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Improvement and Validation of Mn/DOT DCP Specifications for Aggregate Base Materials and Select Granular Test

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The major purpose of this project was to verify and improve the trial Mn/DOT Dynamic Cone Penetrometer (DCP) specification developed in 2002 through additional field tests and implementation on several pilot construction projects.

Eleven construction projects from around the state were selected for testing during the summer of 2003. At each construction project, several locations were randomly selected for testing. At each location, various devices were used to obtain in-situ stiffness, strength, density and moisture data. In addition, samples were also taken for gradation and Proctor tests from the majority of the test locations. The materials included Select Granular, CL3, CL5, CL6, CL7 and full-depth reclamation. The proposed DCP specification from 2002 testing was validated and modified using the 2003 data.

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Improvement and Validation of Mn/DOT DCP Specifications for Aggregate Base Materials and Select Granular

Final Report

Prepared by:
Shongtao Dai
Charlie Kremer

Office of Materials
Minnesota Department of Transportation

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EXECUTIVE SUMMARY

The major purpose of this project was to verify and improve the trial Dynamic Cone Penetrometer (DCP) specification developed in 2002 through additional field tests and implementation on several pilot construction projects.

Eleven construction projects from around the state were selected for testing during the summer of 2003. At each construction project, several locations were randomly selected for testing. At each location, various devices were used to obtain in-situ stiffness, strength, density and moisture data. In addition, samples were also taken for gradation and Proctor tests from the majority of the test locations. The materials included Select Granular, CL3, CL5, CL6, CL7 and full-depth reclamation. The proposed DCP specification from 2002 testing was validated and modified using the 2003 data.

Four pilot construction projects were selected for implementation of the modified specification. Three were Mn/DOT projects on state highways and the fourth was County Road 45 in Steele County. The projects were:

1. S.P. 6920-37, TH 53 & TH 169 in District 1.
2. S.P. 4011-16, TH 112 in District 7.
3. S.P. 4310-45, TH 212 in District 8.
4. SAP.74-645-21, CSAH 45 in Steele County.

A construction testing procedure based on the modified DCP specification was developed for the pilot projects and inserted into the construction plan as a supplemental agreement. The major focus of the field implementation was to verify the modified DCP specification and assess the effectiveness of the specification through inspector evaluation.

In general, good comments were received from inspectors, which include:

1. The procedure is easy to understand. The modified specification uses an Excel spreadsheet to determine failure or pass of a test.
2. The inspectors indicated that the modified specification is easy to use and saves a lot of field-testing time.
3. Comparing the modified specification with sand cone density tests, inspectors also felt that it gives reasonable results, which are consistent with either the sand cone testing results or their experience.
4. One big advantage of the DCP test is that it can be applied to those materials on which the sand cone density test cannot be performed, such as taconite tailings.

However, the inspectors recommend that the minimum thickness for the DCP test should be increased. Based on the results from TH 112 and CSAH 45, they recommend that the minimum thickness be increased to 4 inches or more for aggregate base materials.

Chapter 1
Introduction

Characterization of in-situ strength and stiffness of granular materials and subgrade soils in a pavement evaluation is an expensive and time-consuming effort. Traditionally, the Minnesota Department of Transportation (Mn/DOT) has used the Specified Density Method for control and acceptance of aggregate base and subgrade soil construction. This method compares the optimum dry density obtained from the Proctor test to the dry density obtained from in-situ sand cone test. The method is very time consuming and sometimes difficult to perform. Also, additional Proctor densities may be required if the material has a highly variable gradation. In addition, it does not directly give mechanistic properties of the material, such as stiffness and strength. Furthermore, the safety of the inspector while conducting sand cone testing on a construction site is a concern.

Alternatively, the Dynamic Cone Penetrometer (DCP) has been found to be a useful tool in assessing in-situ strength of geomaterials. The use of the DCP has been increasing in the pavement area as a tool to characterize subgrade and aggregate bases. It is one of the least expensive testing devices and conducts tests rapidly. Furthermore, the DCP is simple to use and provides continuous measurements of the in-situ strength of unbound material layers in a pavement section.

In 1997, Mn/DOT implemented a DCP specification for aggregate base materials. The current Mn/DOT specification requires that the dynamic penetration index (DPI) must be less than 0.4 in/blow (10mm/blow) and a maximum seating penetration is 1.6 inches (40mm). The specification also requires that the material shall be tested and approved within 24 hours of placement and final compaction. Beyond the 24 hours, the material can only be accepted by the Specified Density Method. However, the current specification does not account for the effects of gradation and moisture content. It was felt that an improved DCP specification is needed.

In 2002, the Grading and Base Unit of the Office of Materials conducted a study to collect data from construction projects around the state. A total of 21 projects around the state were visited. 82 locations were tested on different types of materials, which included 38 granular and 39 aggregate base (Class 5, 6, or 7). In addition, 5 locations on full-depth reclamation (FDR) material were tested.

The 2002 data showed that there is a relationship between DCP penetration and gradation and moisture content. Based on the data collected in 2002, a trial DCP specification was proposed (Appendix A). The trial DCP specification is an improvement of the current specification. Compared with the sand cone density test method, it requires less field and lab testing time. It also provides an estimate of optimum moisture content of the material. These characteristics will be very useful for new and in-experienced field inspectors.

However, due to the limited testing data, it was determined that the proposed specification should be further validated using additional field testing data. The major purpose of this project was to verify and improve the trial DCP specification developed in 2002 through additional field tests and implementation on several pilot construction projects. To achieve this, four major tasks were identified:

- Literature review
- Field Experiments
- Implementation of Trial Specification
- Data Analysis

Eleven construction projects from around the state were selected for testing during the summer of 2003. At each construction project, several locations were randomly selected for testing. A total of 89 locations were tested. At each location, various devices were used to obtain in-situ stiffness, strength, density and moisture data. In addition, samples were also taken for gradation and Proctor tests from the majority of the test locations. The materials included Select Granular, CL3, CL5, CL6, CL7 and full-depth reclamation. The proposed DCP specification from 2002 testing was validated and modified using the 2003 data.

Furthermore, the modified DCP specification was implemented into four pilot construction projects. Three were Mn/DOT projects on state highways and the fourth was a county road. A construction testing procedure based on the modified DCP specification was developed for the pilot projects and inserted into the construction plan as a supplemental agreement. The major focus of the field implementation was to verify the modified DCP specification and assess the effectiveness of the specification through inspector evaluation.

The chapter 2 of the report contains literature review on DCP testing. Chapter 3 explains field experiments and testing equipment. The DCP specification has been implemented into several construction projects, which is included in Chapter 4. Chapter 5 contains data analysis and verification procedures of the modified specification. The summary and conclusions are presented in Chapter 6.

Chapter 2
Literature Review

The primary purpose of the literature review is to 1) review the DCP applications on the evaluation of unbound pavement layers and identify if moisture and gradation effects on DCP measurements have been studied and documented; 2) summarize specifications and implementation of the DCP testing in other states.

The early development of the DCP concept was reported by Scala from Australia in 1956 **(1).** In the 1960s, Van Vuuren from South Africa developed a new DCP apparatus and reported the new DCP device in 1969 (**2**). This new apparatus was heavier than the Scala's one and the drop height was a little shorter. Van Vuuren also showed that the DCP was only suitable for soils with CBR values ranging from 1 to 50. The present DCP device was developed by Kleyn **(3)** also from South Africa. He modified Van Vuuren's DCP device and applied the modified DCP for pavement evaluation. The present DCP device has the hammer weight of 17.6 lbs, the drop height of 22.6 inches and cone angle of 60 degrees.

The DCP has been widely used in pavement structure evaluations. In 1975, Kleyn **(4)** developed a relationship between DCP results and CBR values. Later, he further presented a DCP-based pavement design for gravel pavements **(3).** After his study, more researchers related DCP results to measured CBR results for aggregate base and subgrade soils. Ese, et al. **(5)** carried out a comprehensive field and laboratory investigation on the use of the DCP for evaluating low volume roads with gravel base course materials. Twenty-three road sections were selected for the testing. Also samples were taken for laboratory determination of CBR values. A relationship between CBR and DPI (Dynamic Penetration Index, mm/blow) for the gravel materials was established:

$$\text{Log } CBR_{lab} = 2.438-1.065*\log DPI_{field.} \qquad (1)$$

They claimed that this equation takes into account differences of confining pressure in the field and the laboratory. Also, a critical DPI value (2.6 mm/blow) was established as a stability criterion for the gravel materials.

Livneh Moshe **(6)** performed laboratory and field testing and presented a relationship between CBR and DPI based on 56 test results:

$$\text{Log } CBR=2.2-0.71*(\log DPI)^{1.5}. \qquad (2)$$

Later, this relationship was modified using more test results **(7)**. The modified relationship has the form:

$$\text{Log}CBR=2.14-0.69*(\text{Log}DPI)^{1.5} \qquad (3)$$

In addition, Livneh **(6)** showed that the layer thicknesses obtained from the DCP testing corresponded to the thickness from the test pits.

In South Africa, the DCP has been used for pavement rehabilitation design and evaluation (**8**). A complicated rehabilitation design system for gravel roads was developed. The design is based on traffic level, DPI and number of DCP blows to penetrate the pavement to a depth of 800mm. Also, a material classification system based on the DCP penetration was established.

The following relationships are used in South Africa to estimate CBR values from DCP tests:

For DPI > 2: $CBR = 410*(DPI)^{-1.27}$ (4)

For DPI < 2: $CBR = (66.66*DPI^2) – (330*DPI) + 563.33$ (5)

DPI is in mm/blow

Laguros and Miller **(9)** conducted a synthesis study. The study provided information to engineers and other transportation officials with methods to evaluate and improve subgrade conditions to meet the constructability requirements of reconstruction projects. They concluded that the DCP was an excellent tool for providing rapid assessment of subgrade condition and estimates of CBR values.

The US Army Waterways Experiment Station **(10)** conducted a field DCP study on different types of soils. They found a strong relationship between CBR and the DPI. The relationship is in the form of:

$\text{Log CBR} = 2.465 – 1.12\text{Log DPI}$ (6)

DPI is in mm/blow

Currently, several state DOTs have used or are evaluating the DCP as a tool for the evaluation of unbound pavement layers. The Minnesota Department of Transportation (Mn/DOT) was one of the first states to use the DCP for the evaluation of unbound pavement layers. In 1991, the DCP was applied on various projects for different purposes, such as locating high strength layers in pavement structures and identifying weak spots in constructed embankments **(11)**. Extensive DCP testing was performed on the MnROAD project during construction in an attempt to develop a DCP specification for field inspection **(12).** More than 700 DCP tests were conducted on aggregate bases and subgrade soils. Based on the test results, the study recommended the DPI limits for aggregate base and subgrade soil. However, moisture content of the testing material was not determined during the DCP testing and the moisture effect was not quantitatively defined in the recommended limits. Later, the DPI limit for aggregate base was modified based on additional DCP data **(13).**

Recently, the Mississippi Department of Transportation **(14)** performed a study to relate the DPI to resilient modulus (Mr) obtained from laboratory experiments and Falling Weight Deflectometer (FWD) backcalculated moduli for subgrade soils. Twelve subgrade sections were tested during the study using the automatic DCP and FWD. In-situ subgrade soil samples were taken using thin wall Shelby tubes and tested in the laboratory for resilient modulus in accordance to the LTPP P46 protocol. Also, the modulus was backcalculated using software called FWDSOILS. The primary conclusions of the study were: 1. Measurements from the manual DCP and the automatic DCP are statistically identical; 2. Two prediction models for resilient modulus were developed one for fine-grained soil and one for coarse-grained soil. They found that Mr prediction was not only related to the DCP index, but also related to soil physical properties. The general forms of the prediction models are:

For fine-grained soil: $Mr = a0*(DPI)^{a1}(R^{a2} + (LL/w)^{a3})$ $R^2=0.71$ (7)

DPI – Penetration index, mm/blow

R – Density Ratio, field density/maximum dry density.

W – actual moisture content, (%)

LL – liquid limit, (%)

a0, a1, a2 and a3 – regression coefficients

For coarse-grained soil: $Mr = a0*(DPI/\log Cu)^{a1}(w_{cr}^{a2}+R^{a3})$ (8)

Cu – Coefficient of Uniformity

w_{cr} - Moisture ratio, field moisture /optimum mositure

3. The backcalulated modulus using FWDSOIL is generally lower than the resilient modulus obtained from the laboratory experiments.

The Pennsylvania Department of Transportation **(15)** currently allows use of the DCP to estimate a design resilient modulus. In their pavement design procedure, the DCP test results are converted to Mr through the CBR conversion using the following equation from the 1993 AASHTO design guide: Mr = 1500*CBR. However, some CBR testing must be performed to substantiate the calculated CBR from the DPI.

The Kansas Department of Transportation (KDOT) started to use DCP for pavement evaluation in the early 1990s. Currently, the KDOT primarily uses DCP to calculate CBR and assess subgrade strength for certain rehabilitation projects **(16)**.

Auburn University Highway Research Center **(17)** developed an automated DCP device for the Florida Department of Transportation (FDOT) and procedures for its use to evaluate in-situ strength of Florida DOT granular materials and subgrade soils. In the study, a series of field testing was conducted to demonstrate features and capabilities of the automated DCP. They compared the results obtained using manual DCP and automated DCP and showed that no appreciable difference of DPI. Furthermore, the study indicted that for granular and cohesionless materials, confinement and depth affects the strength of the materials. For cohesive materials, confinement has minimal effect on strength. Currently, Florida DOT primarily uses the DCP for research purpose. Recently, they applied the DCP on State Road 65 to check soil stability for paved shoulders **(18)**.

Iowa State University conducted a study for the Iowa Department of Transportation **(19).** The purpose of the study was to field test and refine the proposed soil classification system and construction specifications. For cohesionless materials, they concluded that the DCP is an adequate in-situ testing tool to evaluate field in-place compaction. For cohesive soil, the DCP was also found to be a valuable field tool for quality control. Trial DCP criteria for measuring strengths of granular materials and fine grain soils were established. The DCP criteria are:

Soil Classification		Maximum Mean DCP Index (mm/blow)
Cohesive	Select	75
	Suitable	85
	Unsuitable	95
Granular	Suitable	45
	Select	35

In addition to strength, the results of a DCP test provides indication of compaction uniformity. The study indicated that the soil is considered uniformly compacted if the penetration per blow is consistent through the entire depth of the test. A trial DCP acceptance specification measuring uniformity was proposed. The criteria are:

Soil Classification		Maximum Mean Change in DCP Index (mm/blow)
	Select	35
Cohesive	Suitable	40
	Unsuitable	40
	Suitable	45
Granular	Select	35

Mean DCP Index = [sum of DPI] / [Number of readings]. Mean change in DCP Index = [sum of changes in DPI between consecutive readings] / [Number of readings – 1].

Based on this study, the Iowa DOT slightly modified these criteria and has implemented the modified criteria in their special provisions as a quality control testing method in 2004 **(20).** The specification also requires the moisture content to be within the following limits:

- Cohesive soil (>= 15% passing No.200 sieve): -2 to 3 percent of standard Proctor optimum water content.
- Granular soil (<15% passing No.200 sieve): 7 to16 percent water content.

Currently, Ohio University is conducting a research project for the Ohio Department of Transportation (ODOT) to study the possibility of using DCP as an acceptance method for subgrade and base construction **(21).** Currently, the ODOT uses the nuclear density gauge to measure density and moisture for acceptance criteria. The ODOT realizes that the gauge measurement does not directly give material stiffness. The objectives of the study being conducted by Ohio University are to: 1. Develop and implement a procedure for using the DCP as an acceptance criterion for subgrade and unbound base materials; 2. Develop a threshold for unsuitable materials based on DCP readings; 3. Establish stiffness parameters for pavement design and rehabilitation based on the DCP results; 4. Develop QC/QA procedures for subgrade acceptance. The effects of soil density and moisture content on DCP results will also be considered. The study is expected to complete in August of 2005.

The DCP can also be used to estimate shear strength of fine grain soils and granular materials. Ayer et al**. (22)** conducted a comprehensive study to relate the shear strength of granular materials to the DCP results. In their study, the DCP and rapid loading triaxial tests were conducted on six granular materials. They concluded that the DCP may be used to estimate the shear strength of granular materials. A set of prediction equations of shear strength was established for a variety of granular materials. The predictive equations depend on the confining pressure. Therefore, it requires an estimate of the confining pressure under field loading conditions to select the appropriate equation. Also, the study showed that additional material characteristic inputs increase the accuracy of the prediction. McElvancy and Djatinka **(23)** used the DCP to estimate unconfined compressive strength of lime-stabilized soils. They stated that the DCP could be used to provide a reasonable estimate of the unconfined compressive strength of soil-lime mixtures.

The resilient modulus has been widely used to characterize stiffness of unbound pavement materials and is the required parameter in most of mechanistic-empirical pavement design procedures. Some researchers have attempted relate DCP results to resilient modulus. South Africa **(8)** developed a relationship between DPI and backcalculated modulus based on 86 test data.

$Log(Mr) = 3.04785-1.06166*Log(DPI)$ (9)

Mr is in MPa and DPI is in mm/blow

Hassan **(24)** developed a simple regression between resilient modulus and DCP results for fine-grained soils:

$Mr\ (psi) = 7013.065-2040.783Ln(DPI)$. (10)

Where DPI is in inches/blow

Chen et al. **(25)** performed a field DCP study on base and subgrade soils. The DCP testing sites were instrumented with multi-depth displacement measurement (MDD) devices and were also tested using Texas Accelerated Pavement Tester. They estimated resilient modulus using the following two predictive equations:

$CBR=292/DPI^{1.12}$ (11)

$Mr\ (psi)=2550*CBR^{0.64}$ (12)

Where DPI is in units of mm/blow

The CBR equation was obtained by Webster et al. **(10)** and the Mr equation was proposed by Powell et al. **(26).** These equations are also recommended by the new pavement design guide, which is being developed under the NCHRP 1-37a. Chen et al. found that the estimated modulus from DCP results are compatible with those calculated from MDD measurements under FWD tests. Also, the study indicated that the laboratory determined subgrade soil moduli were only slightly higher than the estimated moduli from the DCP results. Furthermore, they showed that the factor of 0.33 currently recommended in the 1993 AASHTO design guide to convert backcalculated modulus to laboratory tested modulus is not applicable in their case. Later, Chen et al**. (27)** modified the previous equations using their testing data. The new developed equation applicable for both base and subgrade soils has the form:

$Mr\ (ksi) = 78.05*DPI^{-0.6645}$. (13)

Where DPI is in mm/blow

Chen, et al**. (28)** conducted the DCP and FWD tests on six pavements in an attempt to establish a relationship between the DCP results and backcalculated modulus. EVERCALC was used in the study to backcalculate the subgrade resilient modulus. They found that there is a significant correlation between the DCP values and the FWD backcalculated subgrade moduli for individual pavement sections. A global power model was developed to try to describe the relationship between DCP results and backcalculated modulus:

$Mr\ (MPa) = 338(DPI)^{-0.39}$ (R^2 of 0.42) (14)

Where DPI is in units of mm/blow

Munir Nazzal **(29)** studied the potential use of the DCP to reliably measure the stiffness characteristics of highway materials for possible application in the QC/QA procedures during and after the construction of pavement layers and embankments. In the study, DCP and static plate load tests were conducted on Louisiana State highways and the Accelerated Load Facility of Louisiana Transportation Research Center. The study showed that the DCP could be used to evaluate the strength/stiffness properties of pavement materials and estimate the pavement layer thickness. Correlations between the DPI and moduli estimated from the static plate load tests were recommended and a relationship between CBR and DPI was also proposed:

$$E_{PLT(i)}\ (\text{MPa}) = 17421.2/((DPI)^{2.05}+62.53) - 5.71 \qquad (4.8 < DPI < 66.67) \qquad (15)$$

$$E_{PLT(R2)}\ (\text{MPa}) = 5142.61/((DPI)^{1.57} - 14.8) - 3.49 \qquad (4.8 < DPI < 66.67) \qquad (16)$$

Where $E_{PLT(i)}$ is the modulus determined from initial loading under the static plate load test and $E_{PLT(R2)}$ from reloading. DPI is in units of mm/blow.

$$CBR = 2559.44/(-7.35+DPI^{1.84}) + 1.04 \qquad (6.31 < DPI < 66.67) \qquad (17)$$

Where DPI is in mm/blow

The DCP has also been used for other pavement applications. For example, the DCP was used by the US Air Force as a tool to evaluate airfield pavements **(30).** Zhang et at**. (31)** applied the DCP to assess the cause of "dip" problem of asphalt pavement over trenches. They found that the sand used to backfill the trenches constructed under their current specifications is generally weaker than the native subgrade soils in Louisiana and suggested that the DCP can be used for quality control of trench backfill constructions. Also, the DCP results have been related to the measurements from other non-destructive testing devices. Sawangsuriya and Edil **(32)** suggested a relationship between stiffness measured using GeoGauge and the DCP results. In 2003, a standard DCP test method in shallow pavement applications was established by ASTM **(33).**

In summary, based on this literature review and to the authors' knowledge, there are no DCP QC/QA specifications, which quantitatively consider both moisture and gradation effects. The current DCP criteria in other states, such as Iowa, are based on the local material types rather than specific gradations. In 2002, Mn/DOT proposed DCP criteria for aggregate base and select granular materials, which specifically considers both moisture and gradation effects.

Chapter 3
Field Experiments

Eleven construction projects around the state were selected for testing in the summer of 2003. For each construction project, several locations were randomly selected for testing. At each location, different devices were used to obtain in-situ stiffness, strength, density and moisture data. Samples were also taken for gradation and Proctor tests from most locations. The materials included select granular materials, CL3, CL5, CL6, CL7 and reclaimed materials. Table 1 lists the construction projects and associated material types and Fig.3.1 shows the general layout of field test measurements.

The field test data and associated laboratory test information are stored in an ACCESS database. An example of the collected data is shown in Appendix B. The collected data were analyzed to improve the trial specification developed in 2002 and a modified DCP specification was recommended. The detailed analysis and the modified DCP specification can be found in Appendix A. The following table documents the field testing experience on different devices.

Table 3.1 Summary of tested construction projects

DISTRICT	TRUNK HIGHWAY	MATERIAL CLASS	TEST LOCATIONS	NUMBER OF BARREL SAMPLES	TEST NUMBERS
METRO	61	7 C	3	3	3-5
METRO	649 / 94	7 B C	4	4	48-51
1	23	RECLAIM	8	4	87-94
3	10	6	2		1-2
3	371	SELECT GRANULAR	6	4	10, 56-60
3	371	6	10	4	27-36
4	200	RECLAIM	7	4	70-76
6	16	SELECT GRANULAR	5		11-15
6	16	6	11	4	16-26
6	52	SELECT GRANULAR	9	4	78-86
7	14/15	5	6	4	46-47, 52-55
8	23	3	9	3	61-69
Co. Rd.	14	5	9	4	37-45
		TOTAL	89	42	

C – Recycled Concrete
B – Recycled Bituminous mixtures
BC – Recycled Bituminous and Concrete
Reclaim – Bituminous and Aggregate base mixtures

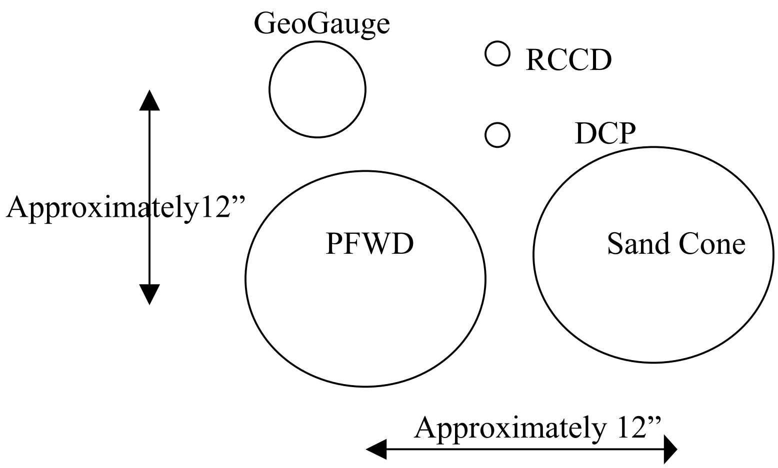


Figure 3.1 Layout of Test Devices

Dynamic Cone Penetrometer (DCP)

The DCP is a well-known device used by inspectors in the field. A modified DCP device was used for field testing during the summer of 2003. The modified DCP has the top rod in two segments that thread together (versus one solid rod), and the bottom rod composed of various length rods that threw together ranging from 6” to 30” (versus one solid rod). The advantage of the modified DCP is that, with the shorter bottom rod, the whole unit is shorter than the traditional DCP. Therefore, it is much easier to operate the modified DCP than the traditional model. Another significant advantage of the modified DCP is the smaller storage case, which makes it easier to transport. The modified DCP operates in the same way as the traditional DCP. Fig.3.2 shows the modified DCP device. Fig.3.3a and 3.3b show the DCP assembly and testing.

Fig. 3.2 The modified DCP device.

Figure 3.3a DCP assembly

Figure 3.3b An example of DCP testing

The procedure for the DCP test can be found in Mn/DOT Grading and Base Manual section 5-692.255 and ASTM D6951-03 (34)

The following is the general procedure used for DCP testing:

1) Determine the length of the bottom rod is needed for the particular test location. Normally a 12" bottom rod was used for aggregate base and a longer rod for Select Granular because greater penetration was expected.
2) Assemble the upper and lower rods, hammer, and anvil via the threads and ensure that all are tight.
3) Place fully assembled DCP at selected location.
4) Hold the DCP steady and plumb.
5) Record an initial penetration depth on measurement rod.
6) Lift the hammer up to the top of the upper section, release it and allow it to fall freely to strike the anvil.

7) Record penetration depth on measurement rod.
8) Repeat steps 6 and 7 until twelve drops have been completed.
9) Pull DCP from the ground and clean off lower rod (if the DCP can not be easily pulled out from the ground, the disposable cone tip or jack should be used).
10) Disassemble the DCP and place it back in the case.

The DCP test location was close to where the PFWD and GeoGauge were tested, normally within an area with 6” radius. Experience shows that the modified DCP is a good test and relatively simple to perform. Also, it gives consistent results. The modified DCP made the test easier than the traditional DCP. Another device that made the DCP test much easier was the DCP Data Acquisition System, which is described next.

DCP Data Acquisition System (DCPDAS)

The DCP Data Acquisition System used in this project is made by Applied Research Associates, Inc (Fig. 3.4) (35). The system is designed to operate with the DCP to automatically measure the depth of penetration and number of drops. The data is displayed on a data acquisition box and recorded electronically.

Fig.3.4 Automatic DCP data acquisition system

The penetration depth of the DCP is measured with a steel wire potentiometer. The wire can be pulled out from the side of the unit and travels over a roller from horizontal to vertical. Then the wire is attached to a hook on the DCP anvil. Fig. 3.5 shows the connection.

Fig. 3.5 Connection of DCPDAS and DCP

The procedure to operate the DCPDAS is as follows:

1) Open up and turn on the DCPDAS.
2) Select “Run DCP Test”.
3) Select “Test ID”.
4) Change the displayed ID to the test ID for the test, then press enter.
5) Place DCPDAS on ground next to DCP test location, approximately 3” to 4” away from test location.
6) Set DCP down gently at the test location.
7) Pull the measuring wire out of the DCPDAS, over the pulley, and up to the hook installed in the DCP anvil.
8) Position DCPDAS to ensure that the wire is parallel to the DCP device.
9) Hold the DCP steady and plumb.
10) Press “Start Test”
11) Wait for a few seconds until DCPDAS takes the initial reading, then start the DCP test.
12) Record the DCP penetration from DCPDAS screen after each drop of the hammer until desired penetration depth is reached.
13) Press “Stop” after the test, then turn the power off by pressing “Power Off.”
14) Remove the wire from the DCP and slowly let it retract into the DCPDAS box.

The total time to setup the DCPDAS was less than one minute. Experience showed that the DCPDAS made it easier to perform DCP tests. Traditionally, without the automatic data acquisition system, the operator has to hold the DCP plumb and simultaneously use a ruler to measure penetration. The precision of the measurement depends on how the operator places the ruler on the ground and how accurately the scale is read. By using the automatic data acquisition system, the operator can easily read the penetration measurements directly from the screen. The other advantage of the system is that the data can be downloaded to a computer for analysis.

Early in the summer a concern was raised as to the accuracy of measurement using the DCPDAS. Therefore, the device was calibrated using a rule, as follows:

1) Place the DCPDAS on the floor.
2) Turn it on.
3) Place a ruler (with the zero point being the furthest from the DCPDAS) firmly against the side of the DCPDAS case directly below where the wire comes out.
4) Pull the wire out to the zero point on the ruler.
5) Press “Start Test” and hold the wire in place for a few seconds to allow the DCPDAS to take the initial reading.
6) Move the wire to any desired position on the ruler, record this position and hold the wire steady on this position.
7) Gently tap the DCPDAS to trigger the data acquisition system to take a reading.
8) Record the measurement shown on the DCPDAS.
9) Repeat steps 6 through 8 as many times as desired.
10) Compare the measurements taken by the DCPDAS and ruler.

Approximately 15 different lengths were tested to check the accuracy of DCPDAS. It has been found that the difference between DCPDAS measurement and the ruler measurement was less than 1 mm on each length. Based on this small difference in measurement, the DCPDAS was found to be accurate.

The DCPDAS is powered by an internal rechargeable battery, which was normally charged each night during the summer. However, even with this regular charging, the battery sometimes still ran out of the power. It would be beneficial if the battery could be replaced so that the operator could change the battery on the testing site without discontinuing testing.

<u>Percometer</u>

The Percometer is a device that measures dielectric constant and specific conductivity of the material (Fig. 3.6) (36). It consists of a control box and a probe. The dielectric constant relates to the volumetric moisture content in the material. The purpose of using the Percometer during this project was to 1) obtain dielectric constants of different grading materials from field; 2) determine the relationship between measured dielectric constant and moisture content obtained from sand cone density test.

Fig. 3.6 Percometer

The procedure followed for the Percometer test is as follows:

1) Turn on the Percometer.
2) Select the procedure that automatically averages six test results (Following the same procedure as used in 2002 data collection. However, future data collection should record all values).
3) Select a location with smooth surface, press the probe firmly against the surface, and then take the reading and record.
4) Select the second location a few inches away from the first and take the reading again and record.

5) Repeat step 4 until all six locations are tested. The surface material dries quickly. Therefore, the six tests must be done quickly to minimize moisture loss between tests.
6) Press “F” button again to obtain the average of four middle values of the six readings.
7) Record the average values of conductivity and dielectric readings obtained on step 6.
8) Turn Percometer off.

Because the Percometer was also needed in the laboratory for testing, it was not used on every project due to scheduling conflicts. It was noticed that the numbers from reading to reading seemed to jump around more if the surface of the soil was rough and the voids on the surface are not completely filled. This was more pronounced with reclaimed materials, which contained bituminous mixtures.

Sand Cone

In order to relate DCP results with field density and moisture content, a sand cone density test was also performed at each location where DCP test was conducted. The sand cone has been the standard test for measuring field density and assessing relative compaction for many years. It is well known that the test is time consuming to conduct in the field. Also it is very difficult to perform the test on some well compacted aggregate base materials, such as CL 5, CL 6, CL7 and reclaimed materials. Furthermore, the materials may contain large gravel. In this case, it is difficult for the operator to perform the test without disturbing large gravel from the side or the bottom of the hole in order to perform the test. During this field testing, the large sand cone (6.5” diameter) was used.

The procedure for a sand cone test can be found in Mn/DOT Grading and Base Manual section 5-692.248.

Portable Falling Weight Deflectometer (PFWD)

The PFWD used was the “Loadman II” (Fig.3.7) (37). This is a portable device, which can be used to measure in-situ material stiffness. The device consists of a closed aluminum tube with dimension approximately 5”x6”x47”. A mass freely falls from a known height inside the tube and impacts a plate at the lower end of the tube. Then the impact load and displacement are displayed. The PFWD weighs about 40 lbs with over half of its weight being in the falling mass (22 lbs).

Fig.3.7 PFWD device

The following is the testing procedure:

1) Locate a relatively smooth and level spot for the test.
2) Remove the PFWD from its case and turn it on.
3) Place the PFWD on the testing location, then rotate it slightly to smooth out the contact surface.
4) Use spoon or screwdriver to mark the ground around the foot of the PFWD to ensure the same spot for sequential tests.
5) Pick up the PFWD and tip gently to allow the mass to slide slowly from the bottom of the tube to the top where it connects with a "click" to the magnet.
6) Place the PFWD back on the marked circle from step 4.
7) Press the reset button.
8) Press the drop button to drop the mass. There is a few second delay from when the drop button is pressed to when the mass is released.
9) Record the load and displacement displayed.
10) Repeat steps 5 through 9 till five tests have been performed.
11) Turn the PFWD off and place it back in the case.

It must be pointed out that the operator should slowly tip and slid the mass back to the top of the tube. If the PFWD is tipped too fast, the mass can slam onto the top and the force generated by the sliding mass could damage the electronic parts mounted on the top of the tube.

The difference between the results from drops 3, 4 and 5 is quite small compared to the first two drops. The reason is that the PFWD impacts the ground with a large force. This force compacts the loose soil near the surface and causes the deflection to decrease and load to increase from drop to drop. Normally, the deflection of the second drop was significantly less than that of the first. Therefore, the first two drops are considered seating drops similar to FWD procedure. During the testing, the PFWD must be held steady and vertical. The operator should ensure that surface is even and smooth. The experience showed that, if the PFWD was tipped during testing, the readings were not correct.

In summary, the PFWD is a simple device. However, it is heavy and somewhat inconvenient to carry and transport.

GeoGauge

The GeoGauge is another field testing device, which is intended to measure in-situ material stiffness. The GeoGauge is manufactured by Humboldt Mfg. Co (38) and is a hand-portable instrument (Fig. 3.8). It works similar in concept to the PFWD, but the load and displacement generated from the GeoGauge are much smaller and its size is smaller too. The GeoGauge weighs about 22 lbs and is 11 inches in diameter and 10 inches in height.

Figure 3.8 GeoGauge Device

The GeoGauge works by imparting small displacements to the soil at 25 different frequencies between 100 and 196 Hz. Stiffness is determined at each frequency and the average from 25 frequencies is displayed. The GeoGauge also automatically calculates and displays the standard deviation of the stiffness.

The GeoGauge testing procedure (39) is as follows:

1) Remove from the case and turn it on.
2) Select a location a few inches away from the PFWD testing location.
3) Inspect this location for loose gravel, remove gravel and fill voids with fines.
4) Make sure the foot of the GeoGauge is clean.
5) Gently place the GeoGauge on the location.
6) Rotate the GeoGauge a quarter turn under its own weight to properly seat it. If the GeoGauge wanders while it being rotated, this usually indicates that the foot is resting on stones. If this happens, pick up the GeoGauge and inspect the location for stones, remove the stones and fill with local fines then reseat.
7) Press the “MEAS” button gently while trying to minimize rocking of the GeoGauge. The test takes approximately 75 seconds to complete.
8) Record the stiffness number that is displayed.
9) Pick up the GeoGauge and inspect the footing mark left on the soil for the contact area. At least 80% of the foot needs to be in contact with the soil.
10) After the first and second tests, smooth the soil and repeat steps 5 through 9 to complete the third test. After the third test, turn off the GeoGauge and place it back into the case.

The GeoGauge was checked each day prior to testing using provided validation mass. The procedure used is as follows (39):

1) Place the validation mass on the tailgate of the truck such that the four feet are firmly contacting the tailgate.
2) Clean the foot of the GeoGauge with a paper towel. Also inspect the foot for any burs in the metal.
3) Place the GeoGauge on the validation mass.
4) Rotate the GeoGauge back and forth a couple of times to make sure it is securely seated on the validation mass.
5) Press the "MEAS" button gently while trying to minimize rocking of the GeoGauge.
6) Check the displayed stiffness to see if it is between the ranges of –8.8 to –9.8 MN/m.
7) If the value is in the range, then proceed with the testing.

On one project at the intersection of TH14/15, the GeoGauge was used on an area where pumping occurred on the granular layer, and then also used only a few feet away on a location where pumping was not occurring. It was observed that the stiffness on the pumping area was approximately one-third the stiffness of the non-pumping area on this particular project.

Other features should be added to the GeoGauge to improve its testing capability. For example, the GeoGauge should have capability to label test number, material type, location, and offset, so that the operator can easily review collected data and later download the information to a computer for analysis. Also, the standard deviation should be easier to be displayed.

The GeoGauge used at the beginning of the project for a short period of time was found not to be calibrated. A second Mn/DOT GeoGauge, which had been calibrated and just returned from Humoldt replaced the first one. However the second one was also discovered to be out of calibration at the field demonstration organized by Humoldt on July 1st of 2003. Therefore, the GeoGauge could not be used through out the summer testing at each project.

A major challenge with the GeoGauge was to get a good seat in course aggregates, such as CL5, CL6, CL7 and reclaimed materials. The surface must be free of stones or moist sand should be used to level the surface.

Rapid Compaction Control Device (RCCD)

The RCCD (44) is basically a DCP type device, which measures material strength (Fig. 3.9).

Figure 3.9 Rapid Compaction Control Device

It is much smaller in dimension and lighter in weight than traditional DCP device. It weights approximately 12 lbs and has dimension of approximately 35”x12”x12”. The RCCD is a penetrometer device that uses a spring loaded cone to penetrate into material. The spring is released manually by a mechanical trigger to drive the cone into the material. The cone tip is significantly smaller than DCP’s cone and is limited to a total penetration of 78mm. The limitation on the penetration makes it impossible to complete three blows in weaker materials without reaching the penetration limits.

The RCCD testing procedure is as follows:

1). Select desired location near to the GeoGauge and PFWD.
2). Remove the protection plate from the bottom of the RCCD
3). Stand on the bottom plate.
4). Slide measuring collar all the way to the top.
5). Make sure measuring rod is in contact with the plate attached to the center rod which travels with the cone tip.
6). Record an initial reading of where the top of the measuring rod lines up with the scale on the measuring collar.
7). Pull up on the handles slowly but firmly until the spring is loaded with a “click” sound.
8). Lower the handles back to their initial position.
9). Rotate the handles clockwise slightly to trigger spring release.
10). Record a penetration reading on measuring collar.
11). Repeat steps 7 through 10 until either the 3 tests have been completed or the penetration reaches the maximum of 78 mm.

12). Lift the RCCD up and clean the probe of any debris.
13). Replace the protection plate to the bottom of the RCCD.

A possible improvement of RCCD is to use a larger cone tip than the current cone tip, which will minimize the possibility of maxing out the penetration depth. This may allow RCCD to test more materials. Another improvement is to make the unit a little taller so that the operator does not have to bend over as far to operate the device. Furthermore, it would be beneficial if the force delivered by the spring could be validated. The validation would ensure similar force generated by the spring could be applied at each test.

Speedy Moisture Tester

The Speedy Moisture Tester is a portable device used to measure in-situ moisture content of aggregate base and fine grain soils (Fig. 3.10). It takes approximately 1 to 3 minutes to get the results once the test is prepared. The total testing time is approximately 10 minutes.

Figure 3.10 Speedy Moisture Tester

The device operates on the principal of that a calcium carbide additive reagent reacts to moisture in the soil sample. The reagent is classified as a Hazardous Material designation. Experience shows that the operator should wear gloves to protect hands from the reagent. The Speedy Moisture Tester is a quick test to obtain the moisture content. But care must be taken when it is used as a method to check moisture on projects because of the physical exhaustion of running the test and the hazardous material involved in the test. Furthermore, it can't be used on any material containing salvaged or reclaimed bituminous, because binder in the bituminous may plug the pressure gauge on the device.

The operator should follow Mn/DOT procedure to handle the Speedy Moisture Tester and run the test. The procedure can be found in Mn/DOT Grading and Base Manual section 5-692.245 sub-section D.

Summary

During the summer of 2003, the DCP along with six different in-situ testing devices were used on eleven construction projects to obtain field data. CL3, CL5, CL6, CL7, select granular and reclaimed materials were tested.

From the field testing, it was observed that the in-situ moisture has a great effect on material strength and stiffness. Therefore, a method to accurately measure the in-situ moisture content should also be used along with the in-situ stiffness and strength measurement.

Regarding the other devices, the GeoGauge has a small size and easy to transport. It is simple to operate as well. The GeoGauge is being or has been evaluated by different agencies (40,41,42,43). The PFWD is also a good in-situ testing device because it is simple to operate and measures material stiffness. However, the PFWD is heavy and somewhat difficult to transport. The following is a table summarizing the devices used and a rating based on limited experience from this summer's testing:

Table 3.2 Summarizing devices used and a rating based on limited experience

Equipment	Ease of Use	Ease of Transport
Modified DCP	1	2
DCP data acquisition	1*	1
Percometer	2	2**
PFWD	1	3
GeoGauge	1	1
RCCD	1	1
Speedy moisture tester	3	2***

1: Easy
2. Moderate
3: Difficult
*: Require frequent charge of internal battery
**: No case to contain the equipment
***: Has to have lockable box to contain the hazardous material.
The box has to be labeled with appropriate information (GNB manual 5-692.245)

Chapter 4
Implementation of Modified Specification

In 2002, the Grading and Base (G & B) Unit of the Office of Materials conducted a study to collect DCP data from construction projects around the state. The DCP testing was the primary focus of the study, therefore it was used on each test location. Other types of equipment were also used but not as frequent as the DCP. Some other tests were also performed, which includes: • Gravimetric moisture content and/or sand cone density • Gradation and/or Proctor maximum density • Loadman II • Percometer • Rapid Compaction Control Device (RCCD) • GeoGauge. A total of 21 construction projects were visited. 82 locations were tested on different types of materials, which included 38 granular and 39 aggregate base (Class 5, 6, or 7). In addition, 5 locations on full-depth reclamation (FDR) material were tested. A trial specification was developed in 2002.

The trial was then modified using the data collected in 2003 as described in Appendix B. The modified specification takes into account the effects of material gradations and moisture content. In 2004, four pilot construction projects were selected for implementation of the modified specification. The purpose is to further verify the modified DCP specification and assess the effectiveness of the specification through construction inspector field evaluation.

A special provision based on the specification was developed and implemented into four pilot construction projects. The special provision is attached in Appendix C.

Construction Project Description

The following four projects were selected as pilot projects to implement the modified DCP specification.

1. S.P. 6920-37. TH.53 & TH.169 in District 1
2. S.P. 4011-16. TH. 112 in District 7
3. S.P. 4310-45. TH. 212 in District 8
4. SAP.74-645-21. CSAH 45 in Steele County

<u>SP. 6920-37. TH.53 & TH.169 in District 1</u>
This project consists of new construction of 4-lane highway and bridge. The project starts from R.P.70+00.10 and ends at 72+00.58 (stationing from 1790+00 to 1918+58.68). Sand is the predominant existing soil type. Non-plastic sandy loam is also prevalent. Due to the bridge construction, the new alignment will almost entirely be a grade raise, which requires fill.

At some locations where the new alignment is proposed, muck, rock quarry and boulder fields were found. Therefore, the project also requires removal of rock, peat and muck. The Soils Letter recommends that embankment construction of T.H.53 will be primarily fill sections. Select Grading Soils can be used to construct the fill up to the bottom of the proposed subcut. The subcut depth should be 48” below grading grade. The Letter further recommends that the subcut should be filled with Select Granular with full width and to compact the Select Granular using Specified Density and Test Rolling.

During the construction of this project, the contractor used taconite tailings as Select Granular to fill the subcuts. DCP test and the modified DCP specification were used as a QC/QA tool to check the compaction. The DCP tests were conducted between approximately Sta. 1829+00 to 1885+00 in this summer. In total, 167 locations were tested.

<u>SP. 4011-16. TH 112 in District 7</u>
This project consists of grading and surfacing to flatten a curve at the intersection of T.H.112 and CSAH. 23 and the removal and replacement of a box culvert. The project starts at R.P.6.87 and ends at R.P.7.44.

According to soil borings, the in-place soil type is predominantly Sandy Clay Loam. Traffic data analysis shows that the current AADT is approximately 950 with an estimated 20-year ESAL of 1,037,000. The Soils Letter recommends the following pavement structures:

For the mainline structure of T.H.112: 8" HMA, 3" Class 5, 19" Class 3 and 24" Select Grading materials.

For the mainline of CSAH.23: 6" HMA, 3" Class 5, 21" Class 3 and 12" Select Grading materials.

DCP tests and the modified DCP specification were used during construction for QC/QA control. The DCP tests were done on both Class 3 and Class 5 materials**.** Approximately 30 tests were done on Class 3 material and 38 tests on Class 5 material. During the construction, the subcut layer with Class 3 material was constructed in 3 lifts. The DCP tests were conducted on each lift with approximately one third of the tests done on each lift.

<u>SP. 4310-45. TH. 212 in District 8</u>
This is a reconstruction project. The project consists of reconstruction of the eastbound lanes of T.H.212 from the west junction T.H.22 to Morningside Drive in Glencoe (R.P.116+00.146 to R.P.121+00.173).

The soil boring indicated that the material in the upper 5' consists mainly of gravel and sandy loam. The average R-value of the in-place subgrade soil in the eastbound is approximately 25. The predicted ESAL is approximately 7 million. The typical pavement section has the following structure:

9.5" PCC, 3" Class 5 and 12-18" Select Granular material.

The DCP tests were conducted on both Select Granular and Class 5 materials. Approximately 57 locations were tested.

<u>SAP.74-645-21. CSAH 45, Steele County</u>

Besides the 3 projects mentioned above, the trial specification was also implemented in a county project. This is a reconstruction project, which is located on CSAH45 between T.H.30 and

North of C.R.55 in Steele County. The majority of the in-place subgrade soil is silty clay. The typical pavement section has the following structure:

6” HMA; 6” Class 7 base and an average of 9” gravel.

The Class 7 material was a mixture of recycled concrete and a virgin Class 5 aggregate. The DCP tests were used on Class 7 material for the acceptance test. A total of 38 tests were conducted and sand cone density tests were also performed at some of DCP test locations. In this project, the acceptance of the compaction of the base material was based on the sand cone method.

Chapter 5
Data Analysis

During the pilot projects, gradation, moisture and density tests were also conducted. In addition, comments on the modified specification from field inspectors were collected for the consideration of improving the modified specification. This chapter documents the verification analysis using the data collected from the four pilot construction projects.

Data Analysis

In total, approximately 330 locations were tested on the pilot projects using the DCP. At some locations, sand cone density and moisture tests were also conducted. Moisture content was determined using either conventional "oven dry" method or the Speedy tester. The tested materials include CL5, CL3, CL7, taconite tailings and select granular. Table 5.1 provides a summary of the projects and tested materials.

Table 5.1 Summary of Projects and Tested Materials

Project	Road	District/County	Materials	Number of DCP tests
SP 6920-37	TH 169	District 1	Taconite Tailings	167
SP 4011-16	TH 112	District 7	CL3 and CL5	68
SP 4310-45	TH 212	District 8	Select Granular & CL5	57
SAP 74-645-21	CSAH 45	Steele County	CL7 (concrete with CL5)	38

Gradation

A single number called grading number (GN) was developed to express the gradation (Appendix B). GN is calculated using the following equation:

$$\text{GN (\% passing)} = \frac{25mm + 19mm + 9.5mm + 4.75mm + 2.00m + 425\mu m + 75\mu m}{100}$$

In the above equation, 25mm means percent passing the sieve size of 25 mm. The same definition applies to 19mm, 9.5mm, 4.75mm, 2.00mm, 425um and 75um.

The following summarizes the gradation test results and associated the grading numbers of each project:

<u>TH169</u>

Taconite tailings were used as Select Granular material. The material was very uniform. The gradation is shown in Figure 5.1.

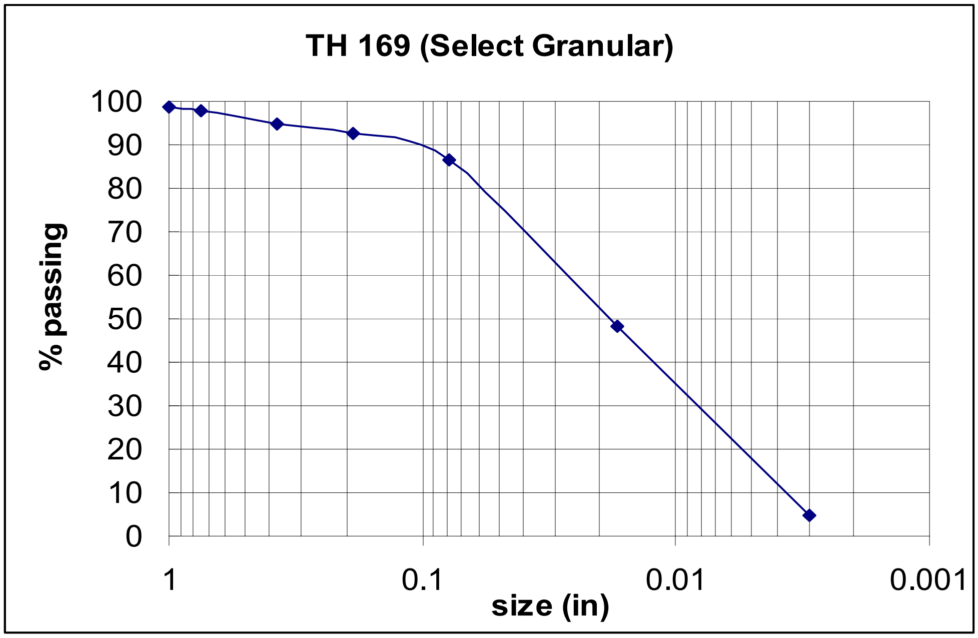


Figure. 5.1 Gradation of Select Granular from TH169.

<u>TH 212</u>

Two different types of granular materials (Select Granular and Class 5) were tested using the modified DCP specification. The gradation results are given in Table 3 and shown in Figure 12 and Figure 13. The results indicated that the gradations are consistent, which means a small variability for each material type.

Table 5.2 Gradation results of TH 212 project

	Select Granular						Class 5		
1"	100	100	100	99.4	100	100	100	100	100
3/4"	99.8	98.9	99.7	97.6	96	99	94.1	99.7	98.9
3/8"	98.5	87.6	95.5	87.9	81	85	80.5	81.6	87.6
#4	94.6	73.1	85.3	80	65	68	68.5	65.3	73.1
#10	86.3	60.7	85.3	66.7	47	54	52.7	49.2	60.7
#40	47.8	22	33.9	27.7	18	18	20.2	18.1	22
#200	3.4	9.1	6.8	10.2	8.0	7.5	9.7	6.9	9.1
GN	5.3	4.5	5.1	4.7	4.2	4.3	4.3	4.2	4.5

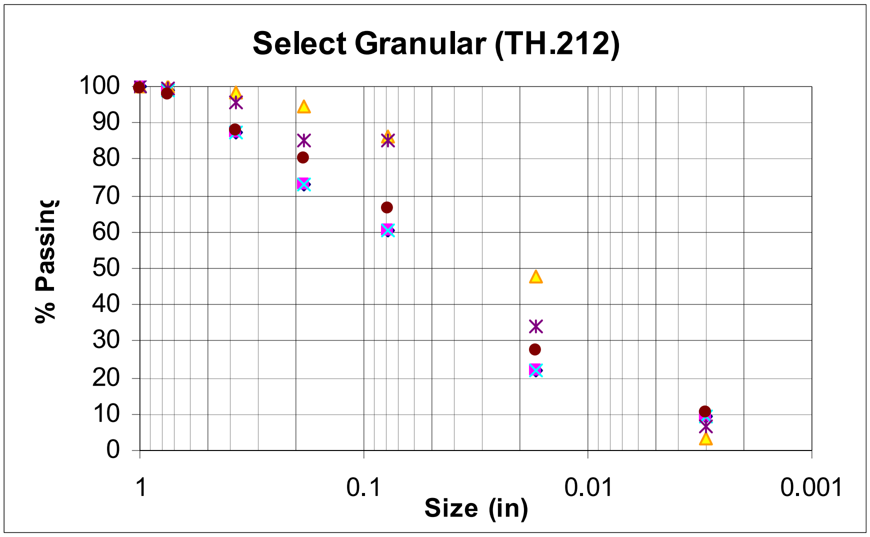


Figure 5.2 Gradation of Select Granular from TH 212 project

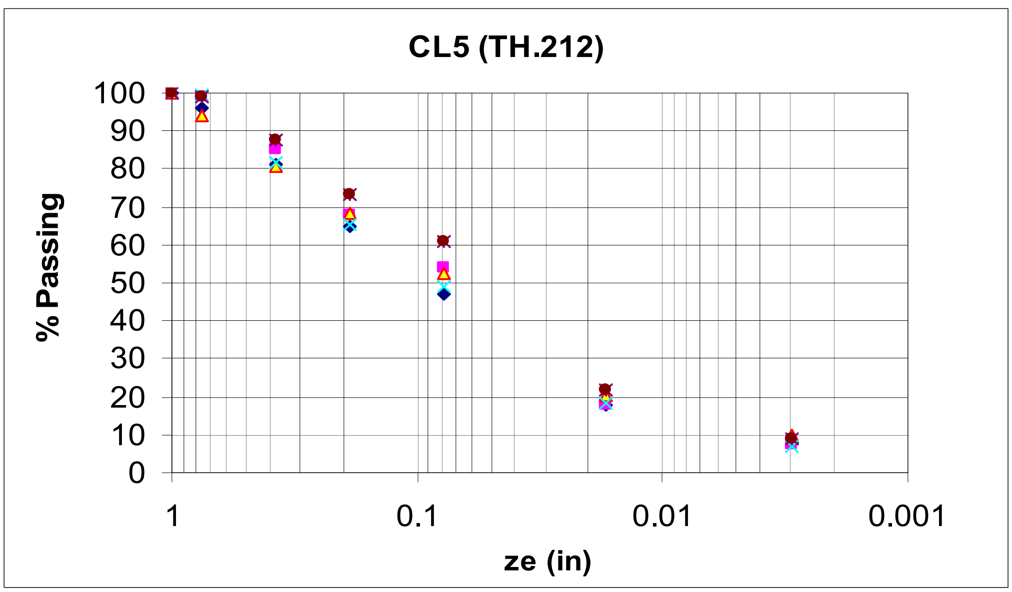


Figure 5.3 Gradation of Class 5 material from TH 212 project

TH 112

DCP tests were conducted on CL 3 and CL 5 materials. However, most of the DCP tests penetrated the CL 5 material layer because the thickness of the layer is only 3 inches. Therefore, the data obtained from the CL 5 material was not included in the analysis. The gradation results of the CL 3 are listed on Table 4 and illustrated on Figure 5.4.

Table 5.3 Gradation results of CL 3 from TH 112 project

	Class 3					
1"	96	95	97	95	94	98.5
3/4"	94	93	94	91	91	95.6
3/8"	90	85	86	85	83	86.1
#4	83	76	77	75	74	76.7
#10	71	62	66	63	62	64.5
#40	39	29	32	30	29	29.1
#200	11.3	7.2	8.6	7.8	7.2	7.7
GN	4.8	4.5	4.6	4.5	4.4	4.6

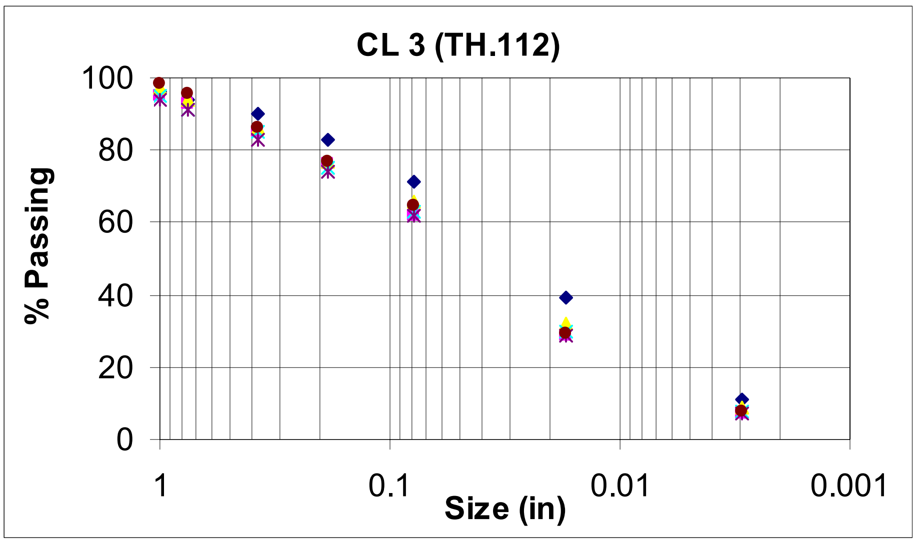


Figure 5.4 Gradation of CL 3 from TH112 project

<u>CSAH 45</u>

Extensive DCP and sand cone density tests were performed on CL 7 aggregate base. Sand cone density and moisture tests were performed along with the DCP tests. Two side-by-side DCP tests with one on each side of the sand cone test location were conducted in an attempt to study repeatability of the DCP test. Table 5.4. gives the gradation results of the Class 7 material from the project. Again, the gradation was very consistent throughout the project (Figure 5.5).

Table 5.4 Gradation of CL 7 Material from CSAH 45 project

1"	100	100	100
3/4"	93	92.9	93.3
3/8"	78	73.2	87.7
#4	69	63.6	76.8
#10	60	54.4	57.6
#40	41	34.2	36.4
#200	13.6	10.0	11.5
GN	4.546	4.283	4.633

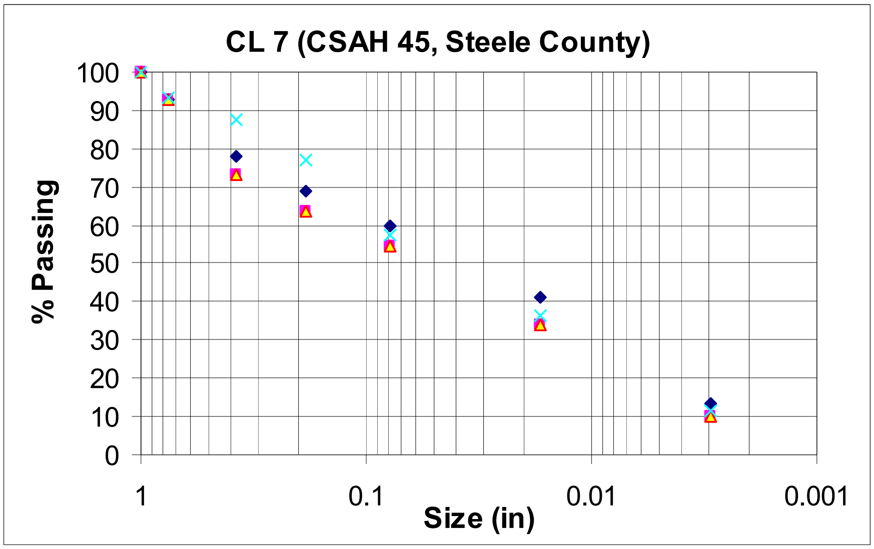


Figure 5.5 Gradation of CL 7 material from CSAH 45 project

Data Verification (GN vs DPI)

The DPI data from these four projects were plotted against GN values and compared with the data collected in 2002 and 2003, which is shown in Figure 5.6. It can be seen that there are some data are stacked at a GN. This is that the inspector did not perform gradation test at each DCP testing location. However, the DPI increases as GN increases in general, which indicate the material strength is dependant on material gradation. Also, it shows that the DPI values obtained from the four pilot projects are in the similar range of the values collected in 2002 and 2003. This means that the data collected during 2004 is validated and the modified specification is applicable for the field construction projects. However, it was identified that moisture and gradation tests were not performed at each DCP test location by field inspectors.

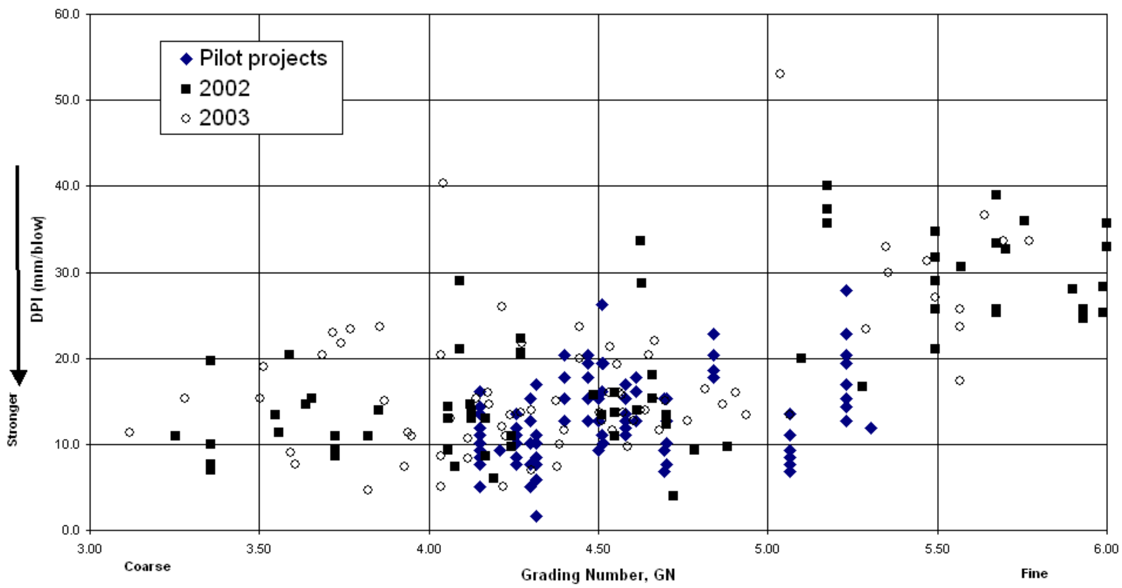


Figure 5.6 Comparison of DCP Results

Data Verification (Moisture vs DPI)

The DPI data from these four projects were plotted against field moisture values supplied by the construction inspectors and compared with the data collected in 2002 and 2003. Figure 5.7 shows the comparison. Also, it can be seen that there are some data are stacked at a moisture content. The reason is that the inspector did not perform gradation test at each DCP testing location. The inspector felt that they either do not have time to perform moisture test at each DCP location or they felt that the material was uniform and assumed that the moisture content collect at a location can represent moisture conditions at several other locations. However, in general, the DPI increases as moisture content increases. Also, the moisture contents obtained from the four pilot construction project are similar to those collect in 2002 and 2003. Again, this means that the data collected in 2004 is validated and the modified specification developed from the data is applicable for field construction projects.

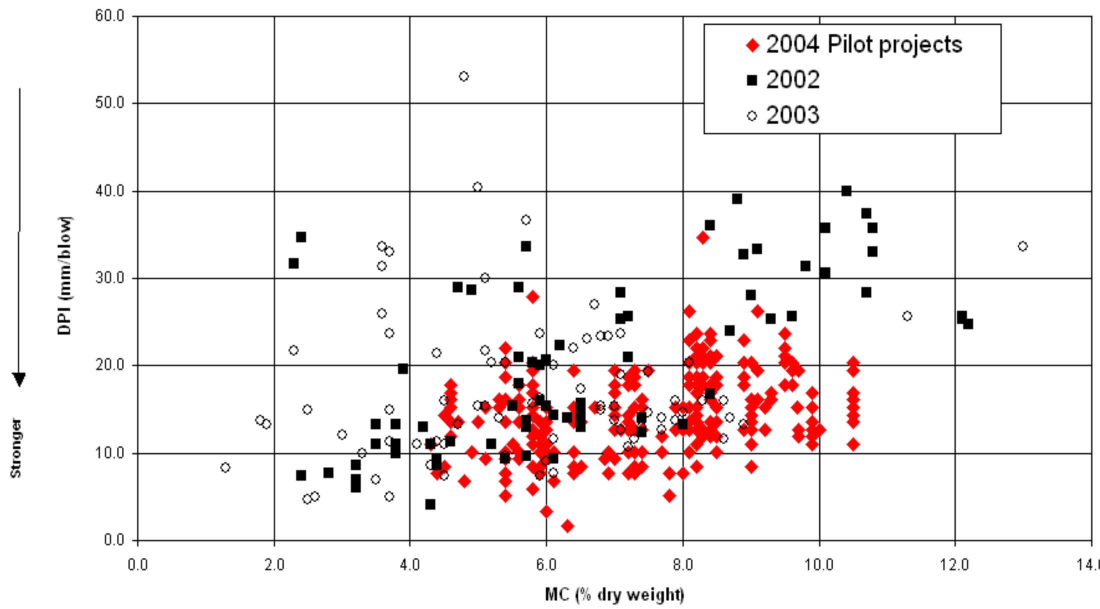


Figure 5.7 Comparison of DCP Test Results

Verification of Modified Specification
The previous data analysis (see the attachment) showed that the data obtained in 2002 and 2003 are consistent and the proposed specification is reasonable. The proposed specification has been modified using the data collected in 2003. The data were collected by two different operators in 2002 and 2003. A relationship between the DPI, moisture content, and gradation was established. Since the data collected in 2003 has a similar range to that collected in 2002, the project panel decided to implement the modified specification on pilot construction projects in 2004. The purpose was to let construction inspectors examine the validity of the specification so that further comments and input could be obtained from construction personnel.

In order to check the applicability of the modified specification, the DCP data collected from the pilot construction projects was plotted against the specification criteria for each project.

<u>TH.169</u>
In this project, the construction plan required Specified Density Method as the acceptance criterion for the select granular material, which was taconite tailings. However, the field inspector could not perform proctor tests on the material because the taconite tailings are very porous and would not hold water. The modified DCP specification was selected to replace the sand cone density test as the acceptance test.

Good comments were received from the construction inspector. The comments include that

1. the DCP specification was easy to follow;
2. the DCP test provides quicker results than sand cone density test;
3. the DCP specification provided reasonable results.

From his experience, the inspector felt that the compacted taconite tailings were stiffer than the other compacted select granular materials.

Figures 5.8 and 5.9 show the DPI and the criteria of the modified specification. In total, 167 DCP tests were conducted on this project. Twelve tests failed the DCP criteria. According to the inspector, the failure occurred because the material was too dry when tested. Most of the DCP test values met the criteria but were within a reasonable range. This matches the observations of the construction inspector, which means that the modified specification provides reasonable results for select granular taconite tailings.

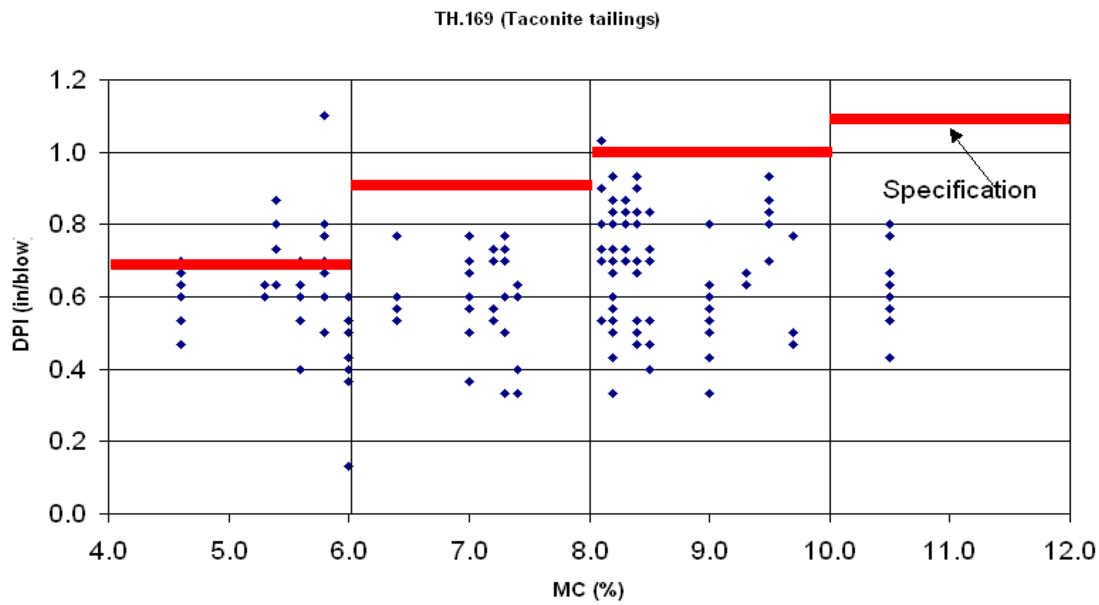


Figure 5.8 Relationship between DPI and moisture content

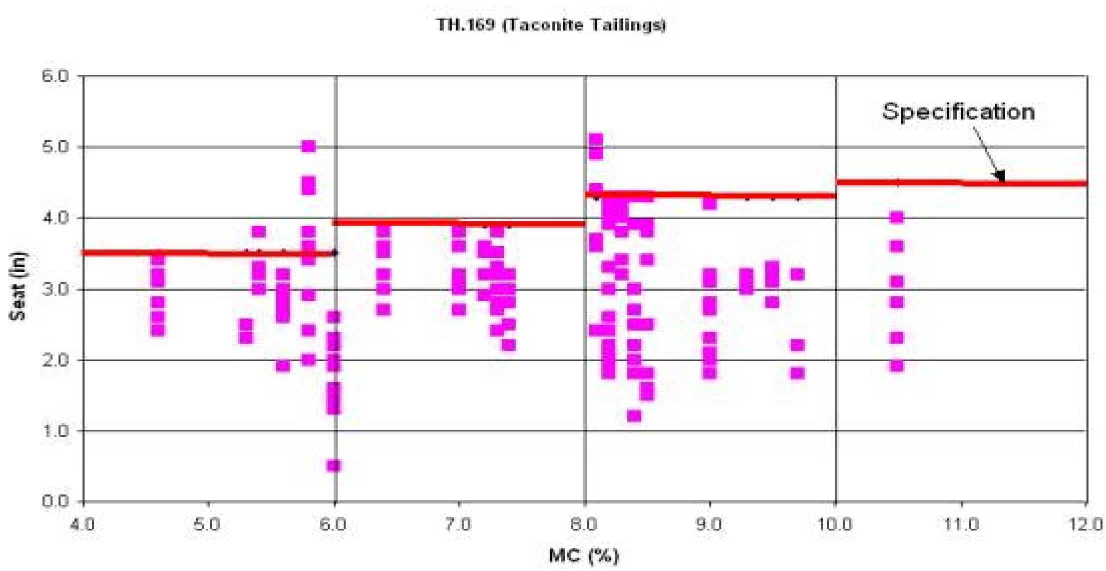


Figure 5.9 Relationship between Seating penetration and moisture content

TH.212

DCP tests were performed at 57 locations on the project. At some locations, sand cone density tests were also conducted along with the DCP tests in an attempt to compare density with DCP results. The tested materials included select granular and CL 5 aggregate base. The following figures (Figure 5.10- 5.12) show the field DCP data, the DCP criteria and relative density from sand cone tests.

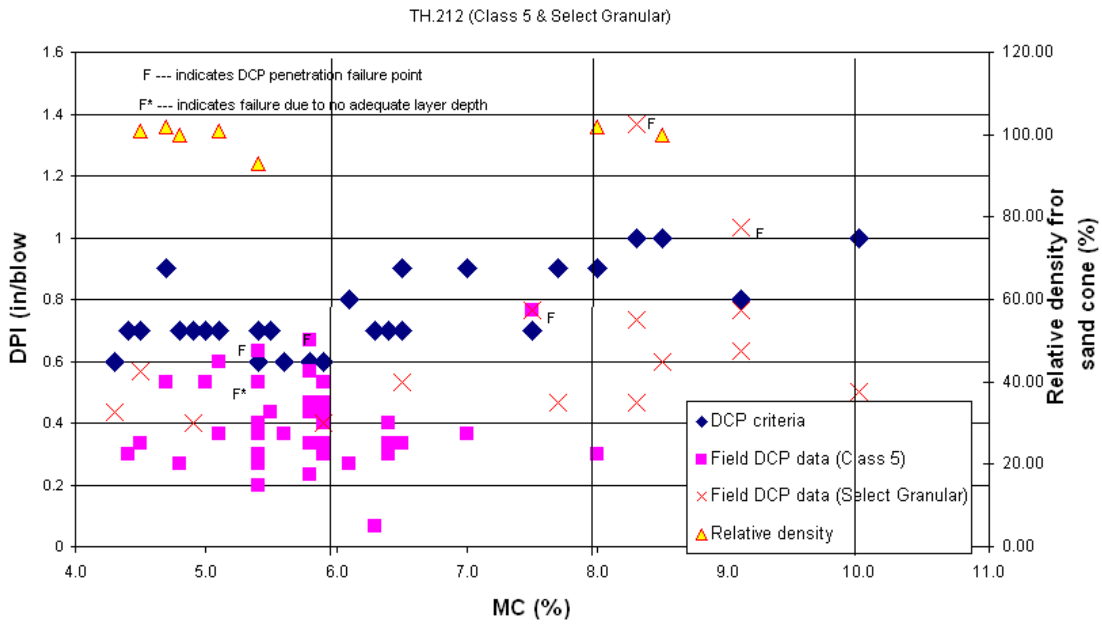


Figure 5.10 Relationship of DPI, relative density and moisture content.

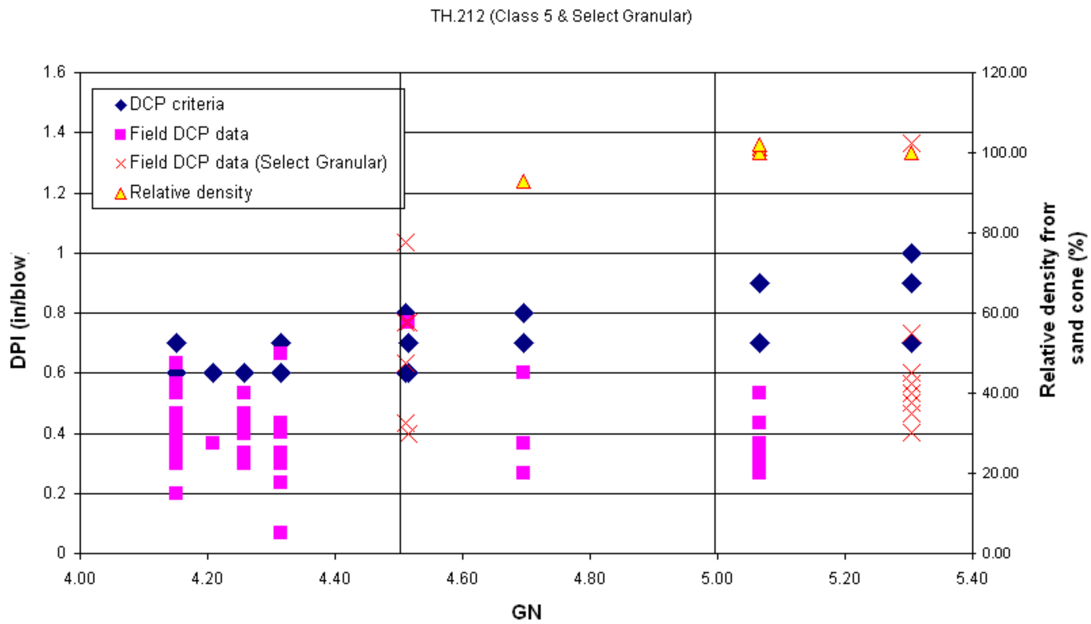


Figure 5.11 Relationship of DPI, relative density and grading number.

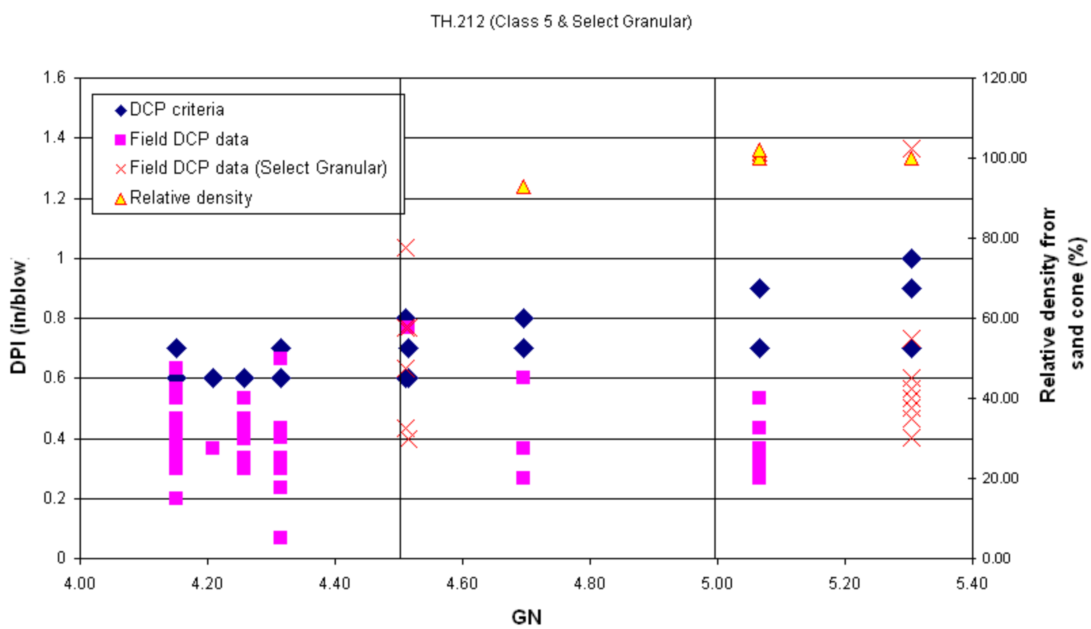


Figure 5.12 Relationship of Seating penetration, DCP criteria and moisture content

In general, the DPI increases with moisture content and grading number. Most of the testing locations met the criteria but were within a reasonable range. Only seven DCP tests did not meet the criterion. Most of the failures were due to high moisture content according to the inspectors. In addition, the densities from sand cone test are also indicated in the figures. Almost all of the sand cone density tests passed the relative density criteria (100%). Only one sand cone test failed density criterion. This trend is consistent with the DCP results, which further validates the DCP criteria.

Also, the inspector provided good comments on the specification. It was indicated that both the DCP and sand cone tests provided consistent results. This gave him confidence in the DCP specification. The inspector felt that the DCP specification provides reasonable results and significantly saves field-testing time. He recommends using the modified DCP specification on more projects.

<u>CSAH 45</u>

This project is located in Steele County. The modified DCP specification was applied on CL 7 aggregate base, which contained virgin CL 5 and crushed concrete. Sand cone density and moisture content tests were also performed to evaluate the DCP results. Furthermore, two DCP tests, approximately one foot apart, were performed at each sand cone test location. The purpose of the two DCP tests was to examine the repeatability of field DCP test results.

On this project, DCP tests were also conducted on two three-inch lifts. Figure 5.13 shows the comparison of the calculated DCP penetration depth using measured DPI and the lift thickness in construction plan. Some of the DCP tests on the first lift slightly penetrated the lift thickness. However, the DPI passed the criteria, which indicates that the minimum thickness requirement (3 inches) in the current specification should be increased.

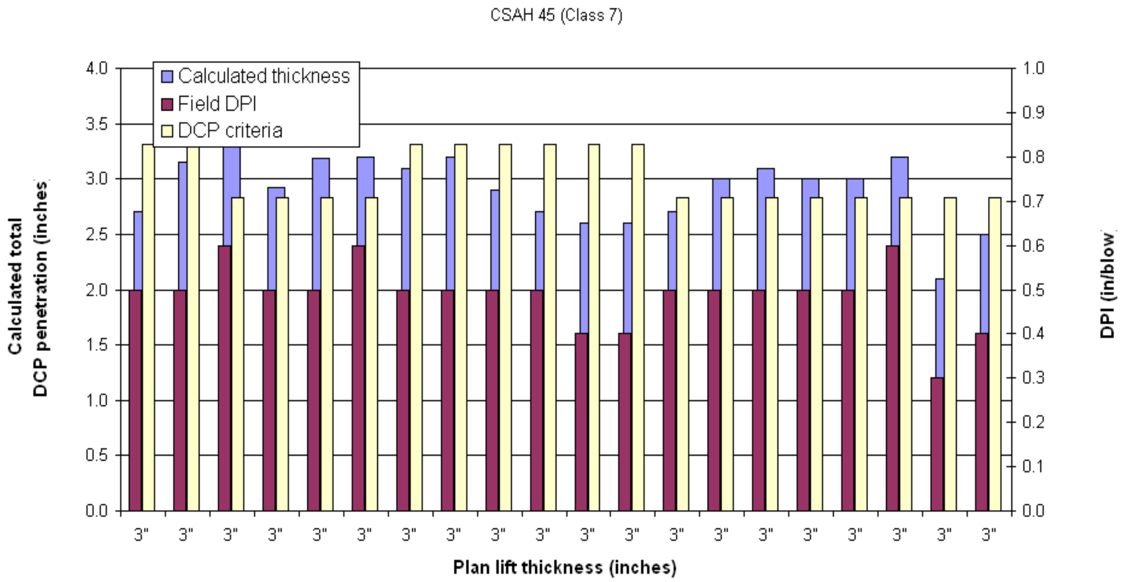


Figure 5.13 Comparison of lift thickness and DPI.

Figure 5.14 shows the duplicated DCP test results as a function of test location. At each location, the results of the two DCP tests are very close. In fact, at some locations, the two DPIs are almost identical (the two dots are overlapped in the figure), which means that the DCP test is repeatable and the results are reasonably accurate.

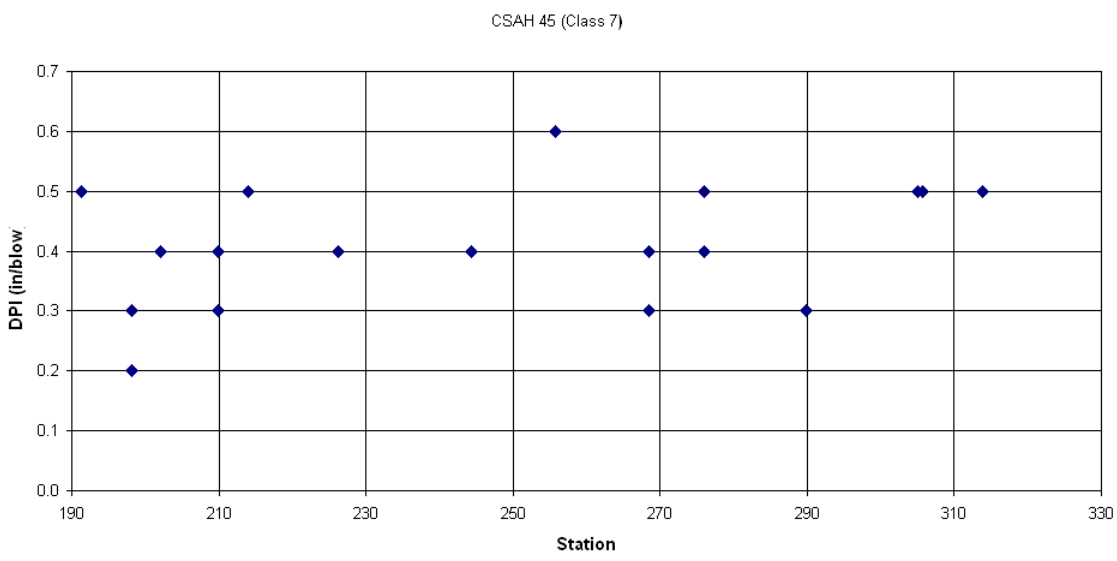


Figure 5.14 Repeatability of DCP tests

Figures 5.15-5.17 illustrate the comparison between the DCP results and sand cone density results and DCP criteria. Again, in general, the DCP results are consistent with the sand cone density results. All of the DCP tests passed the criteria as did most of the relative density tests (two sand cone tests failed by moisture criteria but passed density criteria). This further validates that the modified DCP specification is reasonable and consistent with the current maximum density specification. However, it has been observed that the DPI for this material is not obviously dependant on moisture content within the tested moisture range.

This may be due to the high absorption of the concrete particles. It is known that material strength is affected by free moisture content in the material. If the material has a high absorption, then free moisture in the material will be low for a given moisture content.

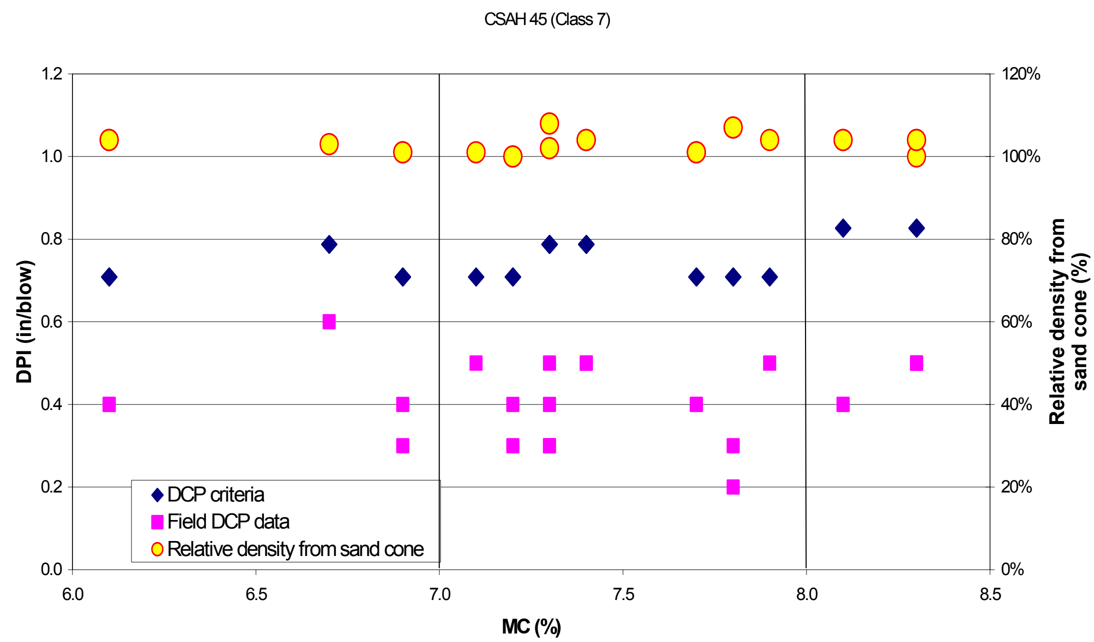


Figure 5.15 Relationship between DPI, relative density and moisture content.

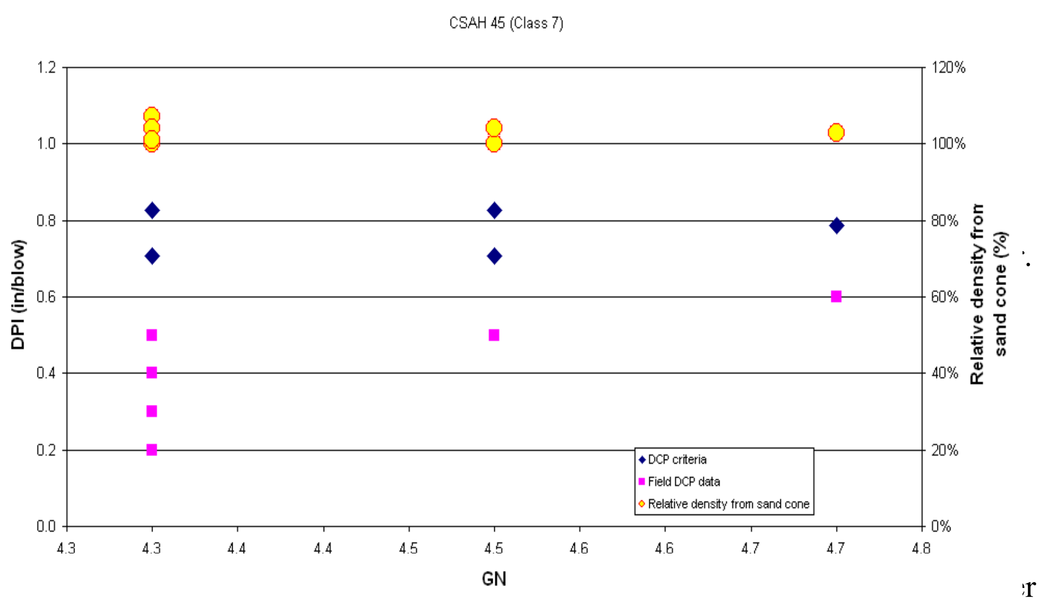
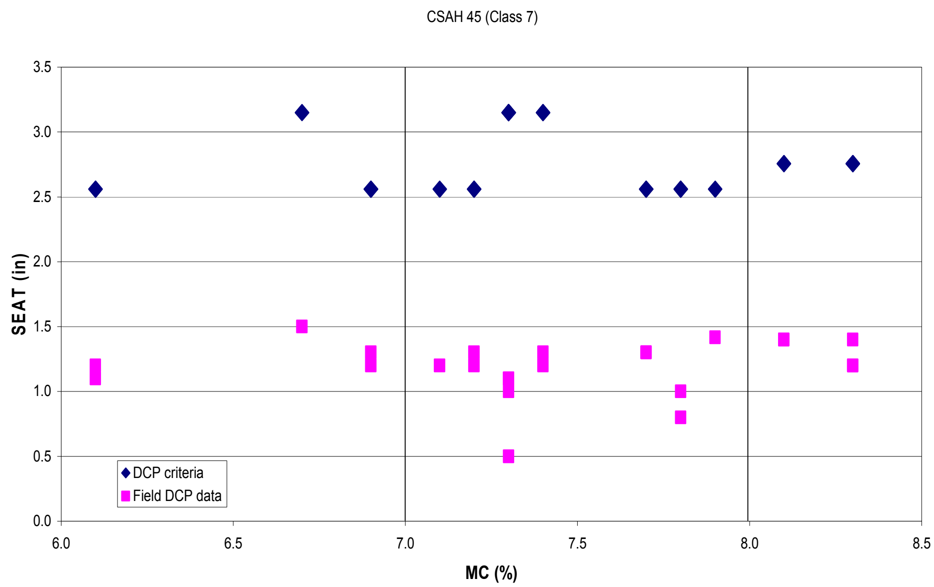


Figure 5.16 Relationship between DPI, relative density and grading number.

Figure 5.17 Relationship between Seating Penetration and moisture content



Again, good comments were received from the inspectors. They also found that the DCP is easy to use and faster than the sand cone test. In addition, the DCP results, generally, agree with sand cone density results.

<u>TH.112</u>

DCP tests were conducted on Class 3 and Class 5 materials on this project. The inspector reported that most of the DCP tests penetrated through the thin (three inches) Class 5 material layer. The current modified specification requires that the minimum thickness for DCP testing is three inch. Based on the results from this project and the CSAH 45 project, it is recommended that the minimum thickness should be increased to 4 inches or more for aggregate base materials**.**

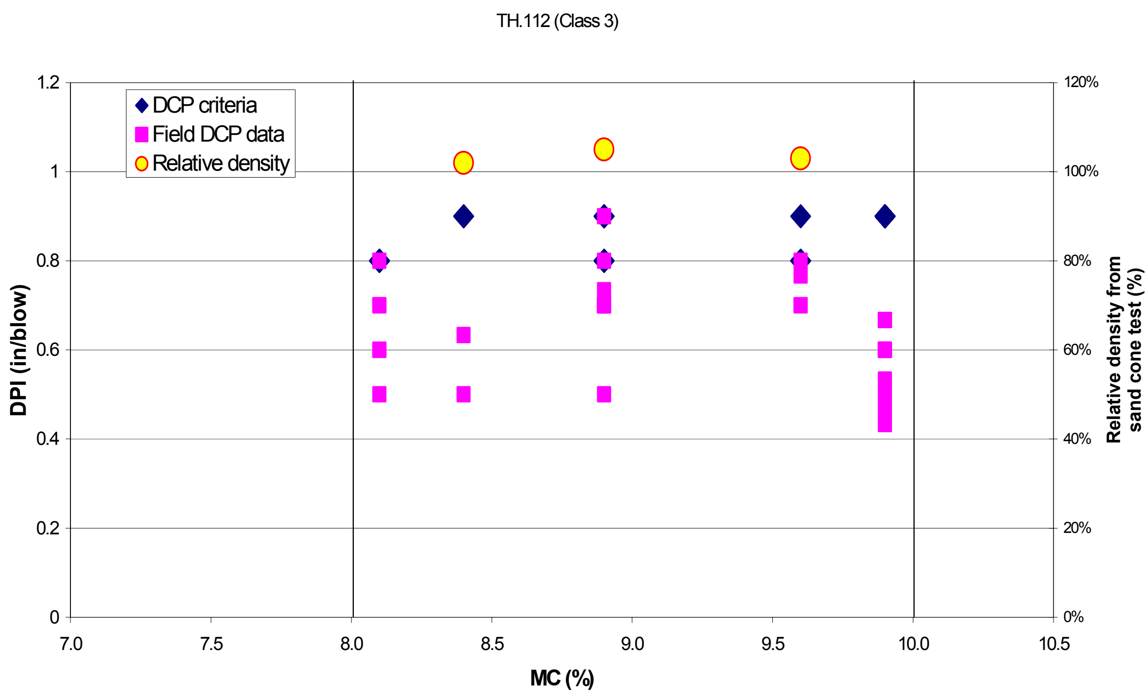


Figure 5.18 Comparison of field DPI, DCP criteria and relative density.

Since most DCP tests on the CL 5 material penetrated the layer, the data obtained from the CL 5 material was not included in the analysis. Figure 5.18 shows the comparison of DPI, DCP criteria and sand cone density results. Once again, it can be seen that DCP test results are consistent with the sand cone density results. The DCP tests passed the modified DCP criteria, while the density also passed density requirement (the relative density requirement is 100% according to the current Mn/DOT grading and base specification).

Figures 5.19 and 5.20 illustrate the DPI, Seating and grading number. Seating also passed the seating criteria, which is also consistent with the inspector's observation. The inspector felt that the CL 3 material was very stiff after compaction. He checked the DCP results with sand cone density tests at a few locations and the results were consistent. The inspector indicated that the modified DCP specification provided reasonable results.

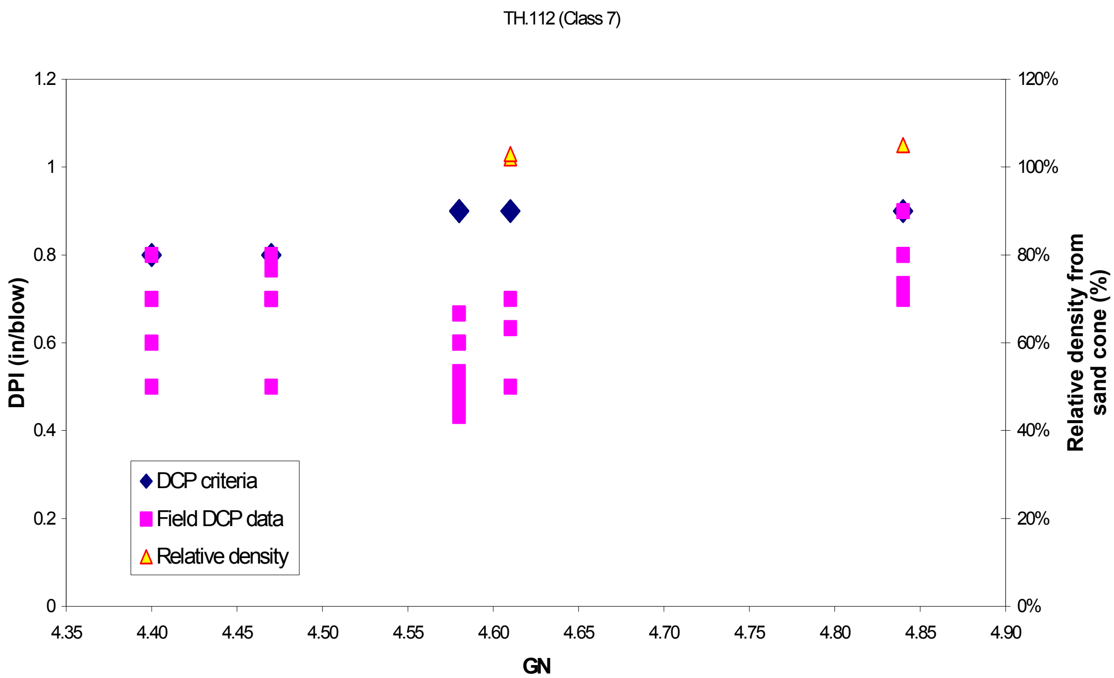


Figure 5.19 Comparison of field DPI, DCP criteria and relative density.

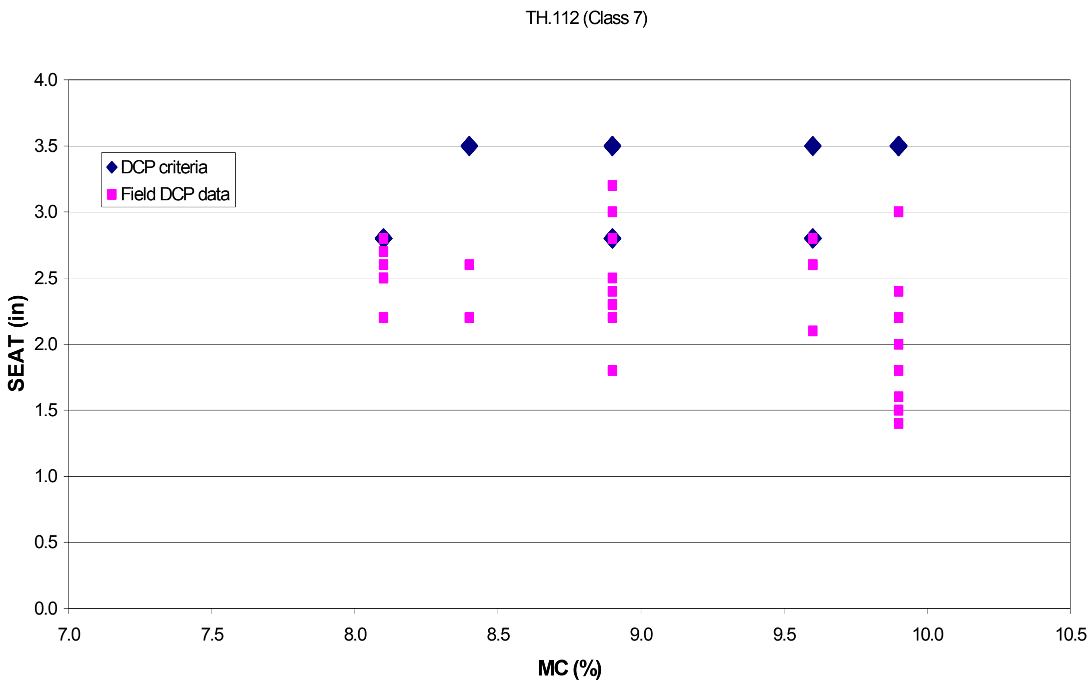


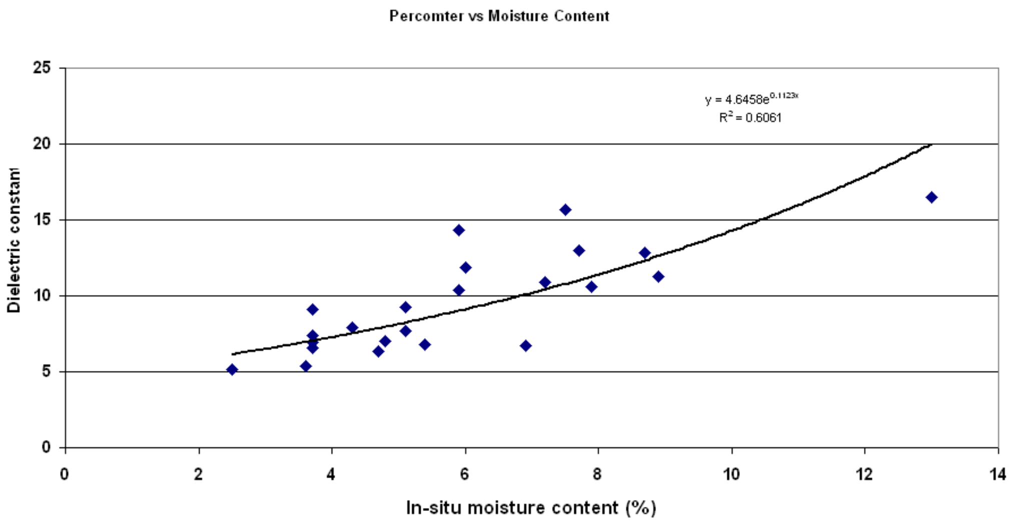
Figure 5.20 Comparison of field seating penetration and DCP criteria.

Field Moisture Test

During the testing of the 2003 construction season, the Pecometer was also used to obtain dielectric values of the material. The experience showed that the Percometer readings seemed to fluctuate more if the testing surface was rough and contained voids. This was more pronounced for reclaimed materials.

Figure 5.21 shows the results from the Percometer tests. In general, the dielectric constant increases as the moisture content increases. However, the data is scattered, which indicates a highly variable test.

Figure 5.21 Relationship between dielectric constant and moisture content.



Chapter 6
Summary and Conclusions

The current Mn/DOT DCP specification was developed during the 1990s. It requires that the dynamic penetration index (DPI) shall be less than 0.4 in/blow (10 mm/blow) and a maximum seating penetration of 1.6 in (40 mm). The specification also requires that the material shall be tested and approved within 24 hours of placement and final compaction. Beyond the 24 hours, the material can only be accepted by the Specified Density Method. However, the effects of gradation and moisture content are not accounted for in the current specification. A trial specification was developed in 2002 to address these problems.

During the summer of 2003, eleven construction projects around the state were selected for additional field testing. The purpose of the 2003 testing was to validate and/or improve the proposed DCP specification. For each construction project, several locations were randomly selected for testing. Sand cone density testing was also performed at most DCP testing locations in an effort to relate DCP results to the measured field density results. Based on the data collected in 2003, a modified DCP specification was recommended. The following table 6.1 is the summary of tested material types and construction projects.

Table 6.1 Summary of tested material types and construction projects

DISTRICT	TRUNK HIGHWAY	MATERIAL CLASS	TEST LOCATIONS	NUMBER OF BARREL SAMPLES	TEST NUMBERS
METRO	61	7 C	3	3	3-5
METRO	649 / 94	7 B C	4	4	48-51
1	23	RECLAIM	8	4	87-94
3	10	6	2		1-2
3	371	SELECT GRANULAR	6	4	10, 56-60
3	371	6	10	4	27-36
4	200	RECLAIM	7	4	70-76
6	16	SELECT GRANULAR	5		11-15
6	16	6	11	4	16-26
6	52	SELECT GRANULAR	9	4	78-86
7	14/15	5	6	4	46-47, 52-55
8	23	3	9	3	61-69
Co. Rd.	14	5	9	4	37-45
		TOTAL	89	42	

The modified DCP specification was implemented into four pilot construction projects in the summer of 2004. The goal of the field implementation is to verify the modified DCP specification and assess the effectiveness of the specification through construction inspector field evaluation. Three of which were Mn/DOT projects and the other was County Road 45 located in Steele County. The projects are:

1. SP 6920-37, TH 53 & TH 169 in District 1;
2. SP 4011-16, TH 112 in District 7;
3. SP 4310-45, TH 212 in District 8.
4. SAP 74-645-21, CSAH 45 in Steele County.

A construction testing procedure based on the modified DCP specification was developed and inserted into the construction plan as special provisions. The data obtained from the pilot projects confirmed the previously demonstrated relationship between the DPI, gradation and the material moisture content. Also, it shows that the DPI values obtained from the four pilot projects are very similar to the values collected in 2002 and 2003. This indicates that the data collected in 2004 is validated and the modified specification developed is applicable for field construction use. Furthermore, the DCP and sand cone density data collected from the four projects showed that the modified specification is consistent with the current sand cone density test specification, which further validates the modified specification. Also, good comments were received from inspectors, which include:

1. The modified specification in the Appendix B uses an EXCEL spreadsheet to determine failure or pass of a test. The procedure is easy to understand.
2. The inspectors indicated that the modified specification is easy to use and saves a lot of field testing time.
3. Comparing with sand cone density tests, inspectors also felt that the modified specification gives reasonable results, which are consistent with either the sand cone testing results or their experience.
4. One big advantage of the DCP test is that it can be applied to those materials on which the sand cone density test cannot be performed, such as taconite tailings.

However, the inspectors recommend that the minimum thickness for the DCP test should be increased. Based on the results from TH.112 project and CSAH 45 project, it is recommended that the minimum thickness should be increased to 4 inches or more for aggregate base materials.

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Appendix A

Draft Report: Advancement of Grading and Base Material Testing

ADVANCEMENT OF GRADING & BASE MATERIAL TESTING

DRAFT FINAL REPORT

Prepared by

Matthew Oman
Graduate Engineer

Minnesota Department of Transportation
Office of Materials
1400 Gervais Avenue, MS 645
Maplewood, MN 55109

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EXECUTIVE SUMMARY

The Specified Density Method has been the standard method for the control and acceptance of grading and base construction in the state of Minnesota for many years. Although it has survived the test of time, there are several drawbacks to this method. Most notably, the field test (sand cone) is very time consuming and demands extreme care to avoid erroneous results.

Another type of equipment, the Dynamic Cone Penetrometer (DCP), can be used to assess construction quality. The DCP provides an indication of strength rather than density, although construction deficiencies can be identified through either approach. Mn/DOT currently allows the DCP to be used as an acceptance testing method, although it is only applicable to aggregate base construction.

As part of a Department-wide streamlining effort, an improved method of construction acceptance was considered necessary. The DCP was selected as the primary focus for this project as it was felt that many inspectors were familiar with the device since the aggregate base specification had been in place for several years. An improved DCP specification would also introduce the lowest cost, as each district already owned several.

Since its introduction with Mn/DOT, several concerns had been raised regarding Mn/DOT's DCP procedures and acceptance criteria; solving those became primary issues. The goal of this project was to develop a simple, improved DCP specification for use on aggregate base and/or granular material that accounts for gradation and moisture effects.

Various types of data were collected during the 2002 and 2003 construction seasons. Analysis of the data introduced very solid trends between DCP penetration and gradation and moisture content. These relationships opened the door to the creation of a DCP specification for use on both aggregate base and granular material under all testing conditions.

The enhanced DCP specification requires less field and lab time than the relative density method, in addition to expanding the capabilities of the DCP. It also provides guidelines for determining moisture levels during compaction. Both of these characteristics will be extremely valuable, as it will allow inspectors to spend more time inspecting rather than testing.

The final product is a very simple to use hand-written form or electronic spreadsheet. The only inputs are gradation data, moisture content at the time of testing, and DCP penetration values.

ADVANCEMENT OF GRADING & BASE MATERIAL TESTING

I. INTRODUCTION

The Specified Density Method has been the standard method for the control and acceptance of grading and base construction in the state of Minnesota for many years. A specified density evaluation requires two separate tests to be completed. Initially, a Proctor density is required to provide the "maximum" dry density for a standard compaction effort. Secondly, the in-situ density is needed and is determined through the use of a sand cone apparatus.

If the relative density (Field ÷ Proctor) is greater than the specified value (95 or 100%), the test location is satisfactorily compacted. Conversely, if it is less than the specified value, the test fails and additional compaction is required.

Although it has survived the test of time, there are several drawbacks to this method. Most notably, the field test (sand cone) is very time consuming and demands extreme care to avoid erroneous results. Additional time is required in the lab to establish the Proctor density for the material in question. Furthermore, if the material has a highly variable gradation, additional Proctor densities may be required.

Another type of equipment, the Dynamic Cone Penetrometer (DCP), can be used to assess construction quality. The DCP provides an indication of (shear) strength rather than density, although construction deficiencies can be identified through either approach. Mn/DOT currently allows the DCP to be used as an acceptance testing method, although it is only applicable to aggregate base construction.

The current specification, developed during the 1990s and introduced in 1997, requires the dynamic penetration index to be less than 10 mm/blow with a maximum seating penetration of 40 mm. It also states that the test shall be conducted within 24 hours of placement and final compaction, otherwise the specified density method shall be used.

II. RESEARCH OBJECTIVE

As part of a Department-wide streamlining effort, an improved method of construction acceptance was considered necessary. The DCP was selected as the primary focus for this project as it was felt that many inspectors were familiar with the device since the aggregate base specification had been in place for several years. An improved DCP specification would also introduce the lowest cost, as each district already owned several.

Since its introduction with Mn/DOT, several concerns had been raised regarding Mn/DOT's DCP procedures and acceptance criteria; solving those became primary issues. The goal of this project was to develop a simple, improved DCP specification for use on aggregate base and/or granular material that accounts for gradation and moisture effects.

III. DATA COLLECTION

During the 2002 construction season, the Grading and Base (G & B) Unit of the Office of Materials gathered data from projects around the state. Since the DCP was the primary focus, it was utilized on every test location. Other equipment was used but not as consistently as the DCP. Supplemental data collected includes:

- Gravimetric moisture content and/or sand cone density
- Gradation and/or Proctor maximum density
- Loadman II
- Percometer
- Rapid Compaction Control Device (RCCD)
- GeoGauge

Figure 1. Test equipment used during the 2002 construction season.

A total of 21 projects were visited in 2002 with at least one in each district. In all, 82 locations were tested with a very nice distribution between material types; 38 granular and 39 aggregate base (Class 5, 6, or 7). In addition, 5 full-depth reclamation (FDR) locations were tested.

PROCEDURE

All tests were conducted within a one to two foot square area. The order of the testing was determined by the destructiveness of each device. A typical site evaluation was as follows:

1. Loadman II
2. Percometer
3. GeoGauge
4. DCP
5. RCCD
6. Moisture sample or sand cone density
7. Bag sample for lab gradation and/or Proctor density.

EQUIPMENT

DCP

The DCP consists of a lower rod with an anvil and 60^{o} cone tip and an 8 kg hammer on the upper rod. The hammer falls a distance of 575 mm where it strikes the anvil and drives the tip into the soil. Penetration measurements can be determined using a number of techniques, but for the 2002 season, measurements were made using a detached ruler.

The penetration of the DCP is a direct indicator of the shear strength of the material. Shear strength (i.e., penetration) can vary for the exact same material as confining stress or moisture content conditions change. The penetration can also be influenced by gradation differences.

To begin the test, the DCP unit is set on the ground and a “zero” reading is established. The hammer is carefully raised to the top of the upper rod and released freely. The penetration is measured and the test continues in the same manner. Under the current specification, five drops constitute a test; however, twelve were recorded for this project. Note that any penetration resulting from its own weight is not included in the test.

The data is processed to determine the total seating penetration (SEAT) and the dynamic penetration index (DPI). The current specification considers the first two drops separately in determining SEAT and includes the third, forth, and fifth drops in the calculation of the DPI. The formulas can be seen in Equations 1 and 2.

$$\text{SEAT (mm)} = \text{Penetration}_{\text{Blow\#2}} - \text{Zero Reading} \qquad \text{Eq. 1}$$

$$\text{DPI (mm/blow)} = \frac{\text{Penetration}_{\text{Blow\#5}} - \text{Penetration}_{\text{Blow \#2}}}{\text{3 Blows}} \qquad \text{Eq. 2}$$

Moisture Content

Gravimetric moisture content, expressed as percent moisture by dry weight, was determined using the “burner” or “Speedy” method (converted from volumetric moisture content). The Speedy device was rarely used, as recycled materials are prohibited. The burner method requires a representative sample to be dried in an oven or on a burner.

Sand Cone

The field density test is a method of determining the in-place density of grading soils or aggregate base. The test consists of digging a hole either 100 mm or 150 mm in diameter, for granular and aggregate base materials, respectively. The depth shall be great enough to evaluate the entire layer. All of the material is carefully removed and weighed. Finally, the volume of the hole is determined by filling the hole with sand of known unit weight. The moisture content is determined and the dry density of the material is calculated.

The majority of aggregate base locations tested in 2002 do not have reliable sand cone data. In the author's opinion, the following, coupled with a lack of experience, caused this problem:

- coarse gradations are difficult to evaluate accurately using the sand cone method, as slightly dislodged large particles can change the volume of the hole;
- the reliability of the sand cone test decreases as the moisture content decreases since the material is extremely difficult to remove without dislodging particles.

Gradation/Proctor

A bag sample of either 30 or 50 lb of material was taken for the gradation or Proctor/gradation lab test, respectively.

Of the 82 tests, 30 had Proctor densities and gradations determined, while 12 had gradation data only. The remaining points were either "duplicate" tests (approximately the same location) or locations with material of the same source as another test.

Final note: More detailed information about the preceding test methods can be found in the Grading & Base Manual. It is available for viewing or downloading at the following website: **www.mrr.dot.state.mn.us/pavement/GradingandBase/gradingandbase.asp**

Other Equipment

RCCD

The RCCD, or rapid compaction control device, is very similar to the DCP in that it measures the penetration of a cone tip into the soil. However, rather than being driven by a hammer striking an anvil, it is spring loaded and fired. The RCCD was developed in South Africa and is used there to monitor construction operations.

Loadman II

The Loadman II is a portable falling weight deflectometer (PFWD) that can be used to determine the stiffness or modulus of the overall system. An internal accelerometer and load cell make it capable of measuring the load magnitude and the resulting elastic deflection. It was developed in Finland and has very promising uses for mechanistic-empirical (M-E) design procedures.

Like the DCP, the first to drops were not included in any analysis; the third, fourth, and fifth drops were averaged to determine the material stiffness.

<u>Percometer</u>
The Percometer measures the conductivity and dielectric constant of the soil mass. Conductivity is related to the volumetric moisture content.

<u>GeoGauge</u>
The GeoGauge is a device for measuring the stiffness or modulus of soil materials. It vibrates at several frequencies and measures the resulting deflections of the load ring. The use of this instrument was very limited as part of this study.

IV. DATA ANALYSIS

<u>GRADATION</u>

It was hypothesized during the early stages of this project that the material's gradation has an influence on the penetration of the DCP. A key to the analysis was the development of an innovative way to represent the gradation as a single number. A typical gradation contains up to twenty sieves but must always contain the following seven sieves: 25 mm, 19 mm, 9.5 mm, 4.75 mm, 2.00 mm, 425 µm, and 75 µm.

A concept to express the gradation, referred to as grading number (GN), was derived from the fineness modulus (FM) equation, which is used in concrete mix design. The GN formula is quite similar in format, although it uses the percent passing each sieve in the calculation. The GN formula is revealed in Equation 3.

$$\text{GN (\% passing)} = \frac{25mm + 19mm + 9.5mm + 4.75mm + 2.00m + 425\mu m + 75\mu m}{100} \qquad \text{Eq. 3}$$

If 100% of the material passes each of the sieves listed in Equation 3, the GN reaches its maximum value of 7.0. That represents an extremely fine gradation. Conversely, if 0% passes all of the sieves, the GN falls to its lowest value of 0.0. This characterizes a tremendously coarse material, as the entire sample would be retained on or above the 25 mm sieve.

The Mn/DOT gradation requirements for Class 5 and 6 aggregate bases can be seen in Table 1. If the extreme cases (finest and coarsest) are applied to the GN formula, boundary values for each material type can be calculated. These limits are also shown in Table 1.

Table 1. Mn/DOT's requirements for Class 5 and 6 aggregate base with GN boundary values.

Sieve	Class 5	Class 6
25 mm	100	100
19.0 mm	90-100	90-100
9.5 mm	50-90	50-85
4.75 mm	35-80	35-70
2.00 mm	20-65	20-55
425 μm	10-35	10-30
75 μm	3.0-10.0	3.0-7.0
GN	3.1-4.8	3.1-4.5

DCP PENETRATION vs GRADATION

To obtain a GN value for each data point, values were assigned to locations without gradation data from "duplicate" test points. The term "duplicate" refers to locations on the same project with material from the same source.

It can be seen in Figure 2, that as the GN increases, the DPI steadily increases as well. Figure 3 shows the same phenomenon except that it demonstrates the relationship between GN and SEAT. These figures validate the hypothesis that gradation, or GN, has an influence on the penetration of a DCP.

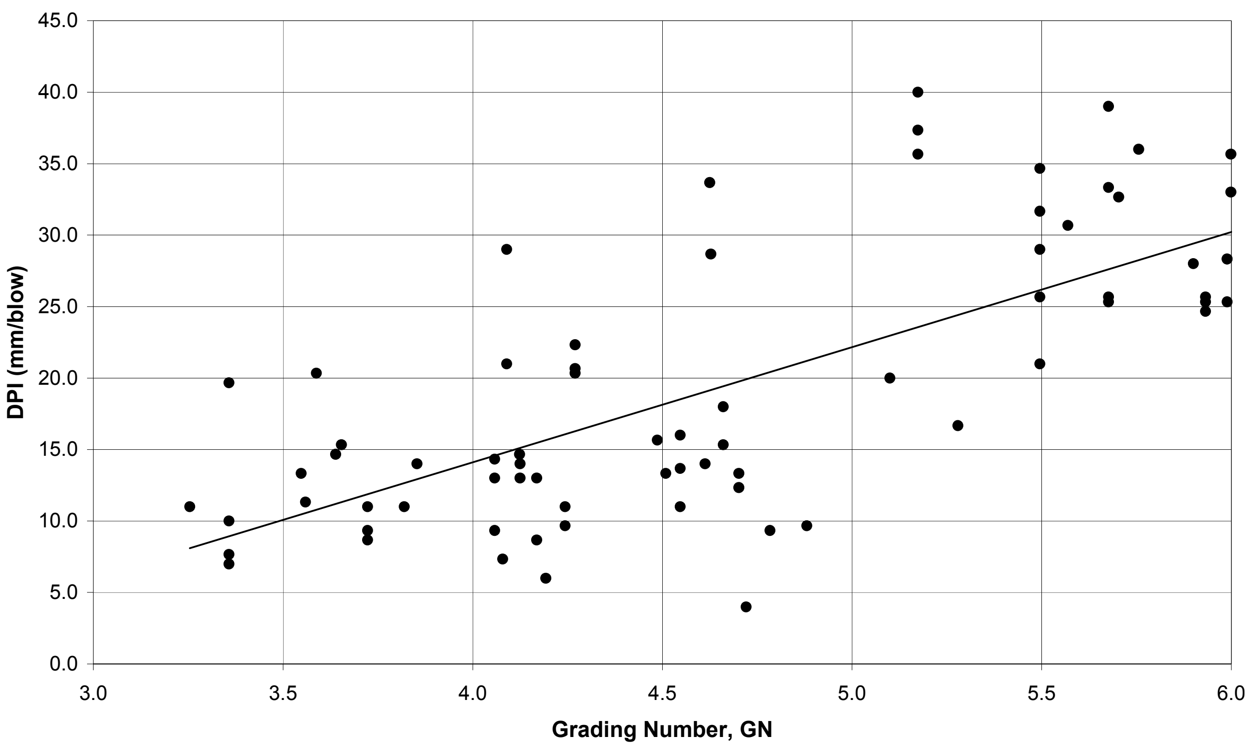


Figure 2. DPI versus GN. $R^2 = 0.53$.

Multiple linear regression analysis was performed using all sieves and interactions. No greater relationship was established than between SEAT or DPI and GN. In addition, a similar concept to the surface area (SA) factors used by the Bituminous Unit was employed. Again, the greatest correlation between DCP penetration and gradation was established using the GN concept.

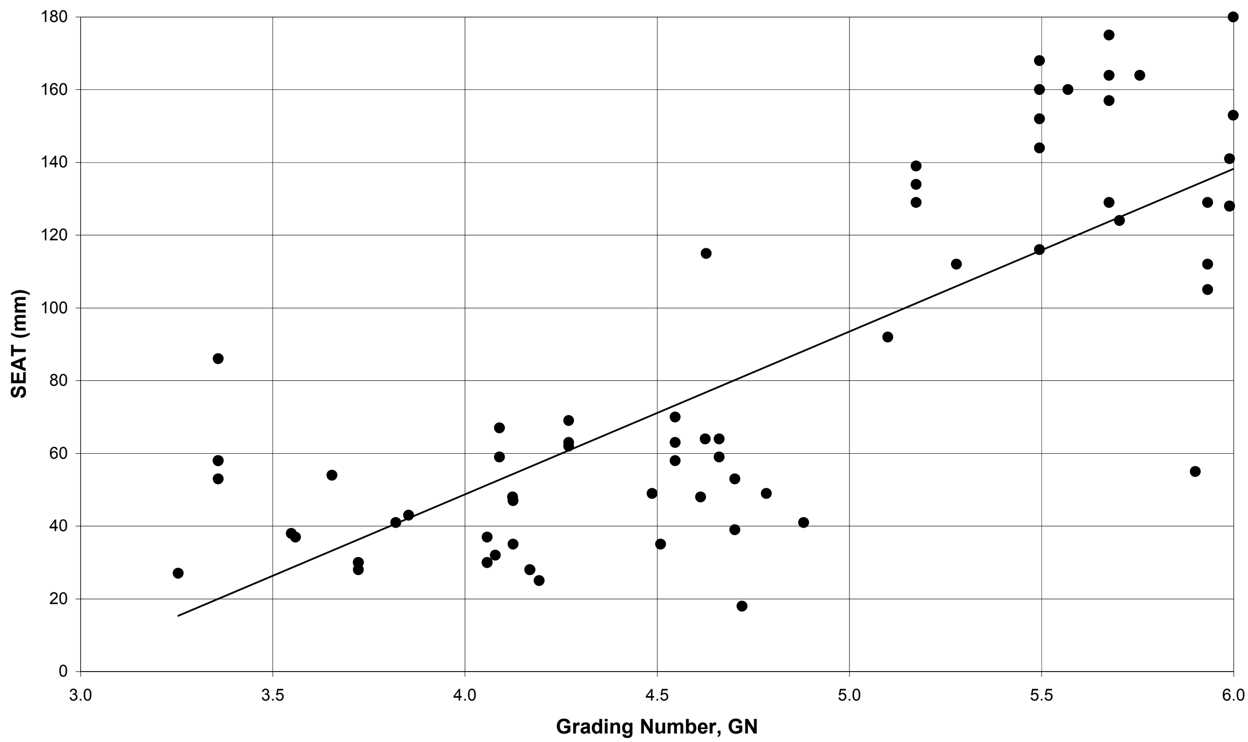


Figure 3. SEAT versus GN. $R^2 = 0.63$.

DCP PENETRATION vs MC

Another factor presumed to affect DCP penetration was moisture content at the time of the test. Figure 4 illustrates a reasonable correlation between DPI and MC, as does Figure 5 for SEAT and MC.

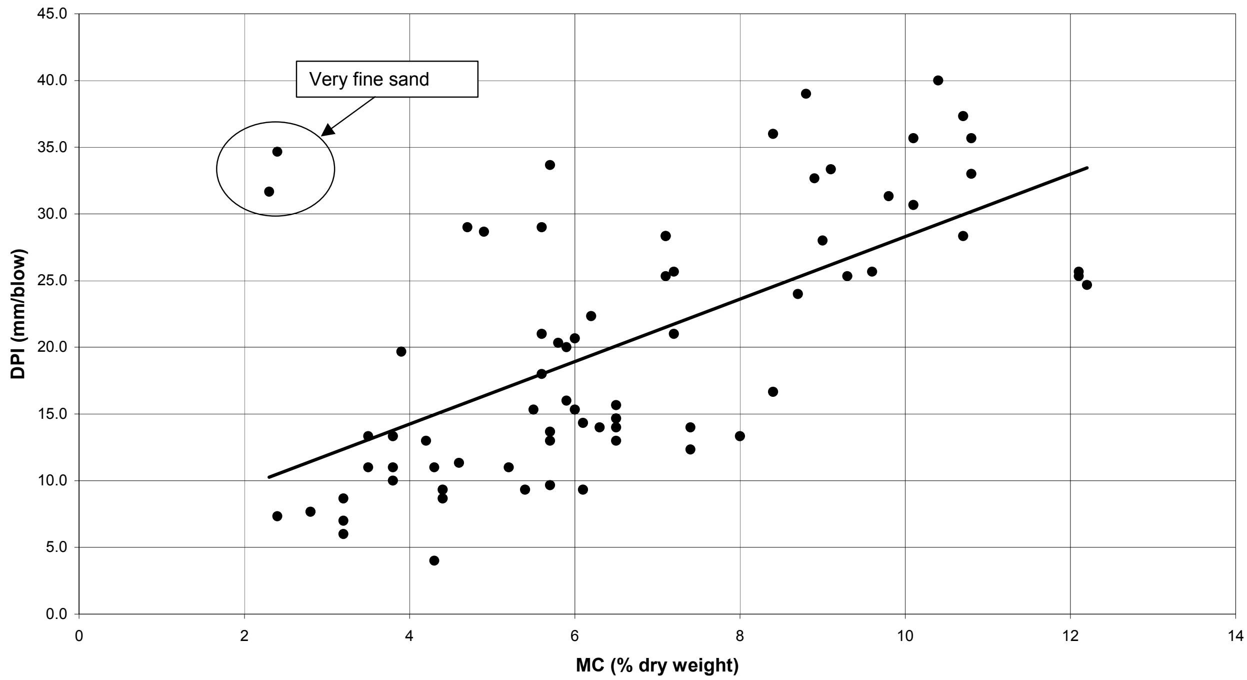


Figure 4. DPI versus MC. $R^2 = 0.39$ ($R^2 = 0.54$ if "very find sand" points removed).

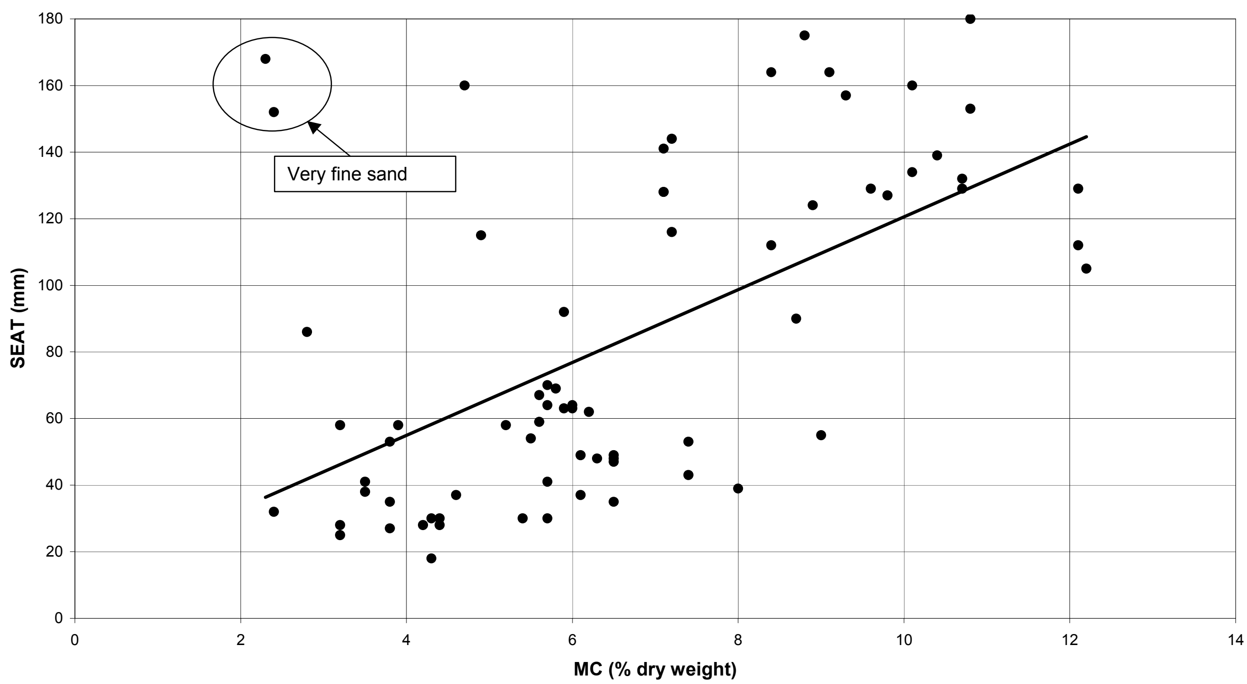


Figure 5. SEAT versus MC. $R^2 = 0.34$ (0.51 if "very find sand" points removed).

DCP PENETRATION THRESHOLD

Field personnel typically notified the Grading & Base Unit one day prior to, or possibly even the same day as, placement and compaction operations. As a result, it was not always feasible to be on site during construction. Consequently, many tests were taken an hour or two or more after compaction which made it nearly impossible at times to quantify the amount of compaction, in terms of density.

Therefore, an assumption was made regarding each of the data points; the G & B engineer evaluated a level of "quality compaction" at each test location. Notes were made in the field about each test section and those that received "quality compaction" ratings were considered passing DCP test locations. A failing "quality compaction" score equated to a failing DCP test.

Using this approach, the number of data points was reduced from 82 to 51. Not all data removed was due to failing "quality compaction" ratings; numerous locations had been placed and compacted a week or more prior to testing, which does not represent acceptance testing.

The following 51 data points were used in developing the regression equations:

- 26 granular or grading materials
- 25 aggregate base.

REGRESSION ANALYSIS

Once it was shown that GN and MC were significant factors and a passing criteria was established the DCP penetration, regression analysis could be executed. ARC statistical software, which was developed at the University of Minnesota, was used to perform the analysis.

The reduced data set was first evaluated for DPI versus GN and MC. The condensed data provided R^2 values higher than those shown in Figures 2 and 4, respectively. The following summarizes the regression results:

- DPI vs MC:
  $R^2 = 0.48$, □ = 7.15

- DPI vs GN:
  $R^2 = 0.58$, □ = 6.42

Multiple linear regressions were utilized to increase the overall R^2 and reduce the standard error (□) in each relationship. The interaction between GN and MC was included but was found to be statistically insignificant. Here is a summary of the multiple linear regressions:

- DPI vs GN, MC:
  $R^2 = 0.65$, □ = 5.93

- SEAT vs GN, MC:
  $R^2 = 0.66$, □ = 29.10

The final equations for DPI and SEAT are shown in Equations 5 and 6.

$$\boxed{\text{DPI (mm/blow)} = 4.76 \times \text{GN} + 1.68 \times \text{MC} - 14.4} \qquad \text{Eq. 5}$$

$$\boxed{\text{SEAT (mm)} = 36.8 \times \text{GN} + 4.12 \times \text{MC} - 124} \qquad \text{Eq. 6}$$

<u>OPTIMUM MOISTURE CONTENT</u>

A common complaint about the current DCP procedure is that it is too difficult to pass in certain situations. In the author's opinion, this is partially due to the fact that moisture control is not addressed in the specification. Therefore, compaction operations are often performed at inadequate levels of moisture content.

Optimum Moisture Content (OMC) is part of the Proctor evaluation and is the moisture content at which the maximum density is achieved. Without the need for a Proctor density on a DCP project, there is very little feeling for the required moisture content during construction. This may especially be a problem when inexperienced personnel replace highly experienced field inspectors.

To address this issue, the G & B Unit investigated the possibility of estimating the OMC. The Maplewood Lab database was searched for aggregate base and granular material samples and 115 Proctor tests were available for analysis.

For this evaluation, it was thought that the fine material (i.e., passing the 2.0mm sieve) should have more influence in the GN equation. Therefore, the GN calculation was broken into two portions; the coarse grading number (CGN) and the fine grading number (FGN). The GN is calculated by summing the CGN and FGN. The equations for the CGN and the FGN are shown in Equations 7 and 8.

$$\text{CGN (\% passing)} = \frac{25.0mm + 19.0mm + 9.5mm + 4.75mm}{100} \qquad \text{Eq. 7}$$

$$\text{FGN (\% passing)} = \frac{2.00mm + 425\mu m + 75\mu m}{100} \qquad \text{Eq. 8}$$

Regression analysis was done for all single sieves and combinations, SA factors, GN, and CGN and FGN. The latter pair provided the best results. Here is a summary of the analysis:

- OMC vs CGN, FGN, CGNxFGN:
  $R^2 = 0.43$, □ = 1.61

The final equation for estimated optimum moisture content (EOMC) is shown in Equation 9.

$$\boxed{\text{EOMC (\%)} = 18.5 - 2.23 \times \text{CGN} - 28.0 \times \text{FGN} + 7.35 \times \text{CGN} \times \text{FGN}} \qquad \text{Eq. 9}$$

TRIAL SPECIFICATION

A trial DCP specification was created using the aforementioned analyses. The specification was broken into two parts and packaged as a complete field procedure. The first half requires general project information and gradation data. After several simple calculations, the CGN, FGN, and GN can be determined. Finally, the EOMC is established for the given gradation. The first page is shown in Figure 6.

The second half of the process is intended to assess construction operations using the DCP. The penetration acceptance table was created by breaking the continuous variables GN and MC into small ranges. To be conservative, the upper limit of each range was used to calculate the maximum penetration values. For instance, a GN ranging from 4.1 to 4.5 would use a value of 4.5 for maximum penetration calculations. In addition, the current specification requirements were used as a lower bound in the table. The second page can be seen in Figure 7.

2003 Grading & Base DCP Procedure: Metric

Project Data

SP ____________ Highway ____________ Inspector ____________

Material ____________ Date ____________ Notes ____________

Procedure

- Perform gradation test on BASE or GRANULAR sample.
- Calculate *CGN* (Coarse Grading Number), *FGN* (Fine Grading Number), and *GN* (Grading Number).
- Estimate the *Optimum Moisture Content* based on *CGN* and *FGN*. This value should only be used as a guide during compaction operations.
- Determine the maximum penetration values for *Seating* and *DPI* based on *GN* and *In-Situ Moisture Content*.

Gradation Data

FORMULAS (use **% Passing** in *CGN* & *FGN* calculations)

$$CGN = \frac{25.0mm + 19.0mm + 9.5mm + 4.75mm}{100} \qquad FGN = \frac{2.00mm + 425\mu m + 75\mu m}{100} \qquad GN = CGN + FGN$$

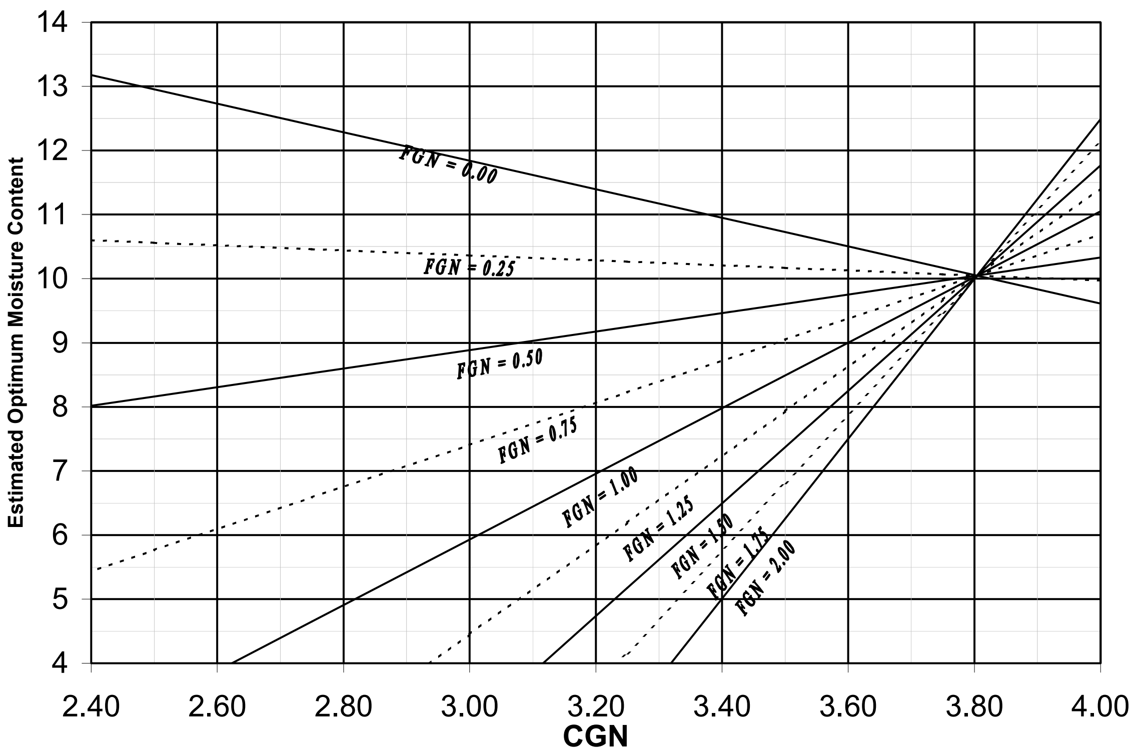
Sieve	% Passing
25.0 mm	
19.0 mm	
9.5 mm	
4.75 mm	

CGN =

Sieve	% Passing
2.00 mm	
425 μm	
75 μm	

FGN =

GN =



Optimum Moisture Content =

Comments or questions? Contact Matthew Oman @ (651) 779-5511 or Cary Efta @ (651) 779-5332

Figure 6. Page 1 of trial DCP field procedure.

SP ____________

DCP Requirements: Metric

Material ________________

Estimated Optimum Moisture Content = ________________

PENETRATION REQUIREMENTS

GN	In-Situ Moisture (% by dry weight)	Maximum Allowable Seating (mm)	Maximum Allowable DPI (mm/blow)	Minimum Layer Thickness for Testing (mm)
< 3.5	< 4.0	40	10	105
	4.1-6.0	40	12	
	6.1-8.0	40	16	
	8.1-10.0	45	19	
3.5-4.0	< 4.0	40	11	130
	4.1-6.0	50	15	
	6.1-8.0	55	18	
	8.1-10.0	65	21	
4.1-4.5	< 4.0	60	14	160
	4.1-6.0	65	17	
	6.1-8.0	75	20	
	8.1-10.0	85	24	

GN	In-Situ Moisture (% by dry weight)	Maximum Allowable Seating (mm)	Maximum Allowable DPI (mm/blow)	Minimum Layer Thickness for Testing (mm)
4.6-5.0	< 4.0	75	16	180
	4.1-6.0	85	19	
	6.1-8.0	95	23	
	8.1-10.0	100	26	
5.1-5.5	< 6.0	105	22	230
	6.1-8.0	110	25	
	8.1-10.0	120	29	
	10.1-12.0	130	32	
> 5.5	< 6.0	120	24	250
	6.1-8.0	130	28	
	8.1-10.0	140	31	
	10.1-12.0	145	34	

Test Information						Requirements		DCP Data						
Test #	Date	Station	Offset	GN	Moisture Content	Maximum Allowable Seating (mm)	Maximum Allowable DPI (mm/blow)	Initial Reading	Reading after seating (2 Blows)	Reading after test (3 Blows)	Total Seating (mm)	Pass or Fail	DPI (mm/blow)	Pass or Fail

Comments or questions? Contact Matthew Oman @ (651) 779-5511 or Cary Efta @ (651) 779-5332

Figure 7. Page 2 of trial DCP procedure.

V. VALIDATION AND CALIBRATION

In January 2003, a proposal to expand this project was written to the Local Road Research Board (LRRB). A graduate engineer was acquired from the Mankato District to undertake Phase II. A short summary of the data collected during the 2003 construction season is listed below:

- 11 projects visited
- 89 data points
    - 9 Class 3
    - 20 select granular
    - 15 Class 5
    - 23 Class 6
    - 7 Class 7
    - 15 FDR

The same test equipment was used during both seasons, although the focus changed regarding several devices. One of the major differences in data collection was the use of an automated data acquisition system for the DCP. Also, the Speedy moisture meter was used more frequently. Finally, the sand cone apparatus was used very consistently, as the graduate engineer was on site for most of the construction operations, and thus, had more success with this method.

PRELIMINARY DATA ANALYSIS

To ensure repeatability in the test methods, data gathered during both construction seasons was analyzed jointly. For the purpose of Phase I of this project, only DCP, moisture content, and gradation data were analyzed from the 2003 data collected.

To verify that the burner and Speedy moisture methods provide comparable results, all locations tested in 2003 that utilized both methods were compared. Figure 8 shows a strong relationship between the two methods. This significantly improved the data set, as all moisture content measurements could confidently be included in the analysis.

To illustrate the consistency of trends observed between DPI and GN and DPI and MC, charts were made using both 2002 and 2003 data. Figures 9 and 10 demonstrate the trends between DPI and GN and DPI and MC, respectively.

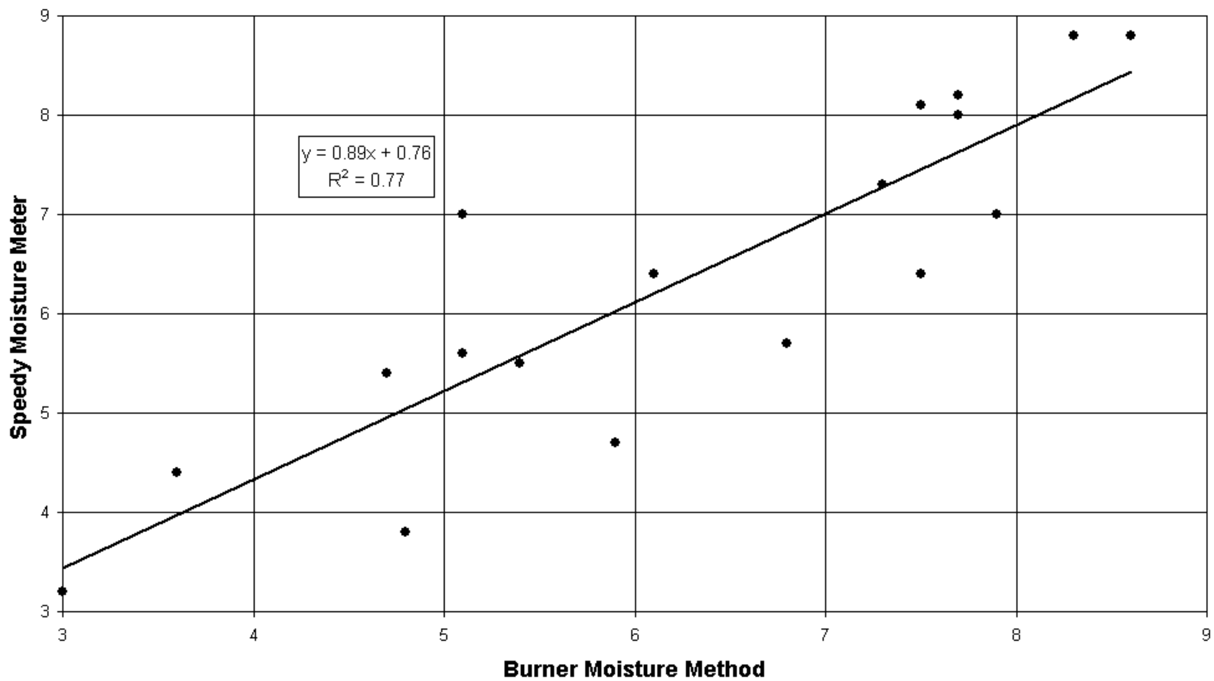


Figure 8. Locations tested in 2003 using both Speedy and burner moisture methods.

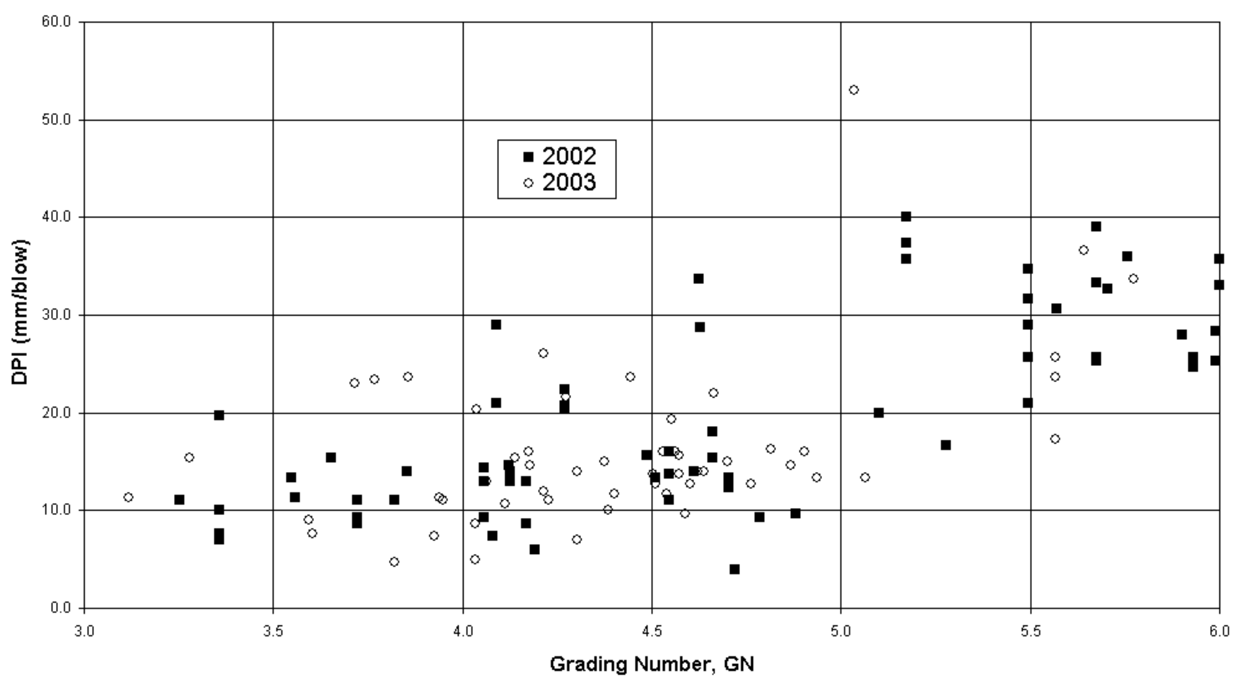


Figure 9. DPI vs GN for 2002 and 2003 data.

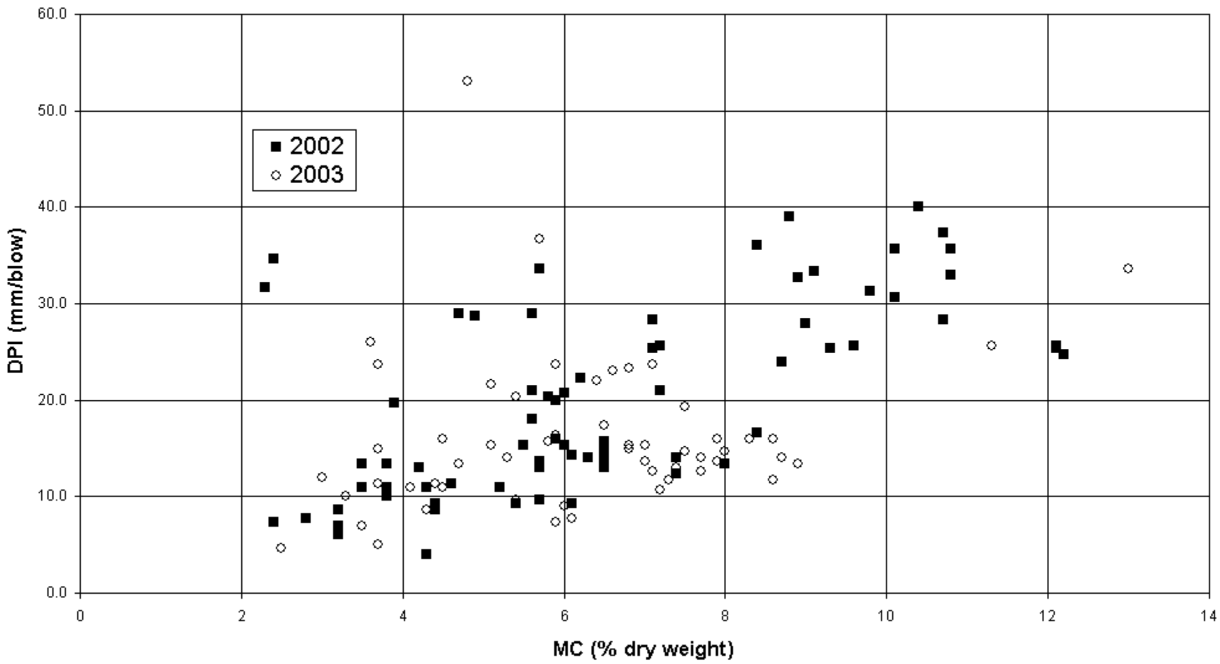


Figure 10. DPI vs MC for 2002 and 2003 data.

SPECIFICATION VALIDATION

Before any additional evaluations were done, the 15 FDR data points were excluded, as it is a highly variable material. Also, the 2002 equations were not established using any FDR data. In addition, several points were removed that did not have moisture data.

The 2003 DCP, moisture content, and gradation data was evaluated via the trial specification table (Figure 7). As with the 2002 data, an assessment was made regarding "quality compaction" based on the field notes. In addition, the large amount of sand cone data provided an excellent opportunity to include an aspect of relative density. The following criteria was used to establish failing locations:

- <95% relative density
  and/or
- failed "quality compaction"

Of the remaining 65 data points, 44 were considered "passing" and 21 "failing". Detailed tables of each group can be found in Appendix A and B, respectively.

Of the 44 data points that should produce a passing DCP test:

- 6 failed the maximum SEAT requirements
- 6 failed the maximum DPI requirements

Of the 21 data points that should produce a failing DCP test:

- 5 passed the maximum SEAT requirements
- 7 passed the maximum DPI requirements

However, for the purposes of fully evaluating a test location, both SEAT and DPI must pass to produce a passing test. Conversely, a single failure of SEAT or DPI produces a failing test. The following equation was used to calculate the success rate of the trial specification (against the expected outcome):

$$\text{Success Rate} = \frac{(\#\text{ of tests - }\#\text{ of incorrect assessments})}{\#\text{ of tests}} \qquad \text{Eq. 10}$$

Based on the 2003 data, the trial specification is 80% successful at accepting a location that should pass. Based on the same data, the specification is 81% successful at rejecting a location that should fail.

It should be noted that the noted success rates are at the extreme values. Any modification to the table would reduce the success rate of accepting passing locations and increase the success rate of rejecting failing locations. This is because the values used to calculate the requirements were at the upper limit of each range (i.e., for a GN between 4.1 – 4.5, 4.5 was used in the equation).

SPECIFICATION CALIBRATION

The original table was very liberal or conservative by design as the upper limits of each range (GN and MC) were used to create the table. Upon evaluation of the 2003 data, though, the specification was calibrated and re-created using the mid-point values of each range. Clearly this created a more restrictive specification; however, only a small portion of the "conservatism" was lost with this modification. Detailed tables, similar to those seen in Appendix A and B, can be found in Appendix C and D that display the effectiveness of the modified specification table.

Of the same 44 data points that should produce a passing DCP test:

- 10 failed the maximum SEAT requirements
- 9 failed the maximum DPI requirements

Of the same 21 data points that should produce a failing DCP test:

- 2 passed the maximum SEAT requirements
- 2 passed the maximum DPI requirements

Therefore, the modified table is 73% successful at accepting a location that should pass, which is reasonably comparable to the 80% success rate of the original table. However, the modified table significantly improves the capability of rejecting a location that should fail increasing the success rate from 81% to 95%.

The most significant change in the specification was the number used to calculate the maximum penetration values. Other small changes were made to the layout, etc. The 2004 DCP procedure can be seen in Figures 11 and 12, pages 1 and 2, respectively.

Modified DCP Procedure: 2004 (Metric)

Project Data

SP ______ Highway ______ Inspector ______

Material ______ Notes ______

Procedure - Part 1

- Perform gradation test on AGGREGATE BASE or GRANULAR material.
- Calculate Coarse Grading Number (***CGN***), Fine Grading Number (***FGN***), and Grading Number (***GN***).
- Compute the Estimated Optimum Moisture Content (***EOMC***):
  - Find the ***CGN*** value on the bottom axis.
  - Move vertically until the ***FGN*** line is intersected (interpolate between lines, if needed).
  - Move horizontally from that point until reaching the vertical axis. This is the ***EOMC***.

NOTE: This value should ONLY be used as a guide during compaction operations.

Gradation Data

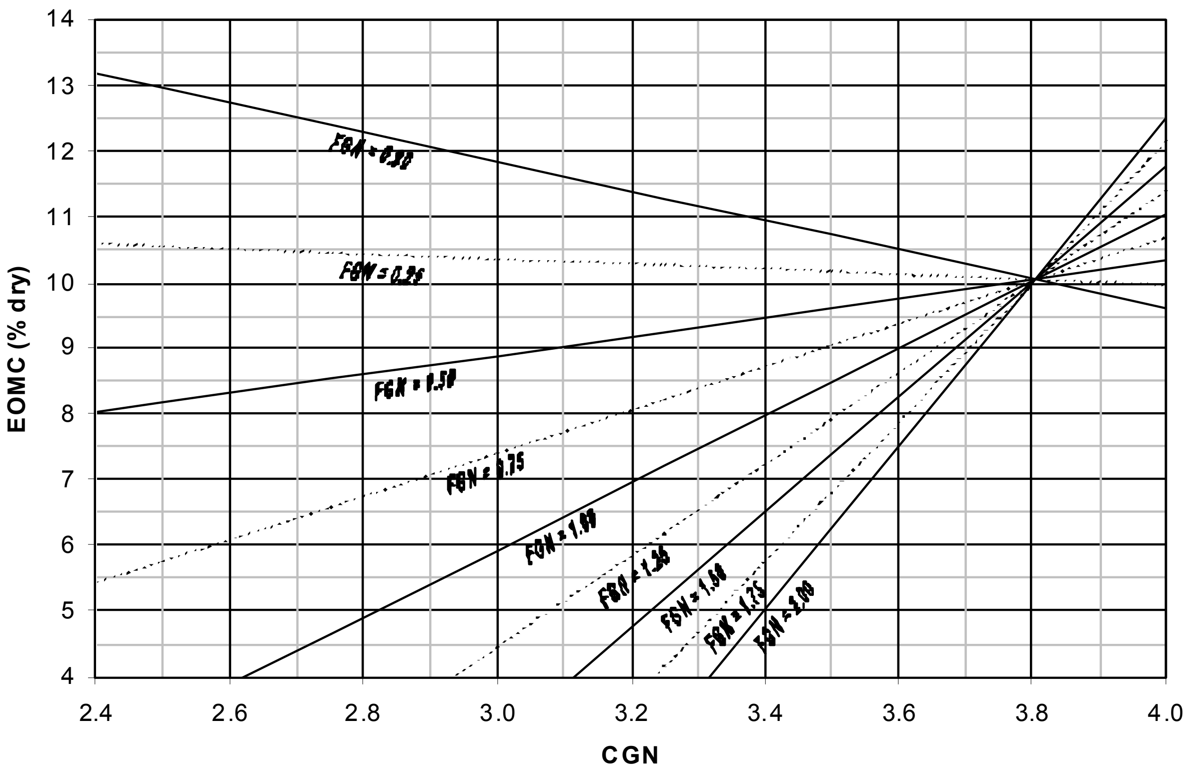
FORMULAS (use **% Passing** in *CGN* & *FGN* calculations)

$$CGN = \frac{25.0mm + 19.0mm + 9.5mm + 4.75mm}{100} \qquad FGN = \frac{2.00mm + 425\mu m + 75\mu m}{100} \qquad GN = CGN + FGN$$

Sieve	% Passing
25.0 mm	
19.0 mm	
9.5 mm	
4.75 mm	
CGN =	

Sieve	% Passing
2.00 mm	
425 µm	
75 µm	
FGN =	

GN =



Estimated Optimum Moisture Content (EOMC) =

Questions? Contact Tim Andersen @ (651) 779-5609 or Cary Efta @ (651) 779-5332

Figure 11. Page 1 of the modified DCP field procedure.

From Page 1:

SP

Material

Modified DCP Procedure: 2004 (Metric)

Procedure - Part 2

- Determine the test location and conduct DCP field evaluation. Also, determine the moisture content (***MC***) at the time of DCP testing.
- Establish the maximum penetration values for ***SEAT*** and ***DPI*** based on ***GN*** and ***MC***.
- Compute ***SEAT*** (total penetration after two blows) and ***DPI*** (average of 3rd, 4th, & 5th blows).
- Compare ***SEAT*** and ***DPI*** to penetration requirements. Both ***SEAT*** and ***DPI*** must pass in order to accept material.

Penetration Requirements

GN	MC (% dry)	Maximum Allowable SEAT (mm)	Maximum Allowable DPI (mm/blow)
3.1-3.5	< 4.0	40	10
	4.1-6.0	40	10
	6.1-8.0	40	13
	8.1-10.0	40	16
3.6-4.0	< 4.0	40	10
	4.1-6.0	40	12
	6.1-8.0	45	16
	8.1-10.0	55	19
4.1-4.5	< 4.0	45	11
	4.1-6.0	55	15
	6.1-8.0	65	18
	8.1-10.0	70	21

GN	MC (% dry)	Maximum Allowable SEAT (mm)	Maximum Allowable DPI (mm/blow)
4.6-5.0	< 4.0	65	14
	4.1-6.0	75	17
	6.1-8.0	80	20
	8.1-10.0	90	24
5.1-5.5	< 6.0	90	19
	6.1-8.0	100	23
	8.1-10.0	110	26
	10.1-12.0	115	29
5.6-6.0	< 6.0	110	22
	6.1-8.0	120	25
	8.1-10.0	125	28
	10.1-12.0	135	32

DCP Data

☐ Englsih DCP Measurements (check if English, un-check to return to Metric)

Test Information							Requirements		DCP Data (**mm**)			Test Results					
Test #	Date	Station	Offset	Test Layer Depth (mm)	GN	MC (%)	Maximum Allowable SEAT (mm)	Maximum Allowable DPI (mm/blow)	Initial Reading	Reading after seating (2 Blows)	Reading after test (3 Blows)	SEAT (mm)	SEAT: Pass or Fail	DPI (mm/blow)	DPI: Pass or Fail	Adequate Layer? (1)	**TEST**: Pass or Fail

(1) Total Penetration (after fifth blow) < Test Layer Depth = Adequate Layer

Questions? Contact Tim Andersen @ (651) 779-5609 or Cary Efta @ (651) 779-5332

Figure 12. Page 2 of the modified DCP field procedure.

VI. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Analysis of the 2002 data introduced very solid trends between DCP penetration and gradation and moisture content. These two relationships opened the door to the creation of a DCP specification for use on both aggregate base and granular material. Furthermore, the ability to test a location immediately following placement now exists as the in-situ moisture content at the time of testing has a quantifiable effect on the DCP penetration.

The enhanced DCP specification requires less field and lab time than the relative density method, in addition to greatly improving the capabilities of the DCP. It also provides guidelines for determining moisture levels during compaction. Both of these characteristics will be extremely valuable, as it will allow inspectors to spend more time inspecting rather than testing.

The 2003 data collection efforts proved to be very useful as it provided an opportunity to evaluate the trial specification. It also offered great insight into the success of the trial specification that ultimately lead to the modification, or calibration, of the specification. The modifications virtually unchanged the success rate of accepting a passing location, but significantly increased the reliability of rejecting a location that should fail.

The final product is a very simple to use spreadsheet. The only required inputs are gradation data, moisture content at the time of testing, and DCP penetration values. The spreadsheet automatically determines the fate of a test location. Of course, the procedure can be used without a computer, although extra time and effort are required.

RECOMMENDATIONS

There are two primary recommendations. First, the typical method of penetration measurement (ruler) should be used with the procedure. At first glance, the 2003 penetration data, collected using an automated device, appears to follow the same trends, etc. as the 2002 data. However, upon closer evaluation, a consistent shift is present between the two groups of penetration values.

This shift was identified through analysis of the Loadman II deflection and load data. In-situ stiffness was calculated by dividing the average load by the average deflection. Figure 13 demonstrates this phenomenon.

The shift may be due to the small data sets that do not incorporate a full range of values, variances in the Loadman II data, or possibly the upward movement of the ground in the vicinity of the DCP rod. The unconfined stress condition at the surface causes this upward movement.

The automated recorder was placed outside the zone affected by the upward movement, thus, the actual DCP penetration is recorded. On the other hand, by placing the ruler several inches from the DCP rod, the ruler has an upward movement (with the ground). That coupled with the downward movement of the DCP rod, creates a penetration that is greater than that measured with the automated device.

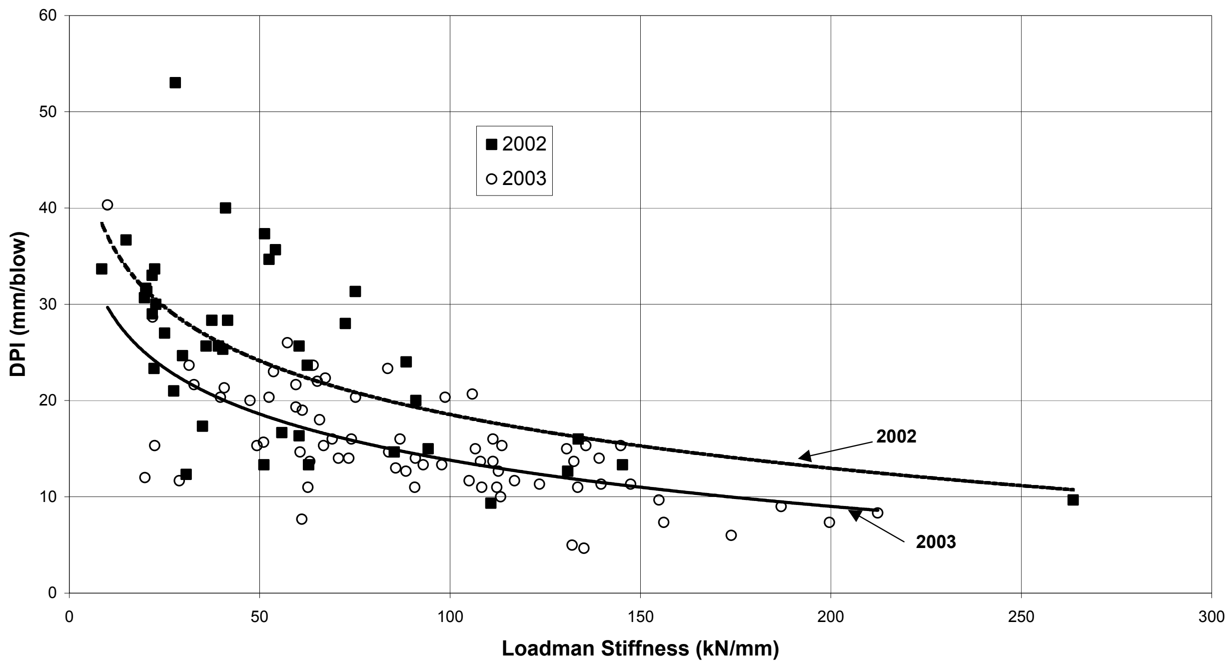


Figure 13. DPI vs. Loadman stiffness.

This is speculation regarding the variances between penetration value obtained in 2002 and 2003. In addition, comparisons with the trial specification table are still valid since the 2003 penetrations are lower than would have been recorded using the traditional method.

The final recommendation is to use the modified procedure on one or two pilot projects. Use on a pilot project will allow further field calibration while exposing the specification to a wide range of conditions. Comments from extremely experienced field personnel will also help to further calibrate the specification.

APPENDIX

Appendix A

2003 "should pass" data versus Trial Specification Table

Material_Tested	GN	MC	Rel Den	SEAT	DPI	Max SEAT	Max DPI	SEAT	DPI	Test
CLASS 7BC	3.1	3.7	111.5%	29	11.3	40	10	Pass	**Fail**	**FAIL**
Class 6	3.3	6.8	104.2%	32	15.3	40	16	Pass	Pass	Pass
CLASS 7BC	3.6	6.0	105.3%	31	9.0	50	15	Pass	Pass	Pass
Class 6	3.6	6.1	97.0%	27	7.7	55	18	Pass	Pass	Pass
Class 6	3.7	6.6	114.6%	56	23.0	55	18	**Fail**	**Fail**	**FAIL**
Class 6	3.8	6.8	98.3%	54	23.3	55	18	Pass	**Fail**	**FAIL**
CLASS 7BC	3.8	2.5	105.5%	17	4.7	40	11	Pass	Pass	Pass
CLASS 7BC	3.9	5.9	103.0%	30	7.3	50	15	Pass	Pass	Pass
Class 6	3.9	4.4	113.6%	56	11.3	50	15	**Fail**	Pass	**FAIL**
Class 6	4.0	4.5	111.7%	48	11.0	50	15	Pass	Pass	Pass
Class 6	4.1	7.4	106.4%	53	13.0	75	20	Pass	Pass	Pass
Class 6	4.1	7.0	108.0%	47	15.3	75	20	Pass	Pass	Pass
Class 6	4.2	4.5	115.8%	86	16.0	65	17	**Fail**	Pass	**FAIL**
Class 6	4.2	8.0	106.6%	47	14.7	75	20	Pass	Pass	Pass
Class 6	4.2	4.1	112.2%	54	11.0	65	17	Pass	Pass	Pass
Class 6	4.3	5.1	105.2%	106	21.7	65	17	**Fail**	**Fail**	**FAIL**
Class 6	4.3	5.3	102.4%	48	14.0	65	17	Pass	Pass	Pass
Class 5	4.4	6.8	105.1%	48	15.0	75	20	Pass	Pass	Pass
Class 5	4.4	7.3	101.3%	39	11.7	75	20	Pass	Pass	Pass
Class 6	4.4	5.9	117.2%	56	23.7	65	17	Pass	**Fail**	**FAIL**
Class 5	4.5	7.9	99.8%	55	13.7	75	20	Pass	Pass	Pass
CLASS 3	4.5	7.1	100.5%	62	12.7	75	20	Pass	Pass	Pass
CLASS 3	4.5	8.6	102.0%	60	16.0	85	24	Pass	Pass	Pass
Class 5	4.5	8.6	103.4%	44	11.7	85	24	Pass	Pass	Pass
CLASS 3	4.6	7.5	95.8%	70	19.3	95	23	Pass	Pass	Pass
Class 5	4.6	8.3	100.2%	52	16.0	100	26	Pass	Pass	Pass
Class 5	4.6	5.8	95.1%	71	15.7	85	19	Pass	Pass	Pass
Class 5	4.6	7.0	101.3%	50	13.7	95	23	Pass	Pass	Pass
CLASS 3	4.6	5.4	95.9%	64	9.7	85	19	Pass	Pass	Pass
Class 5	4.6	7.7	104.3%	45	12.7	95	23	Pass	Pass	Pass
Class 5	4.6	7.7	101.9%	43	14.0	95	23	Pass	Pass	Pass
Select Granular	4.6	8.7	95.0%	62	14.0	100	26	Pass	Pass	Pass
Class 5	4.7	5.1	101.7%	46	15.3	85	19	Pass	Pass	Pass
Class 5	4.8	7.7	109.3%	42	12.7	95	23	Pass	Pass	Pass
Class 5	4.8	5.9	105.7%	61	16.3	85	19	Pass	Pass	Pass
Class 5	4.9	7.5	102.9%	76	14.7	95	23	Pass	Pass	Pass
Class 5	4.9	7.9	105.4%	45	16.0	95	23	Pass	Pass	Pass
Class 5	4.9	8.9	106.6%	46	13.3	100	26	Pass	Pass	Pass
Select Granular	5.1	4.7	112.8%	40	13.3	105	22	Pass	Pass	Pass
Select Granular	5.6	6.5	97.9%	168	17.3	130	28	**Fail**	Pass	**FAIL**
Select Granular	5.6	11.3	119.5%	127	25.7	145	34	Pass	Pass	Pass
Select Granular	5.6	7.1	132.3%	49	23.7	130	28	Pass	Pass	Pass
Select Granular	5.6	5.7	98.4%	137	36.7	120	24	**Fail**	**Fail**	**FAIL**
Select Granular	5.8	13.0	107.0%	137	33.7	145	34	Pass	Pass	Pass
						SUCCESS RATE:		86%	86%	
						COMPLETE TEST SUCCESS RATE				**80%**

Appendix B

2003 "should fail" data versus Trial Specification Table

Material_Tested	GN	MC	Rel Den	SEAT	DPI	Max SEAT	Max DPI	SEAT	DPI	Test
Class 6	3.5	5.0	107.7%	36	15.3	40	12	**Pass**	Fail	Fail
Class 6	3.5	7.1	99.0%	69	19.0	40	16	Fail	Fail	Fail
Class 6	3.7	8.1	91.1%	64	20.3	65	21	**Pass**	**Pass**	**PASS**
Select Granular	3.9	3.7	92.8%	137	23.7	40	11	Fail	Fail	Fail
Select Granular	4.0	5.4	90.4%	90	20.3	50	15	Fail	Fail	Fail
Class 6	4.0	5.0	107.6%	101	40.3	50	15	Fail	Fail	Fail
Select Granular	4.2	3.6	94.6%	99	26.0	60	14	Fail	Fail	Fail
Select Granular	4.2	3.0	78.4%	94	12.0	60	14	Fail	**Pass**	Fail
Select Granular	4.4	3.3	93.9%	35	10.0	60	14	**Pass**	**Pass**	**PASS**
CLASS 3	4.4	6.1	89.6%	95	20.0	75	20	Fail	Fail	Fail
CLASS 3	4.5	4.4	89.6%	80	21.3	65	17	Fail	Fail	Fail
CLASS 3	4.7	5.2	92.3%	110	20.3	85	19	Fail	Fail	Fail
CLASS 3	4.7	6.4	94.3%	80	22.0	95	23	**Pass**	**Pass**	**PASS**
CLASS 3	4.7	6.1	101.4%	101	11.7	95	23	Fail	**Pass**	Fail
Select Granular	4.7	3.7	89.9%	66	15.0	75	16	**Pass**	**Pass**	**PASS**
Select Granular	5.0	4.8	93.4%	141	53.0	85	19	Fail	Fail	Fail
Select Granular	5.3	6.9	100.0%	165	23.3	110	25	Fail	**Pass**	Fail
Select Granular	5.4	5.1	101.7%	124	30.0	105	22	Fail	Fail	Fail
Select Granular	5.5	3.6	103.4%	149	31.3	95	18	Fail	Fail	Fail
Select Granular	5.5	6.7	97.6%	165	27.0	110	25	Fail	Fail	Fail
Select Granular	5.7	3.6	89.4%	129	33.7	115	21	Fail	Fail	Fail
						SUCCESS RATE:		76%	67%	
						COMPLETE TEST SUCCESS RATE				**81%**

Appendix C

2003 "should pass" data versus Modified Trial Specification Table

Material_Tested	GN	MC	Rel Den	SEAT	DPI	Max SEAT	Max DPI	SEAT	DPI	Test
CLASS 7BC	3.1	3.7	111.5%	29	11.3	40	10	Pass	**Fail**	**FAIL**
Class 6	3.3	6.8	104.2%	32	15.3	40	13	Pass	**Fail**	**FAIL**
CLASS 7BC	3.6	6.0	105.3%	31	9.0	40	12	Pass	Pass	Pass
Class 6	3.6	6.1	97.0%	27	7.7	45	16	Pass	Pass	Pass
Class 6	3.7	6.6	114.6%	56	23.0	45	16	**Fail**	**Fail**	**FAIL**
Class 6	3.8	6.8	98.3%	54	23.3	45	16	**Fail**	**Fail**	**FAIL**
CLASS 7BC	3.8	2.5	105.5%	17	4.7	40	10	Pass	Pass	Pass
CLASS 7BC	3.9	5.9	103.0%	30	7.3	40	12	Pass	Pass	Pass
Class 6	3.9	4.4	113.6%	56	11.3	40	12	**Fail**	Pass	**FAIL**
Class 6	4.0	4.5	111.7%	48	11.0	40	12	**Fail**	Pass	**FAIL**
Class 6	4.1	7.4	106.4%	53	13.0	65	18	Pass	Pass	Pass
Class 6	4.1	7.0	108.0%	47	15.3	65	18	Pass	Pass	Pass
Class 6	4.2	4.5	115.8%	86	16.0	55	15	**Fail**	**Fail**	**FAIL**
Class 6	4.2	8.0	106.6%	47	14.7	65	18	Pass	Pass	Pass
Class 6	4.2	4.1	112.2%	54	11.0	55	15	Pass	Pass	Pass
Class 6	4.3	5.1	105.2%	106	21.7	55	15	**Fail**	**Fail**	**FAIL**
Class 6	4.3	5.3	102.4%	48	14.0	55	15	Pass	Pass	Pass
Class 5	4.4	6.8	105.1%	48	15.0	65	18	Pass	Pass	Pass
Class 5	4.4	7.3	101.3%	39	11.7	65	18	Pass	Pass	Pass
Class 6	4.4	5.9	117.2%	56	23.7	55	15	**Fail**	**Fail**	**FAIL**
Class 5	4.5	7.9	99.8%	55	13.7	65	18	Pass	Pass	Pass
CLASS 3	4.5	7.1	100.5%	62	12.7	65	18	Pass	Pass	Pass
CLASS 3	4.5	8.6	102.0%	60	16.0	70	21	Pass	Pass	Pass
Class 5	4.5	8.6	103.4%	44	11.7	70	21	Pass	Pass	Pass
CLASS 3	4.6	7.5	95.8%	70	19.3	80	20	Pass	Pass	Pass
Class 5	4.6	8.3	100.2%	52	16.0	90	24	Pass	Pass	Pass
Class 5	4.6	5.8	95.1%	71	15.7	75	17	Pass	Pass	Pass
Class 5	4.6	7.0	101.3%	50	13.7	80	20	Pass	Pass	Pass
CLASS 3	4.6	5.4	95.9%	64	9.7	75	17	Pass	Pass	Pass
Class 5	4.6	7.7	104.3%	45	12.7	80	20	Pass	Pass	Pass
Class 5	4.6	7.7	101.9%	43	14.0	80	20	Pass	Pass	Pass
Select Granular	4.6	8.7	95.0%	62	14.0	90	24	Pass	Pass	Pass
Class 5	4.7	5.1	101.7%	46	15.3	75	17	Pass	Pass	Pass
Class 5	4.8	7.7	109.3%	42	12.7	80	20	Pass	Pass	Pass
Class 5	4.8	5.9	105.7%	61	16.3	75	17	Pass	Pass	Pass
Class 5	4.9	7.5	102.9%	76	14.7	80	20	Pass	Pass	Pass
Class 5	4.9	7.9	105.4%	45	16.0	80	20	Pass	Pass	Pass
Class 5	4.9	8.9	106.6%	46	13.3	90	24	Pass	Pass	Pass
Select Granular	5.1	4.7	112.8%	40	13.3	90	19	Pass	Pass	Pass
Select Granular	5.6	6.5	97.9%	168	17.3	120	25	**Fail**	Pass	**FAIL**
Select Granular	5.6	11.3	119.5%	127	25.7	135	32	Pass	Pass	Pass
Select Granular	5.6	7.1	132.3%	49	23.7	120	25	Pass	Pass	Pass
Select Granular	5.6	5.7	98.4%	137	36.7	110	22	**Fail**	**Fail**	**FAIL**
Select Granular	5.8	13.0	107.0%	137	33.7	135	32	**Fail**	**Fail**	**FAIL**
						SUCCESS RATE:		77%	80%	
						COMPLETE TEST SUCCESS RATE				**73%**

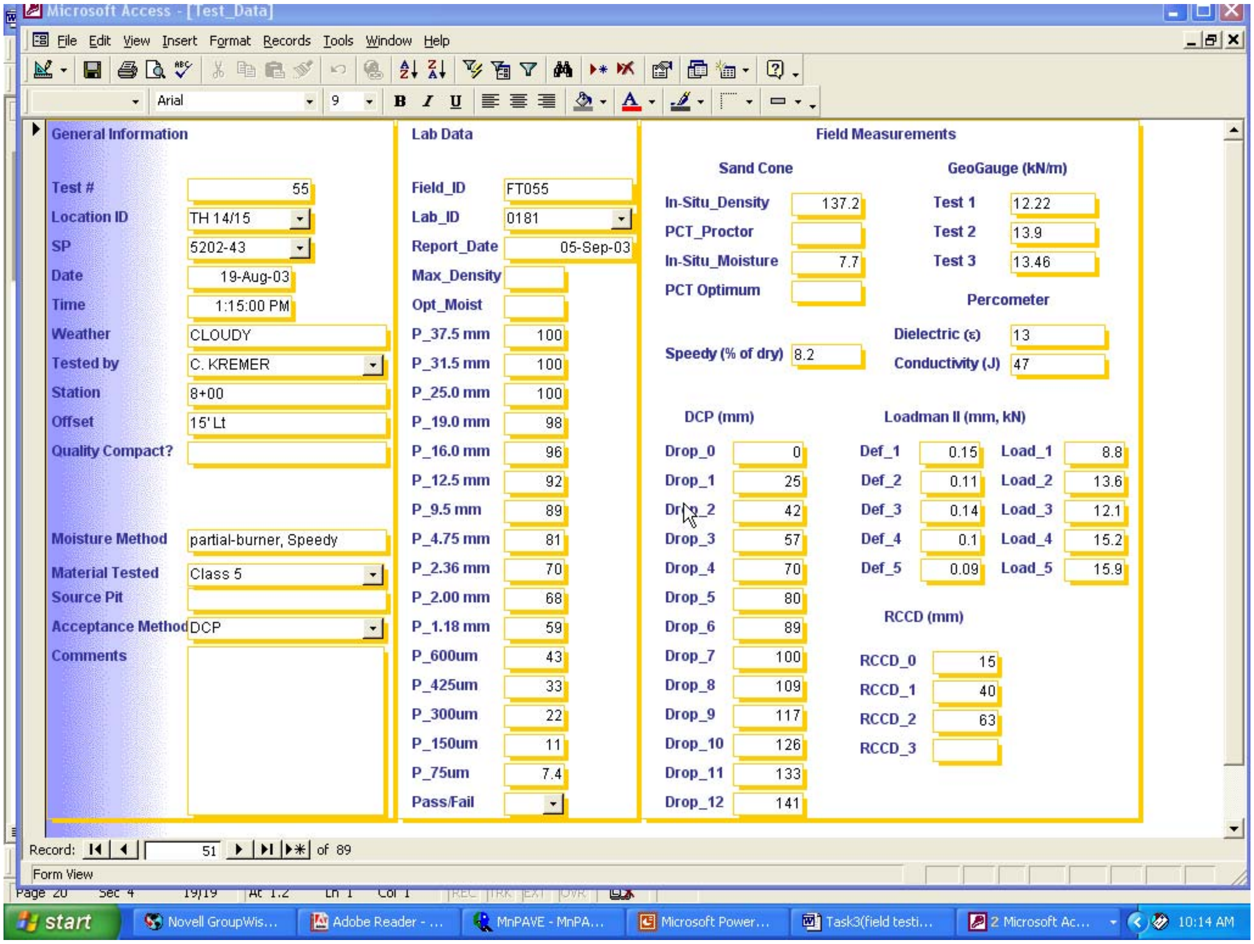
Appendix D

2003 “should fail” data versus Modified Trial Specification Table

Material_Tested	GN	MC	Rel Den	SEAT	DPI	Max SEAT	Max DPI	SEAT	DPI	Test
Class 6	3.5	5.0	107.7%	36	15.3	40	10	**Pass**	Fail	Fail
Class 6	3.5	7.1	99.0%	69	19.0	40	13	Fail	Fail	Fail
Class 6	3.7	8.1	91.1%	64	20.3	55	19	Fail	Fail	Fail
Select Granular	3.9	3.7	92.8%	137	23.7	40	10	Fail	Fail	Fail
Select Granular	4.0	5.4	90.4%	90	20.3	40	12	Fail	Fail	Fail
Class 6	4.0	5.0	107.6%	101	40.3	40	12	Fail	Fail	Fail
Select Granular	4.2	3.6	94.6%	99	26.0	45	11	Fail	Fail	Fail
Select Granular	4.2	3.0	78.4%	94	12.0	45	11	Fail	Fail	Fail
Select Granular	4.4	3.3	93.9%	35	10.0	45	11	**Pass**	**Pass**	**PASS**
CLASS 3	4.4	6.1	89.6%	95	20.0	65	18	Fail	Fail	Fail
CLASS 3	4.5	4.4	89.6%	80	21.3	55	15	Fail	Fail	Fail
CLASS 3	4.7	5.2	92.3%	110	20.3	75	17	Fail	Fail	Fail
CLASS 3	4.7	6.4	94.3%	80	22.0	80	20	Fail	Fail	Fail
CLASS 3	4.7	6.1	101.4%	101	11.7	80	20	Fail	**Pass**	Fail
Select Granular	4.7	3.7	89.9%	66	15.0	65	14	Fail	Fail	Fail
Select Granular	5.0	4.8	93.4%	141	53.0	75	17	Fail	Fail	Fail
Select Granular	5.3	6.9	100.0%	165	23.3	100	23	Fail	Fail	Fail
Select Granular	5.4	5.1	101.7%	124	30.0	90	19	Fail	Fail	Fail
Select Granular	5.5	3.6	103.4%	149	31.3	85	16	Fail	Fail	Fail
Select Granular	5.5	6.7	97.6%	165	27.0	100	23	Fail	Fail	Fail
Select Granular	5.7	3.6	89.4%	129	33.7	105	18	Fail	Fail	Fail
						SUCCESS RATE:		90%	90%	
						COMPLETE TEST SUCCESS RATE				**95%**

Appendix B

Example of Collected Data



Microsoft Access - [Test_Data]

File Edit View Insert Format Records Tools Window Help

General Information

Test #	55
Location ID	TH 14/15
SP	5202-43
Date	19-Aug-03
Time	1:15:00 PM
Weather	CLOUDY
Tested by	C. KREMER
Station	8+00
Offset	15' Lt
Quality Compact?	
Moisture Method	partial-burner, Speedy
Material Tested	Class 5
Source Pit	
Acceptance Method	DCP
Comments	

Lab Data

Field_ID	FT055
Lab_ID	0181
Report_Date	05-Sep-03
Max_Density	
Opt_Moist	
P_37.5 mm	100
P_31.5 mm	100
P_25.0 mm	100
P_19.0 mm	98
P_16.0 mm	96
P_12.5 mm	92
P_9.5 mm	89
P_4.75 mm	81
P_2.36 mm	70
P_2.00 mm	68
P_1.18 mm	59
P_600um	43
P_425um	33
P_300um	22
P_150um	11
P_75um	7.4
Pass/Fail	

Field Measurements

Sand Cone

In-Situ_Density	137.2
PCT_Proctor	
In-Situ_Moisture	7.7
PCT Optimum	
Speedy (% of dry)	8.2

GeoGauge (kN/m)

Test 1	12.22
Test 2	13.9
Test 3	13.46

Percometer

Dielectric (ε)	13
Conductivity (J)	47

DCP (mm)

Drop_0	0
Drop_1	25
Drop_2	42
Drop_3	57
Drop_4	70
Drop_5	80
Drop_6	89
Drop_7	100
Drop_8	109
Drop_9	117
Drop_10	126
Drop_11	133
Drop_12	141

Loadman II (mm, kN)

Def_1	0.15	Load_1	8.8
Def_2	0.11	Load_2	13.6
Def_3	0.14	Load_3	12.1
Def_4	0.1	Load_4	15.2
Def_5	0.09	Load_5	15.9

RCCD (mm)

RCCD_0	15
RCCD_1	40
RCCD_2	63
RCCD_3	

Record: 51 of 89

Form View

TP-02140-03 (8/7/02)

Relative Density Test Grading & Base Construction

Test Identification Data						
Date	6/19/03	7/3/03	7/8/03	7/8/03	7/8/03	7/8/03
Test No.	FT 02	FT 010	FT 011	FT 012	FT 013	FT 014
Soil Class or 3138 Class	CL 6	SELECT GRANULAR	SELECT GRANULAR	SELECT GRANULAR	SELECT GRANULAR	SELECT GRANULAR
Station	22+00	15+073	125+50	1265+00	1266+00	1265+50
Roadway: Position to Center Line	2' RT	5m LT	30' RT	10' RT	15' Lt	20' Lt
Depth Below Grade						
A. Wt. Sand & Container Before	3000.0	3000.0	3000.0	3000.0	3000.0	3000.0
B. Wt. Sand & Container After	307.2	537.6	573.8	587.1	468.4	579.7
C. Wt. Sand in Funnel & Hole A-B	2692.8	2462.4	2426.2	2412.9	2531.6	2420.3
D. Wt. Sand in Funnel (from Calib)	1620.0	1620.0	1620.0	1620.0	1620.0	1620.0
E. Wt. Sand in in Hole C-D	1072.8	842.4	806.2	792.9	911.6	800.3
Inplace Dry Density Determination (Field Density Test)						
Container No.						
F. Wt. Wet Soil + Pan	1760.9	2152.6	1542.7	1502.2	2051.3	1809.1
G. Wt. Dry Soil + Pan	1679.3	2014.8	1489.5	1441.3	1950.4	1681.9
H. Wt Moisture F-G	81.6	137.8	53.2	60.9	100.9	127.2
J. Wt Pan	143.7	955.2	553.0	526.4	525.7	552.6
K. Wt. Wet Soil F-J	1617.2	1197.4	989.7	975.8	1525.6	1256.5
					Contaminated?	Contaminated?
P. % Moisture - ~~Wet~~ Dry Wt. H/K*100 or M*N	**5.3%**	**13.0%**	**5.7%**	**6.7%**	**7.1%**	**11.3%**
R. Total Wt. Wet Mat. From Hole	1617.2	1197.4	989.7	975.8	1525.6	1256.5
S. Wt.Moist. in Mat. from Hole R x P/100	81.6	137.8	53.2	60.9	100.9	127.2
T. Dry Wt.of Mat. from Hole R - S	1535.6	1059.6	936.5	914.9	1424.7	1129.3
U. Unit Wt. of Sand lb/ft^3	93.6	93.6	93.6	93.6	93.6	93.6
V. Dry Density lb/ft^3 T/E x U	**133.9**	**117.7**	**108.7**	**108.0**	**146.2**	**132.0**
Relative Density Determination						
W. Std Maximum Density lb/ft^3	130.7	110.0	110.5	110.5	110.5	110.5
Specs.						
Relative Density % V/W x 100	102.5%	107.0%	98.3%	97.7%	132.3%	119.5%
Curve No.						
Inspector:						
Project Engineer			See Grading and Base Manual 5-692.251 (M) or 5-692.251 (E)			

Appendix C

DCP Special Provision

Pilot Project

The following information is for deleting the Penetration Index Method and replaces it with the Modified Penetration Index Method in the Special Provisions.

2105 Excavation and Embankment

1.) Add the following section in the Standard Specifications: 2105.3F3 Modified Penetration Index Method

F3 Modified Penetration Index Method

The full thickness of each layer of Granular subgrade materials shall be compacted to achieve a penetration index value as described in the modified dynamic cone penetrometer (DCP) method, as determined by an Mn/DOT standard dynamic cone penetrometer (DCP) device. For test purposes, a layer will be considered 1-foot (300 mm) in compacted thickness. Two DCP tests shall be conducted at selected sites within each 3,000 cu. yd. (2,300m^3) (CV) of constructed subgrade. If either of the tests fails to meet the specified requirements, the material represented by the test shall be recompacted and retested for penetration index compliance.

All granular materials prescribed to be tested under the Modified Penetration Index Method 2105.3F3 must be tested and approved within 24 hours of placement and final compaction.

Water shall be applied to the granular material during the mixing and spreading operations so that at the time of compaction the moisture content is no less than 5 percent of dry weight.

2211 Aggregate Base

1.) Delete the following section in the Standard Specifications: 2211.3C3 Penetration Index Method

2.) Add the following section in the Standard Specifications: 2211.3C3 Modified Penetration Index Method

C3 Modified Penetration Index Method

The full thickness of each layer of Class 5, 6, or 7 shall be compacted to achieve a penetration index value as described in the modified dynamic cone penetrometer (DCP) method, as determined by an Mn/DOT standard dynamic cone penetrometer (DCP) device. For test purposes, a layer will be considered 3-inch (75 mm) minimum and 6-inch (150 mm) maximum in compacted thickness. Two DCP tests shall be conducted at selected sites within each 1000 cu. yd. (800m3) (CV) of constructed base course. If either of the tests fails to meet the specified requirements, the material represented by the test shall be recompacted and retested for penetration index compliance.

All aggregates prescribed to be tested under the Modified Penetration Index Method 2211.3C3 must be tested and approved within 24 hours of placement and final compaction.

Water shall be applied to the base material during the mixing and spreading operations so that at the time of compaction the moisture content is no less than 5 percent of dry weight.

5-692.255mod MODIFIED DYNAMIC CONE PENETROMETER (DCP)

A. History and Development

The Dynamic Cone Penetrometer was first introduced to the Minnesota Department of Transportation (Mn/DOT) at the Minnesota Road Research Project (Mn/ROAD). Since 1993 the DCP has been used by Mn/DOT as an acceptance tool for the compaction of pavement edge drain trenches. In 1999, the Penetration Index Method for compaction acceptance of base aggregate Classes 5,6, and 7 was adopted by Mn/DOT, which requires the use of the DCP as the testing device.

B. Description of Device

The Dynamic Cone Penetrometer consists of two 5/8-inch (16 mm) diameter shafts coupled near the midpoint. The lower shaft contains an anvil and a pointed tip, which is driven into the aggregate by dropping a sliding hammer contained on the upper shaft onto the lower anvil. The underlying aggregate strength (density) is determined by measuring the penetration of the lower shaft into the aggregate after each series of a predetermined number of drops. This value is recorded in inches (millimeters) per blow and is know as the Penetration Index (PI).

C. Equipment

The DCP is comprised of the following elements. (See Fig. 1 5-692.255mod)

1. Handle: The handle is located at the top of the device. It is used to hold the DCP shafts plumb and to limit the upward movement of the hammer.

2. Hammer: The 17.61 lb. (8 kg) Hammer is manually raised to the bottom of the handle and then dropped (allowed to free fall) to transfer energy through the lower shaft to the cone tip. The upper shaft guides the hammer.

3. Upper Shaft: The upper shaft is a 5/8-inch (16 mm) diameter steel shaft on which the hammer moves. The length of the upper shaft allows the hammer to drop a distance 22.6 inches (575 mm).

4. Anvil: The anvil serves as the lower stopping mechanism for the hammer. It also serves as a connector between the upper and lower shaft. This allows for disassembly, which reduces the size of the instrument for transport.

5. Lower Shaft: The lower shaft is a 5/8-inch (16 mm) diameter steel shaft, 35 - 47 inch (900-1200 mm) long, marked in 0.2-inch (5mm) increments for recording the penetration after each hammer drop.

6. Cone: The cone measures 0.787-inch (20 mm) in diameter. The cone tip should have a 60-degree angle. (See Fig. 2 5-692.255mod)

D. Operation Points of Caution

1. Always use caution to avoid pinching fingers between the hammer and the anvil during testing, use the handle to hold shafts plumb. Do not hold the DCP near the anvil area.

2. It is important to lift the hammer slowly and drop it cleanly, allowing at least two seconds to elapse between drops. Lifting and dropping too rapidly may affect results because the hammer's full energy may not be allowed to transfer to the lower shaft. This will cause incorrect test results.

E. Test Procedure - Base Aggregate (2211.3C3)

1. Obtain a sample of the aggregate base and run a moisture density test (proctor), at the beginning of placement of the aggregate base. Take a minimum of four relative density tests, as companions to the modified DCP tests. This is to check the correlation of the moisture density test to the Penetration Requirement table in Fig. 4&6 5-692.255mod. If the Grading Number (GN) changes by 0.5 or more, take a new sample and repeat the previous moisture density test (proctor) and relative density tests.

2. Record the gradation % passing values that represent the area to be tested by the DCP, on the attached Modified DCP Procedure 2004 form or spreadsheet. If using the form, calculate the Coarse Grading Number (CGN), Fine Grading Number (FGN), and Grading Number (GN) by using the formulas on the form. Then calculate the Estimated Optimum Moisture Content (EOMC) by using the graph. If using the spreadsheet, the computer calculates this information. (See Fig. 3&5 5-692.255mod)

3. Locate a level and undisturbed area (test site) that is representative of the material to be tested.

4. Record the Test #, Date, Station, Offset, and Test Layer Depth on the Modified DCP Procedure 2004 form or spreadsheet, in the DCP Data table. (See Fig. 4&6 5-692.255mod)

5. Place the DCP device on the base aggregate test site. Record the initial reading using the graduated rule on the DCP. The measurement is taken to the nearest 0.1 inch (2.5

mm). (Place this information on the attached Modified DCP Procedure 2004 form or spreadsheet, in the DCP Data table, under **Initial Reading** column.)

6. To properly seat the DCP (cone tip), two hammer blows are required. Therefore, carefully raise the sliding weighted hammer until it meets the handle, and then release the hammer under its own weight. Repeat this process one more time for a total of two complete blows.

7. Record the penetration measurement after seating using the graduated rule on the DCP. The measurement is taken to the nearest 0.1 inch (2.5 mm). (Place this information on the attached Modified DCP Procedure 2004 form or spreadsheet, in the DCP Data table, under **Reading after seating (2 blows)** column.) (See Fig. 4&6 5-692.255mod)

8. Carefully raise the hammer until it meets the handle, and then release the hammer under its own weight. Repeat this process two more times for a total of three times.

9. Record the final penetration measurement using the graduated rule on the DCP. The measurement is taken to the nearest 0.1 inches (2.5 mm). (Place this information on the attached Modified DCP Procedure 2004 form or spreadsheet, in the DCP Data table, under **Reading after test (3 blows)** column.) (See Fig. 4&6 5-692.255mod)

10. After using the DCP, obtain a sample of material and determine the moisture content of the aggregate base by using the pan drying method or a Super Speedy. Record the moisture content on the Modified DCP Procedure 2004 form or spread sheet, in the DCP Data table, under **MC (%)** column. (See Fig. 4&6 5-692.255mod)

11. If using the Modified DCP Procedure 2004 form, fill in the **Maximum Allowable SEAT** & **Maximum Allowable DPI** columns; this information is in the Penetration Requirements table by using the recorded **GN** & **MC**. Next calculate the **SEAT** by using the following formula:

    SEAT = **Reading after seating (2 blows) - Initial Reading**

    Compare the calculated **SEAT** and compare it the **Maximum Allowable SEAT column**, if **SEAT** is larger than the **Maximum Allowable SEAT**, the **SEAT** fails. If the **SEAT** is smaller than the **Maximum Allowable SEAT**, the **SEAT** passes.

    Next calculate the **DPI** by using the following formula:

    $$\textbf{DPI} = \frac{\{\textbf{Reading after test (3 blows) - Reading after seating (2 blows)}\}}{3}$$

    Compare the calculated **DPI** and compare it the **Maximum Allowable DPI** column, if the **DPI** is larger than the **Maximum Allowable DPI**, the **Ave.**

DPI fails. If the **DPI** is smaller than the **Maximum Allowable DPI**, the **DPI** passes.

Next determine the **Adequate Layer?** by comparing the **Reading after test (3blows)** and **Test Layer Depth** columns. If the **Reading after test (3 blows)** is larger than the **Test Layer Depth,** the answer is No. If the **Reading after test (3 blows)** is less than the **Test Layer Depth,** the answer is Yes.

To determine whether the **Test Pass or Fail**, check the **Seat Pass or Fail**, **DPI Pass or Fail**, and **Adequate Layer?** columns, if any of the three columns has Fail or No, the **Test** Fails. If all three columns have Pass or Yes, the **Test** Passes.

If using the Modified DCP Procedure 2004 spreadsheet, all the above information is calculated by the computer and to determine if the test passes or fails look in the **Test Pass or Fail** column for the answer. (See Fig. 4&6 5-692.255mod)

12. For test purposes, a layer will be considered 3-inch (75 mm) in compacted thickness, but a testing layer can be increased in thickness to a maximum of 6-inches (150 mm), if compacted in one lift by a vibratory roller.

F. Test Procedure - Granular Subgrade Material (2105.3F3)

7. Obtain a sample of the granular material and run a moisture density test (proctor), at the beginning of placement of the granular material. Take a minimum of four relative density tests, as companions to the modified DCP tests. This is to check the correlation of the moisture density test to the Penetration Requirement table in Fig. 4&6 5-692.255mod. If the Grading Number (GN) changes by 0.5 or more, take a new sample and repeat the previous moisture density test (proctor) and relative density tests.

8. Record the gradation % passing values that represent the area to be tested by the DCP, on the attached Modified DCP Procedure 2004 form or spreadsheet. If using the form, calculate the Coarse Grading Number (CGN), Fine Grading Number (FGN), and Grading Number (GN) by using the formulas on the form. Then calculate the Estimated Optimum Moisture Content (EOMC) by using the graph. If using the spreadsheet, the computer calculates this information. (See Fig. 3&5 5-692.255mod)

9. Locate a level and undisturbed area (test site) that is representative of the material to be tested.

10. Record the Test #, Date, Station, Offset, and Test Layer Depth on the Modified DCP Procedure 2004 form or spreadsheet, in the DCP Data table. (See Fig. 4&6 5-692.255mod)

11. Place the DCP device on the granular material test site. Record the initial reading using the graduated rule on the DCP. The measurement is taken to the nearest 0.1 inch (2.5 mm). (Place this information on the attached Modified DCP Procedure 2004 form or spreadsheet, in the DCP Data table, under **Initial Reading** column.) (See Fig. 4&6 5-692.255mod)

12. To properly seat the DCP (cone tip), two hammer blows are required. Therefore, carefully raise the sliding weighted hammer until it meets the handle, and then release the hammer under its own weight. Repeat this process one more time for a total of two complete blows.

13. Record the penetration measurement after seating using the graduated rule on the DCP. The measurement is taken to the nearest 0.1 inch (2.5 mm). (Place this information on the attached Modified DCP Procedure 2004 form or spreadsheet, in the DCP Data table, under **Reading after seating (2 blows)** column.) (See Fig. 4&6 5-692.255mod)

14. Carefully raise the hammer until it meets the handle, and then release the hammer under its own weight. Repeat this process two more times for a total of three times.

15. Record the final penetration measurement using the graduated rule on the DCP. The measurement is taken to the nearest 0.1 inches (2.5 mm). (Place this information on the attached Modified DCP Procedure 2004 form or spreadsheet, in the DCP Data table, under **Reading after test (3 blows)** column.) (See Fig. 4&6 5-692.255mod)

16. After using the DCP, obtain a sample of material and determine the moisture content of the granular material by using the pan drying method or a Super Speedy. Record the moisture content on the Modified DCP Procedure 2004 form or spread sheet, in the DCP Data table, under **MC (%)** column. (See Fig. 4&6 5-692.255mod)

17. If using the Modified DCP Procedure 2004 form, fill in the **Maximum Allowable SEAT** & **Maximum Allowable DPI** columns; this information is in the Penetration Requirements table by using the recorded **GN** & **MC**. Next calculate the **SEAT** by using the following formula:

    SEAT = **Reading after seating (2 blows) - Initial Reading**

    Compare the calculated **SEAT** and compare it the **Maximum Allowable SEAT column**, if **SEAT** is larger than the **Maximum Allowable SEAT**, the **SEAT** <u>fails</u>. If the **SEAT** is smaller than the **Maximum Allowable SEAT**, the **SEAT** <u>passes</u>.

Next calculate the **DPI** by using the following formula:

$$\mathbf{DPI} = \frac{\underline{\{\textbf{Reading after test (3 blows) - Reading after seating (2 blows)}\}}}{3}$$

Compare the calculated **DPI** and compare it the **Maximum Allowable DPI** column, if the **DPI** is larger than the **Maximum Allowable DPI**, the **Ave. DPI** fails. If the **DPI** is smaller than the **Maximum Allowable DPI**, the **DPI** passes.

Next determine the **Adequate Layer?** by comparing the **Reading after test (3blows)** and **Test Layer Depth** columns. If the **Reading after test (3 blows)** is larger than the **Test Layer Depth,** the answer is No. If the **Reading after test (3 blows)** is less than the **Test Layer Depth,** the answer is Yes.

To determine whether the **Test Pass or Fail**, check the **Seat Pass or Fail**, **DPI Pass or Fail**, and **Adequate Layer?** columns, if any of the three columns has Fail or No, the **Test** Fails. If all three columns have Pass or Yes, the **Test** Passes.

If using the Modified DCP Procedure 2004 spreadsheet, all the above information is calculated by the computer and to determine if the test passes or fails look in the **Test Pass or Fail** column for the answer. (See Fig. 4&6 5-692.255mod)

12. For test purposes, a layer will be considered 1-foot (300 mm) in compacted thickness.

G. Test Procedure - Edge Drain Trench Filter Aggregate (2502)

1. After the compaction of the first 50 feet (15 m) of filter aggregate within the edge drain trench has been completed, determine the location of three test sites that are 10-inches (3 m) apart within that first 50 feet (15 m).

2. Calculate the number of hammer drops (blows) necessary to 'properly test the trench filter aggregate but not damage the edge drain pipe by subtracting 6-inches (150 mm) from the depth of the trench to be tested and dividing that total by 3 for English measurements or 75 for metric measurements. If necessary, round this number down to the next whole number. (See Fig. 7 5-692.225mod)

   Example: If the trench depth equals 26-inches (650 mm).
   Then 26-inch (650 mm) minus 6 inches (150mm) equals 20 inch (500 mm).
   Then 20 inches (500 mm) divided by 3 (for English) or 75 (for

Metric) equals 6.7 or 6.

3. Place the DCP on test site #1 and seat the coned tip of the device by slightly taping the lower anvil with the hammer until the coned tip is just out of sight.

4. After seating, record the penetration measurement using the graduated rule on the DCP. The measurement is taken to the nearest 0.1 inch (2.5 mm). (Use form TP-2170mod) (See Fig. 8 5-692.255mod)

5. Carefully raise the hammer until it meets the handle, and then release the hammer under its own weight. Repeat this process until the total number of hammer drops equals the required number of blows as calculated in step 2. Also, beware and avoid the chance of penetrating the edge drain pipe at the bottom of the trench when the compaction of the trench is less than passing.

6. Record the final penetration measurement from the graduated rule on the DCP. The measurement is taken to the nearest 0.1 inch (2.5 mm).

7. Subtract the measurement in step 4 from the measurement in, step 6 and then divide the difference of the measurements by the number of blows required for testing. The result is the penetration index. If necessary, follow the formula on the test form to convert from inches to mm.

8. Use the same procedures as outlined above for testing sites #2 and #3.

9. Add the three penetration index results from test site #1, #2, and #3 and divide that total by 3 in order to calculate the average of al three tests. Round off the average of the tests to the nearest 0.1-inch (1 mm). (See Grading and Base Manual 5-692.805)

H. Maintenance and Handling

Because the Dynamic Cone Penetrometer is driven into the ground, sometimes into very hard soil layers, regular maintenance and care are required. To ensure that the DCP operates properly, the following guidelines must be followed.

a. Monitor the condition of the connection bolt. Extra bolts should be kept in the DCP carrying cases because they frequently become stripped or broken and may need to be replaced during testing.

b. Keep the upper shaft clean. Lubricate very lightly with oil if binding develops. Frequently wipe both shafts clean with a soft cloth during use.

c. Monitor the DCP for excessive wear on any of the components and make repairs as needed. Because the DCP is a standardized testing device, its overall weight and dimensions must not change from specifications.

d. The cone tip should be replaced when the diameter of its widest section is reduced by more than 10 percent (0.08 inch [2 mm]) or rocks gouge the cone's surface. Inspect the cone tip before and after each test. Nevertheless, the cone tip should be replaced at least once a year.

e. Never extract the DCP from the test hole by forcefully striking the hammer against the handle. Striking the handle causes accelerated wear and may lead to broken welds and connections. At least once a year, all welds on the DCP should be critically inspected for hairline or larger cracks.

f. Do not lay the device on the ground when not in use. The DCP should be kept in its carrying case to avoid bending the shafts. Straightness of the shafts is extremely important. The hammer cannot free fall if the shafts are bent. The straightness of the shafts should be critically measured and reviewed each year prior to the start of construction season.