USING THE DYNAMIC CONE PENETROMETER (DCP) AND LIGHT WEIGHT DEFLECTOMETER (LWD) FOR CONSTRUCTION QUALITY ASSURANCE

LRRB Investigation 860

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Chapter 1 - Introduction

The Minnesota Local Road Research Board (LRRB) and the Minnesota Department of Transportation (Mn/DOT) continue to strive to improve testing methods for unbound materials during pavement construction. Mn/DOT has implemented the dynamic cone penetrometer (DCP) and light weight deflectometer (LWD) in place of current methods on several projects. This report focuses on developing standard test methods and model specifications, using both the DCP and the LWD for quality assurance. When compared to current practices, these testing devices are expected to efficiently gather more accurate data using safer procedures.

1.1 History

Mn/DOT has traditionally verified the quality of pavement foundations by comparing lift densities to a "relative maximum" density identified for each unbound material. In order to calculate the relative maximum density, Mn/DOT's Standard Specifications for Construction require that samples of potential subbase and soil foundation materials be compacted at different moisture contents using standard Proctor compactive effort. The densities of the resulting laboratory specimens are calculated and plotted versus moisture content. A curve is fit through the data and the peak represents the optimum moisture content and the maximum dry density. This process is known as a standard Proctor test (ASTM D698, AASHTO T99, Mn/DOT Grading and Base Manual).

A sand cone test (ASTM D 1556-00) is performed on a lift of material in the field to determine whether its density meets or exceeds a designated percentage of the standard Proctor maximum density. The test is performed by scooping a small amount of material from the compacted layer and carefully filling the hole created with a measurable mass of sand. Because the sand used in these tests has a known density, the volume of the hole can be calculated. The density of the layer is calculated using this volume and the dry weight of the material removed from the hole. The compaction is deemed acceptable if the density measured during the sand cone test meets or exceeds a particular percentage (usually 100 percent) of the standard Proctor maximum density. This process is known as the specified density method (Mn/DOT Standard Specification 2105.3 F1).

While the specified density method is simple in theory and still widely practiced in the United States (using a nuclear density gauge), it presents a number of challenges for inspectors and designers. On a practical level, sand cone tests are time consuming, imprecise even when performed by skilled inspectors, difficult to perform in materials containing large aggregate particles, and responsible for placing inspectors in unsafe, low-visibility positions. The Proctor test is limited in that it determines the density of a variable material from a very small sample. Furthermore, the method is based on fitting a curve through a set of density and moisture content values, which are difficult to measure precisely. More Proctor tests could be performed to increase the statistical confidence, but this is impractical as the tests are time consuming (Davich *et al.*, 2006). In addition, the impact method of compaction and the energy applied during the standard Proctor test, which was first implemented more than half a century ago, does not accurately represent the range of compaction methods and energy levels applied on today's construction sites.

Other problems with the specified density method arise from the pavement performance perspective. While relatively easy to understand, a material's density can be a poor indicator of performance compared to parameters such as stiffness and strength, which are sensitive to both moisture content and stress state. Variations in density can have relatively large effects on the properties that determine pavement performance. Therefore, the errors that accumulate during the specified density procedure have the potential to greatly influence the load bearing capacity of the soil. Lastly, design engineers would be better equipped to adapt pavement designs to differing conditions, soil classifications, construction methods, and other innovations if stiffness and strength parameters were used in place of density.

To take advantage of these possibilities, highway agencies, universities, and equipment manufactures have developed in-situ test devices designed to measure the strength and stiffness, particularly modulus, of compacted materials. These devices use several methods to calculate modulus. Some, such as the light weight deflectometer (LWD) and the falling weight deflectometer (FWD), use falling weights to generate a soil response. Other tests, such as the soil stiffness gauge, apply a vibration to the soil. The dynamic cone penetrometer (DCP) and rapid compaction control device (RCCD), drive a cone into the soil to produce a measure of shear strength. Whether measuring density, modulus, or shear strength, the moisture content remains a critical quality control parameter for all compaction operations regardless of the quality control and quality assurance test methodology. Therefore, the moisture content needs to be measured, or estimated with a high degree of confidence, at each location.

1.2 DCP Background

Mn/DOT has used an aggregate base quality assurance specification for the DCP since 1998. The DCP is a non-destructive testing device used for estimating shear strength. The falling mass on the DCP drops from a specific height, providing a constant energy that drives the cone into the pavement foundation material. The depth that the DCP penetrates per drop is known as the DCP penetration index (DPI). Through empirical relationships the DPI is used to estimate the shear strength and modulus of unbound materials.

The original DCP specifications were designed for use on aggregate base. This specification was modified to take gradation and moisture effects into account in order to increase its accuracy and expand its applications to other granular materials. Both the grading number and moisture content have a strong influence on the DPI, therefore target DPI values are determined according to a soil's grading number and moisture content (Oman, 2004). Appendix J details this modified procedure, which is currently in use.

1.3 LWD Background

The falling weight deflectometer (FWD) is a larger trailer mounted device that estimates the in-situ modulus of a material using the impulse load produced by the impact of a falling weight. FWDs are particularly useful for estimating the moduli of asphalt, aggregate base, granular subbase and subgrade pavement layers. These trailer-mounted units began to appear in the United States in the 1990s after initial development in Europe. These devices use a large weight, load cell, and several geophones to calculate the layer moduli through a back-calculation procedure and are most commonly used to investigate pavement moduli following construction of the complete pavement structure.

While FWDs work well on finished pavement structures, they are difficult to use on aggregate base, granular subbase, and soil subgrade due to the irregular surface and the difficulty of maneuvering them on a construction site. Therefore, a second generation of portable falling weight deflectometer devices was developed to meet this need. This device, now commonly referred to as a light weight deflectometer (LWD) (ASTM E 2583-07), consists of a lighter mass (often 10 kg), an accelerometer or geophone, and a data collection unit. LWDs are designed to be light enough to be moved and operated by one person. They are often used to spot check unbound material compaction in some parts of Europe, and are just beginning to be used in the United States (White *et al.*, 2007).

Mn/DOT has purchased many LWD devices and is in the process of refining specifications for their use. An important issue that has arisen during the implementation of LWD technology is whether or not it is necessary to measure, or if it is acceptable to estimate, the load generated by the falling weight. This load estimation is not necessary for all LWD models because some include a load cell that measures the load versus time during impact. Other LWDs use one fixed peak load estimate established during trial testing in the laboratory (see Appendix B and C).

LWD quality assurance procedures offer several advantages over the specified density method. On a practical level, LWD tests take less time, have greater precision, and are able to accurately test more material types (large aggregate creates problems for other tests). In addition, LWD testing is safer because the field inspector is able to remain standing and visible during most of the testing process (Davich *et al.*, 2006).

1.4 Definitions

There is some ambiguity regarding the terminology applied to quality assurance testing and mechanistic pavement design. To provide consistency, the following terms have been defined (Newcomb and Birgisson, 1999):

• *Dynamic Modulus* – The maximum axial stress applied to a material in sinusoidal loading divided by the maximum axial strain occurring during that loading.

• *Elastic Modulus* – The applied axial stress divided by the resulting axial strain within the linear range of stress-strain behavior of a material.

• *Modulus of Subgrade Reaction* – The applied stress imposed by a loaded plate of a specified dimension acting on a soil mass divided by the displacement of the plate within the linear portion of the stress-deformation curve.

• *Resilient Modulus* – The stress generated by an impulse load divided by the resulting recoverable strain after loading.

• *Shear Strength* – A combination of a material's interparticle friction and its cohesion in resisting deformation from an applied stress. This is the largest stress that the material can sustain.

• *Stiffness* – A qualitative term meaning a general resistance to deformation. It is often used interchangeably with elastic modulus, modulus of subgrade reaction, and resilient modulus. It largely determines the strains and displacements of the subgrade as it is loaded and unloaded.

1.5 DCP Equipment

The structure of the DCP consists of two vertical shafts connected to each other at the anvil (ASTM D 6951-03). The upper shaft has a handle and hammer. The handle is used to provide a standard drop height of 575 mm (~22.6 in) for the hammer as well as a way for the operator to easily hold the DCP vertical. The hammer is an 8 kg mass (~17.6 lb) that provides a constant impact force. The lower shaft has an anvil at the top and a pointed cone on the bottom. The anvil is to stop the hammer from falling any further then the standard drop height. When the hammer is dropped and hits the anvil, the cone is driven into the ground. Photos of the DCP are shown in Figure 1.1.

Figure 1.1. Photos of the dynamic cone penetrometer

There are a few options available for the DCP, which include changing the mass of the hammer, type of tip, and recording method. The standard hammer is 8 kg in mass, with an option for 4 kg. For pavement applications, the 8 kg mass is used due to the highly compacted soil. The DCP tip can either be a replaceable point or a disposable cone. The replaceable point stays on the DCP for an extended period of time until damaged, and is then physically taken off and replaced. The disposable cone remains in the soil after every test, making it easier to remove the DCP. A new disposable cone must be placed onto the DCP before the next test. The methods to gather data from the DCP are either a meter stick or an automated ruler. The meter stick can be attached or unattached to the DCP. The automated ruler provides equivalent results as the meter stick and allows for a single operator instead of two. It also electronically records the data, making it more practical to record the penetration for each drop of the hammer and transfer the data to other computing devices.

1.6 LWD Equipment

There are several types of LWDs, the following is a general description of the overall structure (Figure 1.2). Moving from top to bottom, the handle is used to keep the shaft vertical. Next along the shaft is a release trigger, which holds the mass in place prior to dropping, thereby, ensuring a standard drop height. The mass is dropped to provide an impact force. Buffers, made of either rubber pads or steel springs, catch the falling mass and transfer the impact force to the loading plate. Below the buffers is a measurement device that measures the deflection, and for some models the force, when the mass is dropped. On the bottom there is a loading plate, which must be in full contact with the ground.

Figure 1.2. Photo of light weight deflectometer

Seven LWD models have been (or are being) used in Minnesota. There are a variety of differences between these devices, as shown in Table 1.1. Some have a fixed drop height, while others have adjustable drop heights. Some measure deflection using an accelerometer fixed inside the load plate, while others use a geophone that passes through a hole on the bottom of the plate to directly contact the unbound material. Some assume a peak load value established during trial testing, while others include a load cell.

Table 1.1. LWD models

Model	Company	Current Mn/DOT Use	Load Cell	Geophone	Accelerometer	Wireless	Adjustable Drop Height	Adjustable Mass	Adjustable Plate Size
Loadman I	Al-Eng Oy				X				
Loadman II	Al-Eng Oy	X	X		X				X
ZFG 2000	Gerhard Zorn	X			X				
Prima	Carl Bro	X	X	X		X	X	X	X
LWD v1	Dynatest/ Keros	X	X	X		X	X	X	X
LWD 3031	Dynatest/ Keros	X	X	X		X	X	X	X
Mini FWD	Keros		X	X			X	X	X

1.7 DCP Test Procedure

The DCP test procedure is currently standardized by both ASTM D 6951-03 and the Mn/DOT Grading and Base Manual. The following is a brief description of the test procedure.

First, the equipment should be inspected for any fatigue or damaged parts, and that all connections are securely tightened. The operator holds the device vertical by the handle on the top shaft. A second person records the height at the bottom of the anvil in reference to the ground. The operator lifts the hammer from the anvil to the handle, then releases the hammer. The second person records the new height at the bottom of the anvil. In general, this process is repeated until twelve drops are preformed, two for the seating, five for the first DPI calculation, and another five for the second DPI calculation. The DCP should be taken out of the newly formed hole using an extraction jack. If the tip is disposable, hitting the hammer lightly on the handle is acceptable.

Small penetration rates represent good compaction of the soil. The current methods of compacting pavement foundation material involve building many thin individually compacted layers (less than 12 inches or 30 centimeters). This causes the material closer to the surface to be less confined and less compacted then the deeper material. Therefore, the deeper into the soil the DCP penetrates, typically, the stronger the material. For this reason, the DPI is calculated three times; once near the surface (seating drops), and twice more using the deeper drops.

$$DPI_{Seating} = \frac{D_2 - D_{initial\,reading}}{2\ drops} \quad [1.1]$$

$$DPI_1 = \frac{D_7 - D_3}{5\ drops} \quad [1.2]$$

$$DPI_2 = \frac{D_{12} - D_8}{5\ drops} \quad [1.3]$$

where:

DPI = DCP penetration index [mm/drop]

$D_{\#}$ = depth of penetration after drop number # [mm]

The above equations, for DPI, come from Mn/DOT Grading and Base Unit personnel who are currently updating the Grading and Base Manual. The process described above for calculating the DPI will become standard once the new version is published. The DPI_1 value describes the soil near the surface, while the DPI_2 value describes the deeper soil. The modulus of the soil can be estimated using the following equation:

$$E_{DPI} = 10^{3.04758 - [1.06166 \log(DPI)]} \quad [1.4]$$

where:

E_{DPI} = modulus [MPa]

DPI = DCP penetration index [mm/drop]

Equation 1.4 is for standard DCP equipment only: drop height of 575 mm, and a hammer mass of 8 kg. Transportek, a South African research organization, derived the equation from rigorous testing (Lockwood *et al.*, 1992).

1.8 LWD Test Procedure

LWD devices are configured and used differently depending on the model and testing agency. The purpose of the details provided in this section is to make certain that LWD test procedures in the state of Minnesota are standardized. ASTM has recently published a national standard (ASTM E 2583-07).

In a recent report, White *et al.*, 2007, several different LWDs were tested and compared in order to determine how their measurements compare. Some of the differences discussed in the report were: manufacturer, plate diameter, measurement of applied force, and type of deflection sensor. In all Zorn LWDs, the applied force from the falling weight is measured in the factory and used for all future modulus calculations for that particular LWD. Equation 1.5 can be used to estimate the applied load for Zorn LWDs.

$$F_Z = \sqrt{2 \times m \times g \times h \times k} \qquad [1.5]$$

where:

F_Z	=	estimated force [N]
m	=	mass of falling weight [kg]
g	=	acceleration due to gravity [9.81 m/s^2]
h	=	drop height [m]
k	=	spring constant [362396.2 N/m]

Other LWDs include a load cell to measure the load, and combine this load with the deflection to estimate the modulus for each drop. Although it is inevitable that the applied force will not be the same for materials of different stiffnesses, White reported that the "assumption of constant applied force does not lead to significant variations in the estimated modulus" (White *et. al.*, 2007). Please see Appendix B and C of this LRRB Investigation 860 Report for additional discussion and conclusions.

Another factor that affects the estimated modulus in all LWDs is the plate size. Equations 1.6 and 1.7 show the commonly used calculations used to estimate the modulus (Davich *et al.*, 2006).

$$E_{LWD} = 2r_p\sigma(1-\nu^2)\frac{(1\times10^6)R}{\Delta} \qquad [1.6]$$

$$\sigma = \frac{F}{1000\pi r_p^2} \qquad [1.7]$$

where:

E_{LWD}	=	Young's modulus [MPa]
r_p	=	plate radius [m]
σ	=	peak stress applied to the soil [MPa]
ν	=	Poisson's ratio of the soil
R	=	plate rigidity
Δ	=	peak soil deflection [μm]
F	=	peak force applied to the soil [kN]

White *et al.,* 2007 concludes that the greatest factor affecting LWD modulus values estimated by different LWD models stems from the different types of sensors used. Accelerometers, combined with double integration (used in Zorn models), were shown to measure larger deflections, while geophones combined with single integration (used in Keros and Prima models), measured smaller deflections. On average, the study found that Keros moduli were about 1.75 times greater than Zorn moduli when the drop height, mass, and plate size were constant.

A previous study completed by Mn/DOT recommended standardizing the LWD mass at 10 kg (22.0 lb), the drop height at 50 cm (19.7 in), and the plate diameter at 20 cm (7.9 in) for ease of use and in order to have an appropriate influence to test for a lift of compacted pavement foundation material (Davich *et al.*, 2006). Plate size affects the measurement depth, confinement, and stress level applied to stress dependent materials. Standardizing LWD plate size to 20 cm reduces these variables and allows target modulus to be determined. LWD tests in Minnesota are currently conducted using that configuration, along with the following test guidelines and advice contained in the manufacturer's literature.

Prior to placing the LWD on the material to be tested, the surface is leveled. Particularly loose or rutted surface material should be removed to a depth of 10 to 15 centimeters. Three seating drops are performed prior to data collection to make certain that plastic deformation of the surface material does not affect the measurement. Once the LWD has been seated, the data collection should consist of five measurement drops. The five values resulting from these measurement drops are averaged to create one mean value for that test location. The operator will often notice that the modulus values increase slightly during the five measurement drops at a fixed height. If this increase exceeds 10 percent it is probable that the material has not been adequately compacted. Reliable values cannot be measured until the roller completes additional compaction.

LWD devices should not be used when the temperature falls below 5 degrees Celsius (41 degrees Fahrenheit) to ensure that the device's components, particularly the rubber buffers, work as intended. There is no practical upper limit on the temperature. While most LWDs will work in the rain, it should be noted that moisture greatly affects the strength and stiffness characteristics of the unbound materials. It is always necessary to measure the moisture content in conjunction with every test using an in-situ moisture testing device or by removing a sample for an oven-dry test.

When control strips are used to determine the LWD target value, it is important that the layer structure of the control strip matches the layer structure at the LWD test locations during construction. This is because deeper layers within the pavement foundation affect LWD measurements, even though the primary depth of influence is approximately equal to the plate diameter.

Chapter 2 - Soil Descriptions

This chapter describes the granular material and fine grained soils used in this report. The granular material was tested during a Mn/DOT study sponsored by the LRRB (Davich *et al.*, 2006). The fine grained soil was tested during a University of Minnesota study sponsored by Mn/DOT (Swenson *et al.*, 2006).

2.1 Granular Material Description

Mn/DOT District personnel collected granular material samples from different construction sites throughout Minnesota in order to represent each of the eight districts. Fifteen different samples were collected and compared at the Office of Materials. The gradation, optimum moisture content, and standard Proctor maximum density were measured on the granular samples. Of the fifteen samples collected across Minnesota, eight of the samples were chosen for further testing and analysis in Davich *et al.*, 2006 and those same samples are included in this report.

Those eight samples were combined into blended groups of two or three samples creating three blended group samples for testing. The group sample with the largest amount of percent fines was labeled FHJ. In comparison to FHJ, the blended sample DN was a relatively coarse-grained and well-graded with the least percent fines. The blended sample KLO's gradation falls between the gradations of DN and FHJ, but was slightly more similar to DN. The gradation plots of the samples are shown in Figure 2.1. Index properties of the three blended samples are shown in Table 2.1.

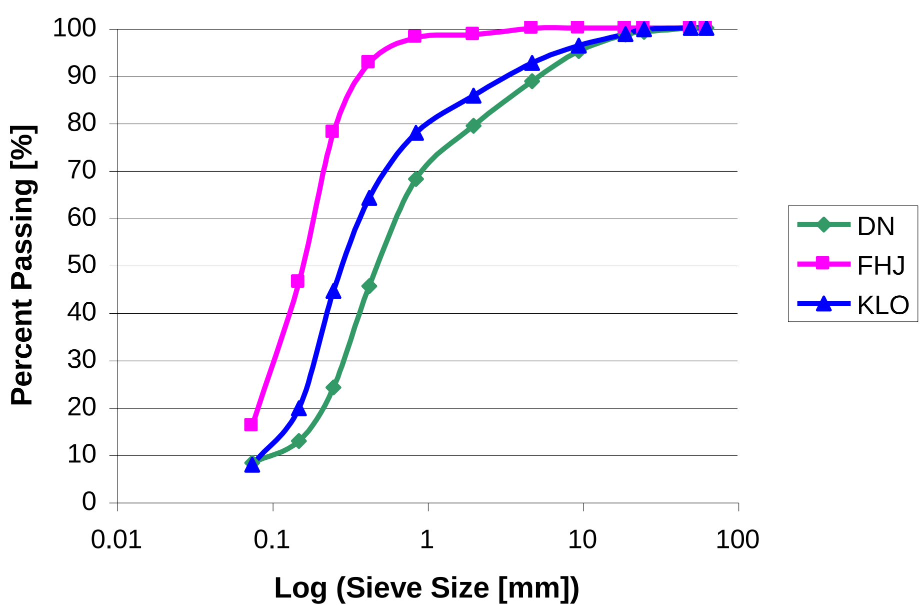

Figure 2.1. Plot of granular sample gradations

Table 2.1. Select granular and granular index properties

Sample	Mn/DOT Class	Grading Number	% Fines [%]	Optimum Moisture Content [%]	Maximum Density Standard Proctor [kg/m^3]
DN	Select Granular	5.1	7.6	8.1	1942.4
FHJ	Granular	6.1	16.0	10.3	1753.4
KLO	Select Granular	5.4	10.6	8.8	1874.2

2.2 Granular Material Preparation

The three different granular samples were each prepared and tested at three different moisture contents. The three different moisture contents were aimed to be below, near, and above the optimum moisture content obtained with the standard Proctor test. The compaction effort was adjusted to obtain the desired density within each of the different moisture contents of the sample. The densities were targeted to be equal to or greater than 100 percent of the standard Proctor test "relative maximum" density. The specimens' densities ranged from 99 to 111 percent of the standard Proctor maximum density. A total of twenty-two different test specimens were prepared. Of these, six were prepared using the select granular sample denoted as DN, eight were prepared using FHJ, and eight were prepared using KLO. The measured values for each specimen are shown in Table 2.2.

These specimens were prepared in a steel cylinder (i.e. bottom-half of a 55-gallon barrel). The specimens were compacted using a scaled-up Proctor hammer, which was used to apply different compaction energies. The scaled-up Proctor hammer is a 23.1 kg (51 lb) hammer dropped from a height of 84.45 cm (33.25 in) producing a compactive effort of 200 kNm/m^3 (4133.3 lbf-ft/ft^3). Four sand cone and thirteen oven-dry moisture content measurements were performed on each specimen in order to verify that these targets were reached uniformly with in the specimen containers. Furthermore, the density of the entire barrel was calculated to verify the accuracy of the sand cone measurements.

Table 2.2. Select granular and granular moisture contents and densities

Specimen	Grading Number	Optimum Moisture Content [%]	Actual Moisture Content [%]	Percent of Optimum Moisture Content [%]	Standard Procotr Density [kg/m^3]	Barrel Density [kg/m^3]	Relative Barrel Compaction [%]
DN05	5.1	8.1	5.1	62	1942.4	1988.6	103
DN5	5.1	8.1	5.1	63	1942.4	-	-
DN07	5.1	8.1	6.4	79	1942.4	2042.8	105
DN7	5.1	8.1	7.2	89	1942.4	1950.7	100
DN10	5.1	8.1	10.0	123	1942.4	1999.1	103
DN10X2	5.1	8.1	10.0	123	1942.4	1976.2	102
DN10S	5.1	8.1	9.7	119	1942.4	1984.9	102
DN10C	5.1	8.1	9.2	113	1942.4	2076.0	107
FHJ8	6.1	10.3	7.8	75	1753.4	1763.9	101
FHJ8X1.125	6.1	10.3	7.5	73	1753.4	1819.8	104
FHJ8X1.333	6.1	10.3	8.0	77	1753.4	1945.3	111
FHJ8X2	6.1	10.3	8.1	78	1753.4	1839.3	105
FHJ10	6.1	10.3	9.5	92	1753.4	1790.6	102
FHJ11	6.1	10.3	10.6	103	1753.4	1801.9	103
FHJ11X.5	6.1	10.3	11.4	111	1753.4	1772.5	101
FHJ13	6.1	10.3	12.7	124	1753.4	1790.1	102
KLO7	5.4	8.8	7.1	80	1862.3	1847.3	99
KLO7X1.33	5.4	8.8	7.1	80	1862.3	1936.6	104
KLO8X1.5	5.4	8.8	7.9	90	1862.3	1962.8	105
KLO9	5.4	8.8	8.9	102	1862.3	1881.3	101
KLO9X.5	5.4	8.8	8.8	100	1862.3	1881.8	101
KLO10	5.4	8.8	10.5	119	1862.29	1915.5	103
KLO10X.5	5.4	8.8	10.3	117	1862.3	1916.3	103
KLO11	5.4	8.8	12.0	137	1862.3	1868.6	100

The specimens were labeled by their sample group, moisture content, and compaction effort. The letters in the specimen label identify the blended granular group. The first number represents the target moisture content. The last number, following an "X" in the name, is the multiplication factor that describes the relative change in compaction energy. The initial compaction energy was targeted at 600 kN-m/m^3 (12,400 lbf-ft/ft^3), the standard Proctor effort which corresponds to X1. For example X2 indicates that the compaction energy was 2 times 600 kN-m/m^3 or 1200 kN-m/m^3 (24,800 lbf-ft/ft^3).

2.3 Fine Grained Soil Description

The fine grained soil samples under analysis in this report were collected by Mn/DOT and provided to the University of Minnesota. In order to represent the range of fine grained soils found in Minnesota, samples were obtained from four locations across the state: MnROAD, Duluth, Red Wing, and Red Lake Falls. Figure 2.2 and Table 2.3 include the gradation plots and index parameters for these four samples.

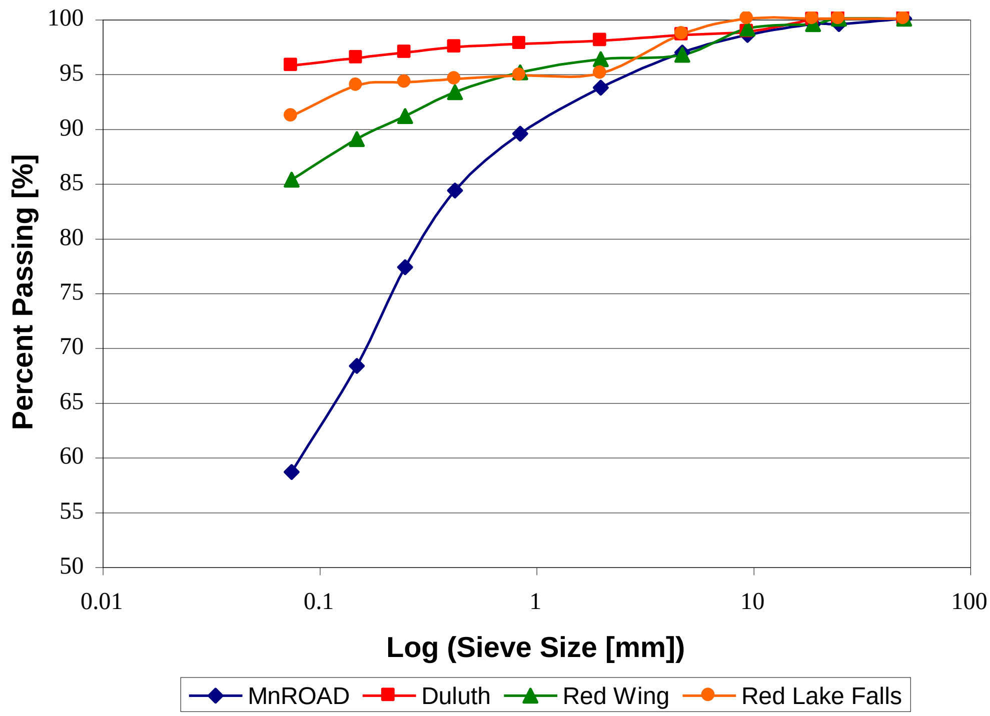

Figure 2.2. Plot of fine grained soil gradations

Table 2.3. Fine grained index parameters

Name	MnROAD		Duluth		Red Wing		Red Lake Falls			
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1*	Trial 2	Trial 3	Trial 4
Standard Proctor Dry Unit Weight [kg/m^3]	1720.1	1684.9	1447.8	1436.6	1789.0	1785.8	1720.1	1592.0	1527.9	1547.1
Optimum Moisture Content [%]	16.1	14.4	26.5	27.0	13.2	13.2	16.3	20.4	22.7	22.4
Liquid Limit [%]	25.8	30.5	84.9	84.3	0.0	0.0	31.8	44.4	48.4	48.9
Plastic Limit [%]	16.4	17.4	32.9	32.6	0.0	0.0	21.7	21.1	23.8	21.9
% Silt	45.3	46.0	21.2	16.9	80.4	82.4	67.0	63.8	51.4	44.1
% Clay	14.5	12.6	75.2	78.8	4.8	5.7	24.3	27.3	41.6	49.0
R-Value	17.5	15.6	12.4	9.3	54.6	52.9	25.6	17.0	10.7	9.3
Mn/DOT Textural Classification	L	L	C	C	Si	Si	SiCL	SiCL	C	C
AASHTO Group	A-4	A-6	A-7-6	A-7-6	A-4	A-4	A-4	A-7-6	A-7-6	A-7-6

*Results from Red Lake Falls, Trial 1, did not represent soil sample well enough to include in this analysis.

Two trials were done on each sample to verify that the index parameters were a good representation of the soil. Results from Red Lake Falls differed significantly; therefore two additional trials were done. It was concluded that data from Red Lake Falls Trial 1 did not represent the sample well, therefore the Trial 1 test results were not used in further analysis.

2.4 Fine Grained Soil Preparation

In order to ensure uniformity of the samples prior to constructing specimens at the target moisture content and density, the following process was preformed. First, the soil was passed through a 1-inch sieve to break up any large clumps. Then, the soil was oven dried in a pan for twenty-four hours at 250°F (211.1°C) to eliminate any pre-existing moisture. Lastly, the soil was pulverized to ease mixing as water was added to reach the target moisture (Swenson *et al.*, 2006).

Specimens were prepared at three different moisture contents and two different densities; resulting in a total of twenty-four specimens. The target values for the moisture contents were determined using a percentage of the optimum moisture content. The target densities were 98 and 103 percent of standard Proctor for all specimens excluding MnROAD, which targeted 100 and 105 percent. The average of two moisture and two density tests from each specimen are shown in Table 2.4 (Swenson *et al.*, 2006).

Table 2.4. Fine grained specimen moisture content and density values

Specimen	Location	Optimum Moisture Content [%]	Target Percent Optimum Moisture Content [%]	Target Moisture Content [%]	Actual Moisture Content [%]	Percent of Optimum Moisture Content [%]	Standard Proctor Density [kg/m³]	Target Percent Standard Proctor [%]	Target Density [kg/m³]	Actual Density [kg/m³]	Standard Proctor [%]
1	MnROAD	15.3	90	13.7	14.1	92	1702.5	105	1787.6	1752.0	103
2	MnROAD	15.3	70	10.7	11.2	73	1702.5	105	1787.6	1678.0	99
3	MnROAD	15.3	50	7.6	7.7	50	1702.5	105	1787.6	1670.0	98
4	MnROAD	15.3	100	15.3	15.6	102	1702.5	100	1702.5	1659.0	97
5	MnROAD	15.3	80	12.2	11.5	75	1702.5	100	1702.5	1685.0	99
6	MnROAD	15.3	60	9.2	10.9	71	1702.5	100	1702.5	1587.0	93
7	Duluth	26.8	90	24.1	23.6	88	1442.2	103	1485.5	1484.0	103
8	Duluth	26.8	75	20.1	19.2	72	1442.2	103	1485.5	1444.0	100
9	Duluth	26.8	60	16.1	17.4	65	1442.2	103	1485.5	1505.0	104
10	Duluth	26.8	100	26.8	26.1	98	1442.2	98	1413.4	1399.0	97
11	Duluth	26.8	80	21.4	22.0	82	1442.2	98	1413.4	1387.0	96
12	Duluth	26.8	60	16.1	16.3	61	1442.2	98	1413.4	1409.0	98
13	Red Wing	13.2	90	11.9	11.3	86	1787.4	103	1841.0	1700.0	95
14	Red Wing	13.2	75	9.9	9.4	71	1787.4	103	1841.0	1777.0	99
15	Red Wing	13.2	60	7.9	8.4	64	1787.4	103	1841.0	1725.0	97
16	Red Wing	13.2	100	13.2	12.4	94	1787.4	98	1751.7	1613.0	90
17	Red Wing	13.2	80	10.6	10.1	77	1787.4	98	1751.7	1721.0	96
18	Red Wing	13.2	60	7.9	8.4	64	1787.4	98	1751.7	1705.0	95
19	Red Lake Falls	21.8	90	19.7	16.3	75	1555.7	103	1602.3	1640.0	105
20	Red Lake Falls	21.8	75	16.4	13.3	61	1555.7	103	1602.3	1697.0	109
21	Red Lake Falls	21.8	60	13.1	10.6	49	1555.7	103	1602.3	1665.0	107
22	Red Lake Falls	21.8	100	21.8	18.6	85	1555.7	98	1524.6	1609.0	103
23	Red Lake Falls	21.8	80	17.5	14.2	65	1555.7	98	1524.6	1614.0	104
24	Red Lake Falls	21.8	60	13.1	10.7	49	1555.7	98	1524.6	1494.0	96

The percent of optimum moisture content varied between 49 and 102 percent. The relative compaction for the specimens ranged from 90 to 109 percent of the standard Proctor maximum relative density (Swenson *et al.*, 2006).

Once the target moisture content and density was determined for a specimen, the soil was mixed with the appropriate amount of water to obtain the desired moisture content. Next, oven-dried tests were preformed on the specimens to determine the actual moisture content. Then the soil was compacted in a prismatic steel container, 23 x 23 x 15 in (~58.4 x 58.4 x 38.1 cm). The moist soil was required to have a volume of 3.2 ft^3 (90600 cm^3) to fill up the steel container to a 10.5 in. (~26.7 cm) depth. The compaction took place with three layers each compacted by a padfoot plate fixed to the crosshead of a load frame. The padfoot plate was used to apply some kneading action to the mostly static compaction method. Once the desired density was obtained the soil specimen was tested (Swenson *et al.*, 2006).

Chapter 3 - DCP for Select Granular and Granular Materials

3.1 Discussion

Tests were done to analyze select granular and granular materials using a dynamic cone penetrometer (DCP). The testing was preformed by Mn/DOT and first analyzed for the Davich *et al.*, 2006 report. Three different granular material samples were tested. The three samples consisted of sample DN with a low amount of percent fines, sample FHJ with a high amount of percent fines, and sample KLO with an amount of percent fines in-between the other samples. The descriptions and preparation of the test samples is explained further in Chapter 2.

A standard Mn/DOT DCP (ASTM D 6951–03) was used to measure the shear strength of the granular material. The DCP used had a 22 mm diameter replaceable cone tip, a 575 mm drop height, and an 8 kg falling mass. The DCP measurements consisted of two seating drops, followed by five measured drops. The top few inches of tested material was not as uniform, confined or as compacted as the material further down, so the data from the seating drops was recorded separately from the deeper measurement drops. The DCP penetration index (DPI) is the depth that the DCP travels per an amount of drops (Mn/DOT standard is currently three measurement drops for aggregate base and five measurement drops for select granular and granular materials). An example of the depth versus the DPI per each drop is displayed in Figure 3.1; more results can be viewed in Appendix G. This figure shows that the first few drops have a greater penetration due to the unconfined material close to the surface, thus requiring at least two seating drops.

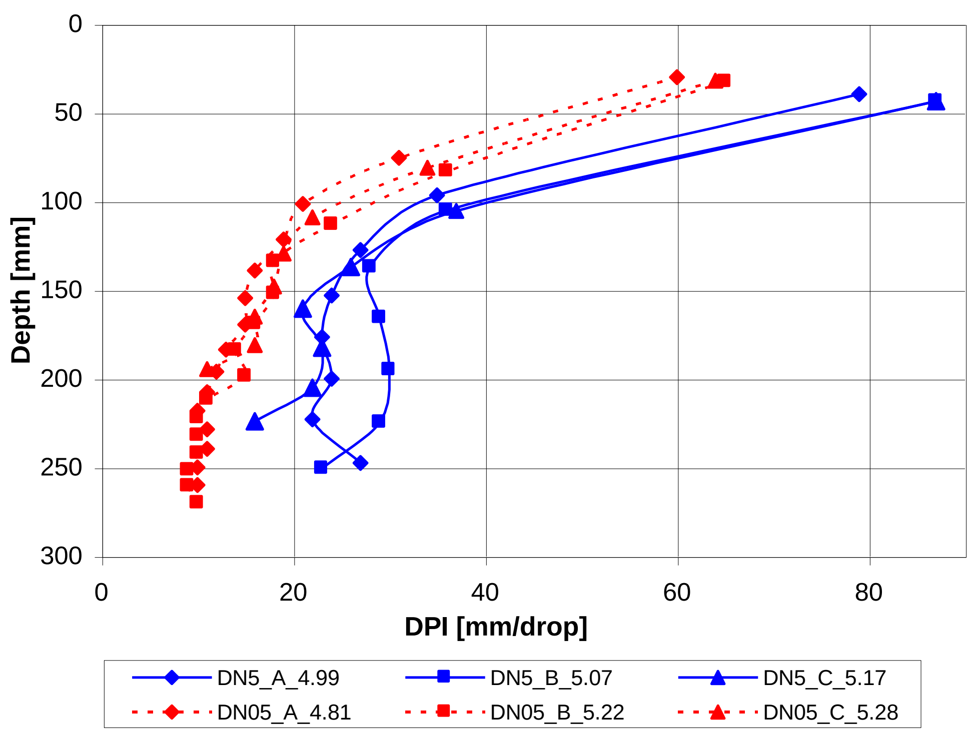

Figure 3.1. Sample DPI versus depth plot

DCP data from the select granular and granular material was analyzed in order to compare how estimates of the materials' modulus were affected by the number of seating drops and the equation used to calculate the DPI. The modulus was first calculated using the Mn/DOT's standard of first performing two seating drops and then calculating the DPI using the readings from the next five drops. In the second method, the modulus was calculated with the weighted average of the five drops that followed two seating drops. These two methods were found to produce similar results because of the small variation in the depth per drop. Therefore, when estimating the average modulus it is not necessary to weight the average using the depth of penetration per drop.

The modulus was also calculated by averaging the five drops that followed three seating drops. This was compared to the modulus results using only two seating drops. The comparison resulted in a significant increase of shear modulus values. This increase in modulus is visible in the select granular and granular material due to their lack of compaction and confinement near the surface. Therefore, it may be advisable to use three seating drops with granular material, as is done during the LWD procedure. The comparison of the different modulus estimates methods with respect to the standard averaging of the five drops after seating is shown in Figure 3.2.

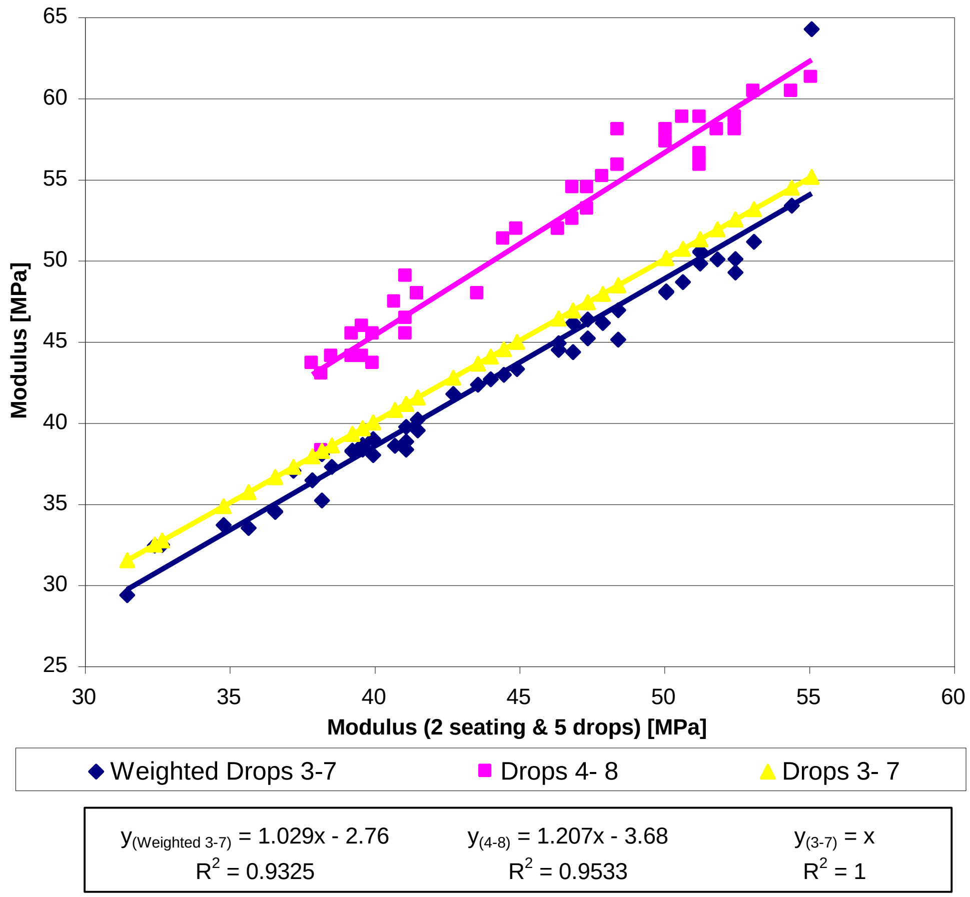

Figure 3.2. Effects of seating drops and weighting on the DPI

The DPI measurements can be used to estimate the modulus of a soil. However, it is more common that only the DPI values are calculated. Figures 3.3-3.5 display the effects of the percent of optimum moisture content and relative compaction on the average DPI values for the tested samples.

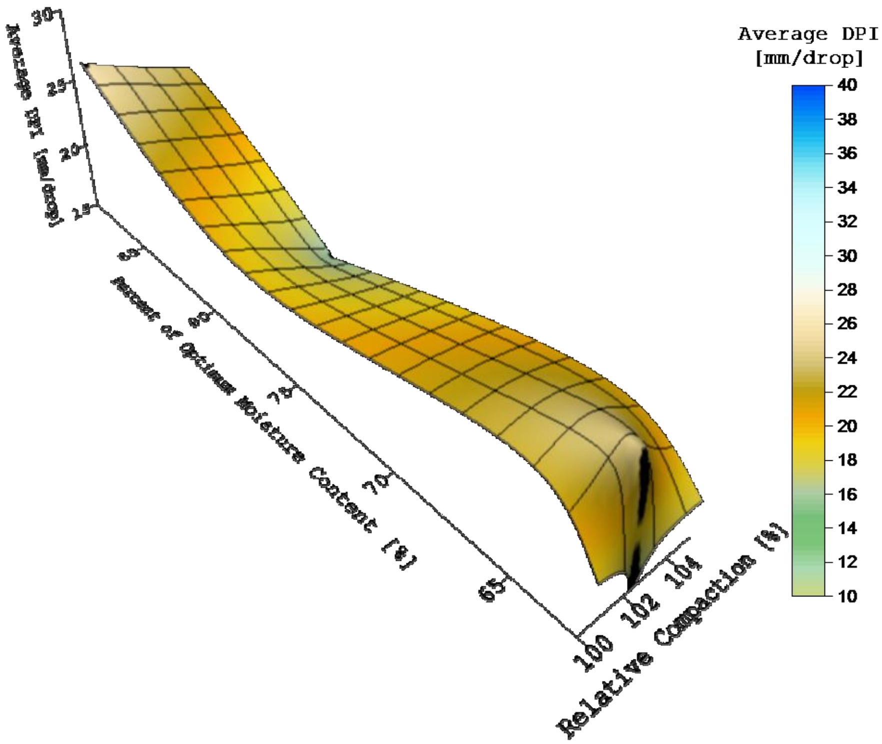

Figure 3.3. Effects of percent of optimum moisture content and relative compaction on average DPI for select granular sample DN

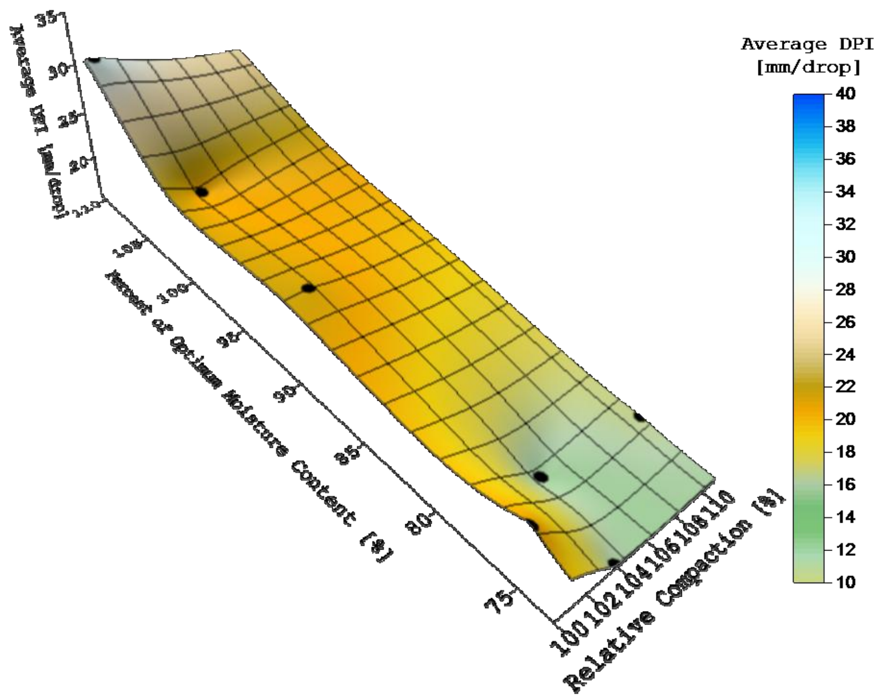

Figure 3.4. Effects of percent of optimum moisture content and relative compaction on average DPI for granular sample FHJ

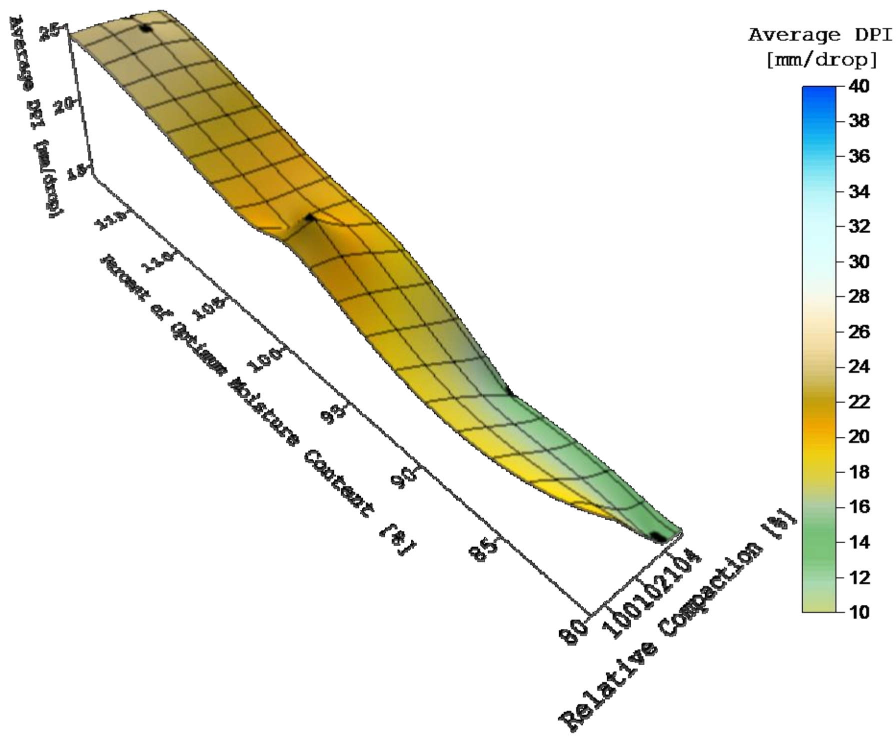

Figure 3.5. Effects of percent of optimum moisture content and relative compaction on average DPI for select granular sample KLO

The moduli were estimated using the DPI_1 value from Equation 1.6. Figures 3.6-3.8, are plots comparing the modulus, percent of optimum moisture content, and the relative compaction of select granular and granular material.

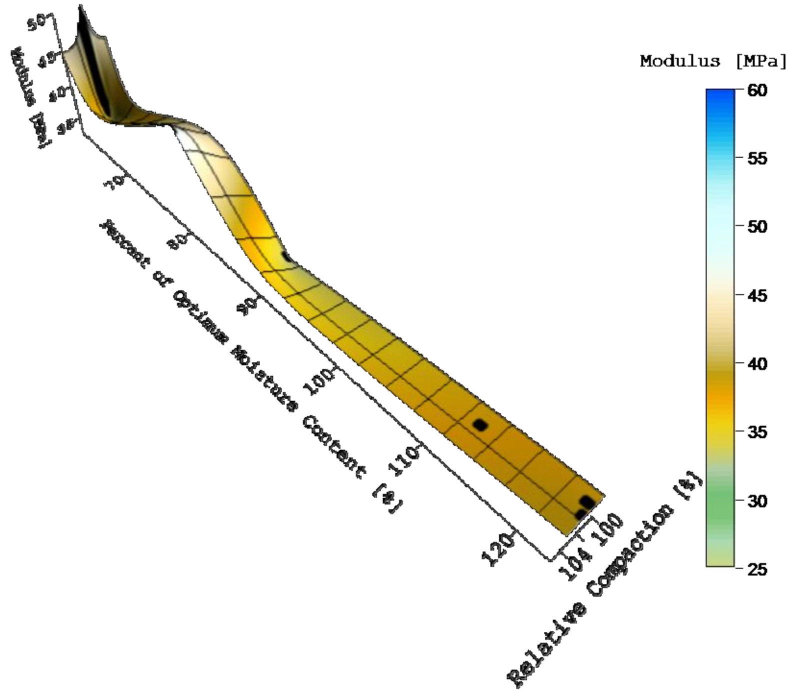

Figure 3.6. Effects of percent of optimum moisture content and relative compaction on DCP modulus for select granular sample DN

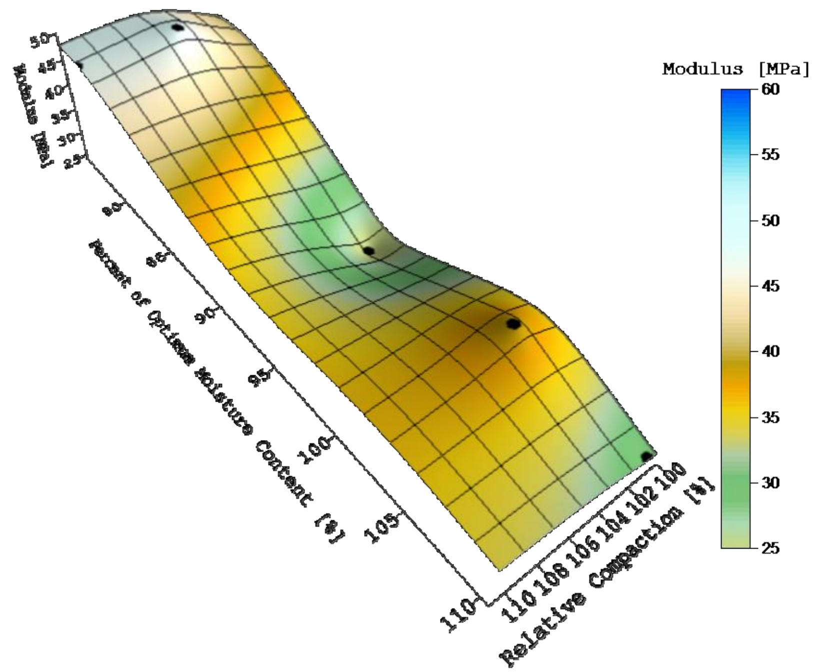

Figure 3.7. Effects of percent of optimum moisture content and relative compaction on DCP modulus for granular sample FHJ

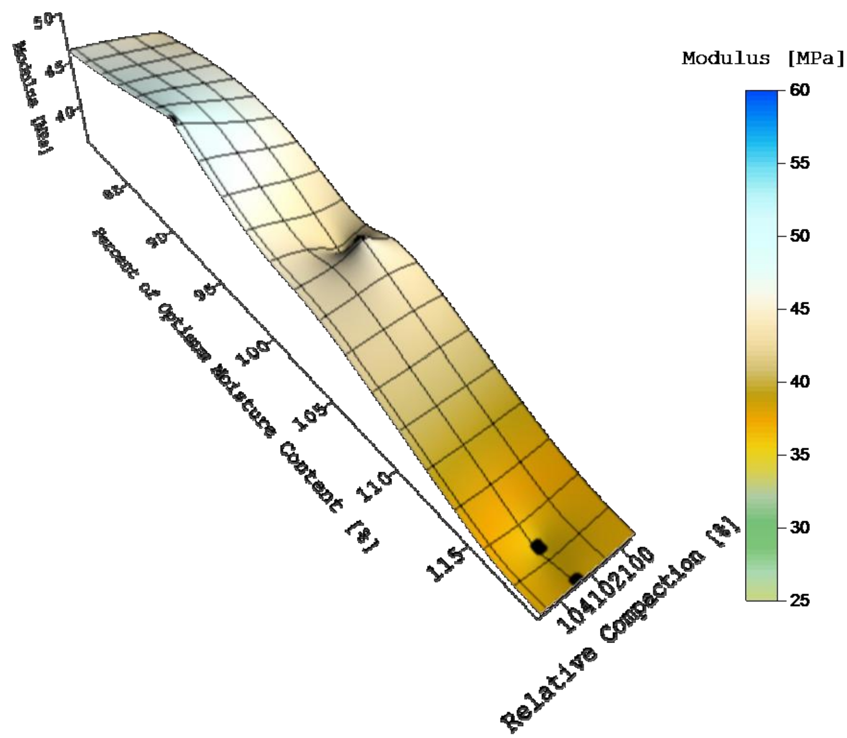

Figure 3.8. Effects of percent of optimum moisture content and relative compaction on DCP modulus for select granular sample KLO

As presented in Figures 3.3-3.5, the material weakens as the percent of optimum moisture content increases and therefore, both the penetration and DPI increase. Similarly, Figures 3.6-3.8 show that as the percent of optimum moisture content increases, the material weakens and the modulus decreases. In all three granular samples there is a sudden drop in strength and moduli around ninety percent of the optimum moisture content. This is more noticeable in the FHJ sample (Figure 3.7) than it is in the DN sample (Figure 3.6) or the KLO sample (Figure 3.8). The relationship between the moduli and the relative compaction is not as clear due to the limited range of density tested. The moduli shows a slight increase as the relative compaction increases on the FHJ sample (Figure 3.7) and sample KLO (Figure 3.8).

3.2 Conclusion

Figure 3.2 shows that the recommended number of DCP seating drops should be increased from two to three for granular and select granular materials. This should be considered for all DCP testing, and would also be consistent with the three seating drops required during LWD testing. Due to the narrow range of density acceptable during road construction, the moisture content has a more significant influence on the DCP penetration rate, and therefore, must be incorporated in the quality assurance procedures. Consequently, DPI target values are determined for moisture content ranges for a material defined by its grading number.

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Chapter 4 - LWD for Select Granular and Granular Materials

4.1 Discussion

The light weight deflectometer (LWD) was also used to test the same select granular and granular samples tested with the DCP explained in Chapter 3. The select granular and granular material tested consisted of three samples: DN with a low amount of percent fines, sample FHJ with a high amount of percent fines, and sample KLO with a percent fines in-between the other two samples. More details on the sample classifications and the preparation prior to testing can be viewed in Chapter 2.

The LWD used for this analysis was the Dynatest/Keros model, which incorporated the Mn/DOT standard 10 kg falling mass and 20 cm diameter base. The testing was done at the following drop heights: 25, 50, and 75 cm. The results and analysis on the drop height versus modulus can be found in Appendix D. For the analysis in this chapter, only the data collected from the Mn/DOT standard drop height of 50 cm was used. The LWD modulus shown is the average of three consecutive drops immediately following the two seating drops on the material. The modulus results from the material were plotted against the percent of optimum moisture content and relative compaction, as shown in Figures 4.1-4.3.

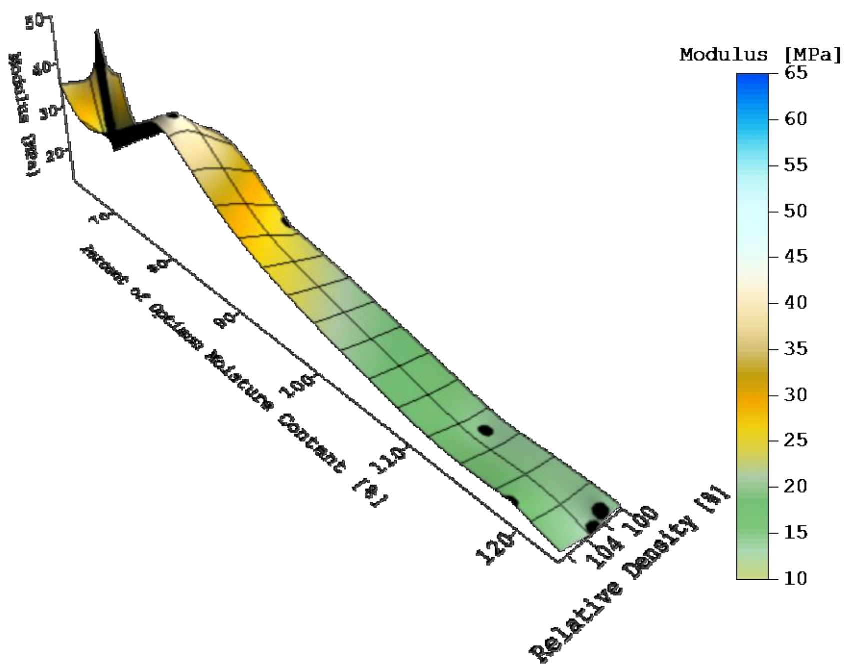

Figure 4.1. Effects of percent of optimum moisture content and relative compaction on LWD modulus for select granular sample DN

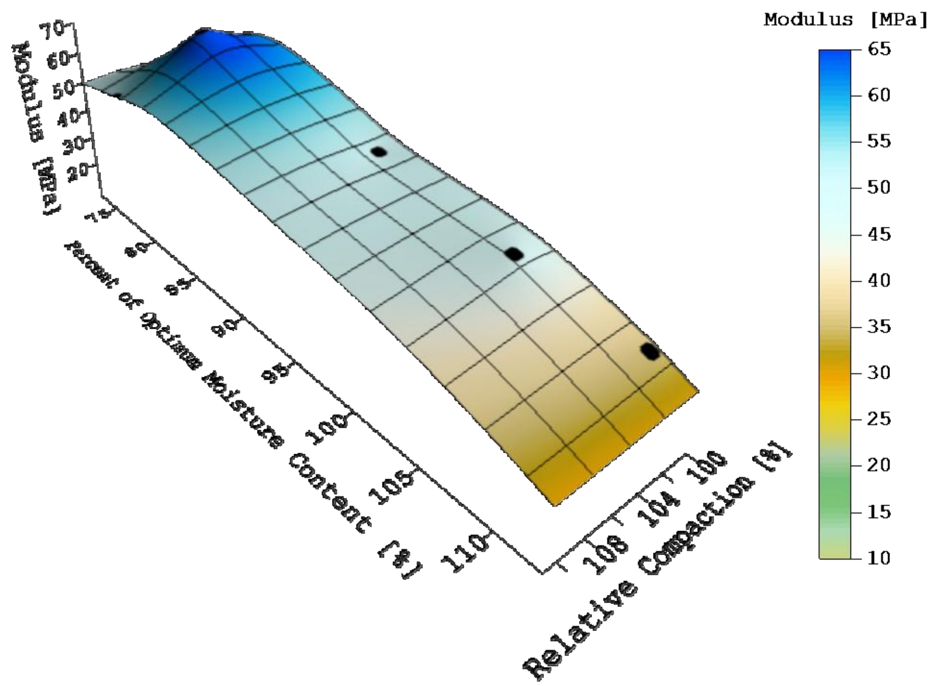

Figure 4.2. Effects of percent of optimum moisture content and relative compaction on LWD modulus for granular sample FHJ

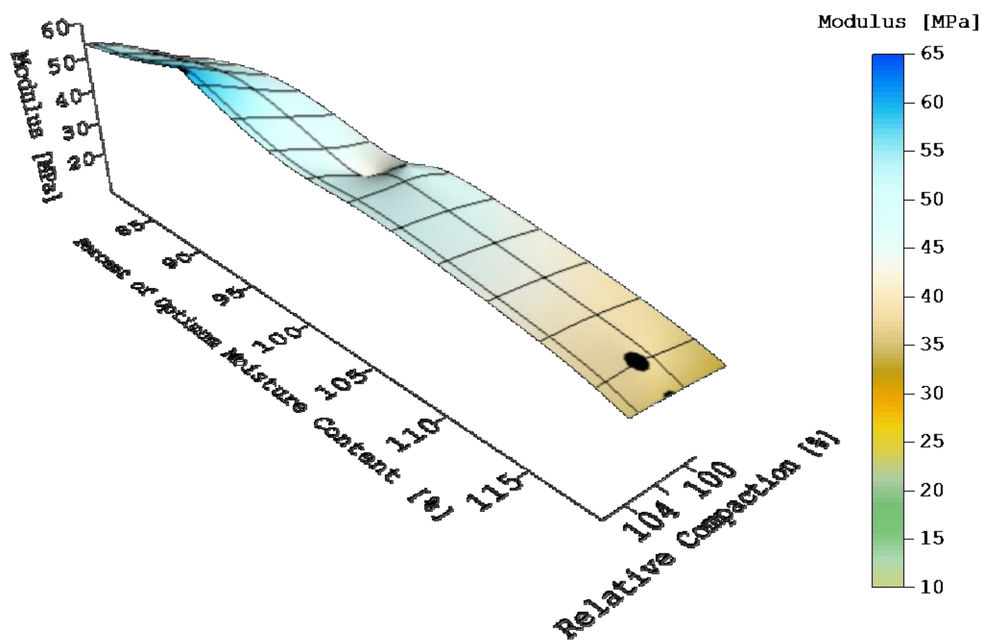

Figure 4.3. Effects of percent of optimum moisture content and relative compaction on LWD modulus for select granular sample KLO

Figures 4.1-4.3 illustrate that the moduli of the select granular and granular materials are influenced by the percent of optimum moisture and relative compaction. The percent of optimum moisture has a strong influence on the modulus; the modulus increases as the percent of optimum moisture decreases. The relative compaction also influences the modulus of the granular material, but to a much lesser degree for only a narrow range of densities are acceptable during road construction.

4.2 Conclusion

The moisture content and gradation have a significant influence on the LWD measured moduli. Therefore, LWD target values can be estimated for select granular and granular materials using the same method applied to the DCP (grading number and moisture content). It is also recommended that three seating drops be used during LWD testing prior to the three measurement drops.

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Chapter 5 - DCP for Fine Grained Soils

5.1 Discussion

The following is an analysis of dynamic cone penetrometer (DCP) measurements, preformed on fine grained soils, during the study done by Swenson *et al.*, 2006. In order to get a range of fine grained soils, four samples were taken from across the state of Minnesota. These locations were MnROAD (loam), Duluth (clay), Red Wing (silt), and Red Lake Falls (silty clay). See Chapter 2 for more information about the description and preparation of these soil samples.

A Mn/DOT standard DCP (ASTM D 6951-03) was used to collect the data for this study. The DCP used had a 22 mm diameter replaceable cone tip, a 575 mm drop height, and an 8 kg falling mass. As part of the Mn/DOT standard DCP procedure, two seating drops followed by five measurement drops were taken. Since the soil is less confined near the surface, the DCP was able to penetrate relatively further per drop, making the first two drops unreliable. Figure 5.1, a diagram of the DCP penetration index (DPI) versus depth, shows how the first drops do not accurately represent the average DPI. For this reason, the first two drops, known as the seating drops, are disregarded. Six DCP tests are shown in Figure 5.1. The red, green, and blue represent results for moisture contents of 71.5, 75.4, and 102.3 percent of standard Proctor optimum, respectively. Two DCP tests were performed in the specimens constructed at these moisture contents. Additional graphs on the effects of depth in DPI, for the tested materials, are presented in Appendix G.

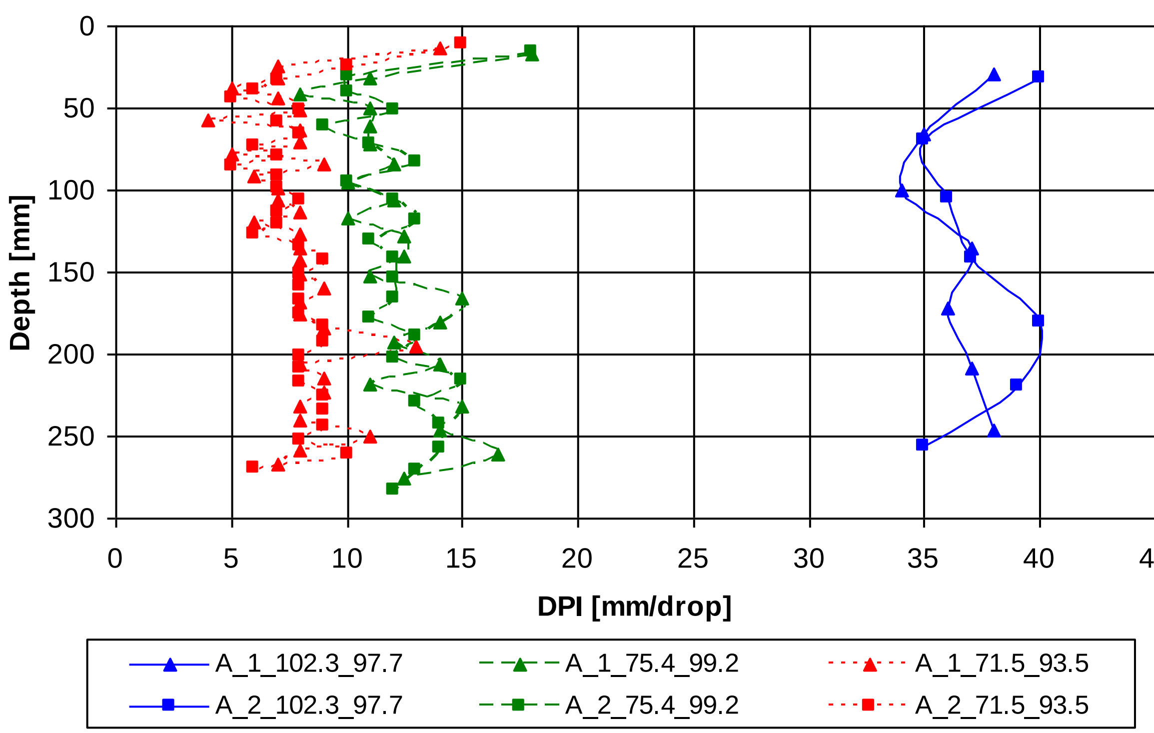

Figure 5.1. Sample DPI versus depth plot

The DPI results for fine grained soil are shown in Figures 5.2-5.5 in comparison to the percent of optimum moisture content and the relative compaction.

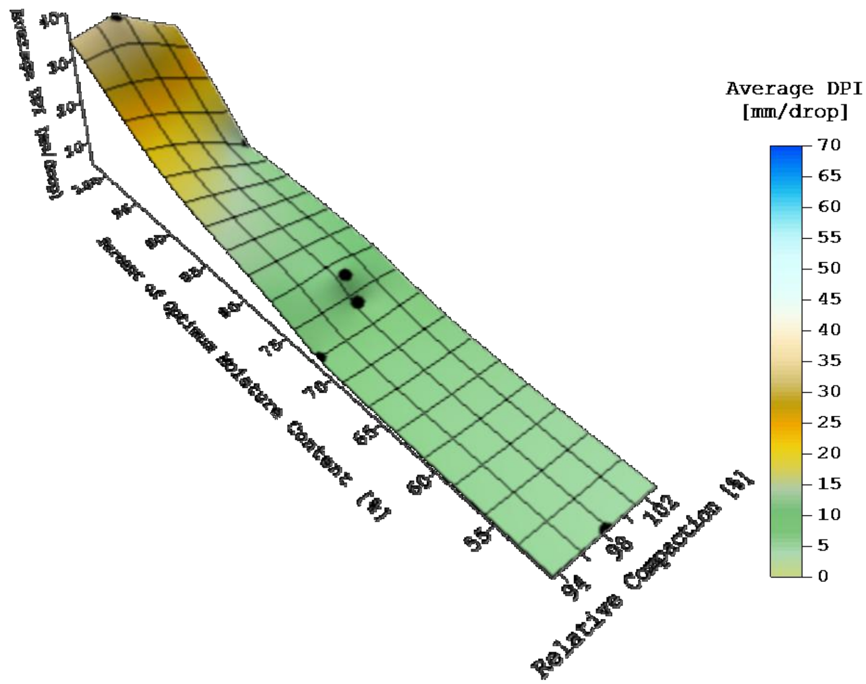

Figure 5.2. Effects of percent of optimum moisture content and relative compaction on average DPI for fine grained sample MnROAD

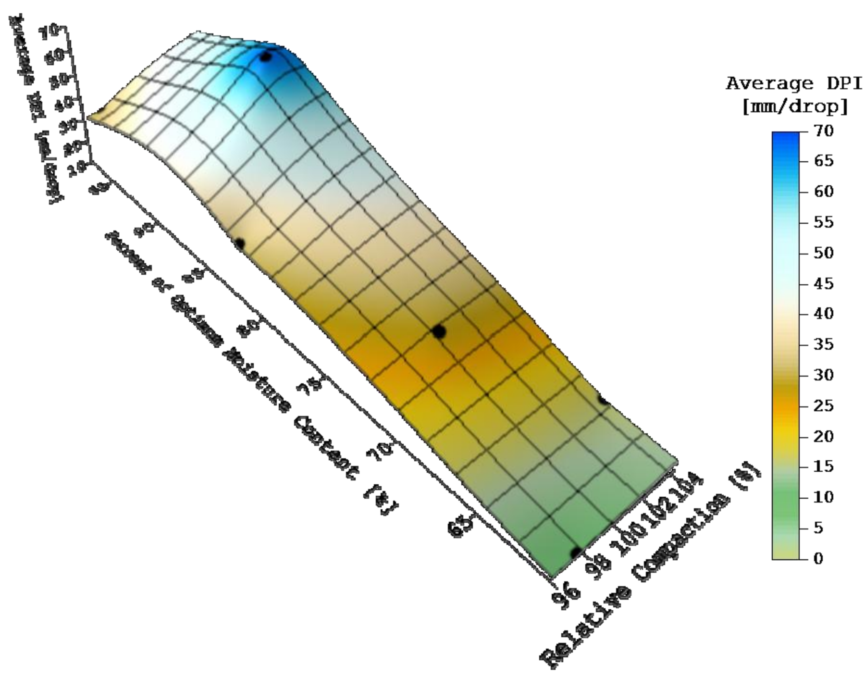

Figure 5.3. Effects of percent of optimum moisture content and relative compaction on average DPI for fine grained sample Duluth

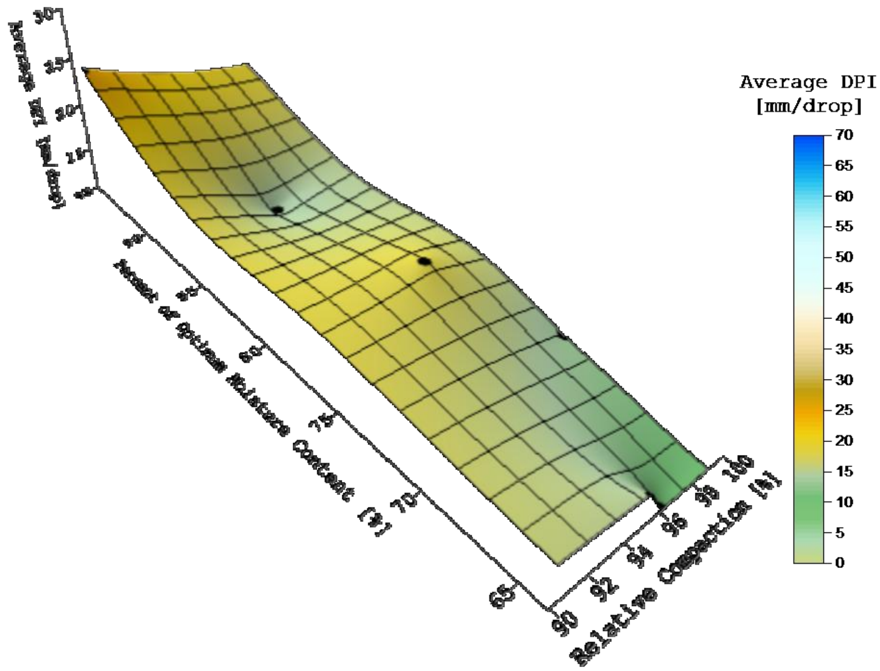

Figure 5.4. Effects of percent of optimum moisture content and relative compaction on average DPI for fine grained sample Red Wing

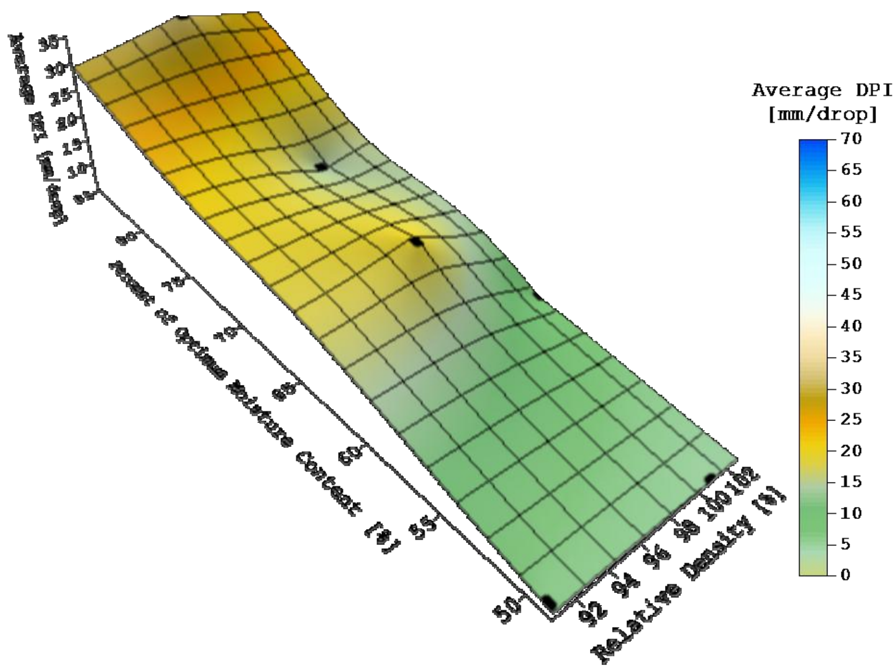

Figure 5.5. Effects of percent of optimum moisture content and relative compaction on average DPI for fine grained sample Red Lake Falls

Using the process described in Chapter 1, the DCP modulus is estimated using the DPI values in Equation 1.6. The DCP modulus of the soil in each of the tests was calculated and compared to the percent of optimum moisture content as well as the relative compaction. These comparisons are represented in Figures 5.6-5.9.

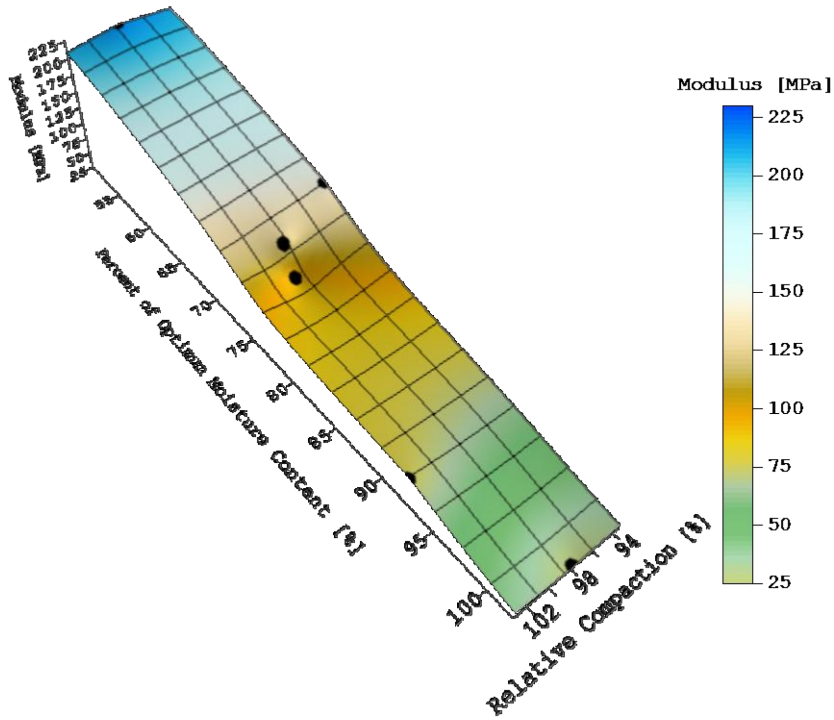

Figure 5.6. Effects of percent of optimum moisture content and relative compaction on DCP modulus for fine grained sample MnROAD

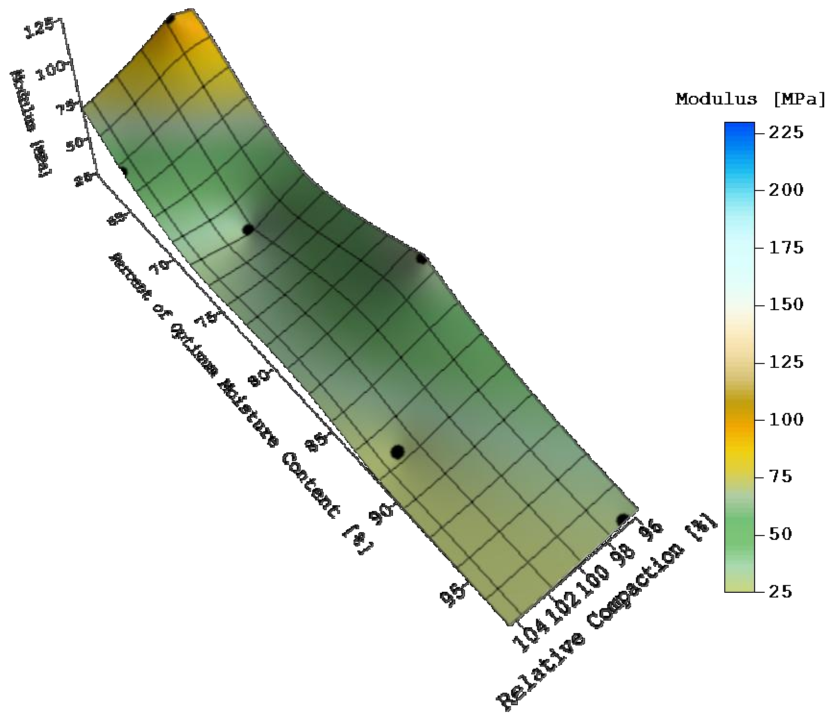

Figure 5.7. Effects of percent of optimum moisture content and relative compaction on DCP modulus for fine grained sample Duluth

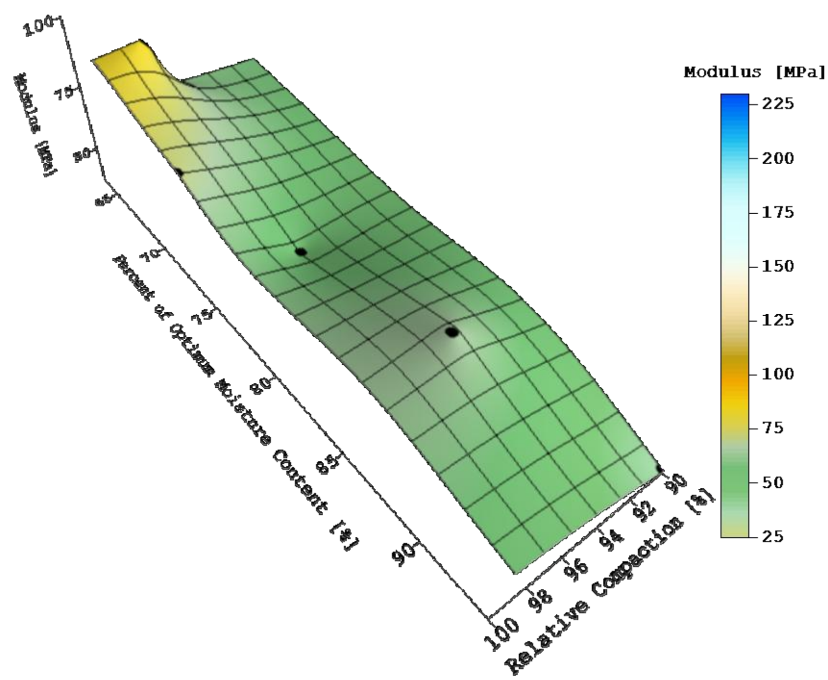

Figure 5.8. Effects of percent of optimum moisture content and relative compaction on DCP modulus for fine grained sample Red Wing

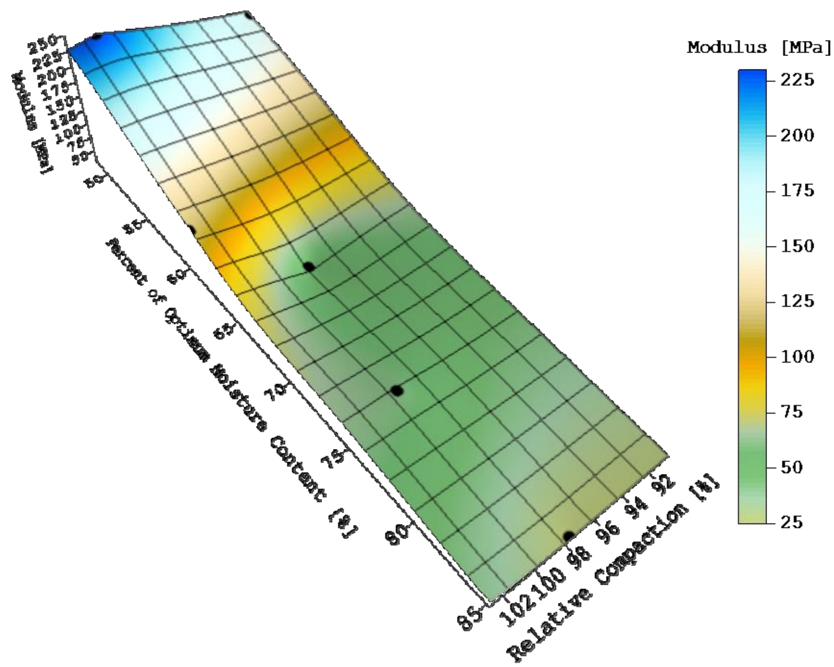

Figure 5.9. Effects of percent of optimum moisture content and relative compaction on DCP modulus for fine grained sample Red Lake Falls

As presented in Figures 5.2-5.5, there is a wide range of average DPI values varying from 5 to 70 mm/drop. Additionally as the percent of optimum moisture content increases, the DPI increases as well. Figures 5.6-5.9 illustrate that as the percent of optimum moisture decreases, the modulus increases, as expected. These moduli values range from 25 to 230 MPa. This can be explained by the unsaturated soil mechanics theory (Gupta *et al.*, 2007): as the soil dries, suction increases resulting in an increase in strength and stiffness. In terms of relative compaction, it is difficult to see a strong relationship with the modulus due to the narrow density range studied.

5.2 Conclusion

The moisture content and the soil type have a significant influence on the DCP penetration rate. Density is less important for the narrow acceptable range during road construction. Therefore, target DPI values can be estimated using the in-situ moisture content and a mechanistic-based description of soil type. Please see Appendix E for a description of how the plastic limit can be used to classify fine grained soil and estimate the optimum moisture.

Chapter 6 - LWD for Fine Grained Soils

6.1 Discussion

The following is an analysis of the light weight deflectometer (LWD) on fine grained soils, from the study done by Swenson *et al.*, 2006. Four soil samples from across Minnesota were used to represent a range of fine grained soils. These locations were MnROAD (loam), Duluth (clay), Red Wing (silt), and Red Lake Falls (silty clay). See Chapter 2 for more detailed information on the fine grained soil description and preparation.

A Prima 100 LWD was used for this study; it had a mass of 10 kg, and a plate diameter of 20 cm. For each specimen, five drops were performed at three different drop heights: 10, 50, and 90 cm (two seating drops, followed by three measurement drops). In this analysis, the modulus for each of the specimens was calculated only using values from a drop height of 50 cm, as recommended by Beyer *et al.*, 2007. An exception to this drop height was made for all MnROAD samples, as only drop height data from 90 cm was collected. For an in-depth analysis on the effects of drop height versus modulus, see Appendix D. Using the LWD testing procedure explained in Chapter 1, the modulus of the soil in each of the tests was calculated and compared to the percent of optimum moisture content and the relative compaction. These comparisons are represented in Figures 6.1-6.4.

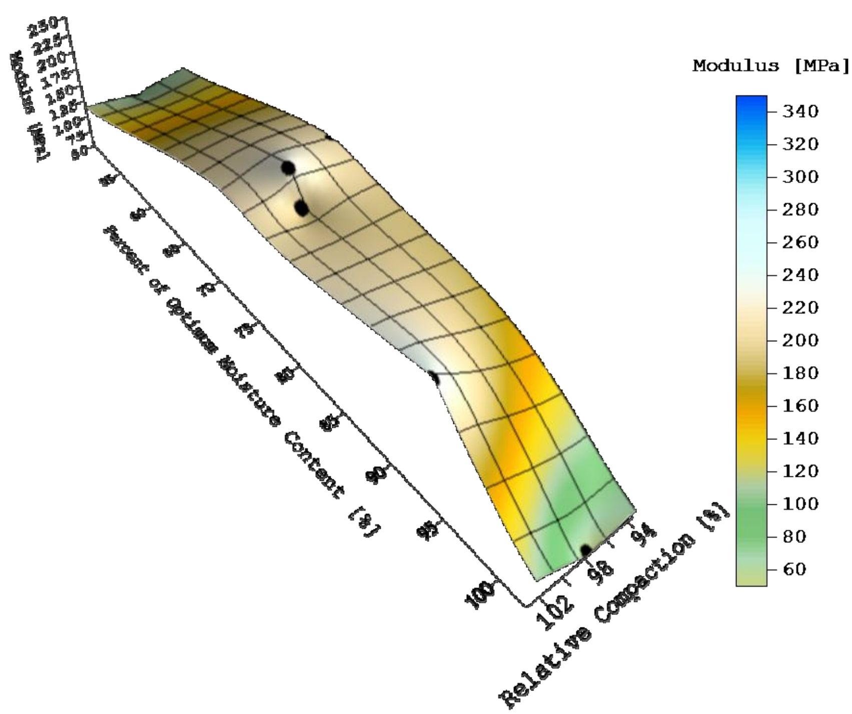

Figure 6.1. Effects of percent of optimum moisture content and relative compaction on LWD modulus for fine grained sample MnROAD

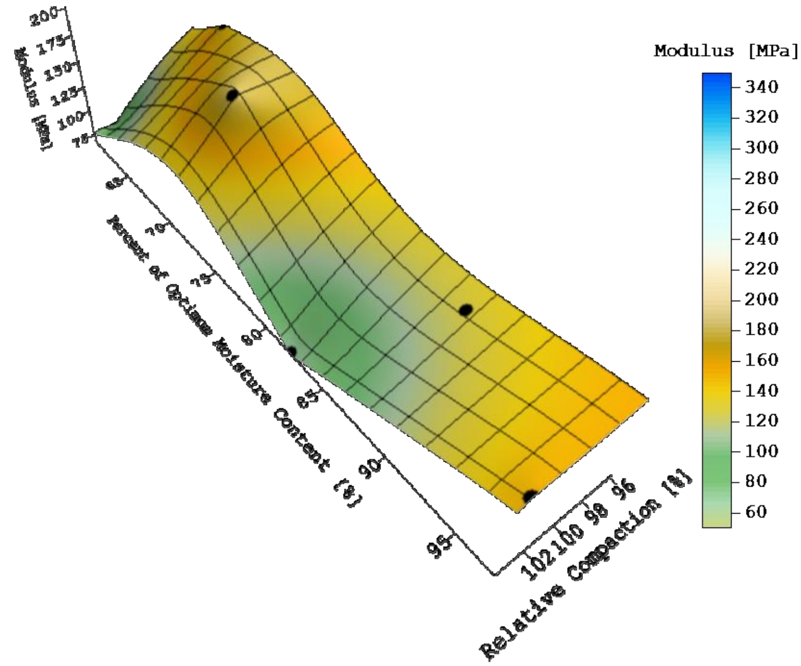

Figure 6.2. Effects of percent of optimum moisture content and relative compaction on LWD modulus for fine grained sample Duluth

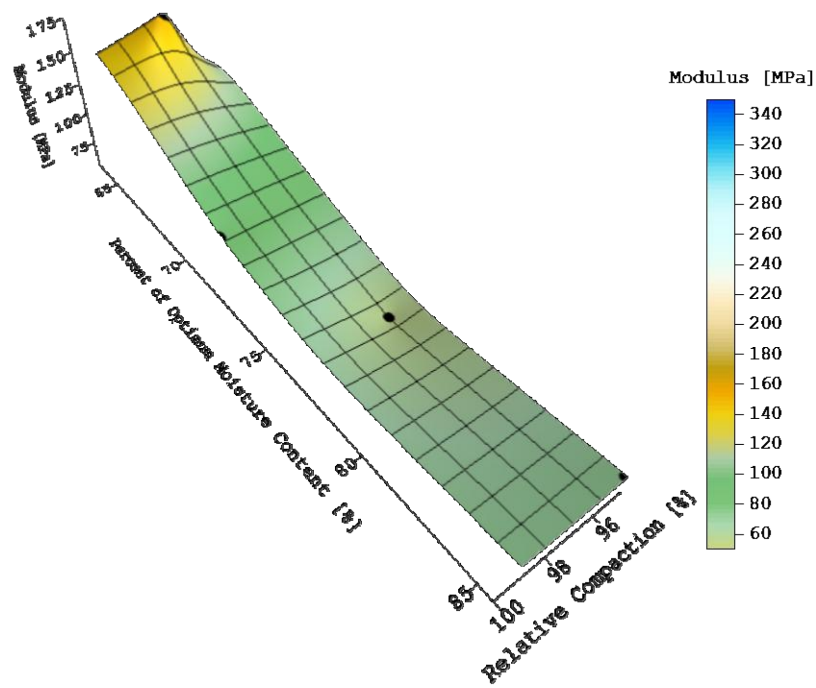

Figure 6.3. Effects of percent of optimum moisture content and relative compaction on LWD modulus for fine grained sample Red Wing

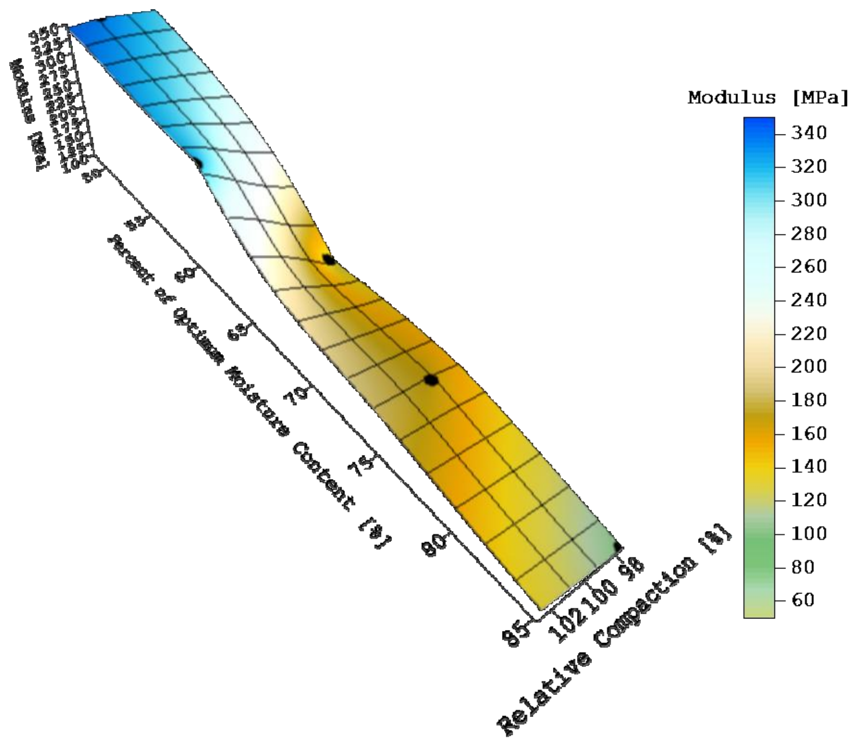

Figure 6.4. Effects of percent of optimum moisture content and relative compaction on LWD modulus for fine grained sample Red Lake Falls

6.2 Conclusion

By examining Figures 6.1-6.4, it can be seen that all of the specimens have highly varied modulus values, ranging from 50 to 350 MPa. In general the percent of optimum moisture decreases, the modulus of the soil increases. However, it should be noted that both the MnROAD and Duluth samples vary from this general trend slightly in some regions of Figures 6.1 and 6.2, respectively. The relative compaction has a low impact, due to the narrow range of density acceptable during road construction. Therefore, the target LWD values can be estimated using the in-situ moisture content and a mechanistic-based description of soil type. Please see Appendix E for a description of how the plastic limit can be used to classify fine grained soil and estimate the optimum moisture.

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Chapter 7 – Target Values and Conclusion

The Minnesota Department of Transportation (Mn/DOT) is currently improving the quality assurance testing methods for unbound materials during pavement construction. This is being done through the implementation of dynamic cone penetrometers (DCPs) and light weight deflectometers (LWDs). Standard testing procedures and model specifications for quality control and quality assurance are being developed for these devices. The objectives are to increase the accuracy, efficiency, and safety during construction testing.

7.1 Introduction

In this report, the unbound materials used in pavement construction were divided into two general groups: granular and fine grained. Granular material is identified as soil with up to 20 percent fines whereas fine grained soil is identified as having more than 20 percent fines. Note that the four different fine grained soils used in this report had fine percentages from about 50 to more than 90 percent. This means that soils with fines in the range of 20 to 50 percent have not been used in the preparation of this report. The DCP and LWD testing was performed on each group separately, ensuring coverage of a wide range of unbound materials. Fortunately, the granular and fine grained groups tested tend to bracket the DPI and LWD target values for materials with fines contents between 20 to 50 percent. The DCP can determine the shear strength and modulus using Equations 1.2 and 1.4. More commonly used, however, is the DCP penetration index (DPI), which is a measurement of how deep the DCP penetrates per drop. The LWD estimates the modulus directly by measuring the deflection due to the impact of a falling weight.

7.2 Granular Target Values

When determining target values of a compacted granular material, the grading number and moisture content are considered. A sieve analysis is used to determine the grading number, and an oven dry test or reagent test is typically performed to determine the moisture content. The grading number is the sum of the percentage of retained weight on particular sieves, as described in Appendix J. The modulus values for the LWD are calculated and reported directly by the display immediately after the time of impact. For the DCP, DPI target values are generally used or the modulus values are calculated using Equations 1.2 and 1.4. Figure 7.1 shows the target LWD and DCP modulus data points calculated during the testing phase of this report.

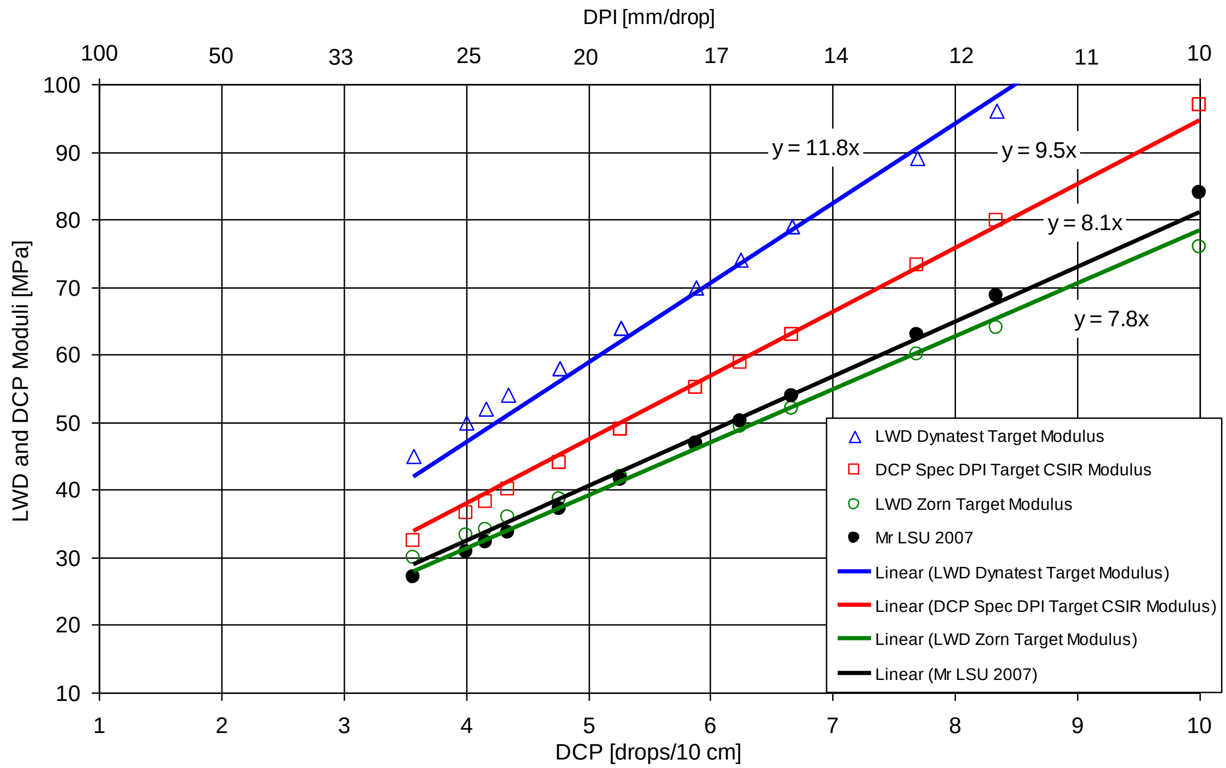

Figure 7.1. DCP and LWD modulus comparison

Table 7.1 provides the target DPI and LWD modulus values according to a material's gradation number and moisture content, derived from Figure 7.1. The modulus values for the Dynatest/Keros LWD were calculated from Equation 1.8. As such, there are two constants that were assumed: Poisson's ratio and the plate rigidity. For the Davich *et. al.*, 2006 report, the Dynatest/Keros LWD used a Poisson's ratio of 0.35 and a plate rigidity of 0.79. The Zorn LWD has these two constants set by the manufacturer: Poisson's ratio of 0.35 and a plate rigidity of 1.0. This difference between the two LWDs has a direct affect on the calculated moduli. Since all of testing that contributed to this report used the Dynatest/Keros model, values for the Zorn were to be calculated using a conversion factor of 1.75 (White *et. al.*, 2007). This, combined with the rigidity factor of 0.79, resulted in an overall conversion factor of 0.72.

Another option would be to use the deflection measured by the Zorn LWD as the target value and thus avoid the extra modulus calculations. A shortcoming of this approach is that the impact force must be specified within a relatively tight tolerance because the target deflections are dependant on the force applied. View Appendix D for a discussion on the influence of drop height (force) on deflection.

Table 7.1. Target DPI and LWD modulus values for granular materials

Grading Number	Moisture Content	Target DPI ♦	Target DPI Modulus	Target LWD Modulus Dynatest *†	Target LWD Modulus Zorn •†	Target LWD Deflection Zorn †‡
GN	%	mm/drop	MPa	MPa	MPa	mm
3.1-3.5	< 6	10	97	113	76	0.38
	6 - 8	12	80	96	64	0.45
	8 - 10	16	59	74	49	0.58
3.6-4.0	< 6	10	97	113	76	0.38
	6 - 8	15	63	79	52	0.55
	8 - 10	19	49	64	42	0.67
4.1-4.5	< 6	13	73	89	60	0.48
	6 - 8	17	55	70	47	0.61
	8 - 10	21	44	58	39	0.74
4.6-5.0	< 6	15	63	79	52	0.55
	6 - 8	19	49	64	42	0.67
	8 - 10	23	40	54	36	0.80
5.1-5.5	< 6	17	55	70	47	0.61
	6 - 8	21	44	58	39	0.74
	8 - 10	25	37	50	33	0.86
5.6-6.0	< 6	19	49	64	42	0.67
	6 - 8	24	38	52	34	0.83
	8 - 10	28	32	45	30	0.96

♦ Please see Appendix J for current DCP specification target values
* Keros/Dynatest LWD target values assume ν = 0.35, and D = 0.79
† All LWD target values assume falling mass = 10 kg, plate diameter = 20 cm, and drop height = 50 cm.
• Zorn LWD target modulus values assume ν = 0.5, and D = 1.0
‡ Zorn LWD target deflection values assume a constant force = 7.080 kN, poisson's ration = 0.5, plate rigidity = 1, and peak force = 6.0 kN resulting in a peak stress of 0.191 MPa (28 psi)

7.3 Fine Grained Target Values

The plastic limit and the moisture content are used to determine target values for the DPI and LWD modulus when evaluating the compacted condition of fine grained soil during embankment construction. In this case, the plastic limit is used in place of the grading number. For fine grained soils, a sieve analysis and a hydrometer test are time consuming; the plastic limit on the other hand is relatively simple and effective. The plastic limit test determines the particular water content at which a soil changes from solid to plastic consistency and begins to crumble when the soil is rolled into a three millimeter thread. The moisture content is then determined by an oven dry test or an alternative test. For this report, a standard Proctor test was used to determine the optimum moisture content. Appendix E demonstrates that using the plastic limit to estimate the optimum moisture content is also feasible. Table 7.2 demonstrates this concept and provides the target DPI and LWD modulus values according to the soil's plastic limit and moisture content (DCP and LWD testing by Swenson *et al., 2006)*.

The soils used by Swenson *et al.*, 2006 in the testing phase of this report were used to determine the target values in Table 7.2 for fine grained soils. Recall that four different soils from different locations from around the state were used: MnROAD, Duluth, Red Wing, and Red Lake Falls. The plastic limit was plotted against the percent of optimum moisture content to produce figures of DPI and modulus values. This method was used to create Figures 7.2 and 7.3, which show the target DPI as well as the target LWD modulus for the Prima 100 model LWD used by Swenson.

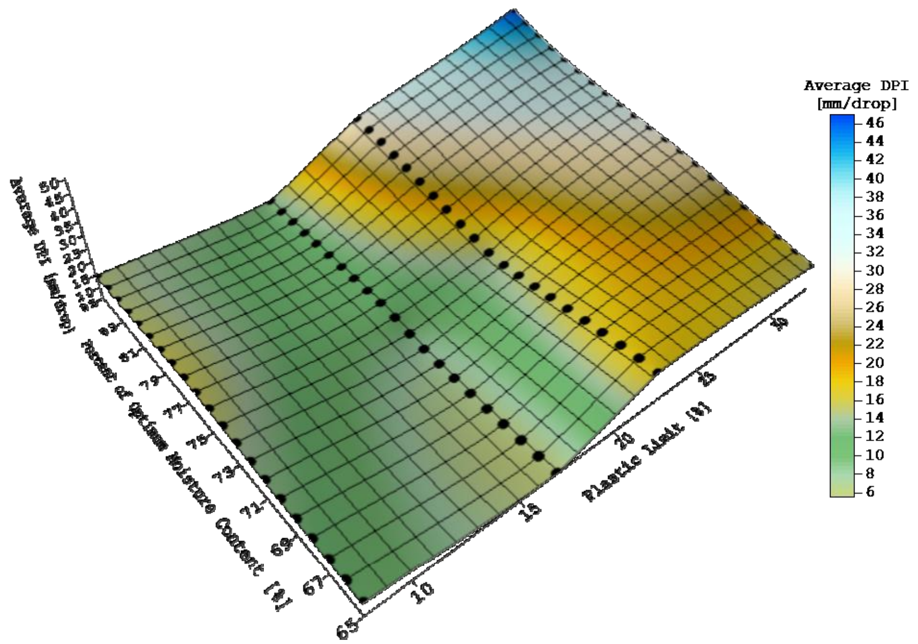

Figure 7.2. Effects of percent of optimum moisture content and relative compaction on average DPI target values for fine grained soils

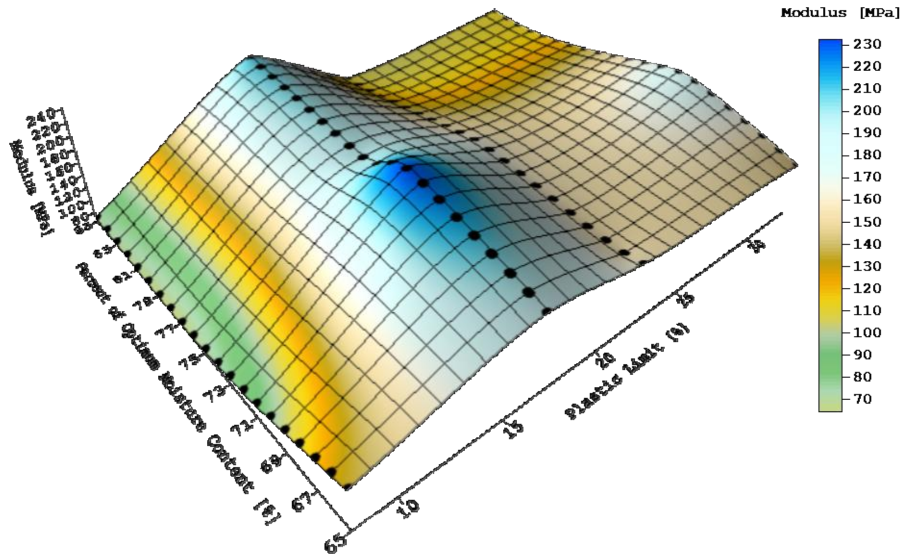

Figure 7.3. Effects of percent of optimum moisture content and relative compaction on LWD modulus values for fine grained soils

Figures 7.2 and 7.3 were incrementally split into sections defined by the plastic limit ranges shown in Table 7.2 and percent of optimum moisture content. The estimated optimum moisture content was also calculated as a reference for quick field use (for more details, please see Appendix E). For example, a soil with a plastic limit of 15 to 20 percent has an estimated optimum moisture content of 5 to 15 percent. When the field moisture content is 65 to 74 percent of optimum moisture content there is a target DPI of 11 mm/drop and a target LWD modulus of 190 MPa. In all, there are eight such divisions with different plastic limit and percent of optimum moisture content boundaries for each set of DPI and modulus values. From there, a large sampling of data points was extracted from each of these sections to produce the target values in Table 7.2. Note that the LWD testing for fine grained soils was performed with a Prima 100 model; this model had a 20 cm plate diameter, 10 kg falling mass, and a 50 cm drop height. More testing will be needed to determine the relationship between this LWD model and other LWD models used in Minnesota.

Table 7.2. Target DPI and LWD modulus values for fine grained soils

Plastic Limit	Estimated Optimum Moisture Content	Field Moisture as a Percent of Optimum Moisture	Target DPI at Field Moisture	Target DPI Modulus at Field Moisture	Target Zorn Modulus at Field Moisture
[%]	[%]	[%]	[mm/drop]	[MPa]	[MPa]
11-14	6-9	65-69	na	na	na
		70-74	na	na	na
		75-79	na	na	na
		80-84	6	167	120
		85-89	10	97	76
		90-94	24	38	34
15-18	10-13	65-69	6	167	120
		70-74	8	123	92
		75-79	10	97	76
		80-84	14	68	56
		85-89	24	38	34
		90-94	32	28	27
19-22	14-17	65-69	10	97	76
		70-74	12	80	64
		75-79	16	59	49
		80-84	24	38	34
		85-89	32	28	27
		90-94	40	22	22
23-26	18-21	65-69	14	68	56
		70-74	18	52	45
		75-79	24	38	34
		80-84	32	28	27
		85-89	40	22	22
		90-94	na	na	na
27-30	22-25	65-69	18	52	45
		70-74	24	38	34
		75-79	32	28	27
		80-84	40	22	22
		85-89	na	na	na
		90-94	na	na	na

These target values may be generally adequate for the Prima LWD, but since some of the sections have a wide range of DPI or modulus values, an averaged target value does not accurately represent the whole range of soil types and moisture contents within the particular plastic limit and percent of optimum moisture content, range described in Table 7.2. In order to select a more appropriate target value, a contour map was created. Instead of rigid increments, the contour map displays contour lines to achieve an accuracy of about 2 mm/drop. As was mentioned before, plastic limits less than 15 percent yield unreliable results. For this reason, this area of the figure was removed. Figure 7.4 shows the average DPI contours versus plastic limit and percent of optimum moisture content for fine grained soils.

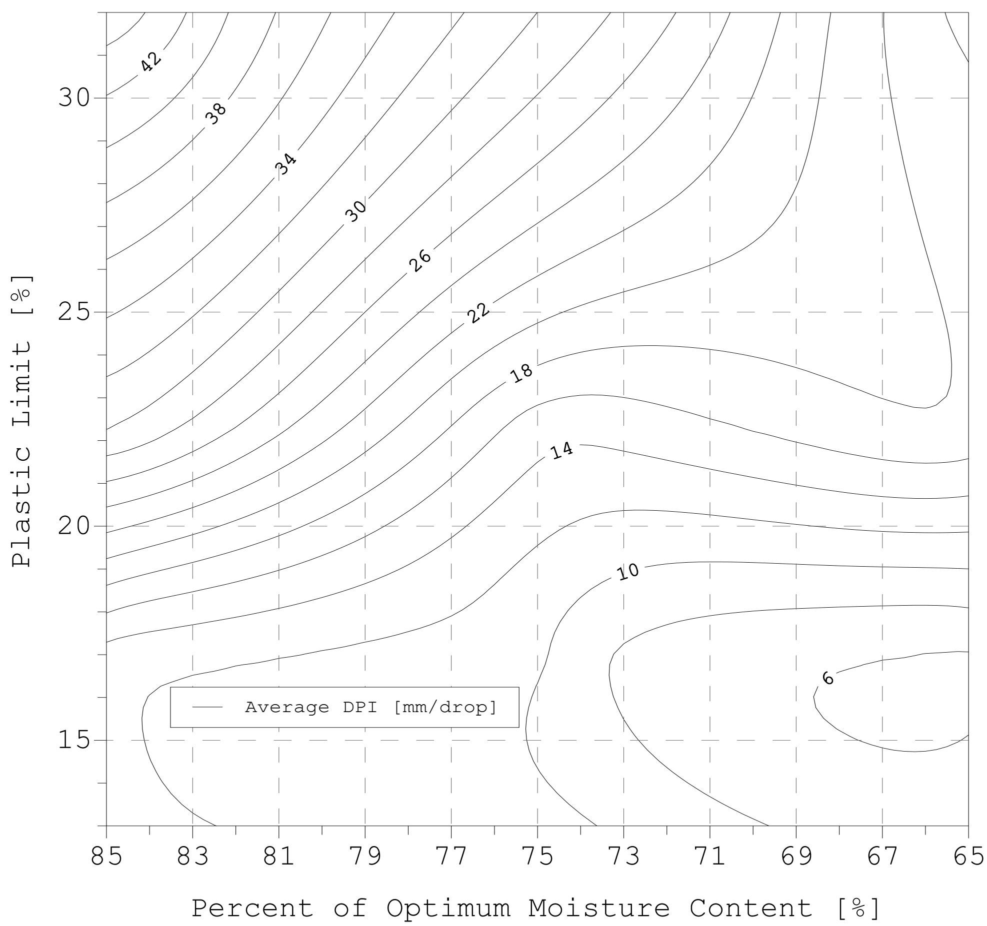

Figure 7.4. Average DPI versus percent of optimum moisture content and plastic limit for fine grained soils

As can be seen, the contours of Figure 7.4 are somewhat irregular. This is due to the fact that there is insufficient data in some regions of the plot. Using Figure 7.4 as a guide, Figure 7.5 shows average DPI target values that have been smoothed out. This was done to ease implementation and prevent the misinterpretation of the target values. Additional field verification testing will be required to validate and/or modify the target values determined using Figure 7.5.

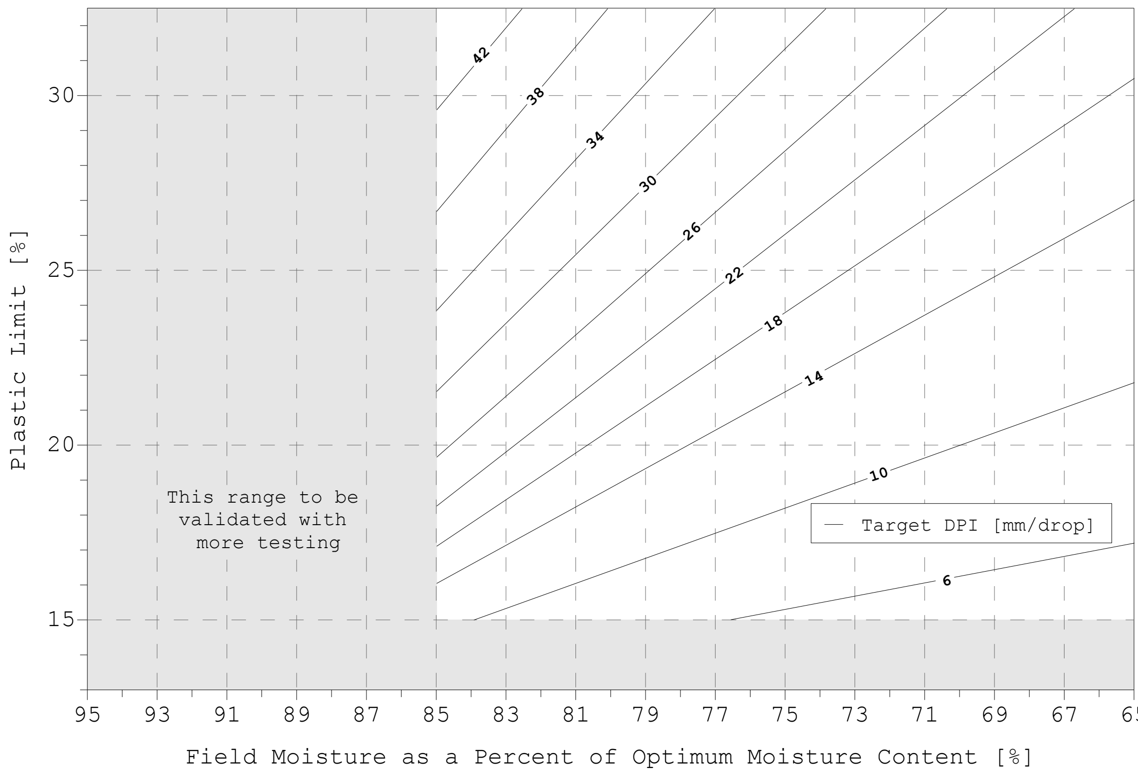

Figure 7.5. Average DPI simplified target values versus percent of optimum moisture content and plastic limit for fine grained soils

Figure 7.5 is an efficient and relatively simple method of for estimating DPI target values on construction sites. To determine the DPI target value, two variables need to be determined: the field moisture content (which must be compared to the estimated optimum moisture content) and the plastic limit (from which the optimum moisture content is estimated).

In order to estimate the target values for the Prima 100 LWD modulus, a contour version of Figure 7.3 was made. Figure 7.6 is a plot of the LWD modulus values versus the plastic limit and the percent of optimum moisture content. Using this figure instead of Table 7.2 will decrease the uncertainty of possible target values. Note the target values shown in Figure 7.6 are for the Prima 100 LWD model; an appropriate conversion factor will need to be applied if testing with a different model.

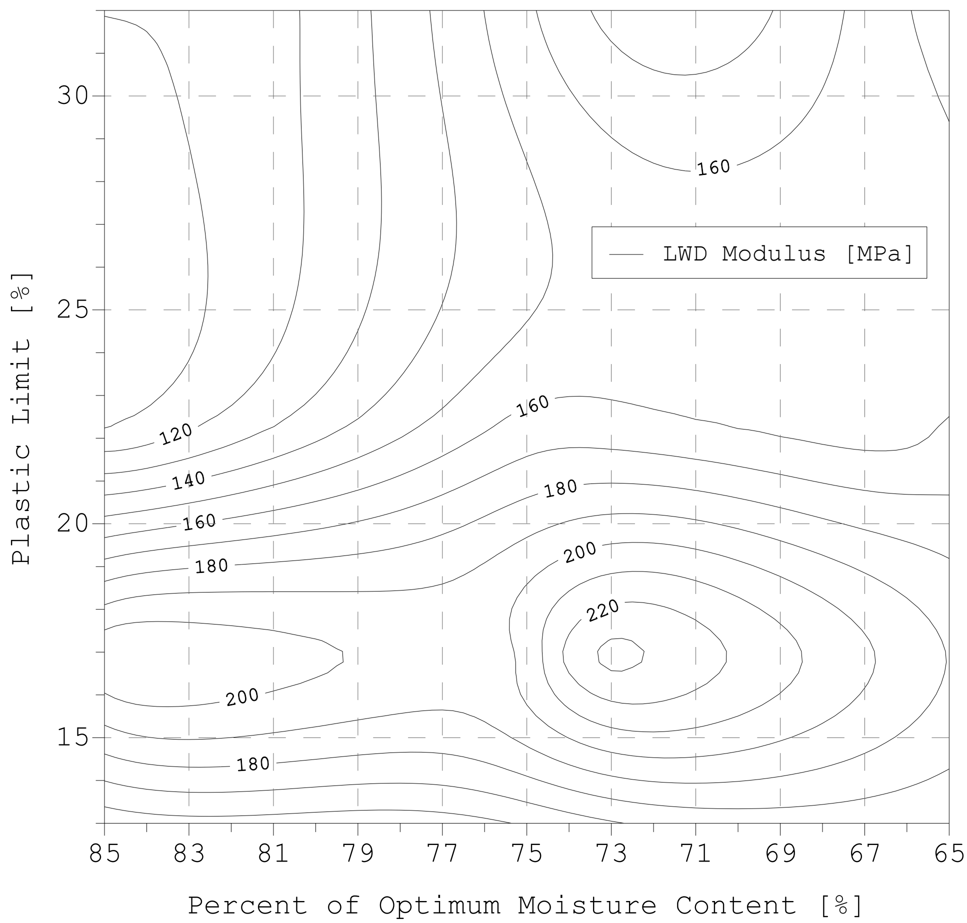

Figure 7.6. LWD modulus versus percent of optimum moisture content and plastic limit for fine grained soils

As can be seen from Figure 7.6, the contours of LWD moduli are highly irregular. For this reason, another figure of LWD moduli values was made. Figure 7.7 shows moduli values estimated from the DPI values in Figure 7.4 using Equation 1.6. This was done in order to determine if the trends of the two figures generally agree. If appropriate, Figure 7.7 will be used to verify the irregular shape of Figure 7.6. Note that values from Figure 7.7 should not be used as LWD modulus target values because it is derived from DCP data, not LWD data.

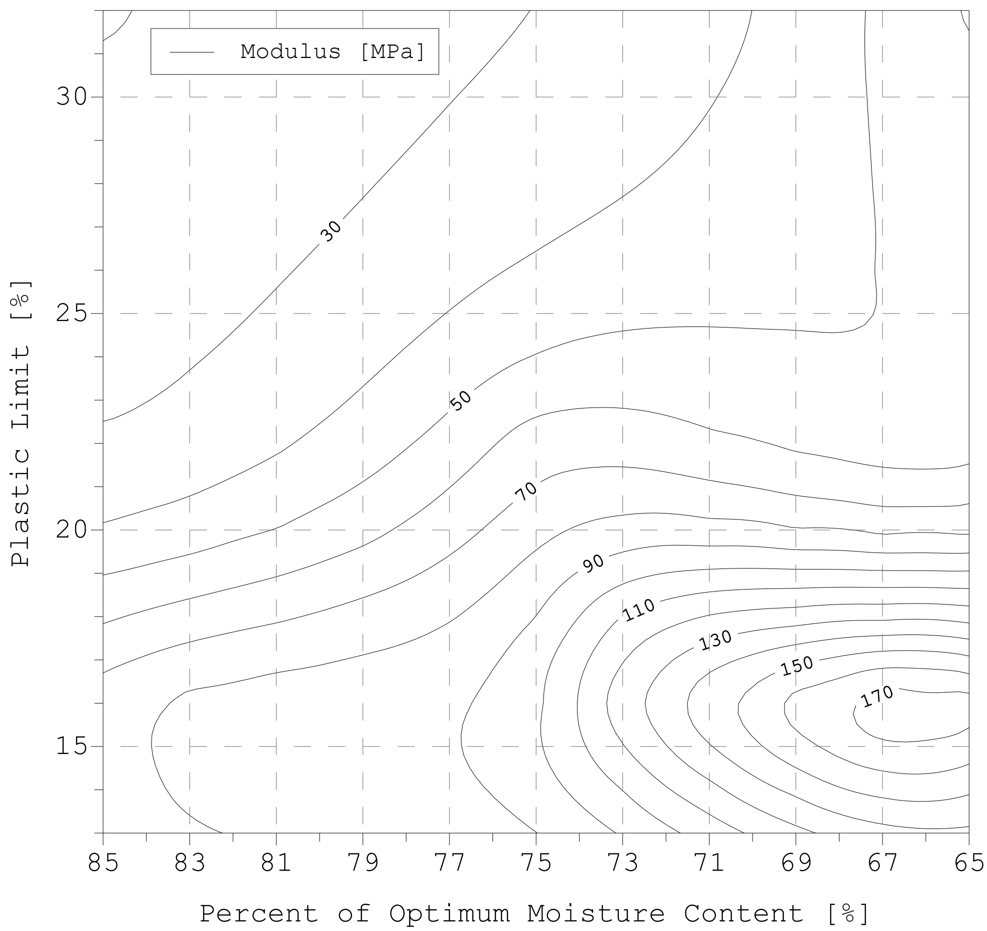

Figure 7.7. Modulus calculated from DPI versus percent of optimum moisture content and plastic limit for fine grained soils

The contours of Figure 7.7 show a general correlation with the trends of Figure 7.6. However, the magnitude of the actual modulus values in Figure 7.7 do not agree with Figure 7.6. This is due to the fact that Figure 7.7 used test data from a DCP while Figure 7.6 used test data from the Prima LWD. In summary, the general trends of Figure 7.7 validate those of Figure 7.6, which was the intent of this analysis.

Similar to the DCP analysis, simplified target values were drawn for both the moduli estimated with the DCP and Prima LWD. Like the actual data contours of Figures 7.6 and 7.7, it is expected that while actual modulus values between the devices will be different, the general trends will be similar. If this theory is correct, then it is shown that different testing methods result in similar methods. Figure 7.8 shows the simplified DCP modulus values calculated from the simplified DPI target values from Figure 7.5 using Equation 1.4. Figure 7.9 shows the simplified LWD modulus target values derived from the contour lines of Figure 7.6.

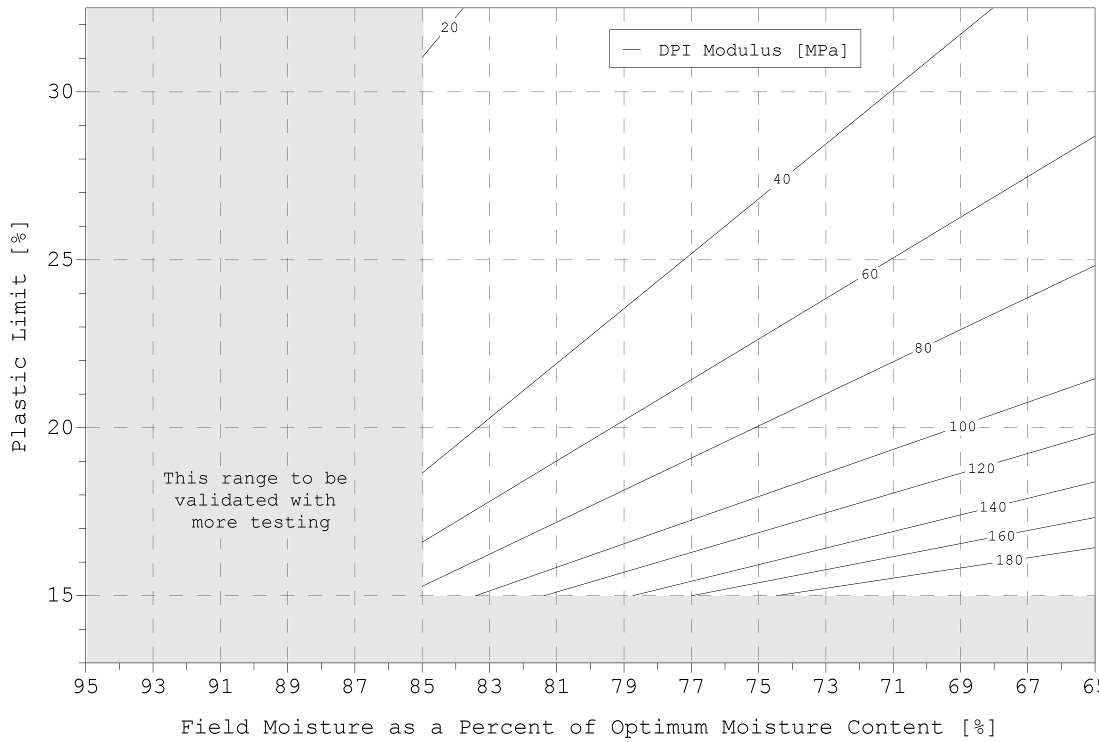

Figure 7.8. Modulus calculated from simplified DPI versus percent of optimum moisture content and plastic limit for fine grained soils

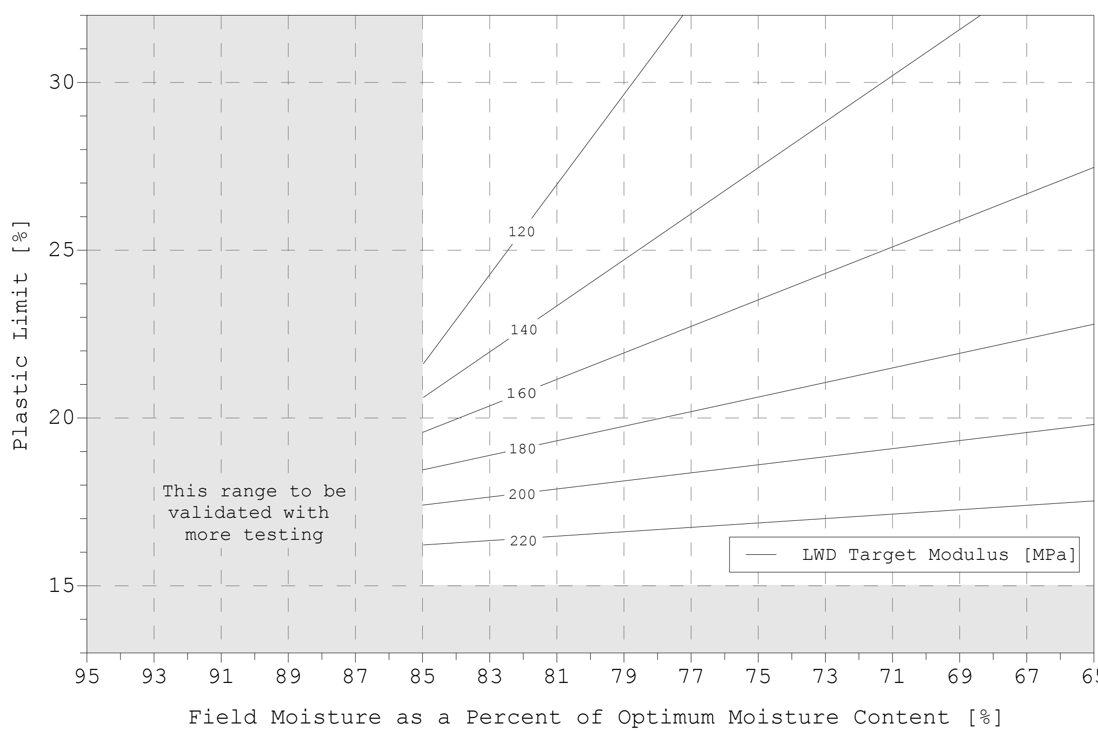

Figure 7.9. Prima modulus simplified target values versus percent of optimum moisture content and plastic limit for fine grained soils

As can be seen from Figures 7.8 and 7.9, the general trend of the modulus values is similar for both devices even though the magnitude of the actual values varies greatly. This shows that while each device produces unique values, there is a reasonable correlation between them.

7.4 Conclusion

Target values for both granular material and fine grained soils can be determined for quality assurance of unbound materials during pavement construction. In addition to target values shown in Table 7.1 and Figures 7.5 and 7.9, standardizing the testing procedures and data collection methods for LWDs and DCPs is also important. This ensures a degree of uniformity, which can be jeopardized by small but significant deviations in the procedures used. Currently, the method for obtaining a DPI value is varied, involving different numbers of seating drops and measurement drops. The primary method used in this report is based on the Mn/DOT Grading and Base Manual, which advises two seating drops and three to five measurement drops, depending on the material tested. Using three seating drops is recommended by this report. LWD testing includes many variations as well. The LWD device is currently non-standardized, allowing manufacturers to develop many different models and different methods of measurement. The degree to which the various LWD models are different can be seen in Table 1.1, Chapter 1. A description of the proposed LWD procedure is found in Chapter 1.

Overall, LWDs and DCPs should be implemented in the state of Minnesota. This should be done using the standardized testing procedures and the defined target values in this report as reasonable starting points from which project specific verification or modification would occur. The recommended target values in this report are intended to be estimates that need to be verified as appropriate for specific projects.

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