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2008 MnROAD
Unbound Quality Control Construction Report

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CNA Consulting Engineers

September 2010

Research Project
Final Report #2010-32

MnROAD
Office of Materials

Your Destination...Our Priority

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16. Abstract (Limit: 250 words)

The objective of this project was to document data for further development and refinement of QC/QA specifications and procedures, enhancement of material property based compaction requirements, development of statistically based requirements and tests, and further development of the link between mechanistic-empirical pavement design and construction. This report details the field and laboratory test results and analyses of the tests performed. A summary of the following tests results is included: intelligent compaction, light weight deflectometer, dynamic cone penetrometer, falling weight deflectometer, nuclear gauge, moisture testing, Proctor, Atterberg limits and gradation.

The report consists of the following topics: Background and Data Summary, Intelligent Compaction Data, Falling Weight Deflectometer (FWD) Data and Companion Test Data. These data are synthesized, compared and correlated. Some of the observations are that the LWD, DCP and nuclear gauge are sensitive to material properties in a relatively thin surface layer of the material, in comparison to the relatively great thickness of material sensed by an IC roller. Also, the various materials and test types are sensitive to material moisture in differing ways. A strong correlation between IC data and small scale point test was not expected for at least three reasons: wide material variations, varying depth sensitivity, and varying material moisture sensitivity. This report confirms this expectation and further clarifies the value of continuous compaction control for contractor quality control. The report also confirms the value of the LWD and DCP for quality assurance by the agency/owner.

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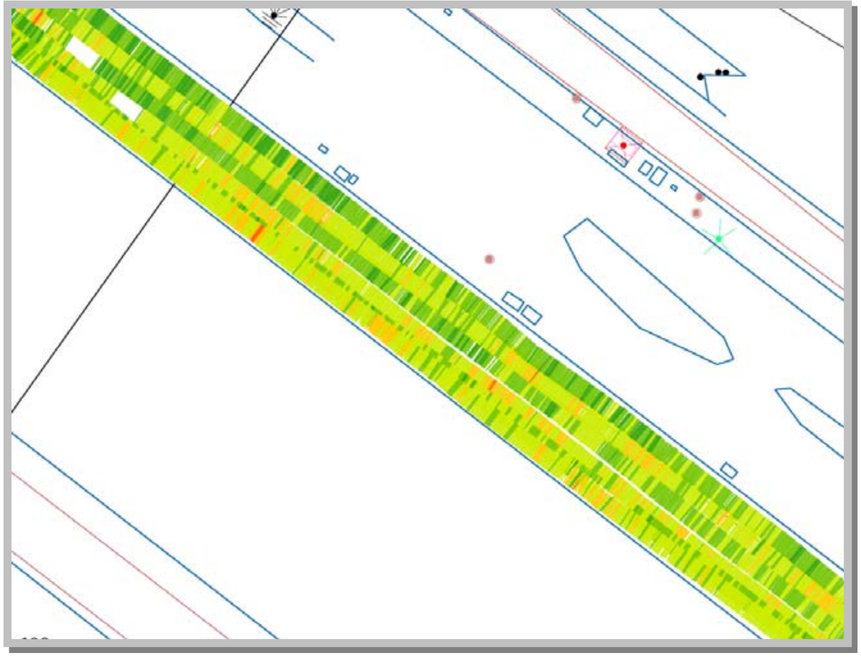

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Introduction

Document Purpose

The objective of this research is to obtain data for further refinement/development of QC/QA specifications and procedures, enhancement of material property based compaction requirements, development of statistically based requirements and tests, and further development of the link between mechanistic-empirical pavement design and construction.

This report details the field and laboratory test results and an engineering analyses of the tests performed. A summary and analysis of the following tests results is included:

- Intelligent Compaction
- Light Weight Deflectometer
- Dynamic Cone Penetrometer
- Falling Weight Deflectometer
- Nuclear Gauge
- Moisture Testing
- Proctor
- Hydrometer
- Atterberg Limits
- Gradation

Contents

The report consists of the following topics

- Background and Data Summary
- Intelligent Compaction Data
- Falling Weight Deflectometer (FWD) Data
- Companion Test Data
- Synthesis, Comparison and Correlation

Two types of illustrations are used in this report. Smaller graphs, GIS procedures and some maps are inserted inline with the text as Figures. Tabloid-format maps are referred to as Exhibits and are included in Appendix A. The following page ranges contain the listed maps:

- A-1—Cell locations
- A-2 to A-14—Maps of IC data illustrating valid, invalid and attempted compaction

- A-15 to A-26—Maps of IC compaction data, grouped by cell
- A-27 to A-36—Maps of IC Compaction data, grouped by material
- A-37—Map of FWD test locations
- A-38 to A-45—Maps of IC data selected for averaging near FWD tests
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Appendix B contains procedures for importing, validating, combining and map-making using intelligent compaction and companion data in GIS.

Cell Description

Thirteen MnROAD cells (Cells 2, 3, 4, 6, 13, 16, 17, 18, 19, 20, 21, 22, 23) with seven unbound material types were within the scope of this study. The seven material types were:

- Class 3
- Class 5
- Class 7 (various formulations)
- Clay
- Various FDR (three different proportions of HMA/gravel)
- Mesabi Ballast (RR)
- Select Granular

Figure 1 illustrates the typical sections of the thirteen cells in the study scope. Note that Cell 6 is composed of two subcells and Cell 13 is composed of four subcells.

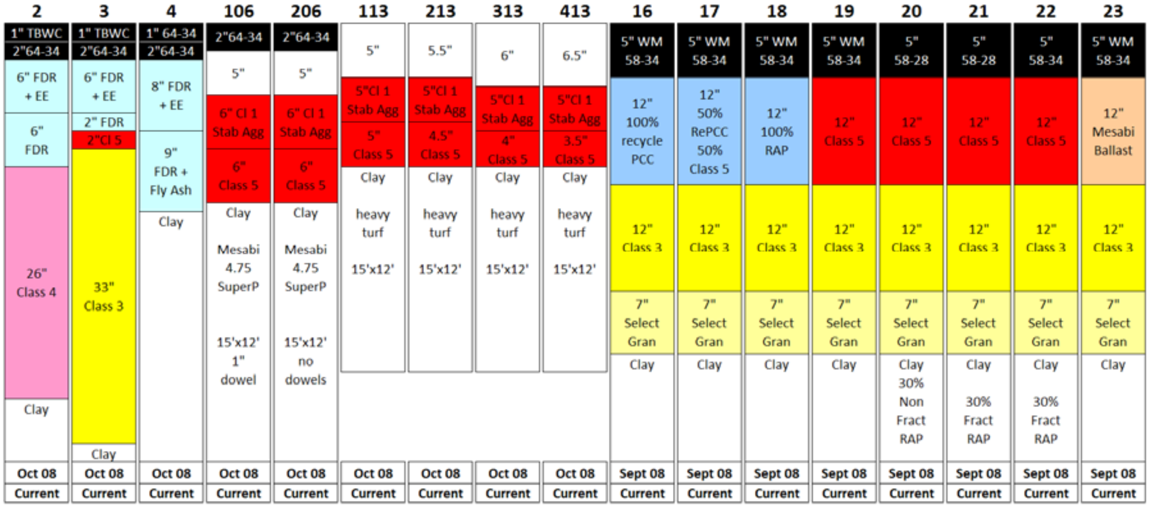

Figure 1—Typical Sections of Thirteen Cells in Study Scope

Intelligent Compaction Data

Scope

The IC data analyzed in this study is for a subset of the data collected during the 2008 reconstruction of MnROAD cells. The data is also limited to the final (proofing) pass on the top of each unbound layer (additional details may be found in the following section). The unbound material types in the thirteen cells included in the study are listed in Table 1. Figure 1 illustrates the typical sections of these cells.

Table 1—Summary of Cells and Unbound Material Type

Cell	Layer Order (higher number is deeper)	Unbound Material
2	2	FDR (50 HMA:50 Class 4SP)
	1	FDR (50 HMA:50 Cl. 4SP) + Emulsion
3	2	FDR (75% HMA - 25% Cl.5)
	1	FDR (75% HMA - 25% Cl.5)+Emulsion
4	3	FDR (Clay + HMA)+flyash
	2	FDR (100% RAP)
	1	FDR (100% RAP)+Emulsion
6	3	Clay
13	3	Clay
16	4	Clay
	3	Select Granular
	2	Class 3
	1	Class 7 (100% RCA)
17	3	Select Granular
	2	Class 3
	1	Class 7 (50RCA:50Cl.5)
18	4	Clay
	2	Class 3
	1	Class 7 (100% RAP)
19	4	Clay
	3	Select Granular
	2	Class 3
	1	Class 5
20	4	Clay
	3	Select Granular
	2	Class 3
	1	Class 5
21	4	Clay
	3	Select Granular
	2	Class 3
	1	Class 5
22	4	Clay
	3	Select Granular
	2	Class 3
	1	Class 5
23	4	Clay
	3	Select Granular
	2	Class 3
	1	Mesabi Ballast (RR)

Exhibit A-1 illustrates the location of each cell listed in Table 1.

Compactor & Data Transfer

The MnROAD 2008 construction project used continuous compaction control (CCC) (intelligent compaction) to map each unbound (subgrade and base) layer after it had passed the QA testing requirements. This step was not part of the quality control or quality assurance process. Caterpillar donated the roller for the entire summer, so that as sections became available for testing they could be rolled.

Roller

The roller was a Caterpillar Model CS-563E, which is a 12-ton vibratory, single, smooth drum compactor. Shown in Figure 2, the roller was equipped with IC and Global Positioning System technology. The receiver attached to the roller communicated with a base station (provided by Caterpillar) set up on site to provide location corrections. Figure 3 shows the IC display in the roller cab.

Figure 2—Caterpillar Roller Used for 2008 MnRoad IC Measurements

Data Transfer

Data was transferred from the roller to the internal Mn/DOT drive via removable disk. Mn/DOT personnel took the *.tag files and opened them through Caterpillar's AccuGrade Office (AGO) software in order to export them in an ASCII format. These files were then sent to CNA for further processing.

Figure 3—IC Display in Roller Cab

Overall Statistics

The IC data set that is the focus of this analysis contains more than 200,000 measurements ranging in value from 0 to 150. However, nearly all the data is in the range of 125 to 150. The jagged line in Figure 4 illustrates the distribution of the IC data for values from 125 to 149.5.

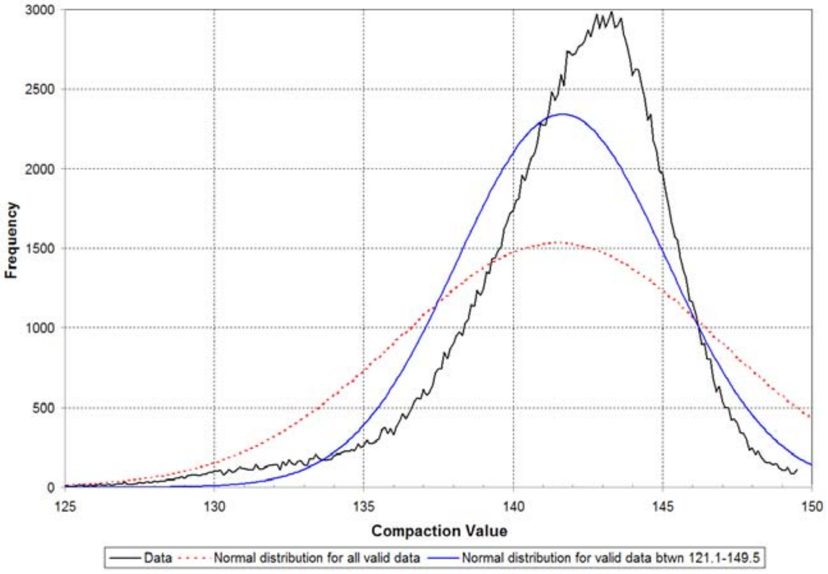

Figure 4—Histogram and Normal Distributions for IC Data

Table 2 lists the summary statistics for the IC data. The entire data set, for all cells and soils, has a mean of 141.5 and a standard deviation of 5.35. The dashed red line in Figure 4 is the normal distribution resulting from these mean and standard deviations values. The graph shows that the normal distribution does not fit the data distribution very well. The cause appears to be anomalous data at specific IC values. Referring to Table 3, there are a significant number of IC data at precise values, specifically at about 0, 30, 60, 90, 120 and 150. Since only 0.4 percent of the data is less than 125, these values are eye-catching. If the anomalous values are eliminated, and considering data between only 121.1 and 149.5, the mean is 141.6 and the standard deviation is 3.51. The normal distribution for these parameters is also plotted as the smooth blue line in Figure 4.

Table 2—IC Data Summary Statistics

Statistic	Value
Total count	205,455
Range	0-150
Nominal range	125-150
Mean	141.5
Mode	143.2
Standard deviation	5.35
Coefficient of variation	0.0378

Coverage and Valid Data

Valid Data and the Concept of “Attempted Compaction”

Several visualization processes are important to assessing and approving coverages. Two processes are typically done together—viewing the physical extent of a coverage and understanding where the roller operator was attempting to take compaction measurements (i.e. attempted compaction). Figure 5 shows the measurement locations for a coverage with the data colored to indicate where the roller operator was or was not attempting to collect measurements. Referring to the figure key, “Invalid” measurements are where the machine produced unreliable compaction measurements. For example, the roller was not vibrating, or was backing up and turning around at each end of the coverage, and was not producing reliable data. The other two categories (“Valid” and “Compaction attempted”) indicate that the operator was attempting to collect valid measurements. For example, at the starts and ends of a pass, where the roller was speeding up or slowing down, the collected measurements were not reliable. Within passes, there are also locations were measurements were attempted, but loss of GPS signal or other aberrations prevented reliable measurement. Finally, there are locations with no data at all—these often seem to be related to GPS signal.

Table 3—Selected IC values Showing Anomaly

Compaction Value	Number of Values
0.00	65
0.10	12
30.10	41
60.10	99
90.00	158
99.90	1
108.70	1
Many rows missing	
119.80	2
119.90	2
120.00	152
120.10	1
120.20	1
Many rows missing	
149.80	113
149.90	139
150.00	831

Validation Criteria

The following items are the validation criteria used during this study:

- Roller compaction value is numeric & between the ranges of 0 and 150
- Roller speed is less than 4 mph
- Valid GPS position must be “Yes”
- GPS mode must be “RTK Fixed”
- RMV must be between zero and 17
- Roller vibration frequency must be between 28 hz and 34 hz
- Machine gear must be “Forward”
- Vibration must be “On”
- Vibration amplitude must be less than 0.5 mm
- Automatic mode must be “Manual”

Attempted compaction is occurs when the machine gear is “Forward”, vibration is “On” and automatic mode is “Manual”.

Cell and Layer Review

Exhibits A-2 through A-14 are the maps showing where valid and invalid data collected, and were compaction was attempted. The legend on each map distinguishes the colors used for each data type.

All unbound soil layers show good coverage of the cell surface, except:

- The first layer of Cell 3 has some invalid coverage near the southeast end of the cell, and the second layer has extensive zones of invalid coverage, mostly along the passes in the driving lane (to the northeast).
- The Class 3 layer and the Class 7 layer of Cell 16 has some 20-ft to 50-ft long zone of zone data (not invalid, completely missing)
- Twenty five-ft long zones of completely missing data also exist in all layers of Cell 17 and Cell 18
- A 150-ft long zone of completely missing data exists in the northwest end of the passing lane of Cell 21

Soil Type Comparisons

There were seven unbound material types measured using IC technology during the 2008 MnROAD reconstruction: Class 3, Class 5, Class 7, clay, various implementations of full-depth reclamation (FDR), taconite ballast, and select granular. Figure 5 illustrates the mean and one standard deviation above and below the mean, of the IC data collected for each cell and material type. Eight cells had Class 3, four cells had Class 5, three cells had Class 7, ten cells had clay subgrade, six cells had FDR, one cell had taconite ballast, and seven cells had select granular. The mean and standard deviation of the entire dataset is illustrated in the far left data point.

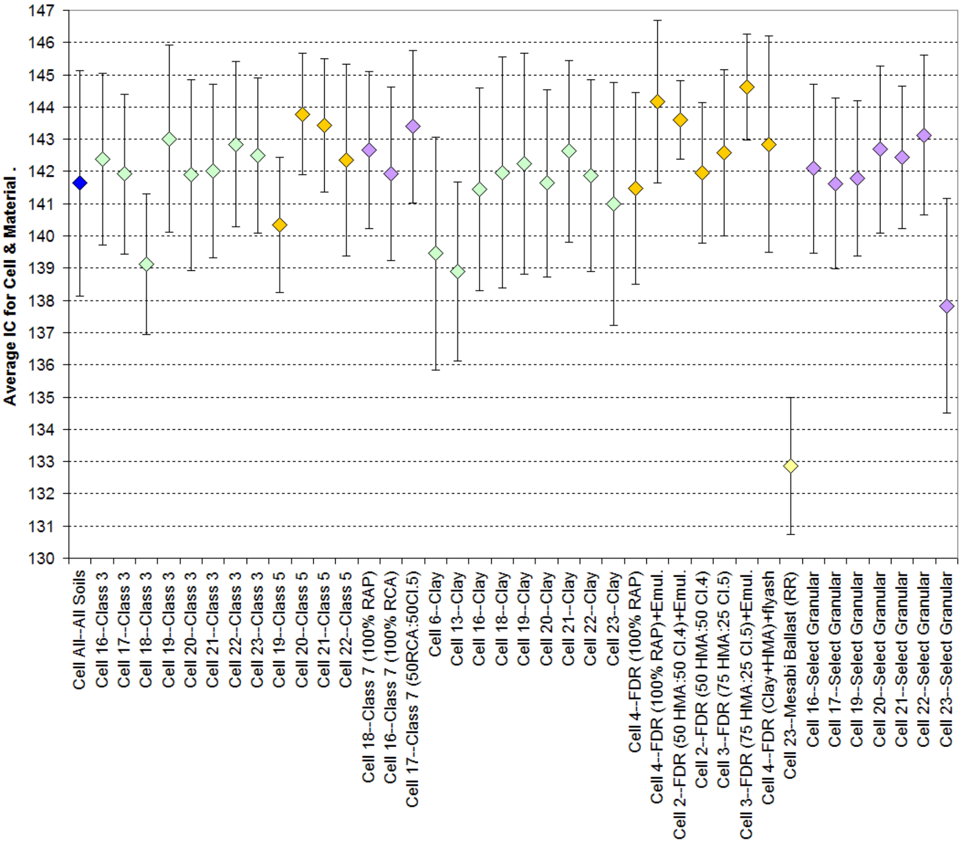

Figure 5—Summary Statistics for All Cell-Material Combinations

Seven of the eight cells with Class 3 average between about 142 and 143, with only Cell 18 significantly lower at 139.12 (see Table 4). The low compaction level of Cell 18 may clearly be seen in the IC maps on Exhibits A-28 and A-29. The coefficient of variation is about 2 percent, again except for Cell 18, with a coefficient of variation of 1.56 percent (see Figure 6).

The cause for the low compaction value for Cell 18 Class 3 is unclear—the compaction value for the underlying clay subgrade is about average compared to the other clay cells. Four cells included Class 5 soils in the pavement base layers. Three of the layers are between 142.35 and 143.78, with the fourth (140.35 in Cell 19) is significantly lower. Cell 22 has a relatively high coefficient of variation, over 2 percent, compared to values of 1.3 percent to 1.5 percent for the other Class 5 cells. The three cells with Class 7 (16, 17, 18) are all relatively similar, although the Class 7 formulation varies slightly. The compaction value averages are 141.93 to 143.39. Cell 16 had the highest coefficient of variation.

Six cells had clay subgrade—these cells are 6, 13, 16, 18, 19, 20, 21, 22 and 23. Seven of these cells had average compaction values of 141 to 142.6. Cells 6 and 13 were lower, though, at 138.89 and 139.45. Referring to Exhibit A-32, Cell 6 had significant zones of compaction measurements below 135, and a few short zones below 130. Cell 6 also had a significant number of measurements above 145, especially in the right-hand pass of the driving lane. Hence, the cell had a relatively high coefficient of variation of 2.60 percent. Only Cell 23 was higher in this group, with a coefficient of variation of 2.67 percent.

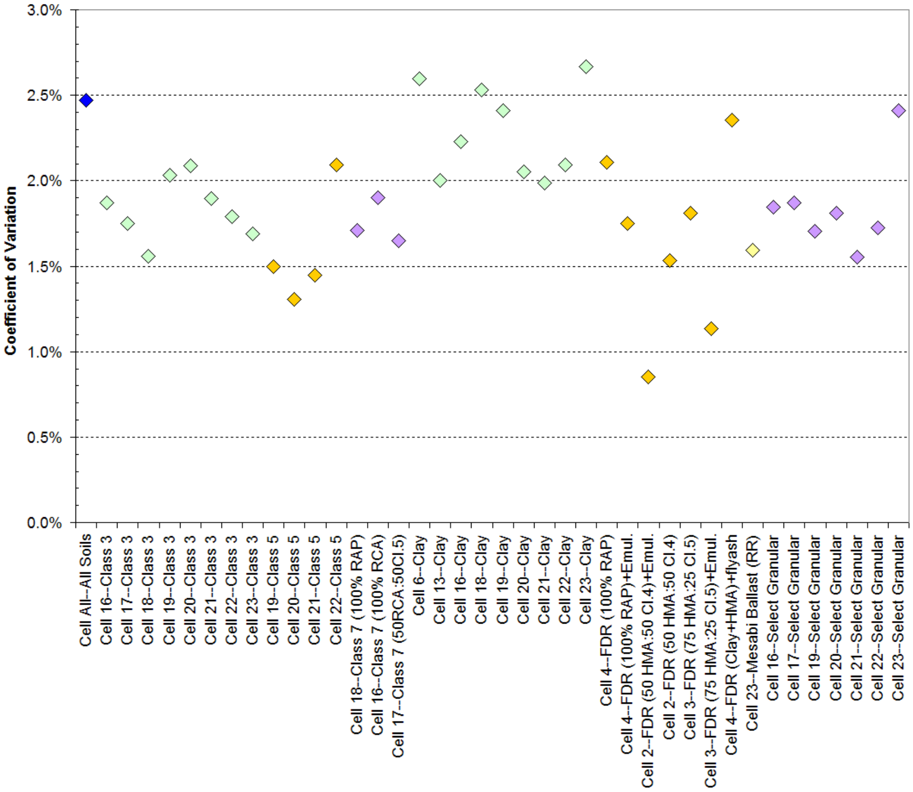

Figure 6—Coefficient of Variation for all Cell-Material Combinations

Seven cells had some variation of full depth reclamation (FDR). Because of the variation of materials, comparing the compaction results may indicate either the compaction effort, or the influence of material differences. The average compaction value is relatively widely spread, from about 141.5 to about 144.6.

Cells 2, 3 and 4 have FDR. Cell 2 has 50 percent hot mix asphalt (HMA) and 50 percent Class 4. Cell 3 has FDR with 75 percent HMA and 25 percent Class 5. Cell 4 has 100 percent recycled asphalt pavement. All three cells have layers with and without emulsion—the top layer has emulsion and the second layer does not. Cell 2 FDR without emulsion has average compaction of 141.96, and this improves to 143.60 in the later layer with emulsion. Similar improvements occur in Cells 3 and 4. Cell 3 increases from 142.58 to 144.63 with the addition of emulsion. Cell 4 increases from 141.48 to 144.17 with the addition of emulsion.

The addition of emulsion also appears to reduce variability. The coefficient of variation improves from 1.53 percent to 0.85 percent for Cell 2, 1.81 percent to 1.13 percent for Cell 3, and 2.11 percent to 1.75 percent for Cell 4.

Layer 3 of Cell 4, the remaining layer:cell combination with FDR, did not have an non-emulsion:emulsion pair. The average compaction value was 142.84, intermediate compared to the other FDR cells, but the coefficient of variation was highest among the FDR cells at 2.35 percent. The high coefficient of variation may be due to the presence of clay in the FDR.

Table 4—Summary Statistics for All Soil Types

Cell	Material	Mean	Standard Deviation	Coefficient of Variation
All	All Soils	141.64	3.50	2.47%
16	Class 3	142.39	2.66	1.87%
17	Class 3	141.93	2.48	1.75%
18	Class 3	139.12	2.17	1.56%
19	Class 3	143.02	2.91	2.03%
20	Class 3	141.89	2.96	2.09%
21	Class 3	142.01	2.69	1.89%
22	Class 3	142.85	2.56	1.79%
23	Class 3	142.50	2.41	1.69%
19	Class 5	140.35	2.10	1.50%
20	Class 5	143.78	1.88	1.31%
21	Class 5	143.42	2.07	1.44%
22	Class 5	142.35	2.98	2.09%
18	Class 7 (100% RAP)	142.66	2.44	1.71%
16	Class 7 (100% RCA)	141.93	2.70	1.90%
17	Class 7 (50RCA:50Cl.5)	143.39	2.37	1.65%
6	Clay	139.45	3.62	2.60%
13	Clay	138.89	2.78	2.00%
16	Clay	141.45	3.15	2.23%
18	Clay	141.97	3.60	2.53%
19	Clay	142.25	3.43	2.41%
20	Clay	141.64	2.91	2.05%
21	Clay	142.62	2.83	1.98%
22	Clay	141.87	2.97	2.09%
23	Clay	140.99	3.76	2.67%
4	FDR (100% RAP)	141.48	2.98	2.11%
4	FDR (100% RAP)+Emul.	144.17	2.52	1.75%
2	FDR (50 HMA:50 Cl. 4SP)+Emul.	143.60	1.22	0.85%
2	FDR (50 HMA:50 Class 4SP)	141.96	2.18	1.53%
3	FDR (75 HMA – 25 Cl.5)	142.58	2.58	1.81%
3	FDR (75 HMA - 25 Cl.5)+Emul.	144.63	1.64	1.13%
4	FDR (Clay + HMA)+flyash	142.84	3.36	2.35%
23	Mesabi Ballast (RR)	132.86	2.12	1.59%
16	Select Granular	142.09	2.62	1.84%
17	Select Granular	141.63	2.65	1.87%
19	Select Granular	141.79	2.42	1.71%
20	Select Granular	142.68	2.58	1.81%
21	Select Granular	142.44	2.21	1.55%
22	Select Granular	143.13	2.47	1.73%
23	Select Granular	137.83	3.32	2.41%

One cell (Cell 23) used a taconite process byproduct, called Mesabi ballast. Based on the IC data, this material did not compact very well, having an average compaction value of about 132.9. This value is roughly 10 points below the average compaction values of the other materials. This cell:layer did have a below average coefficient of variation.

Seven cells had layers of select granular: 16, 17, 19, 20, 21, 22 and 23. Six cells had average compaction values of about 141.6 to 143.1. Cell 23 was an outlier, with an average compaction value of only about 137. 8, nearly 4.5 less than the average of the other six cells. This cell was also more variable, with a coefficient of variation of 2.47 percent. The low compaction and high variability of Cell 23 is immediately apparent from the maps of select granular compaction in Exhibits A-37 and A-38.

Noteworthy Data Patterns

One of the most striking advantages of the visual display of IC data is identifying potential "problem areas" of some sort. In this context, potential "problem areas" are those locations that appear to be significantly different than surrounding ares. Several possible problem area types are: undercompacted zones, overcompacted zones, abrupt changes in compaction value, and missing compaction data. The following sections identify some possible problem areas identified in the 2008 MnROAD IC compaction data.

Possible Problem Areas

Table 5 identifies the cell and layer combinations that contain possible problem areas. The identification of these areas was based solely on visual appearance and judgment. The problem area categories are:

- Significant missing IC data—the maps indicate significant zones where no valid IC data was recovered. Without valid data, the inspectors have no indication of the compaction level achieved. Some of the missing data is near either sensor areas or very stiff layers (e.g. Class 3 or FDR with emulsion)[1]
- Misaligned passes—passes do not follow the lane geometry, with either significantly overlapping passes, or separated passes leaving areas unmeasured. This category is like missing data, because the inspectors have no indication of the compaction level achieved.
- Low or high zones—some portion of a pass, or adjacent passes have significantly higher or lower compaction values than adjacent locations.
- Abrupt changes—zones with low compaction values are adjacent to zones with high values

Cyclical Data Patterns

The IC data for clay subgrade of Cell 19 showed an interesting pattern of colors. In Figure 7, The pattern of alternating colors from high to low values in the pass along the top left of the clay subgrade is striking. Figure 8 clearly shows the rapid variation from high to low IC values as a function of time. Excel was used to compute the Fourier transform of selected sections of the data. The Fourier transform computes the relative content of frequencies in the time domain (raw CCV)—the results are plotted in Figure 9. There is a well-defined peak at about 0.31 hz (or about 3.2 sec period). This result matches closely with the spacing of the peaks of the data in Figure 8.

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[1] Timothy Cline, Mn/DOT, personal communication, 2010.

Table 5—Summary of Potential Problem Areas

Cell	**Layer**	**Material**	**Sig. Missing IC Data**	**Mis-aligned Passes**	**Low or High Zones**	**Abrupt Changes**
16	2	Class 3	**X**			
17	2	Class 3	**X**	**X**	**X**	
18	2	Class 3			**X**	**X**
19	2	Class 3				
20	2	Class 3			**X**	
21	2	Class 3				
22	2	Class 3				
23	2	Class 3				
19	1	Class 5		**X**		
20	1	Class 5				
21	1	Class 5			**X**	
22	1	Class 5				
18	1	Class 7 (100% RAP)				
16	1	Class 7 (100% RCA)	**X**			
17	1	Class 7 (50RCA:50Cl.5)				
6	3	Clay			**X**	
13	3	Clay			**X**	
16	4	Clay		**X**		
18	4	Clay				
19	4	Clay				
20	4	Clay			**X**	**X**
21	4	Clay			**X**	**X**
22	4	Clay			**X**	**X**
23	4	Clay			**X**	**X**
4	2	FDR (100% RAP)			**X**	
4	1	FDR (100% RAP)+Emul.				
2	1	FDR (50 HMA:50 Cl.4)+Emul.				
2	2	FDR (50 HMA:50 Cl.4)				
3	2	FDR (75 HMA:25 Cl.5)	**X**			
3	1	FDR (75 HMA:25 Cl.5)+Emul.	**X**			
4	3	FDR (Clay+HMA)+flyash				
23	1	Mesabi Ballast (RR)			**X**	
16	3	Select Granular				
17	3	Select Granular				
19	3	Select Granular				
20	3	Select Granular				
21	3	Select Granular	**X**			
22	3	Select Granular				
23	3	Select Granular			**X**	

Similar patterns are visible in many of the IC data sets in this study.

The source and nature of the data patterns is unclear. Mooney[2] reports the following:

- "The cyclic behavior in the data is not the same as what we observed when the Cat roller was malfunctioning."

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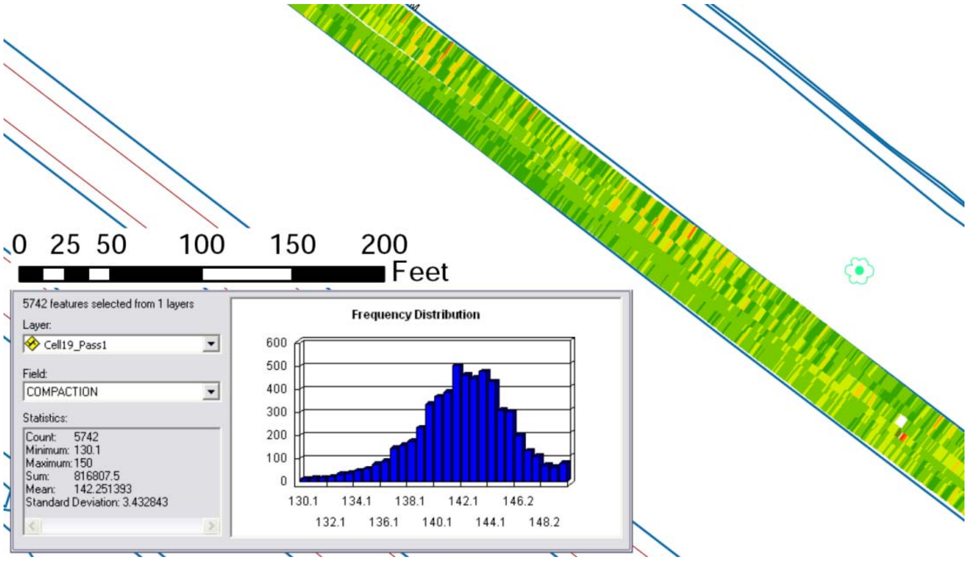
[2] Michael Mooney, personal communication, 2010

- “One very plausible explanation for your cyclic CCV data is ‘washboarding’ – similar to what occurs during vehicle travel on unsurfaced roads.”
- “The cyclic behavior doesn’t occur everywhere in your data – this is consistent with washboarding because moisture influences the presence/absence of washboarding (and moisture varies spatially). A malfunction would be more consistently present. The cyclic response in the base layer data would be a reflection of subgrade behavior (given 1 m measurement depth).”

This phenomenon deserves additional study.



5742 features selected from 1 layers

Layer: Cell19_Pass1

Field: COMPACTION

Statistics:

Count: 5742
Minimum: 130.1
Maximum: 150
Sum: 816807.5
Mean: 142.251393
Standard Deviation: 3.432843

Figure 7—Data Patterns in IC Data for Cell 19, Clay Subgrade

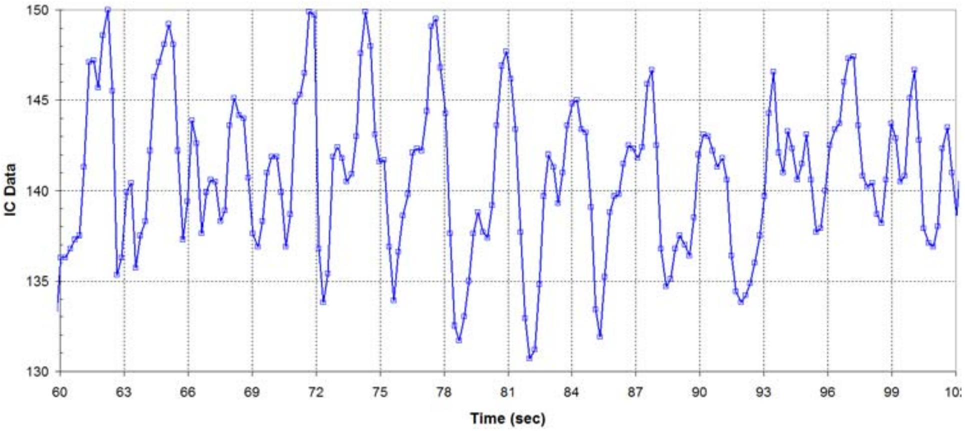


Figure 8—IC Data versus Time

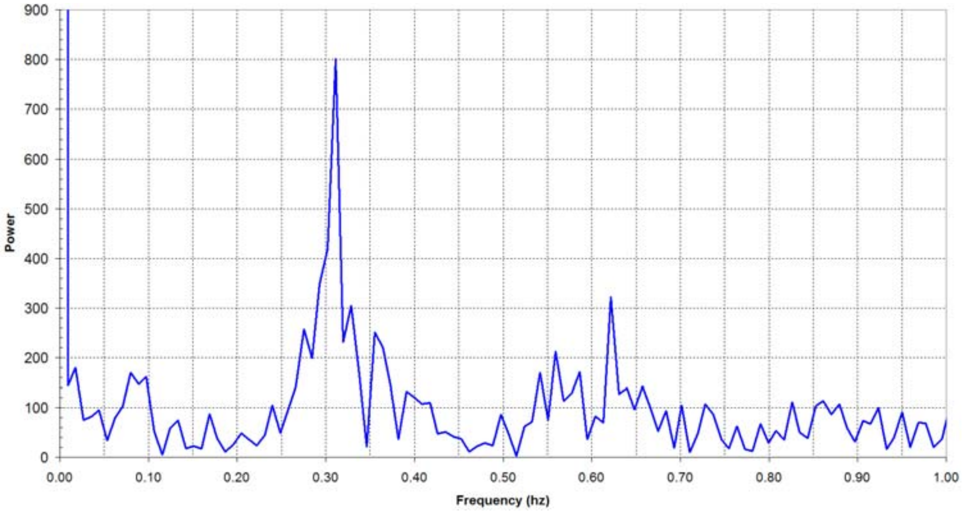


Figure 9—Fast Fourier Transform of IC Data in Figure 8

Falling Weight Deflectometer (FWD) Data

FWD Data Assembly

Falling weight deflectometer tests were conducted in many cells during the 2008 reconstruction. The FWD location information and actual FWD data for this study were delivered in different files. The following bullet points summarize the data delivered:

- One spreadsheet (FWD 2008 Construction.xls) had accurate FWD test values but inaccurate location values
- Another spreadsheet (MnRoad FWD Points.xls) had accurate location values but no test values
- A third spreadsheet (MnRoad 08 FWD subgrade 020410 to CNA.xlsx) had accurate test values and no location values. The file also contained multiple tests per location that required averaging.
- The second and third spreadsheets were linked to provide both accurate test values and location values

Because of the difficulties associated with developing FWD location data, Mn/DOT limited the FWD study to tests on the clay subgrade in Cells 6, 13, 19 and 23.

Later, it was discovered that some of the accurate location data was also suspect, and it was necessary to calculate the test locations using alignment station and offset. The final summary of location source information is:

- Cell 6—locations calculated from station and offset
- Cell 13—locations calculated from station and offset
- Cell 19—used original location data (from MnROAD FWD Points.xls)
- Cell 23—locations calculated from station and offset

FWD Data Description

The result was 69 FWD tests on the clay subgrade in four cells, as illustrated in Figure 10. The FWD data provided by Mn/DOT “should be considered an index since it is based on an elastic half space solution and the average FWD measured load and deflection beneath the measured load only. The many simplifying assumptions included in this approach result in a composite modulus that does not consider any layer geometry or differences in layer moduli. However, this composite modulus estimate is believed to be a useful index because it compares favorably to the volume of material tested by the IC roller."[3]

Summary statistics for the four cells are listed in Table 6. The location of these FWD tests within the cells is illustrated in Exhibit A-37, and the IC data selected for averaging is illustrated in Exhibits A-38 to A-45.

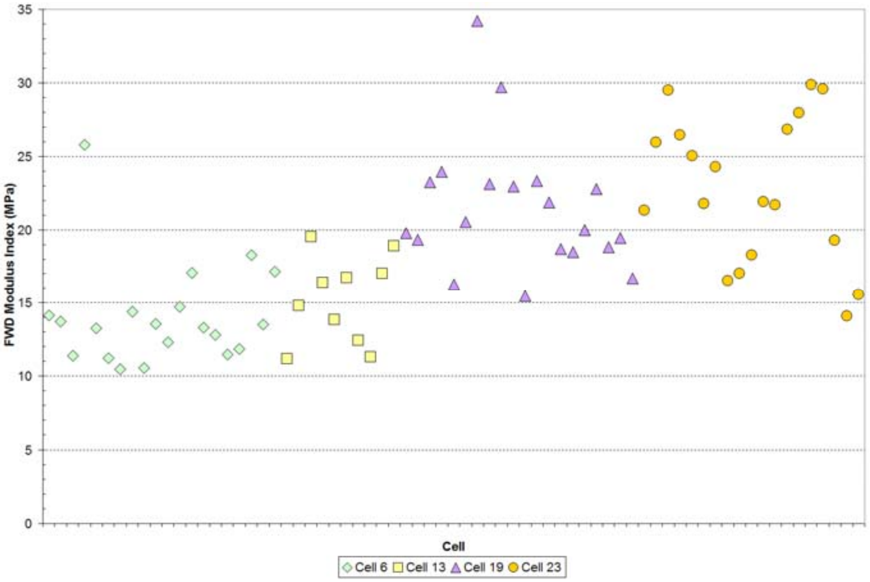


Figure 10—FWD Modulus Index Values by Cell

Figure 10 shows that the FWD modulus index is least in Cell 6, and is greater for each succeeding cell. Cell 6 results are also relatively consistent except for one outlier at about 26 MPa. Results from Cell 13 are from about 11 to 19 MPa, mostly from 15 to 25 MPa in Cell 19 (except for one higher outlier) and 15 to 30 MPa in Cell 23. Table 6 shows that Cell 6 data is most variable, due to the single outlier. Excluding that outlier, the Cell 6 coefficient of variation is least at 15.6 percent

Table 6—FWD Modulus Index Summary Statistics

Cell	Number of Tests	Average (MPa)	Standard Deviation (MPa)	Coefficient of Variation
6	20	14.05	3.50	24.9%
13	10	15.22	2.98	19.6%
19	20	21.43	4.44	20.7%
23	19	22.78	5.02	22.0%

FWD-IC Correlations

The following paragraphs compare FWD measurements to nearby IC measurements. FWD measurements occur at a precise, known locations. IC measurements occur as the roller is passing over the unbound material surface, and there may not be a measurement close to a specific FWD test. The procedures described in Appendix B were developed in ArcInfo to

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[3] John Siekmeier, personal communication, 2010.

identify several representations of the IC data near a companion or FWD test., In general, the data within a specified radius of the companion or FWD test is selected and averaged.

The representation of IC data must be considered. Intelligent compaction vibratory rollers generate data at the drum vibration rate, typically about 30 Hz. However, output data records may be provided at a slower rate, typically about 5 Hz, or about 4 inches to 12 inches apart in the direction of compactor travel. The data records from intelligent compaction may be represented in several ways, depending upon the purpose, and analysis method. The representations used here are:

- Line representation—The line representation is the principal method of depicting IC data used in this project. This representation best fits the nature of an IC measurement, since a single measurement results from the drum contact with the ground. Depending upon the scale of the view in GIS, the line thickness may be varied. This representation is not useful for comparison with FWD tests.
- Multi-point representation—This representation is useful for “percent improvement” assessments and for comparing to companion or FWD tests. Nine points, each having the same compaction value are spaced uniformly across the width of the roller drum. Using this representation, one point is at the left end, another point is at the right end, and one point is in the center of the drum. For comparison with FWD tests, radii of 1-ft, 2-ft and 5-ft were tried.
- Center-point representation—This representation may be used for comparison with companion or FWD tests, or for geostatistical analysis. A single point at the center of the drum best represents the data for this type of analysis. For comparison with FWD data, radii of 2-ft, 5-ft and 10-ft were tried. The smaller radius sometimes did not yield any IC data.

Figure 11 compares the average IC data at the locations of Cell 6, 13, 19 and 23 FWD tests, for center point IC data. This figure illustrates that the averaging process may induce a bias. The heavy black line in the figure denotes equal x and y values, and the red line is the linear trendline. The trendline is shallower than the x=y line, indicating that the 10-ft average value tends to be higher for lower 2-ft average values, and lower for higher 2-ft average values. A similar, though less pronounced bias occurs for multipoint averages, as illustrated in Figure 12.

Refer to Exhibits A-38 to A-45 for the IC data points selected for averaging for each case. The map for Cell 23 centerpoint data is interesting, because the driving lane FWD points, for smaller radii, are near only a single IC pass. In comparison, the passing lane has two very closely spaced IC passes, so each FWD point averages IC data from both passes.

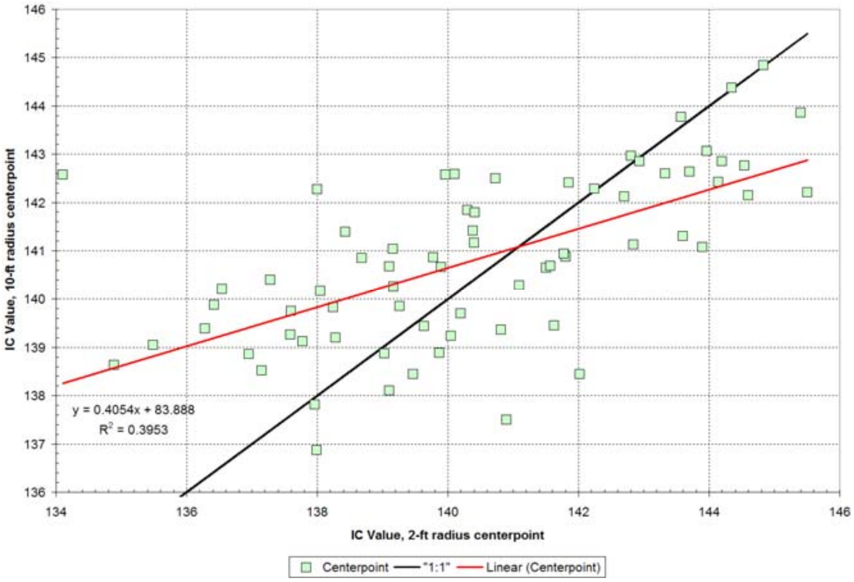


Figure 11—Comparison of IC Data for Different Selection Radii (center point)

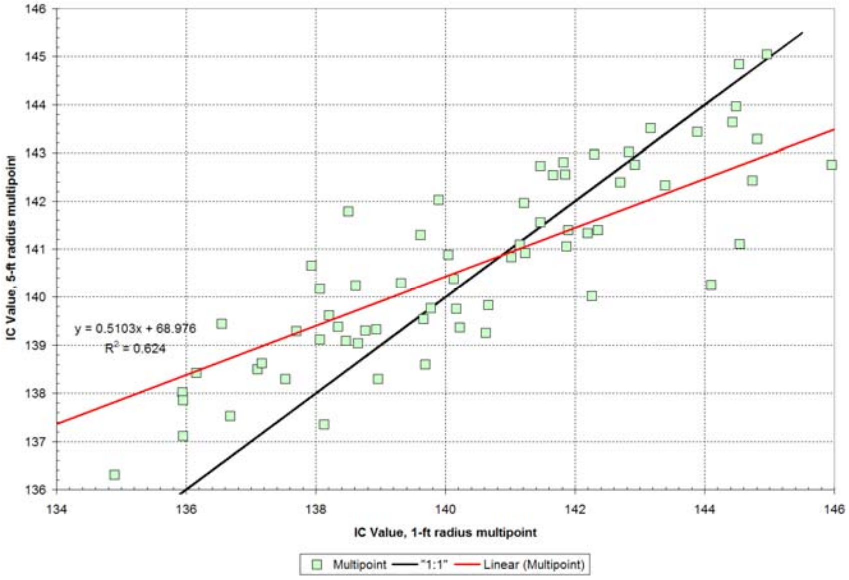


Figure 12—Comparison of IC Data for Different Selection Radii (multipoint)

Graphs and correlations were made for FWD data compared to 2-ft, 5-ft and 10-ft radius centerpoint averages, and 1-ft, 2-ft and 5-ft multipoint data. Better correlations were obtained for larger radius values. The best correlation was for 5-ft radius multipoint IC data. Figure 13 shows the data and trendline. There is a lot of scatter, as indicated by the 0.4145 correlation coefficient, but there is clearly a correlation between the FWD and IC data.

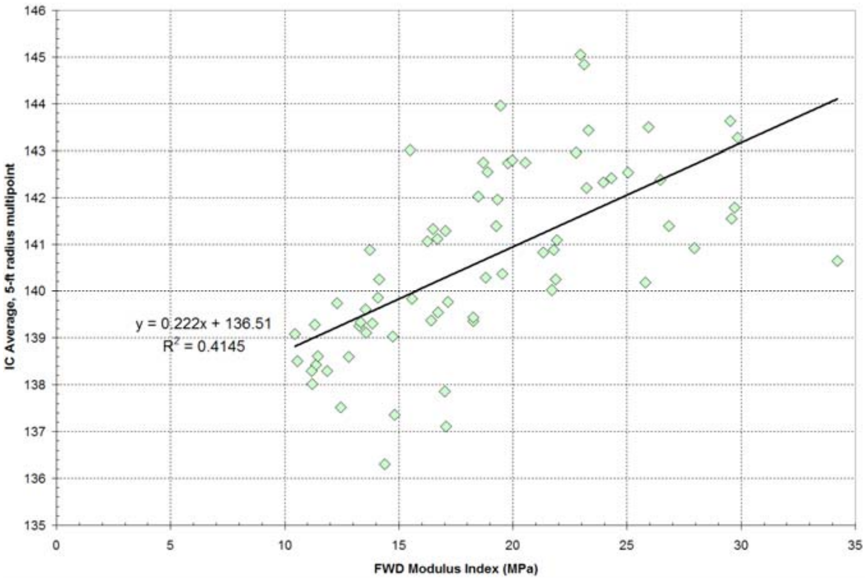


Figure 13—FWD Modulus Index and IC Averages, 5-ft Multipoint

Companion Test Data

Companion quality assurance tests were performed at selected locations in the MnROAD cells. The companion tests included field light-weight deflectometer (LWD), dynamic cone penetrometer (DCP), nuclear density and moisture content, oven-dried moisture content, Proctor tests and gradations. Table 7 lists the companion test results validated during the quality control and quality assurance tasks of this study. There are 64 companion tests in the data set, although not all test locations have valid test results for all test types. Companion tests were performed on seven unbound material types:

- Class 1, Class 3, Class 5, Class 7
- Clay
- Full depth reclamation (of varying compositions)
- Select granular

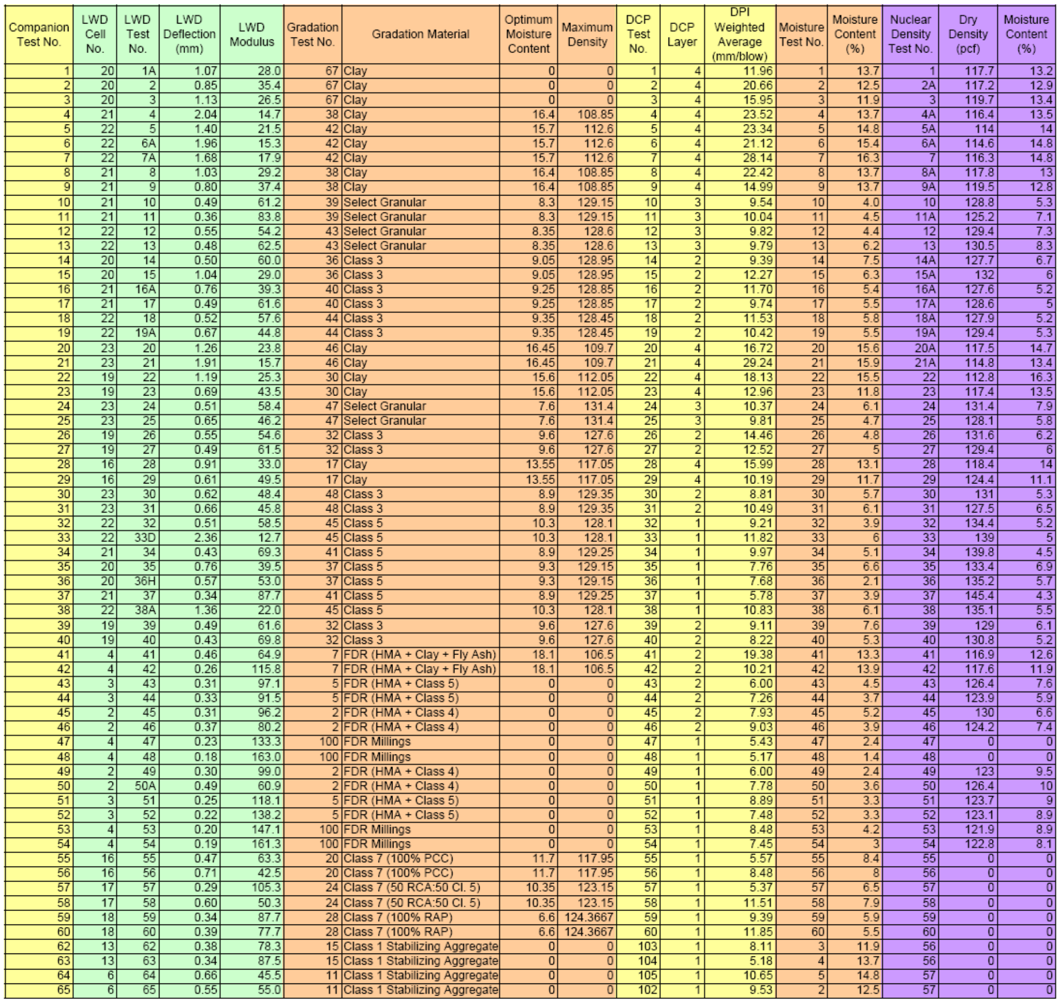
The following sections analyze the data from the LWD, DCP, gradation and moisture-density tests individually and then consider relationships between data types.

Lightweight Deflectometer (LWD) Data

LWD deflection test data is plotted by unbound material type in Figure 14. The graph shows large variations in LWD test results between materials, and in some cases, within materials. Except for a few outliers, the stronger/stiffer materials (Class 1, Class 3, Class 5, Class 7, FDR and select granular) produce LWD values between 0.25 mm and 0.75 mm. The outliers include a Class 3 test about 1 mm, and Class 5 tests about 1.4 mm and 2.3 mm.

Table 8 lists the mean, standard deviation and coefficient of variation of LWD tests by material type. Both the graph and the table show that the FDR material is clearly the lowest, with Class 1 and Class 7 the next lowest. Class 5 is the most variable, due to the outliers mentioned above. Select granular is the least variable. The remaining materials have similar variability, with coefficient of variation from roughly 28 percent to 38 percent.

Table 7—Summary of Companion Tests and Results



Companion Test No.	LWD Cell No.	LWD Test No.	LWD Deflection (mm)	LWD Modulus	Gradation Test No.	Gradation Material	Optimum Moisture Content	Maximum Density	DCP Test No.	DCP Layer	DPI Weighted Average (mm/blow)	Moisture Test No.	Moisture Content (%)	Nuclear Density Test No.	Dry Density (pcf)	Moisture Content (%)
1	20	1A	1.07	28.0	67	Clay	0	0	1	4	11.96	1	13.7	1	117.7	13.2
2	20	2	0.85	35.4	67	Clay	0	0	2	4	20.66	2	12.5	2A	117.2	12.9
3	20	3	1.13	26.5	67	Clay	0	0	3	4	15.95	3	11.9	3	119.7	13.4
4	21	4	2.04	14.7	38	Clay	16.4	108.85	4	4	23.52	4	13.7	4A	116.4	13.5
5	22	5	1.40	21.5	42	Clay	15.7	112.6	5	4	23.34	5	14.8	5A	114	14
6	22	6A	1.96	15.3	42	Clay	15.7	112.6	6	4	21.12	6	15.4	6A	114.6	14.8
7	22	7A	1.68	17.9	42	Clay	15.7	112.6	7	4	28.14	7	16.3	7	116.3	14.8
8	21	8	1.03	29.2	38	Clay	16.4	108.85	8	4	22.42	8	13.7	8A	117.8	13
9	21	9	0.80	37.4	38	Clay	16.4	108.85	9	4	14.99	9	13.7	9A	119.5	12.8
10	21	10	0.49	61.2	39	Select Granular	8.3	129.15	10	3	9.54	10	4.0	10	128.8	5.3
11	21	11	0.36	83.8	39	Select Granular	8.3	129.15	11	3	10.04	11	4.5	11A	125.2	7.1
12	22	12	0.55	54.2	43	Select Granular	8.35	128.6	12	3	9.82	12	4.4	12	129.4	7.3
13	22	13	0.48	62.5	43	Select Granular	8.35	128.6	13	3	9.79	13	6.2	13	130.5	8.3
14	20	14	0.50	60.0	36	Class 3	9.05	128.95	14	2	9.39	14	7.5	14A	127.7	6.7
15	20	15	1.04	29.0	36	Class 3	9.05	128.95	15	2	12.27	15	6.3	15A	132	6
16	21	16A	0.76	39.3	40	Class 3	9.25	128.85	16	2	11.70	16	5.4	16A	127.6	5.2
17	21	17	0.49	61.6	40	Class 3	9.25	128.85	17	2	9.74	17	5.5	17A	128.6	5
18	22	18	0.52	57.6	44	Class 3	9.35	128.45	18	2	11.53	18	5.8	18A	127.9	5.2
19	22	19A	0.67	44.8	44	Class 3	9.35	128.45	19	2	10.42	19	5.5	19A	129.4	5.3
20	23	20	1.26	23.8	46	Clay	16.45	109.7	20	4	16.72	20	15.6	20A	117.5	14.7
21	23	21	1.91	15.7	46	Clay	16.45	109.7	21	4	29.24	21	15.9	21A	114.8	13.4
22	19	22	1.19	25.3	30	Clay	15.6	112.05	22	4	18.13	22	15.5	22	112.8	16.3
23	19	23	0.69	43.5	30	Clay	15.6	112.05	23	4	12.96	23	11.8	23	117.4	13.5
24	23	24	0.51	58.4	47	Select Granular	7.6	131.4	24	3	10.37	24	6.1	24	131.4	7.9
25	23	25	0.65	46.2	47	Select Granular	7.6	131.4	25	3	9.81	25	4.7	25	128.1	5.8
26	19	26	0.55	54.6	32	Class 3	9.6	127.6	26	2	14.46	26	4.8	26	131.6	6.2
27	19	27	0.49	61.5	32	Class 3	9.6	127.6	27	2	12.52	27	5	27	129.4	6
28	16	28	0.91	33.0	17	Clay	13.55	117.05	28	4	15.99	28	13.1	28	118.4	14
29	16	29	0.61	49.5	17	Clay	13.55	117.05	29	4	10.19	29	11.7	29	124.4	11.1
30	23	30	0.62	48.4	48	Class 3	8.9	129.35	30	2	8.81	30	5.7	30	131	5.3
31	23	31	0.66	45.8	48	Class 3	8.9	129.35	31	2	10.49	31	6.1	31	127.5	6.5
32	22	32	0.51	58.5	45	Class 5	10.3	128.1	32	1	9.21	32	3.9	32	134.4	5.2
33	22	33D	2.36	12.7	45	Class 5	10.3	128.1	33	1	11.82	33	6	33	139	5
34	21	34	0.43	69.3	41	Class 5	8.9	129.25	34	1	9.97	34	5.1	34	139.8	4.5
35	20	35	0.76	39.5	37	Class 5	9.3	129.15	35	1	7.76	35	6.6	35	133.4	6.9
36	20	36H	0.57	53.0	37	Class 5	9.3	129.15	36	1	7.68	36	2.1	36	135.2	5.7
37	21	37	0.34	87.7	41	Class 5	8.9	129.25	37	1	5.78	37	3.9	37	145.4	4.3
38	22	38A	1.36	22.0	45	Class 5	10.3	128.1	38	1	10.83	38	6.1	38	135.1	5.5
39	19	39	0.49	61.6	32	Class 3	9.6	127.6	39	2	9.11	39	7.6	39	129	6.1
40	19	40	0.43	69.8	32	Class 3	9.6	127.6	40	2	8.22	40	5.3	40	130.8	5.2
41	4	41	0.46	64.9	7	FDR (HMA + Clay + Fly Ash)	18.1	106.5	41	2	19.38	41	13.3	41	116.9	12.6
42	4	42	0.26	115.8	7	FDR (HMA + Clay + Fly Ash)	18.1	106.5	42	2	10.21	42	13.9	42	117.6	11.9
43	3	43	0.31	97.1	5	FDR (HMA + Class 5)	0	0	43	2	6.00	43	4.5	43	126.4	7.6
44	3	44	0.33	91.5	5	FDR (HMA + Class 5)	0	0	44	2	7.26	44	3.7	44	123.9	5.9
45	2	45	0.31	96.2	2	FDR (HMA + Class 4)	0	0	45	2	7.93	45	5.2	45	130	6.6
46	2	46	0.37	80.2	2	FDR (HMA + Class 4)	0	0	46	2	9.03	46	3.9	46	124.2	7.4
47	4	47	0.23	133.3	100	FDR Millings	0	0	47	1	5.43	47	2.4	47	0	0
48	4	48	0.18	163.0	100	FDR Millings	0	0	48	1	5.17	48	1.4	48	0	0
49	2	49	0.30	99.0	2	FDR (HMA + Class 4)	0	0	49	1	6.00	49	2.4	49	123	9.5
50	2	50A	0.49	60.9	2	FDR (HMA + Class 4)	0	0	50	1	7.78	50	3.6	50	126.4	10
51	3	51	0.25	118.1	5	FDR (HMA + Class 5)	0	0	51	1	8.89	51	3.3	51	123.7	9
52	3	52	0.22	138.2	5	FDR (HMA + Class 5)	0	0	52	1	7.48	52	3.3	52	123.1	8.9
53	4	53	0.20	147.1	100	FDR Millings	0	0	53	1	8.48	53	4.2	53	121.9	8.9
54	4	54	0.19	161.3	100	FDR Millings	0	0	54	1	7.45	54	3	54	122.8	8.1
55	16	55	0.47	63.3	20	Class 7 (100% PCC)	11.7	117.95	55	1	5.57	55	8.4	55	0	0
56	16	56	0.71	42.5	20	Class 7 (100% PCC)	11.7	117.95	56	1	8.48	56	8	56	0	0
57	17	57	0.29	105.3	24	Class 7 (50 RCA:50 Cl. 5)	10.35	123.15	57	1	5.37	57	6.5	57	0	0
58	17	58	0.60	50.3	24	Class 7 (50 RCA:50 Cl. 5)	10.35	123.15	58	1	11.51	58	7.9	58	0	0
59	18	59	0.34	87.7	28	Class 7 (100% RAP)	6.6	124.3667	59	1	9.39	59	5.9	59	0	0
60	18	60	0.39	77.7	28	Class 7 (100% RAP)	6.6	124.3667	60	1	11.85	60	5.5	60	0	0
62	13	62	0.38	78.3	15	Class 1 Stabilizing Aggregate	0	0	103	1	8.11	3	11.9	56	0	0
63	13	63	0.34	87.5	15	Class 1 Stabilizing Aggregate	0	0	104	1	5.18	4	13.7	56	0	0
64	6	64	0.66	45.5	11	Class 1 Stabilizing Aggregate	0	0	105	1	10.65	5	14.8	57	0	0
65	6	65	0.55	55.0	11	Class 1 Stabilizing Aggregate	0	0	102	1	9.53	2	12.5	57	0	0

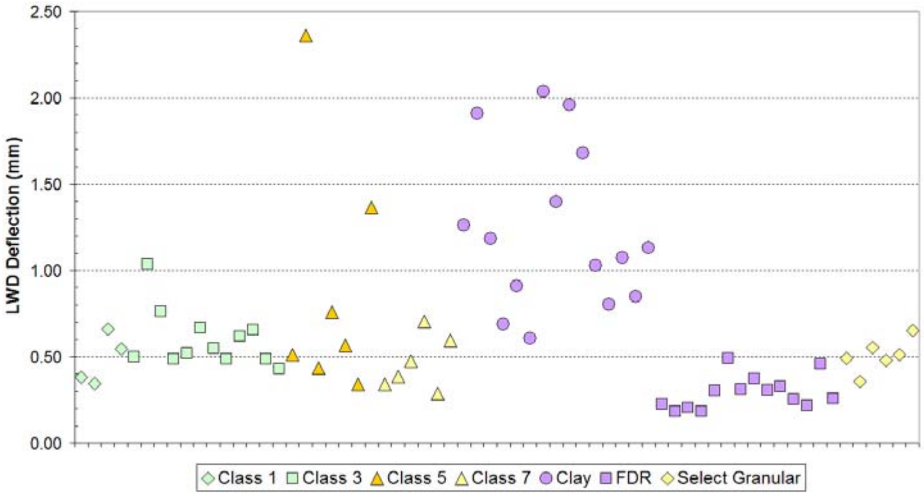


Figure 14—LWD Data by Unbound Material Type

Table 8—Summary Statistics of LWD Tests by Unbound Material Type

Material	Mean LWD Deflection (mm)	Standard Deviation	Coefficient of Variation
Class 1	0.48	0.147	30.4%
Class 3	0.60	0.168	28.0%
Class 5	0.91	0.725	80.1%
Class 7	0.46	0.161	34.6%
Clay	1.23	0.468	37.9%
FDR	0.29	0.096	32.8%
Select Granular	0.51	0.096	18.9%

Dynamic Cone Penetrometer (DCP) data

Figure 15 illustrates DCP penetration data by unbound material type. The DCP data is similar in form to the LWD data discussed above, except there are fewer outliers. Tests of stiffer/stronger materials (Class 1, Class 3, Class 5, Class 7, FDR and select granular) are generally between 5 and 15 mm/blow. These materials average between about 8.3 and 10.7 mm/blow, as shown in Table 9. There is an FDR outlier at about 19 mm/blow. The softest/weakest material (clay) has higher penetration, ranging from 10 to 35 mm/blow, averaging 19 mm/blow.

Select granular is by far the least variable, with a coefficient of variation of only 2.8 percent. Class 3 is the next least variable, with a coefficient of variation of 17 percent. The remaining materials in order of increasing variability are: Class 5, Class 1, clay, Class 7, and FDR. The high variability of the FDR tests is due to the outlier mentioned above.

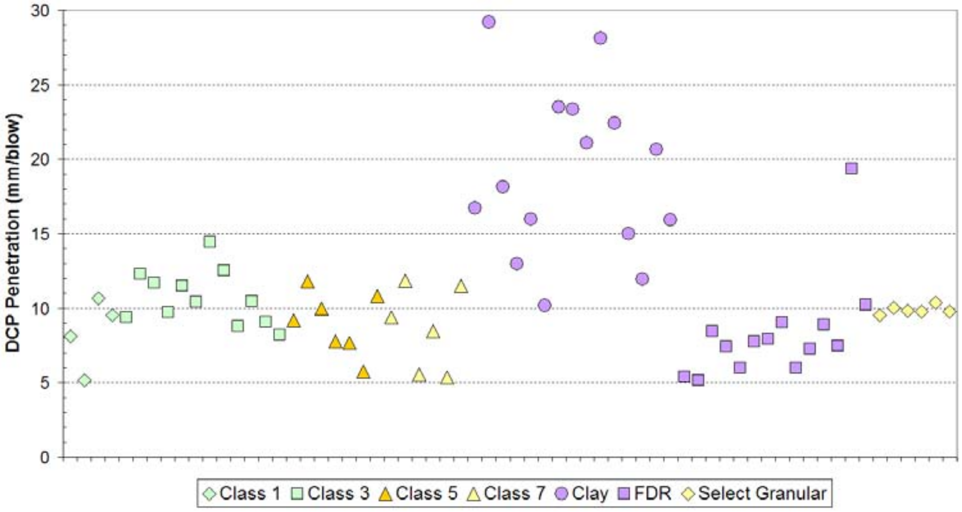


Figure 15—DCP Data by Unbound Material Type

Table 9—Summary Statistics of DCP Tests by Unbound Material Type

Material	Mean DCP Penetration (mm/blow)	Standard Deviation	Coefficient of Variation
Class 1	8.37	2.365	28.3%
Class 3	10.72	1.825	17.0%
Class 5	9.01	2.079	23.1%
Class 7	8.69	2.804	32.2%
Clay	19.02	5.673	29.8%
FDR	8.32	3.494	42.0%
Select Granular	9.89	0.282	2.8%

Laboratory and Field Data

Proctor Test Data

Proctor tests produced the optimum moisture content versus maximum dry density data displayed in Figure 16. This data distribution is generally similar to the distribution for all non-MnROAD Minnesota soils[4]. The data point that falls outside the narrow band of other data, at about 125 pcf and 6.5 percent, is for a Class 7 material.

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[4] John Siekmeier, personal communication, July 2010.

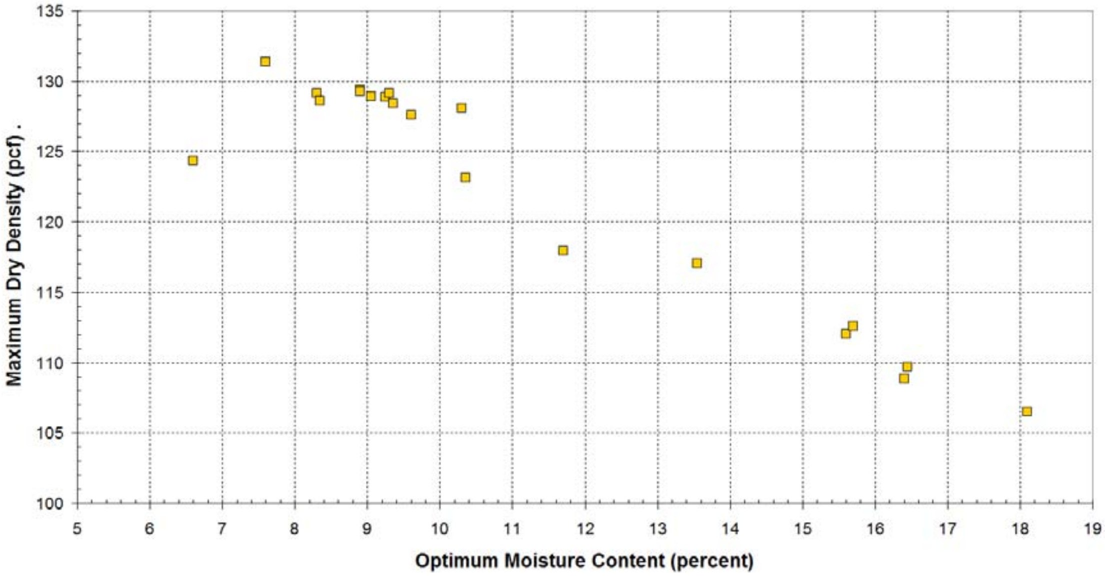

Figure 16—Optimum Moisture Content vs. Maximum Dry Density

Figure 17 illustrates the as-tested moisture content of the unbound materials at the companion test locations. The thick line in the figure is the as-test equals optimum line. The figure shows that all but one test occurred below, sometimes significantly below the optimum moisture content. Many of the tests were conducted on materials below 75 percent of optimum.

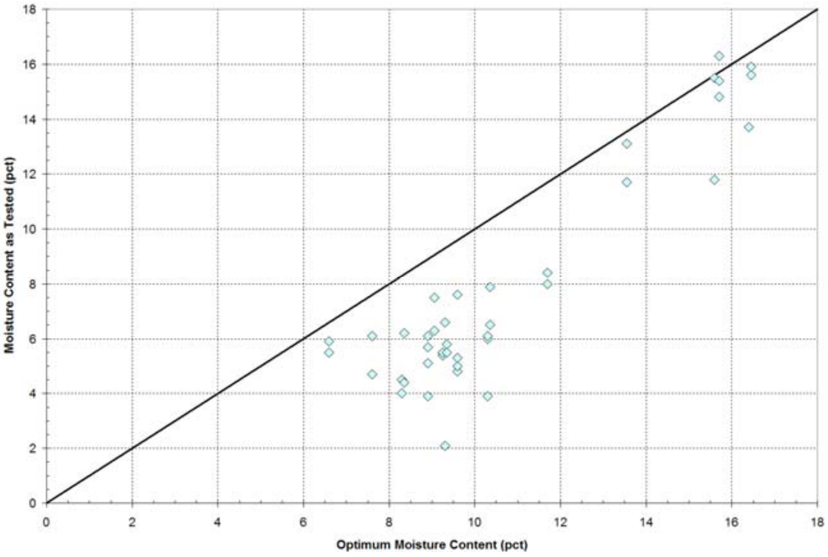

Figure 17—Optimum versus As-Tested Oven Moisture Content

Moisture-Density Data

Figure 18 illustrates the relationship between oven-dried moisture content and nuclear gauge moisture content. The figure separates the data for all eight unbound material types. Based on visual assessment of the figure, nuclear gauge moisture content is reasonably reliable for clay, Class 3 and Class 5. (Note that no Class 1 or Class 7 was tested by both means.) However, the nuclear gauge significantly over estimates the moisture content of many FDR compositions with low moisture content (say below 6 percent). The two FDR compositions at 12 to 14 percent are reliably estimated. The nuclear gauge also over estimates the moisture content of select granular materials with low moisture content. Since there are no select granular tests with higher moisture content, this conclusion cannot be extrapolated.

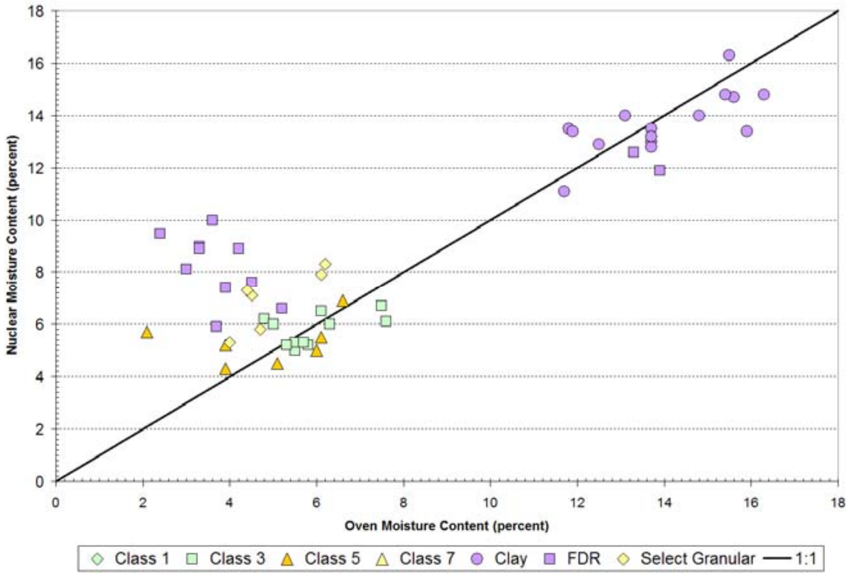

Figure 18—Comparison of Oven-Dried vs. Nuclear Moisture Content

Synthesis, Comparison and Correlation

FWD-IC Correlations

This correlation is discussed in "FWD-IC Correlations" on page 14 above.

LWD versus DCP Correlations

LWD and DCP test data typically show some correlation. Figure 19 shows the correlation for the 2008 MnROAD data. While there is a significant amount of scatter, especially in the softer/weaker materials (high DCP or LWD values), there is clearly a correlation between the two tests. The correlation coefficient is 0.566.

There are no tests in the data set with LWD deflection less than 0.2 mm, or with DCP penetration less than 5 mm/blow. The data is clustered between these lower limits and upper limits of LWD of 0.8 mm and DCP of 13 mm/blow.

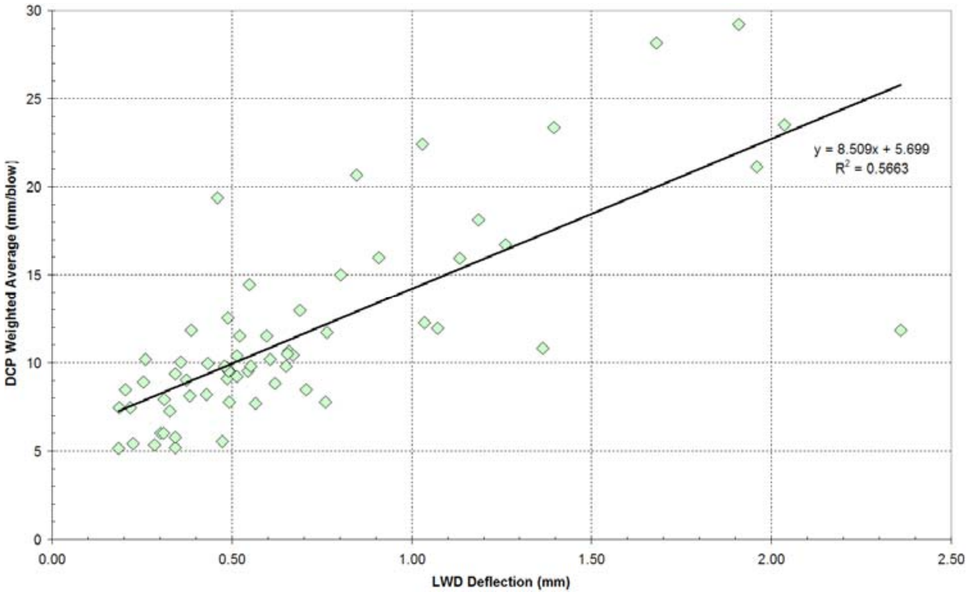

Figure 19—LWD versus DCP Test Data

Moisture Effects

Figure 20 and Figure 21 illustrate the effect of moisture content on LWD and DCP measurements, respectively. Disregarding Class 5 outliers, and considering all materials together there appears to be an increase in LWD deflection with increasing moisture content, as would be expected. However, there is a significant spread in the LWD data for the clay data. Considered separately, the clay data appears to have a significant dependency on moisture content. The clay samples vary from about 0.5 mm to 2.0 mm over a moisture range of 12 percent to 16 percent. Similar conclusions are apparent in the DCP data in Figure 21.

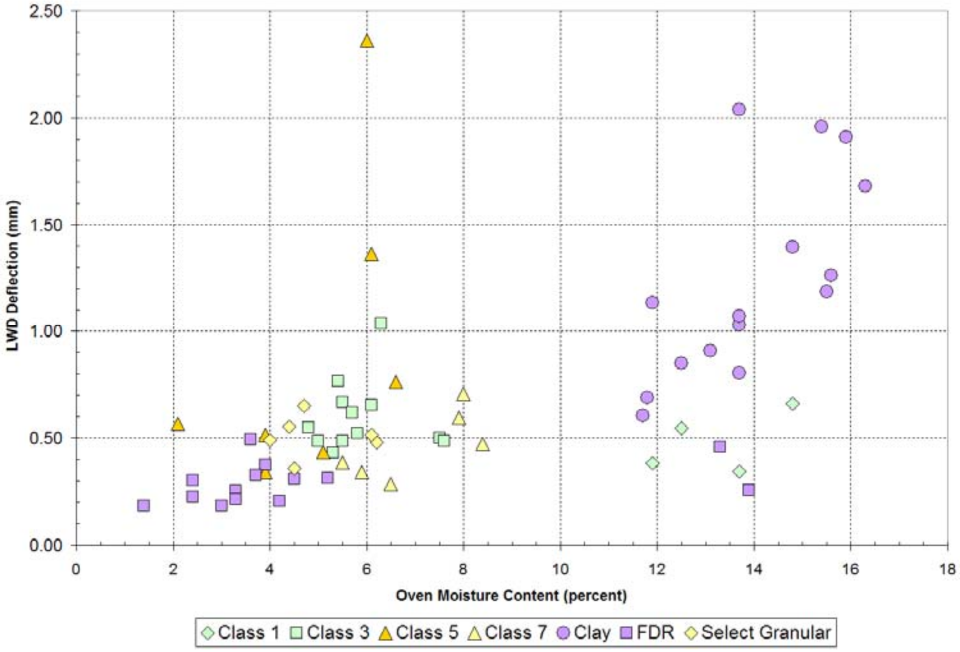

Figure 20—Moisture Effect on LWD Deflection by Material Type

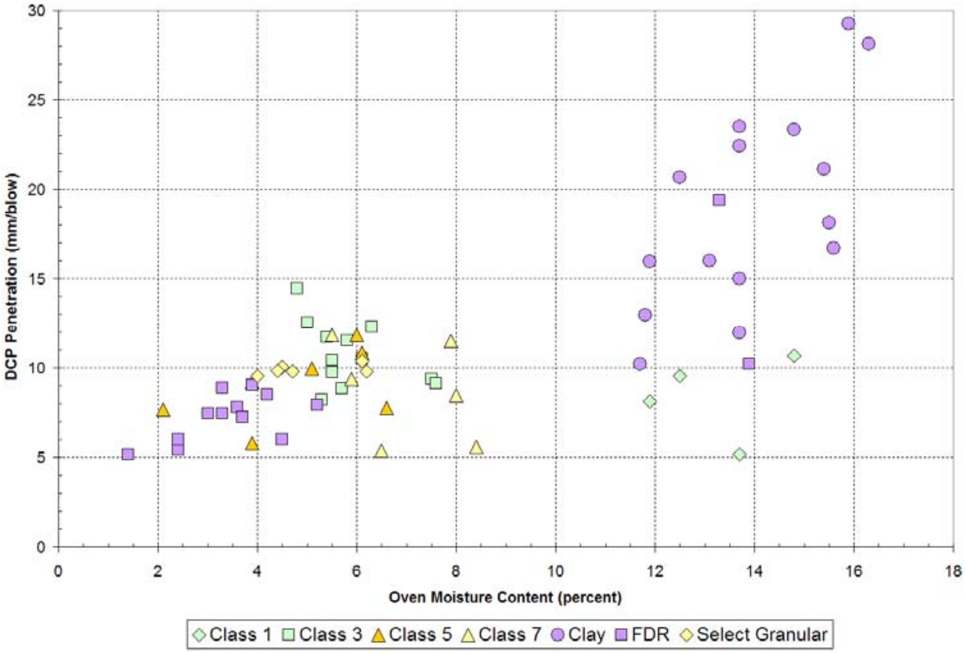

Figure 21—Moisture Effect on DCP Penetration by Material Type

Correlation Between IC Data and Other Data Types

The companion test data was collected at locations and for layers different than the FWD tests. Hence, the IC data at companion test locations is potentially different than the IC data at FWD locations. The following three figures compare IC data from the multipoint representation to the data from the centerpoint representation. Figure 22 is for IC data within

1-ft of companion test locations, Figure 23 is for IC data within 5-ft of companion test locations, and Figure 24 is for IC data within 10-ft of companion test locations. There are significantly fewer data points for centerpoint data within 1-ft of the companion tests, because the line of centerpoint data is, of course, at the centerline of the roller drum (see Figure 22, and the discussion of IC data representation options on page 14 and following. Comparing these three figures, selection of IC data from a larger radius tends to reduce the scatter and eliminate differences between the IC data averages from multipoint and centerpoint representations (see the tight grouping of data points near the 1:1 line in Figure 24).

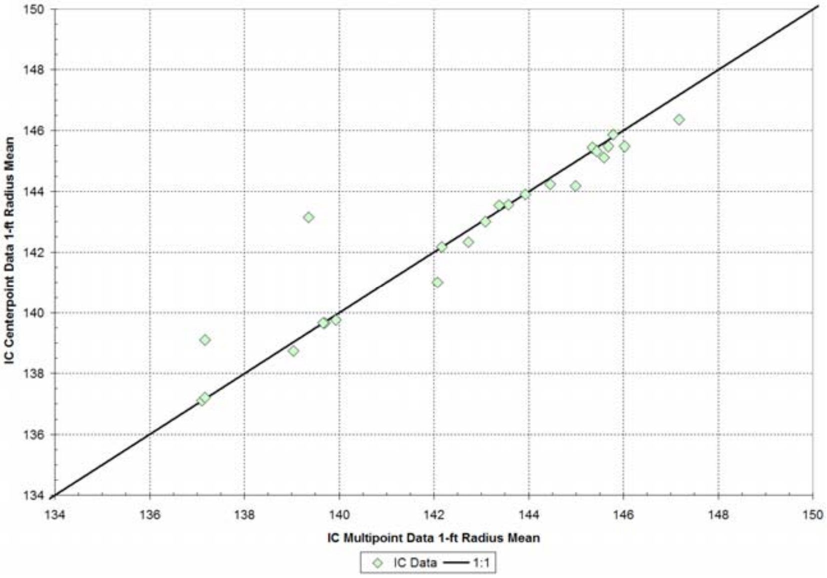

Figure 22—Multi- & Centerpoint IC Data within 1-ft of Companion Tests

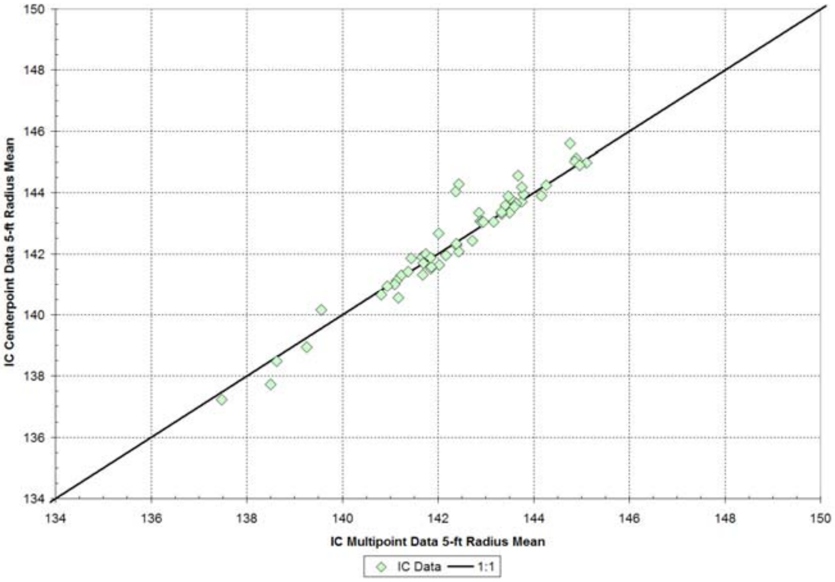

Figure 23—Multi- & Centerpoint IC Data within 5-ft of Companion Tests

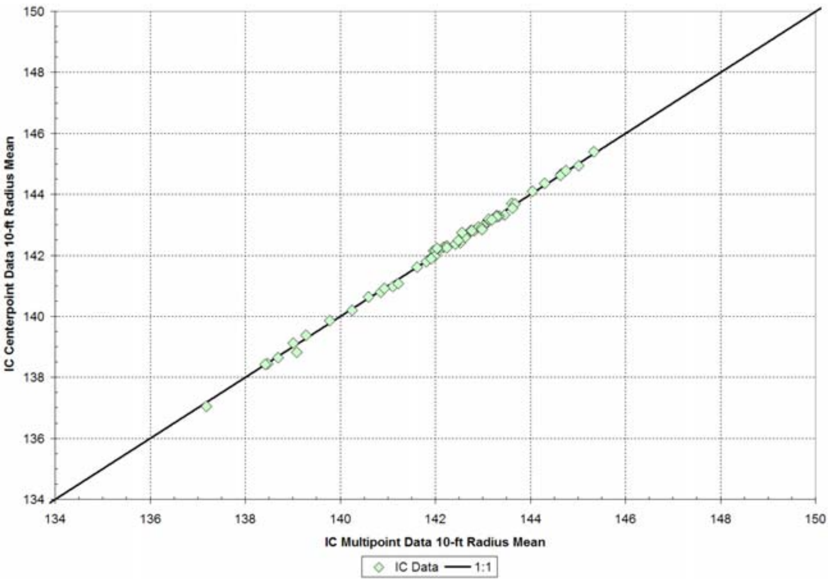

Figure 24—Multi- & Centerpoint IC Data within 10-ft of Companion Tests

Six IC data options are available for comparison with companion test data: 1-ft, 5-ft and 10-ft radius multipoint averages, and 1-ft, 5-ft and 10-ft centerpoint averages. Based on the preceding graphs and discussion, the 10-ft multipoint average will be used, to maximize the number of data points and reduce the scatter.

The following three figures compare three companion tests with the 10ft radius multipoint IC data means. Figure 25 illustrates the relationship between LWD deflection and IC mean. Most of the LWD deflection data is between about 0.2 mm and 0.8 mm, i.e. the relatively stiffer materials. The IC data for this LWD data range is between about 138 and 145. There is no visual indication of correlation between these two data types.

Figure 26 illustrates the relationship between DCP penetration and the IC mean. Most of the DCP data is between 5 and 15 mm/blow, and the IC data for these limits is, like for Figure 25, limited to the range from about 138 and 145. There is no visual correlation between these two data types.

Figure 27 illustrates the relationship between nuclear dry density and the IC mean. There is no visual correlation between these two data types.

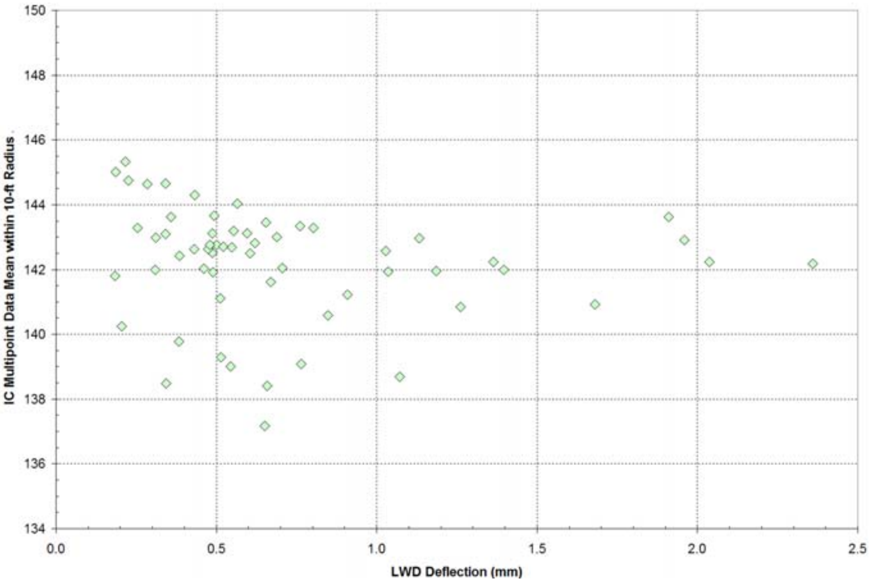

Figure 25—LWD Deflection and IC Multipoint 10-ft Radius Mean

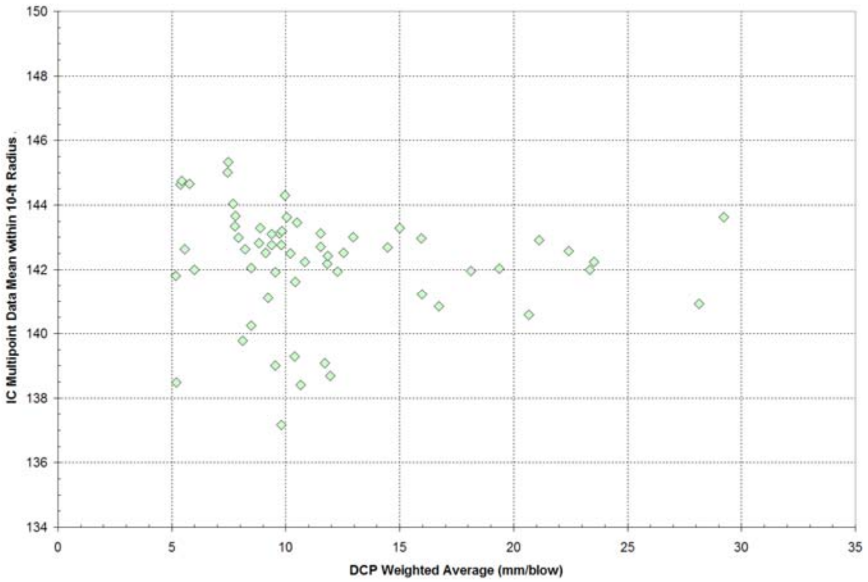

Figure 26—DCP Penetration and IC Multipoint 10-ft Radius Mean

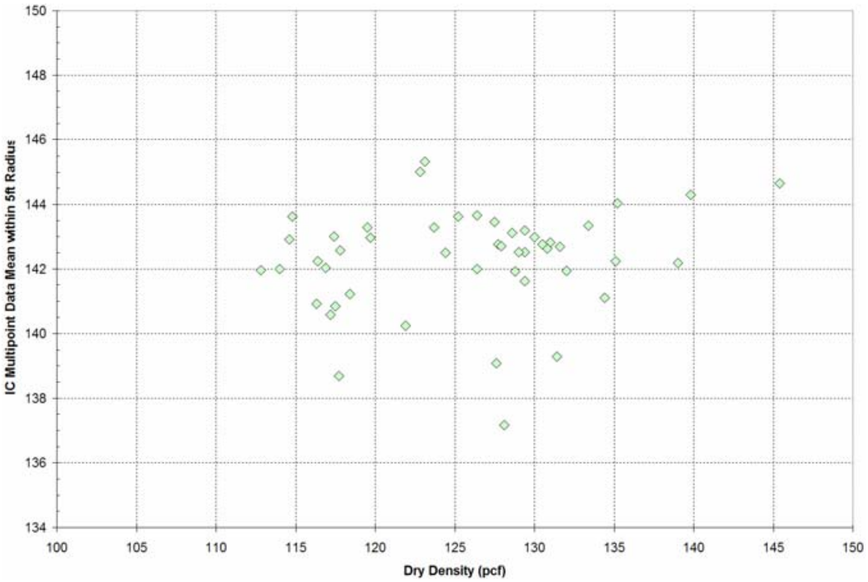

Figure 27—Dry Density and IC Multipoint 10-ft Radius Mean

The LWD, DCP and nuclear dry density data depicted in the preceding three figures is from six material types, including two (Class 7 and the FDR) that have varying formulations:

- Class 3
- Class 5
- Class 7 (various formulations)
- Clay
- Various FDR (three different proportions of HMA/gravel))
- Select Granular

(Refer to Figure 1 for the details of the subsurface profiles.) A few of the material types were measured only a few times.

The LWD, DCP and nuclear gauge are sensitive to material properties in a relatively thin surface layer of the material, in comparison to the relatively great thickness of material sensed by an IC roller.

The various materials and test types are sensitive to material moisture in differing ways.

In view of these three facts (wide material variations, varying depth sensitivity, varying material moisture sensitivity) the lack of correlation between IC data and companion tests is expected.