
7	253	CLY	2.75	A-7-6(25)	10.1	125.5	15.1	16
9	293	CLY	2.75	A-7-6(28)	16.5	110.9	21.5	23.5
9	295	CLY	2.75	A-7-6(22)	13.2	120.8	18.2	18.9
9	298	CLY	2.75	A-7-6(24)	16.5	110.3	21.5	23.8
9	299	CLY	2.75	A-7-6(17)	14	116.5	19	20.5
9	301	CLY	2.75	A-7-6(21)	16.1	109.8	21.1	24.1

Table 19: Workable Range Specifications for T-180 Proctors (continued)

Report No	Lab No	TextClass1	Specific Gravity (Gs)	AASHTO1	OptMoist1	MaxDryDen1	Moisture Content(RHS) with current specification	Workable range on wet side for Min Compaction
9	303	CLY	2.75	A-7-6(30)	13	120.9	18	19
9	304	CLY	2.75	A-7-6(31)	12.8	120.2	17.8	18.9
9	309	CLY	2.75	A-7-6(16)	12	122.9	17	17.8
9	310	SLTY CLY	2.75	A-7-6(21)	11.8	122.4	16.8	18
9	318	CLY LM	2.7	A-7-6(13)	11.1	124.8	16.1	17.2
9	321	SLTY CLY LM	2.7	A-7-6(21)	12	119.7	17	18.8
9	322	CLY	2.75	A-7-6(22)	15.3	114.2	20.3	21.5
9	323	CLY	2.75	A-7-6(22)	12	120.7	17	19
37	843	CLY	2.75	A-7-6(17)	12.7	119.4	17.7	19
43	942	CLY LM	2.7	A-7-6(10)	13	117.8	18	20
43	944	CLY	2.75	A-7-6(18)	12.6	120.5	17.6	19
43	953	CLY LM	2.7	A-7-6(12)	15.5	109.9	20.5	22.9
43	956	CLY LM	2.7	A-7-6(10)	13.5	116.6	18.5	20
43	957	CLY LM	2.7	A-7-6(11)	14.2	115.7	19.2	21
43	958	CLY LM	2.7	A-7-6(14)	15.5	112.4	20.5	22
43	960	CLY	2.75	A-7-6(14)	15.2	110.8	20.2	22.5
43	961	CLY	2.75	A-7-6(15)	15.8	112.5	20.8	22
43	963	CLY	2.75	A-7-6(14)	14.7	114.7	19.7	21.1
43	967	CLY LM	2.7	A-7-6(13)	14.3	114.1	19.3	21.2
43	970	CLY	2.75	A-7-6(19)	13.7	116.6	18.7	20.4

3.6. Correlation of Plastic Limit with Workable Moisture Range of Minimum Compaction

Above analysis were performed to verify the current specification for compacting moisture range set by NDDOT. Upon analysis, it was observed that there was no significance difference between when tabulated with actual workable moisture range. Chapter 2 of this research study came up with conclusions as Plastic Limit is better correlated with Maximum Dry Density and Optimum Moisture Content and is used as predicting factor to determine compaction characteristics using empirical equations for A-7-6 soil types. A verification analysis was performed with index properties and calculated workable moisture range to check there variation and correction. It was observed that workable moisture range correlates well with Plastic limit and more significance results were obtained for T-180 Proctor test type as shown in Figure 31 and Figure 32.

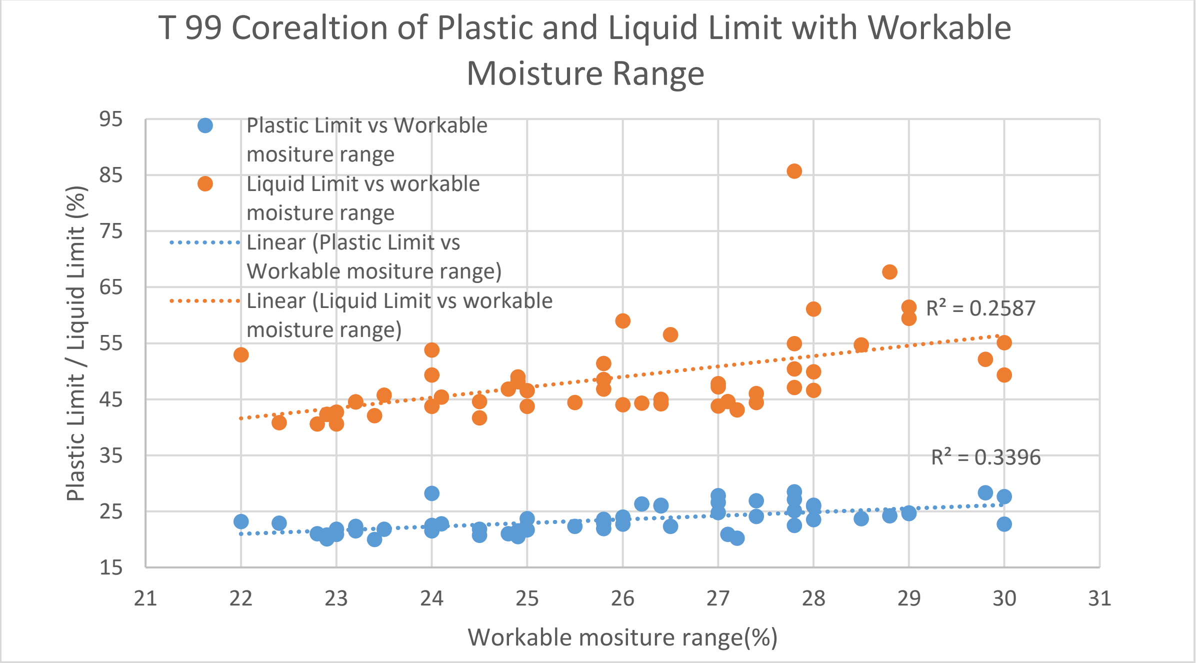

Figure 31: T-99 Correlation of Plastic and Liquid Limit With Workable Moisture Range

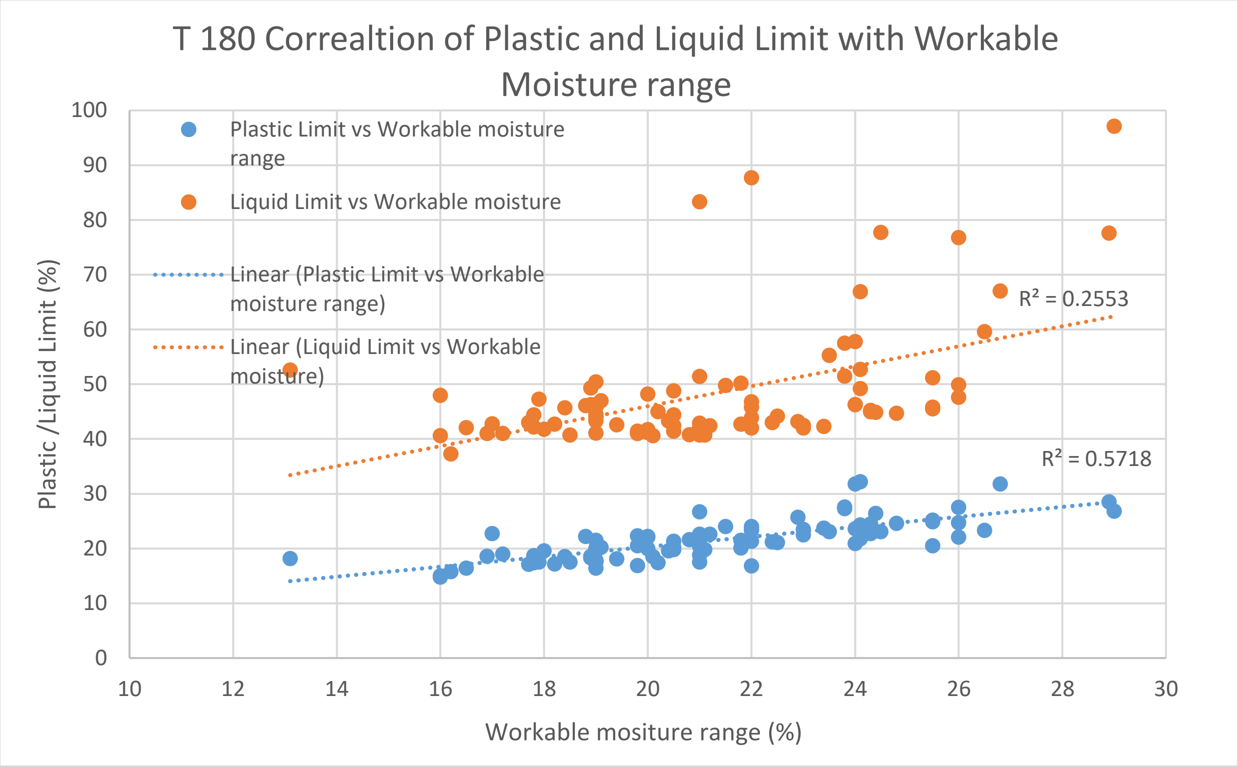

Figure 32: T-180 Correlation of Plastic and Liquid Limit With Workable Moisture Range

3.7. Variation of Moisture Range with Increase in Maximum Dry Density (S_{peak} Concept)

Previous analysis in Chapter 2 gave us the workable moisture range for a specified amount of Maximum Dry Density and Optimum Moisture Content by utilizing the concepts of Li of degree of saturation. But, as the maximum dry density increases the curves follow a peak similar to S_m line there by narrowing the moisture range specifications. The situation may arise when a project engineer requests to increase the specified compaction in field where the curve shifts vertically upwards while limiting the current moisture range specifications. To determine the shift in the curve and its limiting moisture range a concept of peak saturation (S_{peak}) is developed and is illustrated with a following example.

Consider a soil of specific gravity (G_s) 2.70 produced a MDD of 100 lb/ft^3 and OMC of 20% for T-180 specifications providing a moisture range variability from 20% to 25% for 90% compaction. As discussed in previous analysis one can only reach upto maximum degree of saturation. The specifications of moisture range and minimum compaction are shown in Figure 33.

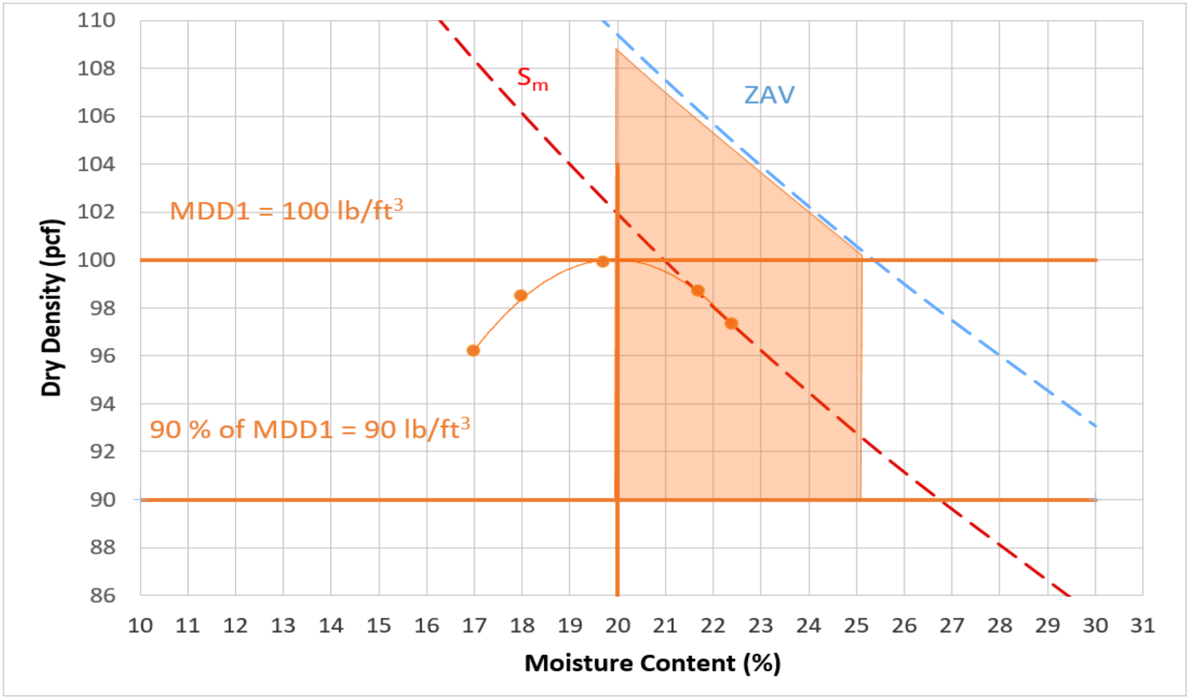

Figure 33: S_{peak} concept for T-180 specifications

Now, if the project engineer requests to increase the compaction density by 5% in MDD which will be 105 lb/ft^3 with a new minimum compaction of 94.5 lb/ft^3 then to determine the new moisture content, saturation peak concept is developed as an approach with the following equations.

$$S_{peak\ (\%)} = \frac{(OMC)G_s}{\frac{\gamma_w G_s}{MDD} - 1} \tag{17}$$

The saturation peak for the above example is 78.9 %. Following this a saturation peak line is plotted similar to degree of saturation line (S_m) and the S_{peak} line will pass through the Maximum Dry Densities of the plotted curves providing the Optimum Moisture Content of required increased densities. The following equation is made use of in plotting S_{peak} line.

$$S_{peak\ (w)} = \frac{\gamma_w G_s}{\frac{w G_s}{S_{peak}} + 1} \tag{18}$$

The peak saturation line (S_{peak}) will help determine the new compactible moisture range. From Figure 34 as the required density is increased the contractor will have a limiting range to achieve the desired density and is highlighted with a blue triangle in the figure. With this the current specifications will have to be adjusted to achieve the required compaction. This methodology will help the project engineers and NDDOT to adjust their moisture range specifications depending upon the change in increased densities.

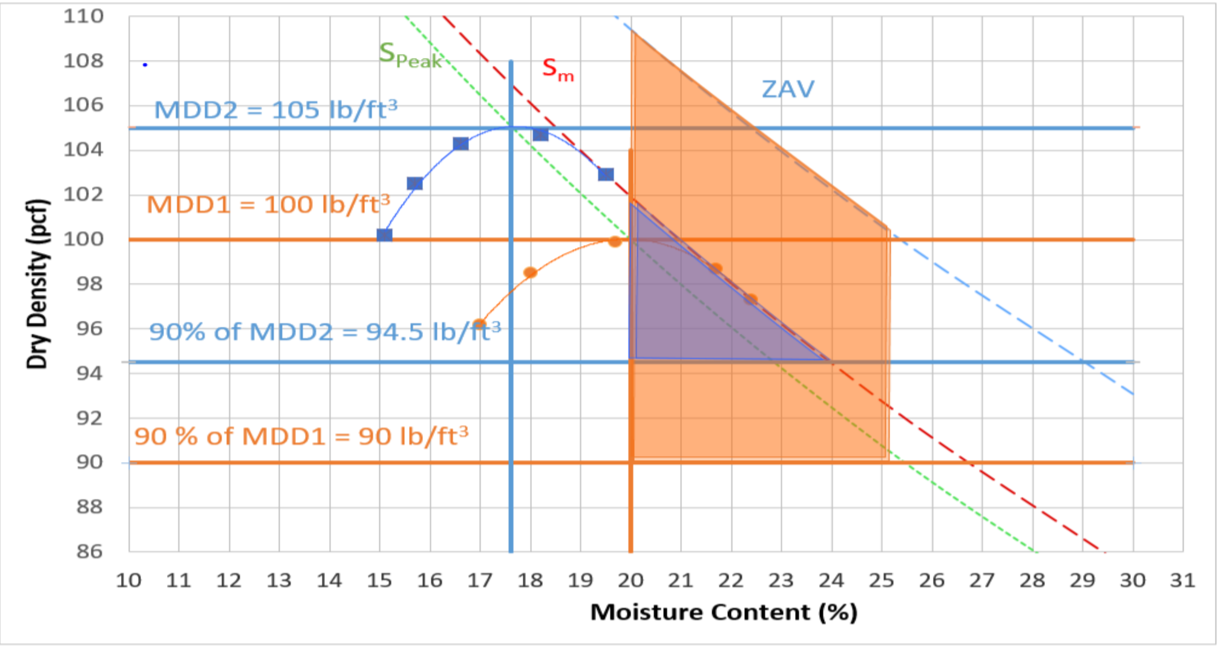

Figure 34: S_{peak} concept for T-180 specifications

However, the concept of peak saturation (S_{peak}) assumes the V_w/V_v ratio will not change significantly as the compaction increases. The concept cannot be fully pursued due to lack of information regarding specific gravities (G_s) and soil samples to run the tests for validation. The peak saturation (S_{peak}) is an approach developed that will aid in adjusting the moisture range specifications provided all the data is available.

3.8. Conclusions

As we know ensuring proper strength and stability of soil are the foremost important criteria for engineers. Compaction is the process where the desired strength and stability of soil is achieved for the desired purpose of engineering principles. Maximum Dry Density and Optimum Moisture Content are two important compaction parameters required when compacting the soil on field. A minimum of 90% for T-180 and 95% for T-99 of maximum dry density is required based upon standard test type. Sometime the situation becomes difficult for a contractor as they have to achieve the strength over a range of moisture content. As per North Dakota state specifications, moisture range for compacting a soil with T-99 test type is -4% to +5% of Optimum moisture content and that of T-180 test type is OMC to +5%. Chapter 3 analysis was focused on verifying the current specifications for the T-99 and T-180 Proctor test type. Each proctor curve for soil type A-7-6 was analyzed for the current specification by calculating the actual workable moisture range on wet side. From the results it was observed that, workable moisture range for T-99 proctor curves had a wide range on wet side accounting upto +6% of OMC range in contrast with current specification of +5% on wet side of OMC. On the other hand, workable moisture range for T-180 Proctor curves observed was of about +4% on wet side to current specifications of +5%. Overall there was no significant deviation of moisture ranges for both Proctor types and can be concluded that current specifications of North Dakota State are well within achievable range for moisture control.

Saturation Peak (S_{peak}) concept is proposed that will help NDDOT and project engineers to determine the moisture range specifications when an increased density is requested in field.

Results from Chapter 2 conclude that Plastic Limit for A-7-6 soil types can be made use of for predicting Optimum Moisture Content and Maximum Dry Density. However, the prediction empirical equations were more suitable to T-180 Proctor type and for soil type A-7-6 which is clayey soil having liquid limit 41 percent and above. A validation analysis was performed with Atterberg limits and workable moisture range at the end and the results shows Plastic Limit is better correlated than Liquid Limit with workable moisture range. Analysis on degree of saturation (S_m) and Atterberg limits showed no significance in their correlation.

3.9. Recommendations for Future Research

- Prediction of compaction parameters with different soil properties and soil types.
- How to predict changes to the shape of the curve as the dry density increases. We know from the family of curves and from experience that the shape has a more pronounced "peak" and the moisture range decreases. New curves for the NDDOT could be developed for common soil types and properties found in the state of North Dakota.
- Determine if, for a given soil sample, the peaks follow the S_{Peak} line that we discussed earlier. This would require a larger soil sample to run tests with increasing energy (more blows per layer, heavier hammer, etc.). Together with the shape of curve and S_{peak} concept will allow the NDDOT to have a better understanding of how soils in the state react to increased compaction and how this affects the moisture requirements to reach increased levels of compaction.

REFERENCES

Aashto, M. (2009). 145—Standard Specification for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes,(2004). *Plan for Evaluation of HDPE (High Density Polyethylene) Thermoplastic Pipe.‖ Revised*.

ASTM. (2007). ASTM-D698-12: Standard test methods for laboratory compaction characteristics of soil using standard effort. *ASTM International*, *3*, 1–13. http://doi.org/10.1520/D0698-12E01.1

ASTM D1557. (2012). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000ft-lbf/ft3 (2,700 kN-m/m3)). *ASTM International*, 1–14. http://doi.org/10.1520/D1557-12.1.3.1.3

Astm, & International, A. (2006). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). *ASTM Standard Guide*, *D5521-05*, 1–5. http://doi.org/10.1520/D2487-11.

Attom, M. F. (1997). The effect of compactive energy level on some soil properties. *Applied Clay Science*, *12*(1–2), 61–72. http://doi.org/10.1016/S0169-1317(96)00037-3

Basma, A. A. (1993). Prediction of Expansion Degree for Natural Compacted Clays. *ASTM Technical Note*, 542–549.

Caterpillar. (2000). *Soil and Asphalt Compaction Manual. Manual No. QECB9729 (01/00).* Caterpillar.

Di Matteo, L., Bigotti, F., & Ricco, R. (2009). Best-Fit Models to Estimate Modified Proctor Properties of Compacted Soil. *Journal of Geotechnical and Geoenvironmental Engineering*, *135*(7), 992–996. http://doi.org/10.1061/(ASCE)GT.1943-5606.0000022.

Gurtug, Y., & Sridharan, A. (2002). Prediction of compaction characteristics of fine-grained soils. *GEOTECHNIQUE-LONDON-*, *52*(10), 761–763.

Hammond, A. A. (1980). Evolution of one point method for determining the laboratory maximum dry density. In *Proc., ICC* (Vol. 1, pp. 47–50).

Hausmann, M. R. (1990). *Engineering principles of ground modification*. McGraw-Hill New York.

Hilf, J. W. (1991). Compacted fill. In *Foundation engineering handbook* (pp. 249–316). Springer.

Horn, H. M., & Deere, D. U. (1962). Frictional characteristics of minerals. *Geotechnique*, *12*(4), 319–335.

Howell, J. L., Shackelford, C. D., Amer, N. H., & Stern, R. T. (1997). Compaction of sand-processed clay soil mixtures. *Geotechnical Testing Journal*, *20*(4), 443–458.

Johnson, A. W., & Sallberg, J. R. (1960). Factors that influence field compaction of soils. *Highway Research Board Bulletin*, (272).

Jumikis, A. R. (1958). Geology of Soils of the Newark (NJ) Metropolitan Area. *Journal of the Soil Mechanics and Foundations Division*, *84*(2), 1–41.

Lambe, T. W. (1958). The structure of compacted clay. *Journal of the Soil Mechanics and Foundations Division*, *84*(2), 1–34.

Lee, P. Y., & Suedkamp, R. J. (1972). Characteristics of Irregularly Shaped Compaction Curves of Soils. *Highway Research Record*, *381*, 1–9.

Li, H., & Sego, D. C. (2000). Equation for complete compaction curve of fine-grained soils and its applications. In *Constructing and Controlling Compaction of Earth Fills*. ASTM International.

Li, H., Sego, D. C., Li, R. :, Sego, H., Shanklin, D. W., Rademacher, K. R., & Talbot, J. R. (n.d.). *Equation for Complete Compaction Curve of Fine-grained Soils and Its Applications “Equation for Complete Compaction Curve of Fine-grained Soils and Its Applications,” Constructing and Controlling Compaction of Earth Fills, ASTMSTP 1384*. Retrieved from www.astm.org

Mohammed, A. (2017). Property Correlations and Statistical Variations in the Geotechnical Properties of (CH) Clay Soils. *Geotechnical and Geological Engineering*, *36*(1), 1–16. http://doi.org/10.1007/s10706-017-0418-2

Monahan, E. J. (1986). *Construction of and on Compacted Fills* (Vol. 21). Wiley-Interscience.

Nagaraj, H. B., Reesha, B., Sravan, M. V., & Suresh, M. R. (2015). Correlation of compaction characteristics of natural soils with modified plastic limit. *Transportation Geotechnics*, *2*, 65–77. http://doi.org/10.1016/j.trgeo.2014.09.002

Parsons, A. W. (1992). *Compaction of soils and granular materials: a review of research performed at the Transport Research Laboratory*. HMSO.

Rodriguez, A. R., & Sowers, G. F. (1988). *Soil mechanics in highway engineering*.

Saikia, A., Baruah, D., Das, K., & Jyoti, H. (2017). Predicting Compaction Characteristics of Fine-Grained Soils in Terms of Atterberg Limits. *International Journal of Geosynthetics and Ground Engineering*, *3*(2), 1–9. http://doi.org/10.1007/s40891-017-0096-4

Schmertmann, B. J. H. (1989). Density tests above zero air voids line, *115*(7), 1003–1018.

Seed, H. B., Mitchell, J. K., & Chan, C. K. (1961). *The strength of compacted cohesive soils*.

Smooth Drum Roller. (n.d.). Retrieved from https://www.google.com/search?q=smooth+drum+roller&source=lnms&tbm=isch&sa=X&ved=0ahUKEwj2p4744jdAhXHwFkKHTEHBXIQ_AUICygC&biw=1280&bih=566#imgrc=PxjQ0Iy5-rOYwM

Sridharan, A., & Nagaraj, H. B. (2005). Plastic limit and compaction characteristics of fine-grained soils. *Ground Improvement*, *9*(1), 17–22. http://doi.org/10.1680/grim.9.1.17.58544

Vibratory Roller. (n.d.). Retrieved from https://www.google.com/search?q=vibratory+roller&source=lnms&tbm=isch&sa=X&ved=0ahUKEwj_gsPM5IjdAhUCd98KHWZsDFAQ_AUICigB&biw=1280&bih=566#imgrc=lvWFxJtIoJEp6M

Vipulanandan, C., & Mohammed, A. S. (2014). Hyperbolic rheological model with shear stress limit for acrylamide polymer modified bentonite drilling muds. *Journal of Petroleum Science and Engineering*, *122*, 38–47. http://doi.org/10.1016/j.petrol.2014.08.004

Winterkorn, H. F., & Fang, H.-Y. (1991). Soil technology and engineering properties of soils. In *Foundation engineering handbook* (pp. 88–143). Springer.

Yoder, E. J., & Witczak, M. W. (1975). *Principles of pavement design*. John Wiley & Sons.