ADVANCEMENT OF GRADING & BASE MATERIAL TESTING

FINAL REPORT

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March 30, 2004

ACKNOWLEDGEMENTS

The author would like to thank the following individuals for their contributions to this project:

- Dave Van Deusen, Mn/DOT Office of Materials
- Cary Efta, Mn/DOT Office of Materials
- Charlie Kremer, Mn/DOT District 7
- Shongtao Dai, Mn/DOT Office of Materials
- Tim Andersen, Mn/DOT Office of Materials
- Dave Mohar, Mn/DOT District 2
- Zach Demmer, Mn/DOT District 6
- Every construction inspector and engineer that helped organize field testing

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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.

March 31, 2004

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.

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

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

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

<u>RCCD</u>

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.

<u>Loadman II</u>

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.

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

GeoGauge
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

GRADATION
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.

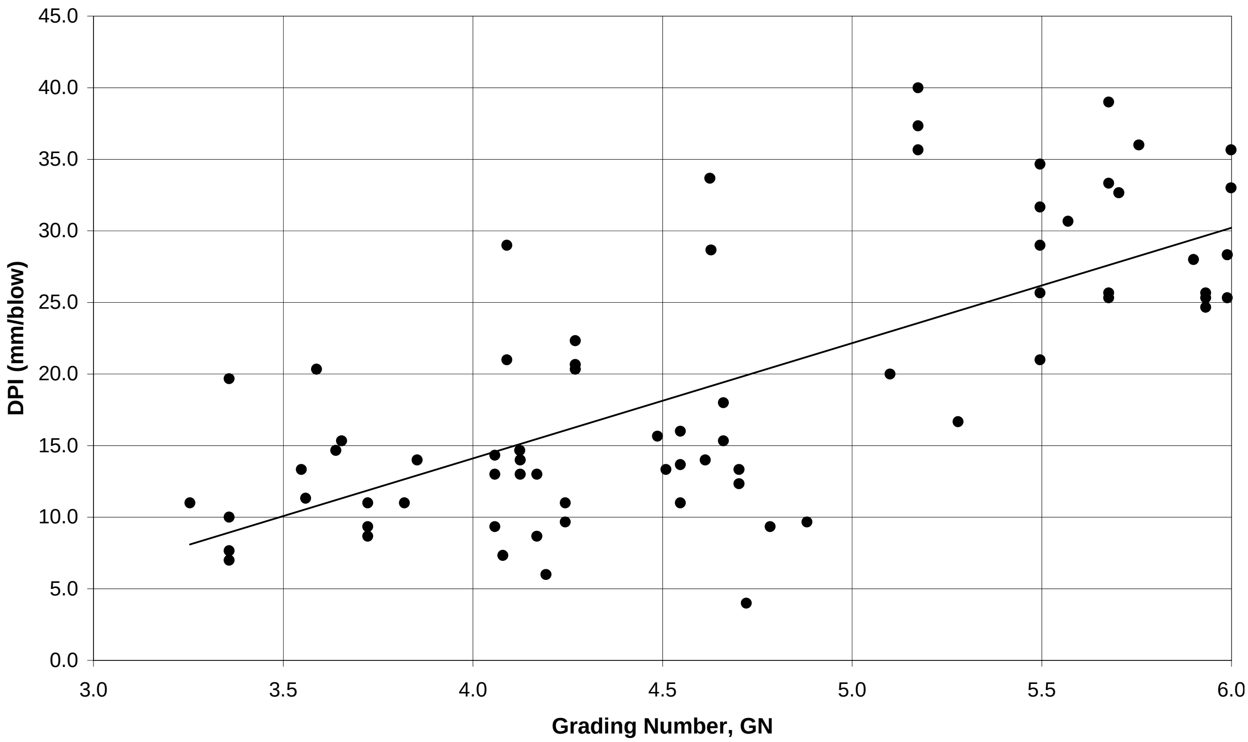


Figure 2. DPI versus GN. $R^2 = 0.53$.

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.

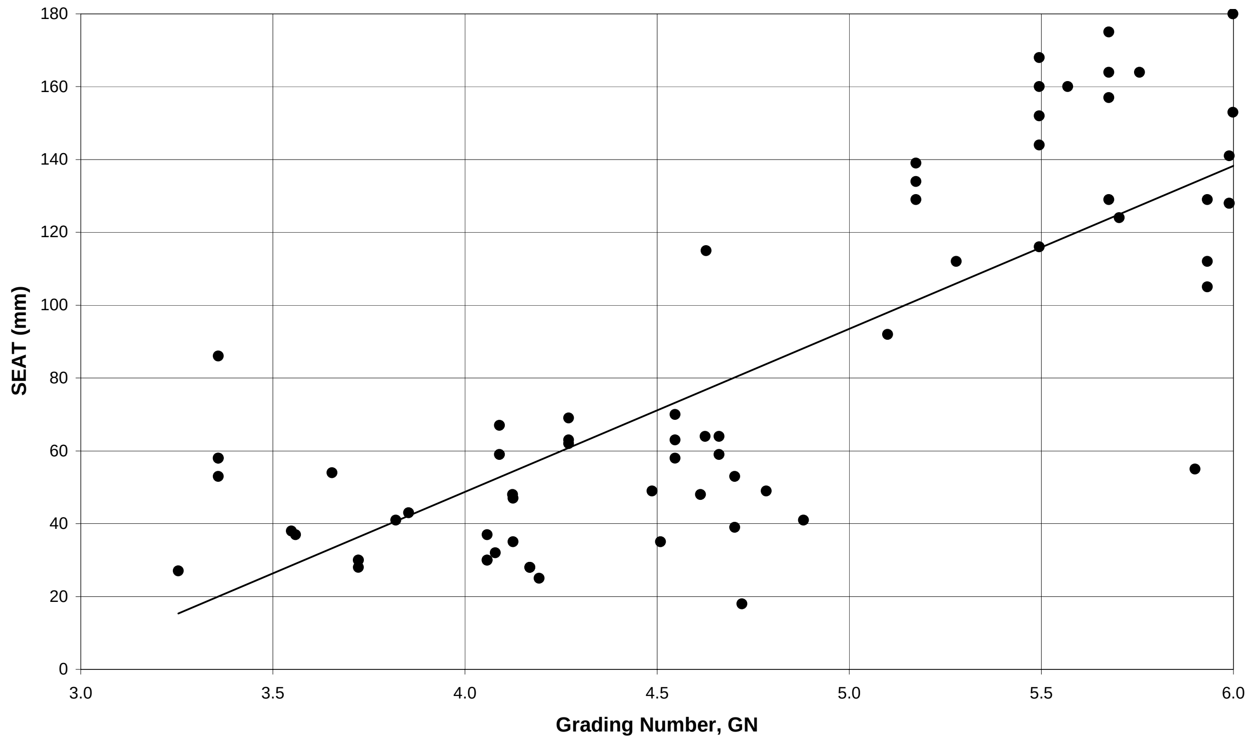


Figure 3. SEAT versus GN. R^2 = 0.63.

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.

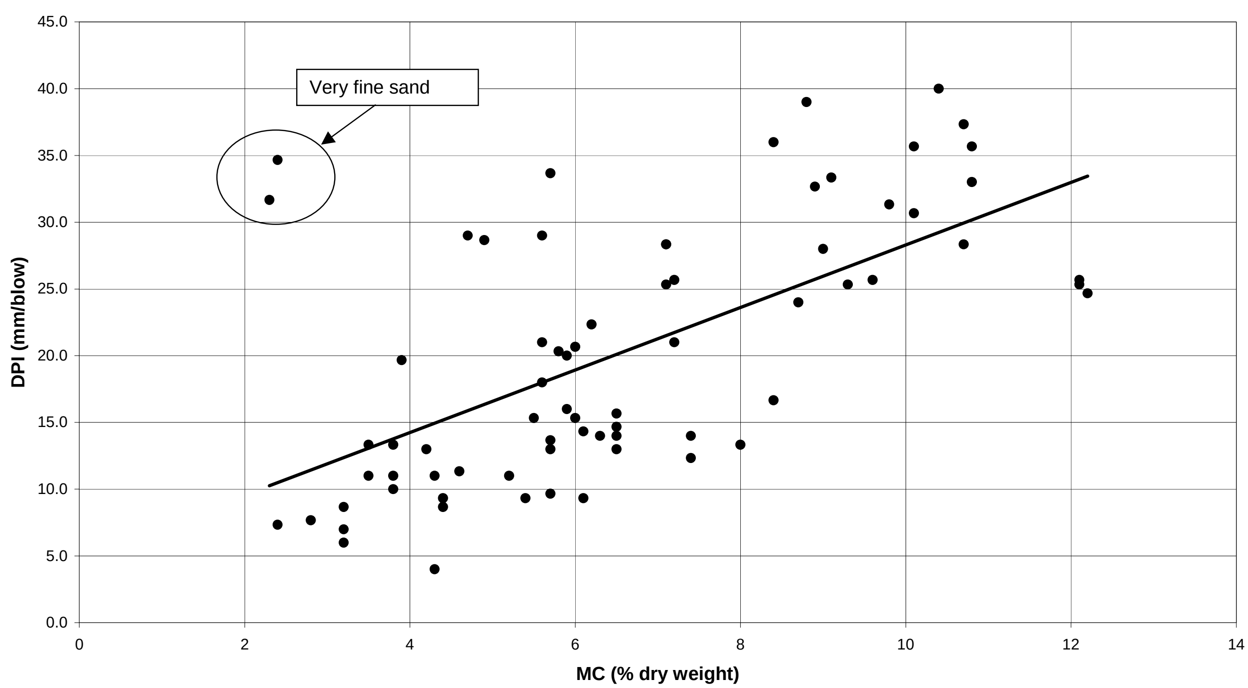


Figure 4. DPI versus MC. R^2 = 0.39 (R^2 = 0.54 if “very find sand” points removed).

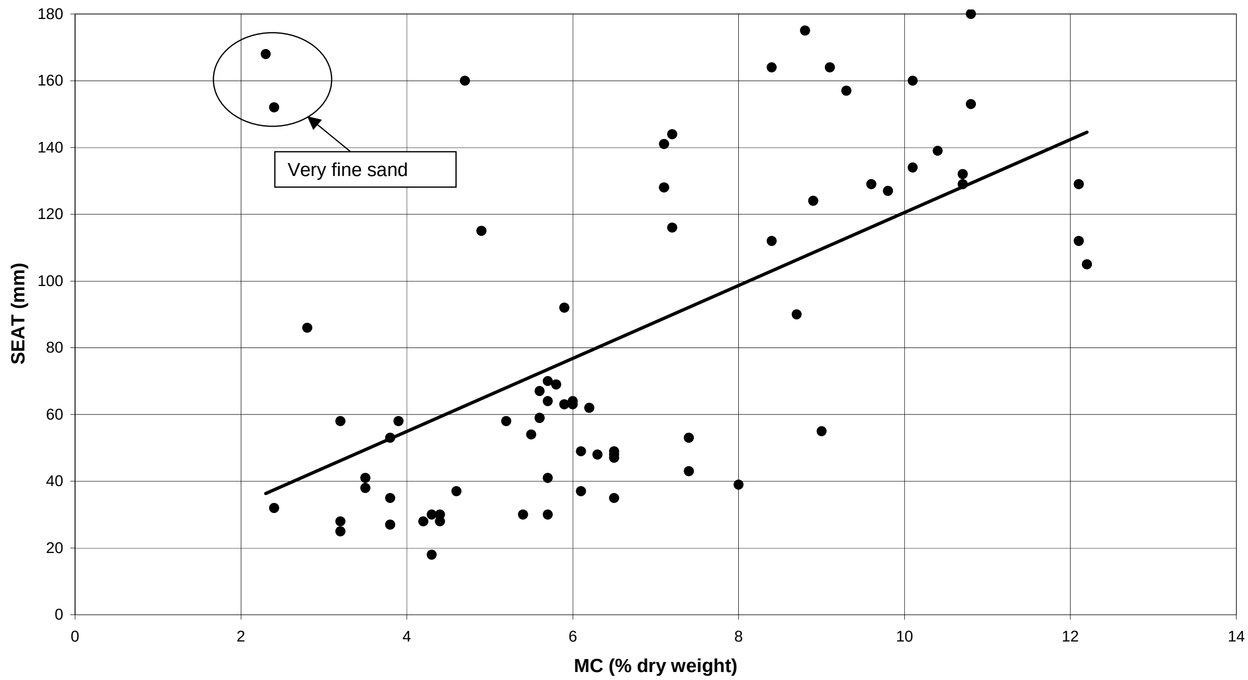


Figure 5. SEAT versus MC. R^2 = 0.34 (0.51 if "very find sand" points removed).

<u>DCP PENETRATION THRESHOLD</u>

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.

<u>REGRESSION ANALYSIS</u>

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:
  $R^2 = 0.48$, $\sigma = 7.15$

- DPI vs GN:
  $R^2 = 0.58$, $\sigma = 6.42$

Multiple linear regressions were utilized to increase the overall R^2 and reduce the standard error (σ) 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:
  $R^2 = 0.65$, $\sigma = 5.93$

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

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

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

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

<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.

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

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

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:
  $R^2 = 0.43$, $\sigma = 1.61$

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

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

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)

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

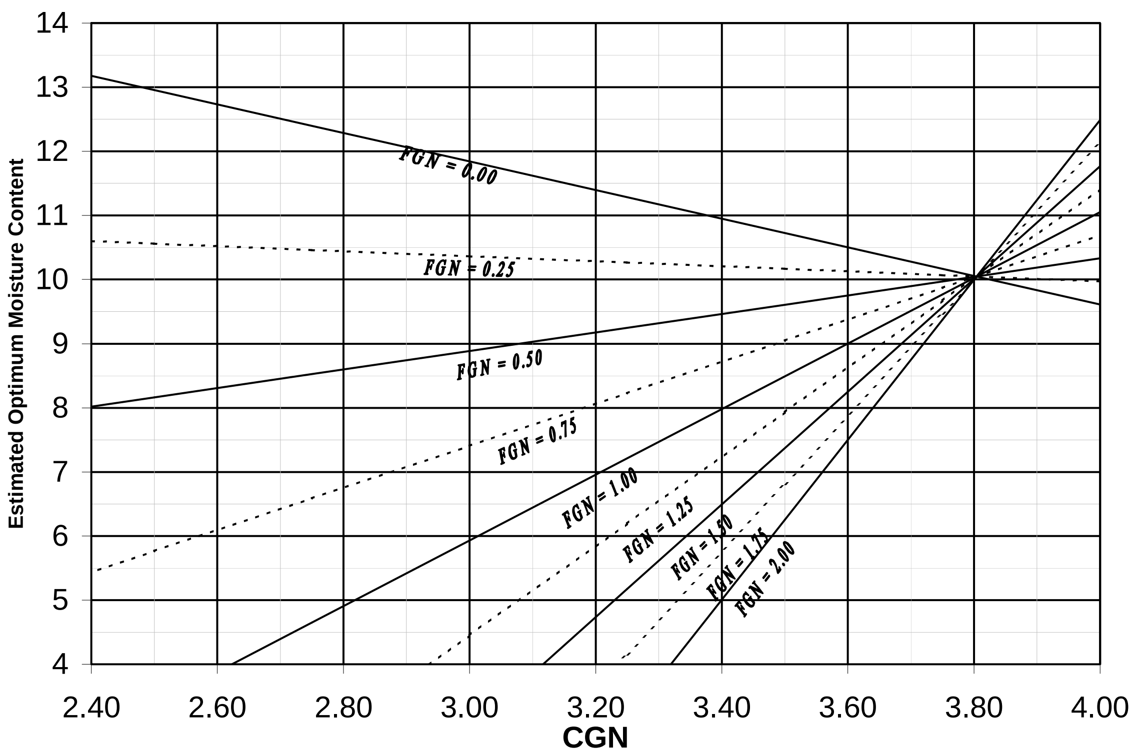
Sieve	% Passing
25.0 mm	
19.0 mm	
9.5 mm	
4.75 mm	

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.

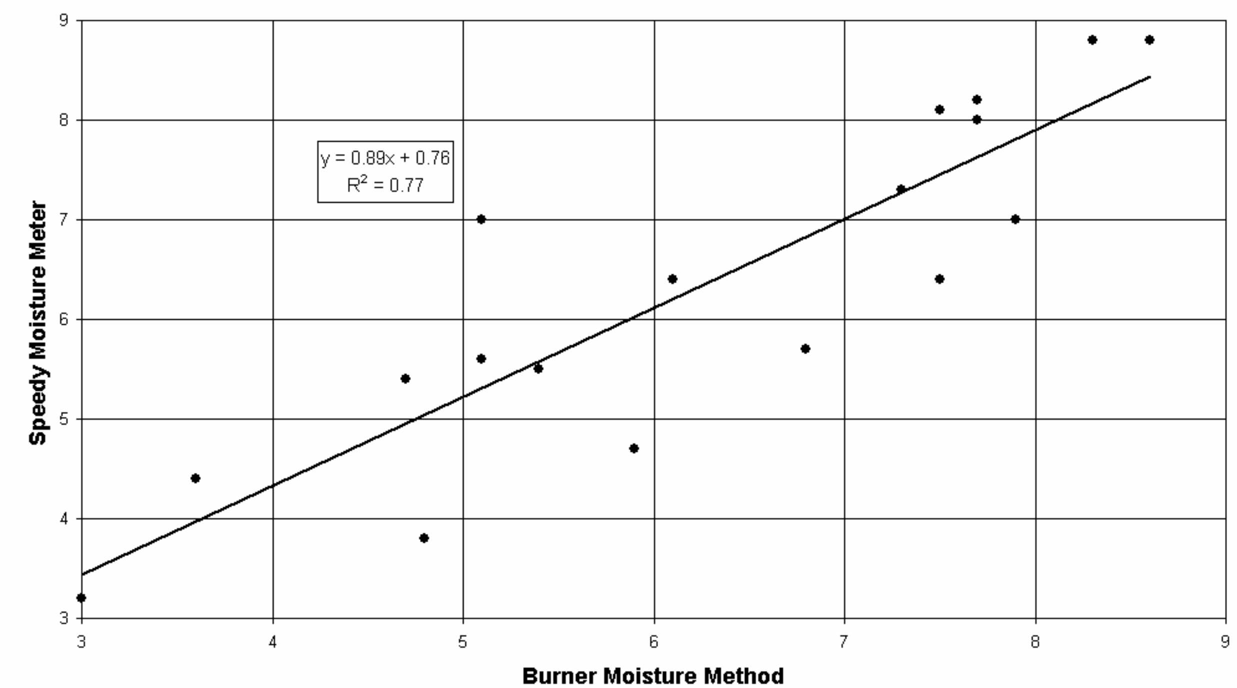


Figure 8. Locations tested in 2003 using both Speedy and burner moisture methods.

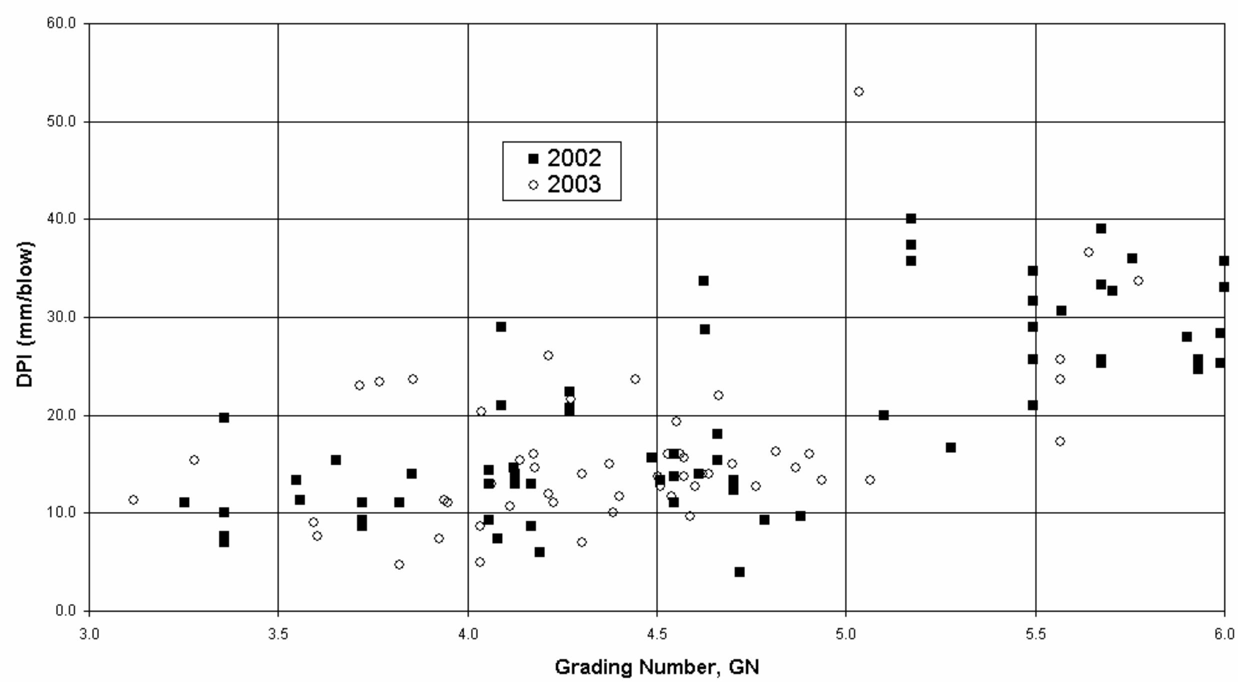


Figure 9. DPI vs GN for 2002 and 2003 data.

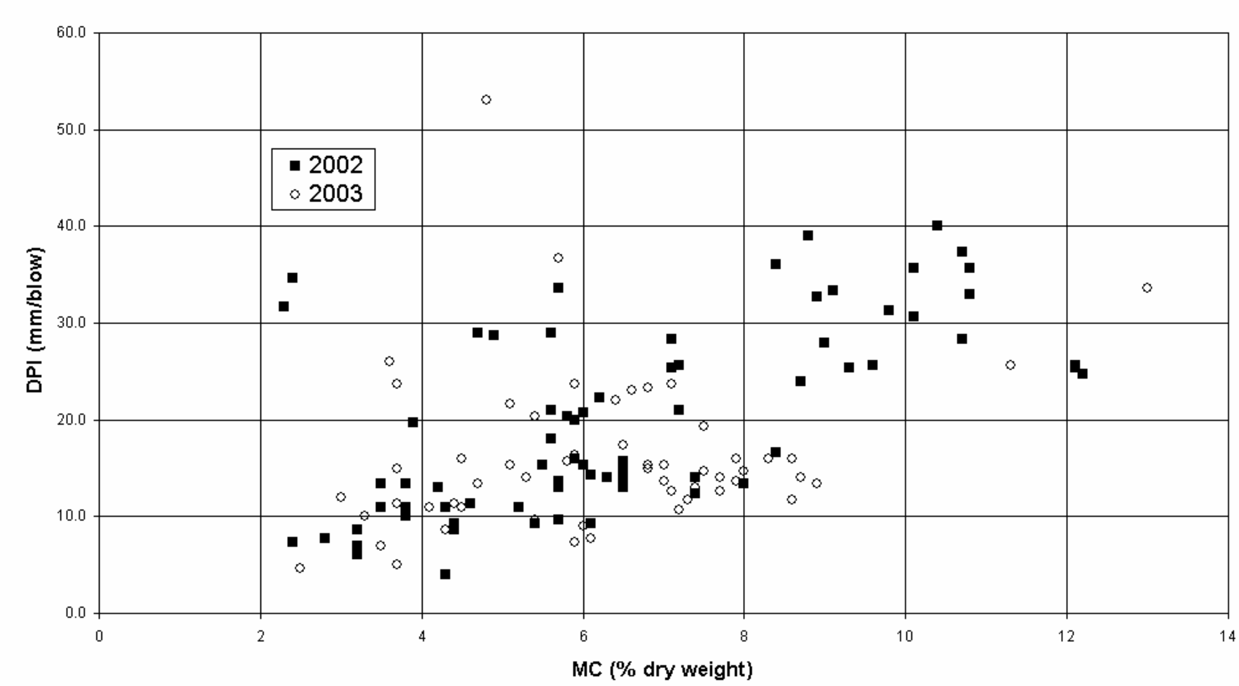


Figure 10. DPI vs MC for 2002 and 2003 data.

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).

<u>SPECIFICATION CALIBRATION</u>

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

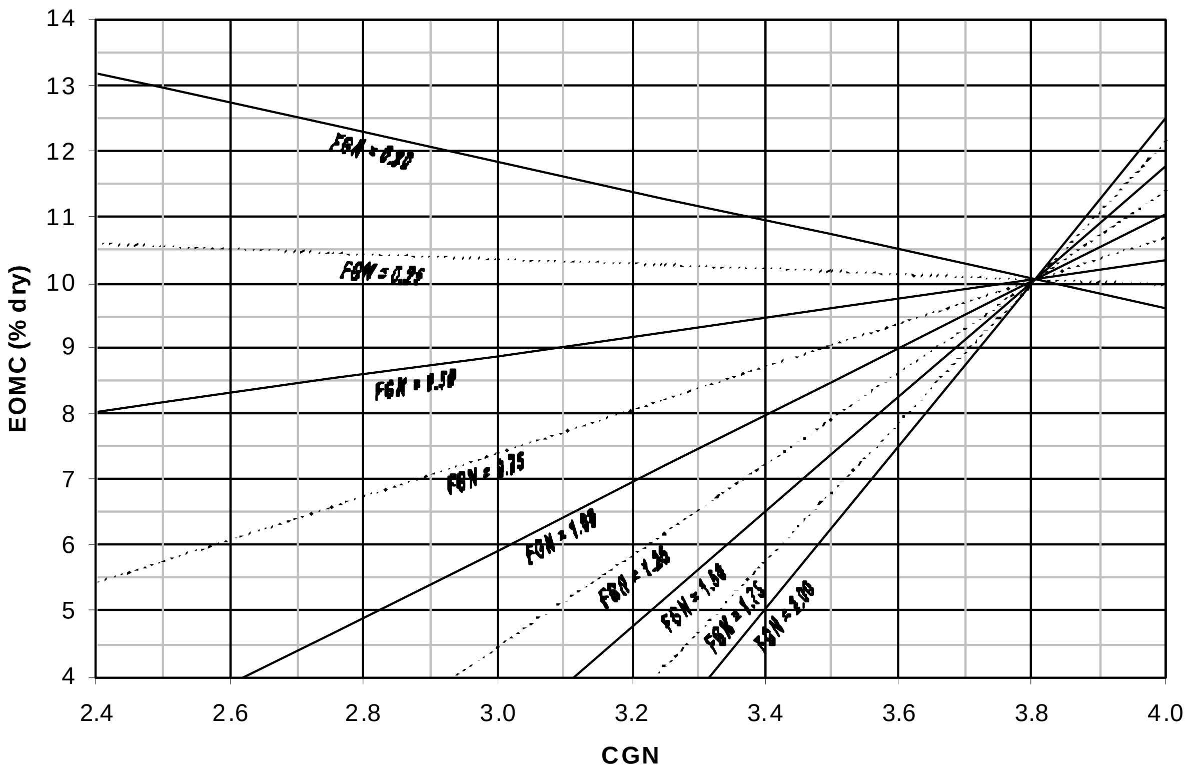
FORMULAS (use **% Passing** in *CGN* & *FGN* calculations)

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

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:

Modified DCP Procedure: 2004 (Metric)

Page 2

SP

Material

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)	GN	MC (% dry)	Maximum Allowable SEAT (mm)	Maximum Allowable DPI (mm/blow)
3.1-3.5	< 4.0	40	10	4.6-5.0	< 4.0	65	14
	4.1-6.0	40	10		4.1-6.0	75	17
	6.1-8.0	40	13		6.1-8.0	80	20
	8.1-10.0	40	16		8.1-10.0	90	24
3.6-4.0	< 4.0	40	10	5.1-5.5	< 6.0	90	19
	4.1-6.0	40	12		6.1-8.0	100	23
	6.1-8.0	45	16		8.1-10.0	110	26
	8.1-10.0	55	19		10.1-12.0	115	29
4.1-4.5	< 4.0	45	11	5.6-6.0	< 6.0	110	22
	4.1-6.0	55	15		6.1-8.0	120	25
	6.1-8.0	65	18		8.1-10.0	125	28
	8.1-10.0	70	21		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	(1 Adequate Layer?	**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.

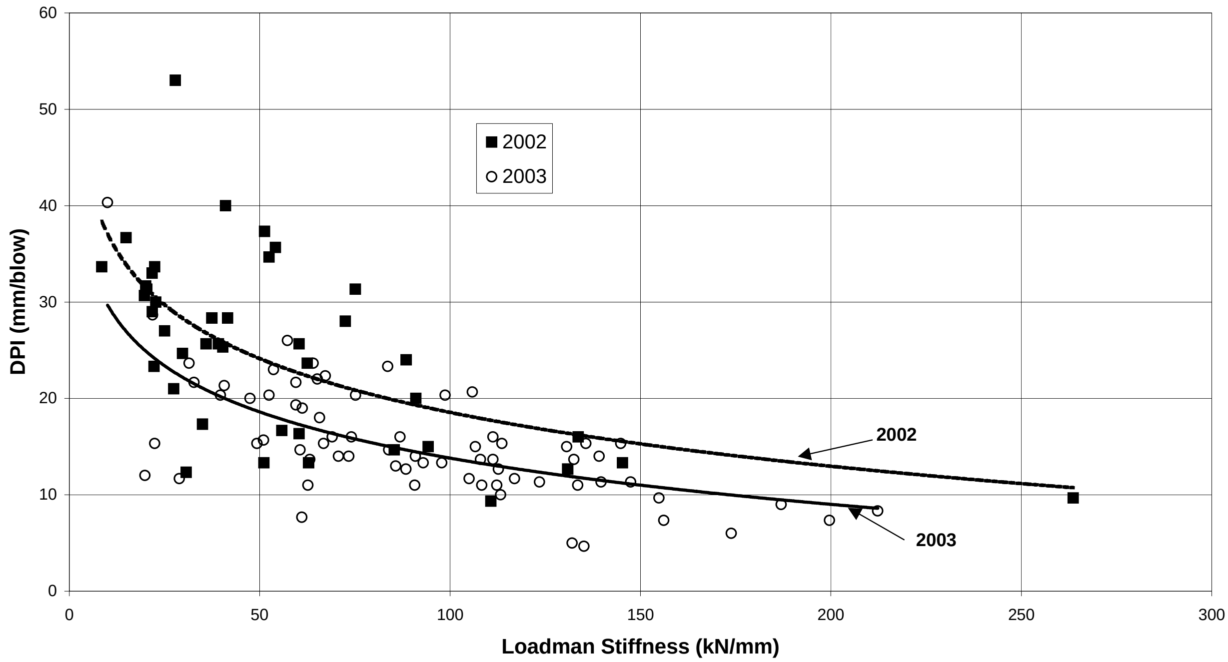


Figure 13. DPI vs. Loadman stiffness.

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.

March 31, 2004

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%**