

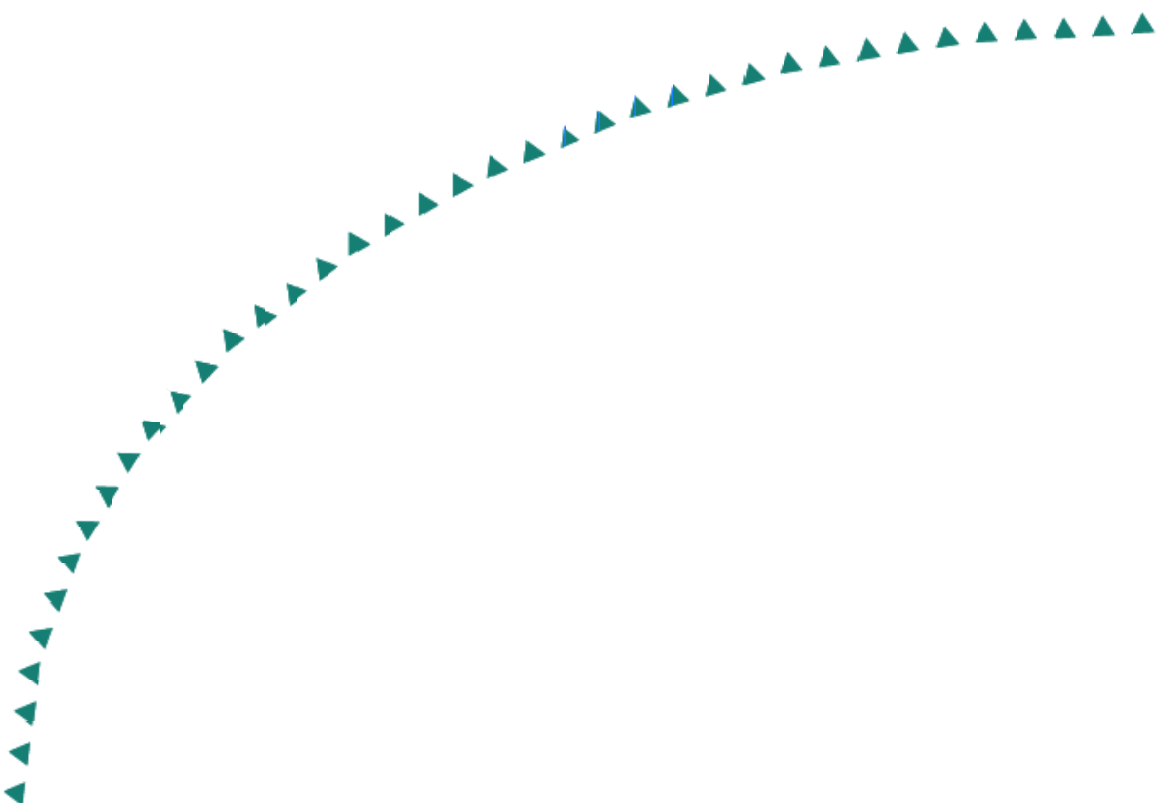
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Final Report

Intelligent Compaction and  
In-Situ Testing at  
Mn/DOT TH53



# Research



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16. Abstract (Limit: 200 words) <p>This report describes an intelligent compaction demonstration project on Mn/DOT TH 53 in Duluth, MN, and the associated field and laboratory testing. The project was conducted during September 2005, using a Caterpillar Model CS-563E vibratory soil compactor, equipped with Intelligent Compaction (both Compaction Meter Value (CMV) and energy or power) and global positioning system (GPS) technology. A Prima light-weight deflectometer (LWD), dynamic cone penetrometer (DCP) and Humboldt GeoGauge were used to collect in situ companion test data at 42 locations. Mn/DOT conducted gradation, moisture content and Procter tests.</p> <p>Location and Compaction Meter Value (CMV) were downloaded for comparison with the in situ testing. CMV data was compared to the in situ data on a point-by-point basis and on the basis of the overall distribution. In general, poor correlations were obtained on a point-by-point basis, likely due to the depth and stress dependency of soil modulus, and the heterogeneity of the soils. Good correlations were obtained between CMV values and DCP measurements for depths between 8-inches and 16-inches deep.</p> <p>The Caterpillar Compaction Viewer software, although still in development at the time of testing, is functional and is well integrated with GPS. It is easy to extract data and do more sophisticated analyses. Surface-covering documentation adds value by identifying potential problem areas where compaction is limited by material, moisture or subgrade deficiencies. LWD testing protocol must be followed to obtain useful results, since measurements vary significantly between successive tests. Relatively good correlations were obtained between LWD and GeoGauge. The GPS technology used for the demonstration is not adequate to distinguish between lifts.</p>			
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# **Intelligent Compaction and In-Situ Testing at Mn/DOT TH53**

## **Final Report**

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# Intelligent Compaction and In-Situ Testing at Mn/DOT TH53



Prepared for:  
Minnesota Department of Transportation

Prepared by:  
CNA Consulting Engineers  
May 2006

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# 1 Introduction

## 1.1 Report Background and Purpose

Road authorities across Minnesota spend millions of dollars each year on the construction of pavement structures. Unfortunately, the quality control and quality assurance (QC/QA) testing used during pavement construction currently has little connection to the material properties used during mechanistic pavement design. In order to more efficiently design and construct these pavements, the Local Road Research Board (LRRB) and State have invested significant resources to develop and advance the use of compactor-based compaction control technology, and non-destructive testing devices aimed at assessing the design-related pavement parameters in situ.

In addition to local and state agency contributions, a contract with the University of Minnesota completed in 2003 recommended specific enhancements to the Light Weight Deflectometer (LWD) (Hoffman et al, 2003). A current barrier to an effective use of in situ testing devices is the complexity of consistent data interpretation. In this regard, the LWD shows great promise for Quality Control and Quality Assurance (QC/QA) if the consistent processing of collected data can be made more user friendly.

The original objective of the project was to upgrade a LWD device and implement FFT (Fast Fourier Transformation) time history analysis software developed by the manufacturer. The upgraded components included a handheld device to collect and process all data, a Bluetooth GPS to give location of the test, wireless Bluetooth to allow the device to communicate with the handheld and the FFT software to provide consistent processing of the data. Carl Bro upgraded the unit with Bluetooth and shipped us both the handheld and GPS in June 2005. The software included with the handheld did not work properly at first, but with a couple of software revisions by the manufacturer, it functioned with relative ease. The GPS unit never functioned properly. The manufacturer did not have the FFT software ready for implementation until after the Mn/DOT trunk highway project was underway and therefore, Mn/DOT requested a change to the original project scope.

In October 2005, CNA agreed to change the scope of the contract from focusing on LWD implementation to analysis of compaction data from the intelligent compaction-equipped Caterpillar Compactor, and the companion testing conducted. The LWD upgrade is not discussed further in this report.

## 1.2 Intelligent Compaction

### 1.2.1 Description

Intelligent Compaction is based on measuring the stiffness of the compacted soil. Initiatives in both the U.S. and Europe, started more than 10 years ago, have demonstrated the technical viability of measuring in situ soil stiffness. Commonly, the measured soil stiffness is used to estimate or compute in situ soil modulus, based on assumptions about soil behavior and the interaction between the compaction machine and the base or subgrade materials.

### 1.2.2 Terminology

In any emerging technology, terminology varies among those involved until a standard develops. For the sake of clarity, the following definitions are used herein:

1. Surface covering documentation—This phrase describes the combined location and compaction level data (typically stiffness, modulus, strength or a similar parameter) produced by a compactor over the entire surface of a compaction lift.
2. Intelligent Compaction—Intelligent Compaction technology describes the ability of a compactor to measure compaction level, and may also include feedback to adjust the compactive effort depending upon the compaction level measured. The Caterpillar compactor used for this demonstration project measured compaction level and prevented double jump by automatically adjusting compaction effort. Caterpillar intends to produce compactors that will automatically adjust compactive effort based on measured compaction level beginning in 2006.
3. Vibratory versus non-vibratory compaction measurement—The three preceding definitions do not distinguish between vibratory and non-vibratory compaction measurement methods. Most of the European technologies use vibratory methods similar to the methods used in this study. Caterpillar has developed a non-vibratory technology named “power” mode (White et al, 2005), but this technology was not assessed in this demonstration.

### 1.2.3 General Description of the Technology

Intelligent vibratory compaction machines typically include the following:

1. Accelerometers to measure movement of the drum
2. Onboard electronics to record and process sensor output, and record the stiffness
3. Linkages to the machine controls to adjust compaction effort according to the measured stiffness
4. Systems to record machine location and time
5. Local storage and/or wireless communications systems for data transfer

Process control is achieved in real time as the compaction process proceeds. The stiffness of the material is measured continuously as the compactor moves along. If the material stiffness is below the target value, the compactor applies compactive effort to the soil. If the material stiffness is at or above the target value, the compactor may also change drum vibration characteristics to eliminate additional compaction of the material. The compactor used in this demonstration project varied compaction effort to prevent double jump, but did not vary it based on measured compaction level.



## 2 Field Testing Protocol

### 2.1 Site Location and Schedule

The test site was located along a portion of the Mn/DOT TH 53 Trinity Road project, as illustrated in Figure 1. The project consisted of reconstruction of the two-lane T.H. 53 along a 2.5-mile stretch from Piedmont Avenue to TH194 into a four-lane highway with continuous two-way left turn lane. The reconstructed segment consisted of 8" hot mix asphalt layer over a 6" Class 6 aggregate base, over a 3' subcut filled with select granular borrow. The select granular borrow was compacted using the Caterpillar Intelligent Compaction compactor. The area of focus for the demonstration was between South Arlington Avenue and Anderson Road. Testing took place September 20 through September 29, 2005, and CNA performed companion tests from September 20 to 22, and September 27 to 29, 2005.

Mn/DOT based acceptance of the compacted material on test rolling (Specification 2111) and reserved the option of performing sand cones and moisture testing if needed.

### 2.2 General Description of Companion Testing

Light Weight Deflectometer (LWD) tests were performed at 25 locations, GeoGauge tests were performed at 40 locations, and DCP tests were performed at 22 locations. Forty-eight soil samples were collected for determination of moisture content. Mn/DOT performed 4 sandcones and DCP tests at select test locations on 9/27/2005.

### 2.3 Construction Sequence

Contractor was removing approximately 4 feet of in-place material and filling with select granular borrow. The fill material was compacted in lifts of 4 to 10 inches. The cut operation was followed closely behind with the fill operation. Fill was placed and compacted in relatively short spans, which led to a very busy site. For this reason, the majority of testing was performed on the final lift, after construction traffic had moved further down the alignment.

### 2.4 Caterpillar Compactor

The machine used for the demonstration was a Caterpillar Model CS-563E vibratory soil compactor, equipped with Intelligent Compaction (both Compaction Meter Value (CMV) and energy or power) and global positioning system (GPS) technology. Figure 2 shows the machine in operation, and the GPS base station used. Pertinent data about this model compactor is in Table 1.

The Compaction Meter Value (CMV) method uses a drum-mounted accelerometer that measures G-force at vibratory frequency and harmonics. Typically, only vertical accelerations are measured. Referring to Figure 3, the CMV is the ratio of the G-force at the second harmonic to the G-force at the first harmonic. This value indicates the soil compaction level.

The machine was also equipped with the energy or power method instrumentation. Referring to Figure 4, sensors measure driveline power used to roll over the soil, with corrections made for grade and machine acceleration. This technique works on both vibratory and non-vibratory compactors.

For this demonstration test, only CMV values were evaluated.

**Table 1—Caterpillar Machine Characteristics**

Item	Value
Operating weight	24,520 lb
Axle load, drum	12,877 lb
Axle load, wheels	11,643 lb
Static linear load	153.3 lb/in
Working drum width	7 ft
Speeds	3.5 mph 7.0 mph
Performance ISO 3046	
Tire size	23.1 x 26 in
Frequency	1914 vpm
Amplitude (vertical)	0.3 mm - 2.0 mm
Centrifugal force	60,000 lb

## 2.5 Compactor and Companion Tests

### 2.5.1 Test Sequence

The general sequence of testing at each location was as follows:

1. Compactor measurement.
2. Three GeoGauge measurements, each one followed by an LWD measurement.
3. A final GeoGauge measurement.
4. A DCP measurement.
5. Finally a soil sample was collected for moisture content determination.

Figure 5 shows the companion test hardware.

### 2.5.2 Intelligent Compaction Machine Data

The Caterpillar compactor has a GPS unit and an onboard computer running a Windows operating system. The computer records CMV measurements as it compacts and stamps each measurement with time and x,y,z coordinates. The data is stored on a portable storage device, which can store roughly a week of field data. Data is downloaded one of two ways, either with a cable from the onboard computer connected to a laptop or via the portable storage device. Once transferred, the data can be viewed in plan view with software developed by Caterpillar (see a partial screen capture in Figure 6). The software allows export of the raw data in ASCII format for further analysis.

### 2.5.3 Light Weight Deflectometer (PRIMA 100)

The PRIMA 100, shown in Figure 5, is a portable Light Falling Weight Deflectometer (LWD), which can be used to measure in-situ material modulus. The device consists of a handheld computer, mass, guide rod, load cell, velocity transducer and a 200mm-diameter plate. A mass freely falls from a known height along the guide rod and impacts a load cell at the lower end of the rod. A velocity transducer, which protrudes through the center of the plate, measures velocity. Velocity is integrated to determine displacement and a time history of the impact load and displacement are displayed. The LWD weighs about 40 lbs with approximately half of its weight being in the falling mass (22 lbs). One advantage of the PRIMA 100 over other LWDs is that distance the mass falls can be adjusted by the technician resulting in the possibility of measuring modulus at different stress states.

The following is the testing procedure:

1. Locate a relatively smooth and level spot for the test.
2. Assemble LWD and turn it on.
3. Turn on the handheld computer and load the program.
4. Place the LWD on the testing location, then rotate it slightly to smooth out the contact surface.
5. Set the trigger mechanism to the desired drop height (25, 50 or 75cm).
6. Lift the weight until it connects with the trigger mechanism.
7. Press the go button on the handheld computer.
8. Activate the trigger mechanism while holding the top of the guide rod to keep the instrument steady.
9. Record the load and displacement displayed.
10. Repeat steps 6 through 9 until five tests have been performed.
11. Turn the LWD and handheld computer off and place it back in the case.

In general, the difference between the results from drops 3, 4 and 5 is small compared to the first two drops. The reason is that the LWD impacts the ground with a large force. This force compacts the loose soil near the surface and causes the deflection to decrease and load to increase from drop to drop. Normally, the deflection of the second drop was significantly less than that of the first. Therefore, the first two drops are considered seating drops similar to standard FWD procedure. During the testing, the LWD must be held steady and vertical. The operator should ensure that surface is even and smooth. The experience showed that, if the LWD was tipped during testing, the readings were not correct. Mn/DOT has performed many tests with the LWD and written a paper that contains recommendations for LWD testing specifications and procedures (Davich et al, 2006). In summary, the LWD is a simple device to operate and provides repeatable results.

#### 2.5.4 GeoGauge

GeoGauge measurements were performed according to ASTM D 6758-02. The Humboldt GeoGauge, shown in Figure 5, was used to conduct companion tests. The 22-lb device directly measures the stiffness of a 4.5-inch outside diameter by 3.5-inch inside diameter plate (foot) resting on the soil surface. The stiffness is measured dynamically in the frequency range from 100 Hz to 200 Hz, and the average stiffness across the frequency range is reported to the user. Measurements may be taken about every 75 seconds if the device is not moved, and every few minutes if the device is moved to a new location nearby. The Young's modulus of the soil may be calculated from the measured stiffness, foot geometry and an assumed Poisson's ratio.

Seating of the GeoGauge involves setting it on the test location and giving a slight twist. Twisting the GeoGauge is performed to ensure a minimum of 80% contact between the foot and the soil. Humboldt recommends using a small layer of sand when the 80% contact cannot be achieved. The field engineer determined that contact between the foot and soil was sufficient for all tests without the use of sand.

#### 2.5.5 Dynamic Cone Penetrometer

Dynamic Cone Penetrometer (DCP) measurements were performed according to ASTM D 6951-03. The DCP, shown in Figure 5, is a device that measures soil shear strength. It functions by striking a cone tipped rod with a freefalling weight, thereby driving the cone into the soil. The distance the cone penetrates is measured and the process is repeated until the desired depth is achieved. The recorded data is most commonly plotted as the penetration of the cone divided by the number of blows. This value is referred to as the DCP Penetration Index (DPI). The following correlation is used to determine the soil modulus from a DCP measurement:

$$\text{Log } (E_{\text{DCP}}) = 3.04785 - 1.06166 (\log (\text{DPI})), (\text{DeBeer}, 1991)$$

where  $E_{\text{DCP}}$  is the effective elastic modulus.

## 2.6 Description of Laboratory Work

### 2.6.1 Sieve Analysis

The results of a sieve analysis performed by Mn/DOT is provided in Appendix D.

The results of Proctor testing performed by Mn/DOT are also shown in Appendix D.

## 3 Field Measurements and Analysis

### 3.1 Test Locations

### 3.2 Companion Test Summary

Companion tests were conducted at 42 locations along the alignment. LWD companion tests were performed at 28 locations. LWD testing ended early due to a broken trigger mechanism. GeoGauge companion tests were performed at 42 locations and DCP tests were performed at 22 locations. Moisture content was measured at all locations. Sand cone tests were performed by Mn/DOT at locations 33, 34, 35 and 36. A composite chart of test results by location is shown in Figure 7. Table 2 summarizes the location for each companion test in South St Louis County Coordinates.

**Table 2—Companion Test Locations**

Test Location	Easting (ft)	Northing (ft)	Elevation (ft)
1	577582.8	149570.0	1109.5
2	577608.3	149544.6	1108.2
3	577743.0	149314.9	1095.9
4	577772.0	149252.6	1093.4
5	577778.3	149239.2	1092.9
6	577877.4	149037.9	1086.4
7	577881.9	149029.0	1086.0
8	577885.1	149020.1	1085.8
9	577888.2	149009.9	1085.5
10	577827.3	149106.1	1088.0
11	577826.3	149170.3	1091.1
12	577818.7	149188.0	1091.7
13	577808.7	149205.6	1092.4
14	577798.3	149222.3	1092.9
15	577785.0	149247.1	1094.0
16	577769.2	149266.0	1094.9
17*	577788.8	149258.2	1094.1
18	577782.0	149270.8	1095.4
21	577801.2	149239.3	1093.7
22	577808.6	149222.5	1093.1
23	577958.0	148732.4	1076.4
24	577967.5	148666.0	1073.9
25	577518.7	149646.5	1107.9
26	577521.0	149611.6	1106.1
27	577538.9	149590.0	1104.7
28	577549.5	149576.6	1104.1
29	**	**	**
30	**	**	**
31	576323.2	150359.2	1146.8
32	576293.3	150367.5	1147.1
33	575227.0	150674.2	1179.7
34	575268.2	150667.2	1178.5
35	575308.1	150652.6	1176.5
36	575343.7	150635.3	1175.3
37	575806.9	150515.6	1161.8
38	575891.9	150491.3	1160.0
39	575888.7	150460.8	1161.1

40	575966.5	150416.8	1158.9
41	576037.4	150419.3	1157.3
42	576087.1	150406.2	1156.5
43	576088.1	150424.1	1156.6
44	576081.7	150405.7	1156.6

\* Test performed 5.4 inches below surface.

\*\* GPS base station was not in operation during these tests.

### 3.2.1 Dynamic Cone Penetrometer

Table 3 summarizes the Dynamic Cone Penetrometer (DCP) testing done during the demonstration. A DCP test was conducted at each test location. Drive depths ranged from about 16 inches to 20 inches. Data reduction followed the procedures described in Section 2.5.5.

A statistical summary of the DCP data is shown in Figure 8. Comparisons with other companion tests are shown in Figures 13 and 14.

**Table 3—Summary of Dynamic Cone Penetrometer Testing**

Location	DCP Weighted Average of Top 4in (MPa)	DCP Weighted Average of Top 8in (MPa)	DCP Weighted Average of Top 12in (MPa)	DCP Weighted Average of Top 16in (MPa)
2	8	8	12	16
4	10	16	22	29
5	12	18	24	30
6	8	10	16	21
7	9	11	18	24
11	8	10	15	20
12	9	12	17	22
13	12	20	27	33
15	7	7	12	16
16	7	8	12	17
22	8	12	17	21
23	8	10	16	20
24	11	12	21	27
26	10	14	19	23
27	9	11	16	21
28	11	16	21	27
31	8	8	13	18
32	7	8	13	17
33	10	14	21	27
34	8	11	16	16
35	11	16	23	29
36	10	13	20	25

The DCP is the sole device used in the demonstration that provides an estimated modulus profile with depth. (Of course, the companion test devices that measure on the soil surface may be used to obtain a profile by excavating down and testing of the new surface.) Measuring the estimated modulus profile is a benefit of the DCP, but makes comparison with other methods more difficult.

The difficulty of comparing DCP results to other methods is compounded by the depth (i.e. stress) dependence of modulus. The methods that measure soil modulus from surface contact (Caterpillar, LWD, GeoGauge) produce a composite modulus that is a complex function of the loading geometry and soil properties. In this analysis the weighted average (of drive length) with a cutoff of the bottom of the lift was used to calculate a single DCP modulus from the measured profile.

### 3.2.2 GeoGauge

Typically 12 Geogauge measurements were made at each location: three prior to the low drop height LWD, three after the low drop height LWD, three after the mid drop height LWD and three after the high drop height LWD. Table 4 summarizes the test results. In the table, the GG<sub>0</sub> column is the average of the three measurements prior to low drop height LWD measurement, the GG<sub>1</sub> column is the average of the three measurements after the low stress LWD, the GG<sub>2</sub> column is the average of the three measurements after the medium stress LWD and the GG<sub>3</sub> column is the average of the three measurements after the high stress LWD.

A statistical summary of the GeoGauge data is shown in Figure 8. Comparisons with other companion tests are shown in Figures 11, 14 and 15. Figure 15 demonstrates the increased modulus after each LWD test.

**Table 4—Summary of GeoGauge Modulus Data**

Test Location	GG <sub>0</sub> (MPa)	GG <sub>1</sub> (MPa)	GG <sub>2</sub> (MPa)	GG <sub>3</sub> (MPa)
1	-	-	-	48.9
2	34.5	-	-	48.4
3	28.8	35.5	44.0	44.4
4	33.8	43.0	47.8	-
5	37.2	47.7	52.1	55.5
6	36.3	45.3	51.0	54.0
7	35.0	43.5	49.2	54.2
8	42.9	48.8	51.3	54.5
9	44.5	42.7	46.1	51.8
10	28.3	40.9	45.3	49.6
11	41.1	47.2	51.4	54.7
12	46.4	55.0	60.4	64.0
13	53.0	58.2	63.2	65.3
14	44.8	51.4	56.5	57.3
15	33.0	46.1	51.7	52.3
16	27.8	44.0	49.7	51.0
17*	48.8	49.8	55.9	59.2
18	30.9	40.3	45.2	47.0
21	45.7	54.0	58.7	61.6
22	44.9	55.3	59.5	63.0
23	26.5	45.5	51.5	54.5
24	33.7	49.4	54.0	54.8
25	26.1	45.3	49.4	55.6
26	39.9	-	51.3	53.9
27	34.1	44.0	49.4	-
28	37.9	44.3	48.6	50.7
29	30.8	37.7	42.5	-
30	26.0	40.3	-	-
31	23.0	-	-	-

32	29.5	-	-	-
33	37.8	-	-	-
34	35.9	-	-	-
35	36.7	-	-	-
36	31.1	-	-	-
37	31.5	-	-	-
38	32.7	-	-	-
39	41.6	-	-	-
40	40.6	-	-	-
41	41.5	-	-	-
42	41.1	-	-	-
43	26.3	-	-	-
44	32.1	-	-	-

\* Test performed 5.4 inches below surface

### 3.2.3 Sand Cone Density

The sand cone method was used by Mn/DOT to measure dry density and moisture content at selected locations. Appendix B summarizes the dry density measurements.

### 3.2.4 Moisture Content

Samples were obtained from each test location for determination of moisture content. Table 5 summarizes the moisture content results. Moisture content by location is shown in Figure 7 and Appendix A.

**Table 5—Summary of Moisture Content at Test Locations**

Test Location	Moisture Content (%)	Test Location	Moisture Content (%)
1	6.6%	24	5.6%
2	8.3%	25	5.2%
3	14.3%	26	5.3%
4	13.4%	27	5.1%
5	10.3%	28	4.8%
6	10.9%	29	6.3%
7	10.0%	30	NA
8	10.3%	31	5.9%
9	11.0%	32	7.4%
10	13.1%	33	6.4%
11	7.8%	34	10.2%
12	8.4%	35	6.7%
13	9.6%	36	4.0%
14	12.8%	37	3.6%
15	12.1%	38	3.7%
16	6.9%	39	9.8%
17*	6.1%	40	9.7%
18	5.3%	41	7.3%
21	5.5%	42	7.1%
22	6.4%	43	6.4%
23	7.8%	44	12.9%

\* Test performed 5.4 inches below surface



### 3.2.5 Lightweight Deflectometer

LWD tests were conducted at twenty-seven locations, producing the results are shown in Table 6. As explained in Section 2.5.3, the LWD tests may be conducted at various drop heights, yielding different stress states during testing. The heights used for testing were 25, 50, and 75cm.

A statistical summary of the LWD data is shown in Figure 9. Comparisons with other companion tests are shown in Figures 12, 14 and 15. Figure 15 demonstrates why it is necessary to seat the LWD in order to achieve consistent measurements. The first two points on each of the three LWD curves are the seating drops. The remaining three drops are averaged to determine a measurement value. The low (25cm) and mid (50cm) drop heights indicate that the modulus has not yet “leveled off” and more drops should have been performed at these heights to properly seat the device.

**Table 6—LWD Modulus for all Stress States**

Test Location	Low Stress (MPa)	Medium Stress (MPa)	High Stress (MPa)
1	22.3	33.7	32.0
2	25.3	34.5	41.0
3	35.3	44.7	60.7
4	31.0	43.0	49.7
5	40.3	50.7	61.3
6	39.0	59.3	68.7
7	32.3	51.3	58.0
8	43.7	49.7	57.7
9	38.7	50.3	54.7
10	33.0	47.0	50.3
11	42.0	52.3	58.3
12	48.0	46.3	53.3
13	NA	63.3	70.7
14	35.0	41.7	49.3
15	27.3	36.7	44.7
16	33.0	40.0	48.3
17*	64.7	75.0	72.0
18	25.3	34.0	42.3
21	35.0	47.3	52.3
22	39.3	44.0	54.7
23	35.3	44.0	59.7
24	35.3	44.3	62.7
25	41.0	53.7	68.0
26	36.3	42.0	49.7
27	35.7	45.0	54.0
28	38.3	47.0	46.3
29	18.3	NA	NA

\* Test performed 5.4 inches below surface

### 3.2.6 Modulus Data for the Principal Test Methods

Table 7 provides the average, standard deviation, coefficient of variation, minimum value, maximum value and number of measurements for the four principal test methods. Statistics are based on all locations except 17 due to the depth below the surface that the measurements were taken. LWD statistics are shown for the three drop heights. GeoGauge statistics are based on those measurements made prior to testing with the LWD. DCP statistics are based on the weighted average modulus of the top 16 inches.

**Table 7—Statistical Measures for the Principal Test Methods (Normal Distribution)**

Method	Average (MPa)	Standard Deviation (MPa)	Coefficient of Variation	Minimum (MPa)	Maximum (MPa)	Count
CMV (Unitless)	28.0	10.4	37%	9.0	47.2	34
LWD - Low Stress	34.7	6.9	20%	18.3	48.0	25
LWD - Medium Stress	45.8	7.3	16%	33.7	63.3	25
LWD - High Stress	53.9	9.1	17%	32.0	70.7	25
GeoGauge	45.1	9.7	21%	23.0	65.3	111
DCP	22.6	5.2	23%	15.5	33.5	22

Figure 8 compares the histograms for the GeoGauge, DCP and CMV test methods associated with the data shown in Table 7. The plots include the equivalent normal distribution for comparison with the actual histograms. Although no statistical tests were conducted, a normal distribution seems to fit the GeoGauge and DCP data fairly well. In contrast, the CMV data seems to be more scattered.

Figure 9 includes the histogram of all LWD data. The plot includes the equivalent normal distribution for comparison with the actual histogram. Although no statistical tests were conducted, a normal distribution seems to fit fairly well.

Table 8 provides the average, standard deviation, coefficient of variation, minimum value, maximum value and number of measurements for CMV in the vicinity of companion tests. The sample was collected over a period of seven days and includes CMV values between 1 and 100.

**Table 8—Statistical Measures for a Large Sample of CMV Measurements**

Method	Average	Standard Deviation	Coefficient of Variation	Minimum	Maximum	Count
CMV - All Amplitudes	22.6	9.8	44%	1	100	361238
CMV - Amplitude > 0.5mm	22.9	9.8	43%	1	100	326081

The compactor records measurements at a rate of roughly 10 per second resulting in a large amount of data. For the seven-day sample, the compactor collected more than 300,000 measurements. The distribution of the sample is shown in Figure 9. Both the normal and lognormal distributions are slightly skewed with respect to the sample distribution, so don't fit the data very well.

## 3.3 Laboratory Test Results

Appendix D list results from all laboratory measurements conducted on the select granular borrow. Measurements conducted are as follows:

- Proctor tests were conducted by Mn/DOT.

- Sieve analyses, were conducted by Mn/DOT.

### 3.4 Comparisons and Correlations

Figures 11 through 13 illustrate the relationships between CMV and GeoGauge, LWD and DCP data on a point-by-point basis. The graphs show little correlation between CMV and the companion tests. There are at least two reasons for this result:

- The depth and stress dependency of soil modulus.
- The heterogeneity of the soils used precludes correlations. Figure 16 illustrates cobbles found when removing the top 5.4 inches of soil at location 17. The compactors measurement of a location such as this may vary greatly with the LWD or GeoGauge. This is because the compactor senses the properties of a large volume of soil, while the companion tests are clustered near the surface in a small area in the middle of the drum.

Note that in Figure 13, CMV is compared to the DCP modulus from 8" to 16". The correlation of this comparison is much better than any of the other CMV comparisons. This is likely a result of the depth of the DCP measurement being nearer the depth range that the compactor senses.

## 4 Conclusions

### 4.1 Conclusions from Observation of Caterpillar Compactor

1. The Caterpillar compactor appears to be well made, rugged and easy to operate.
2. Data transfer between the compactor and a field computer is straightforward and intuitive.
3. The Caterpillar Compaction Viewer software, although still in development at the time of testing, is functional and is well integrated with GPS. It is easy to extract data and do more sophisticated analyses.

### 4.2 Conclusions from the Demonstration

1. Surface-covering documentation adds value by identifying potential problem areas where compaction is limited by material, moisture or subgrade deficiencies.

### 4.3 Conclusions from Companion Testing

1. As expected from existing research and experience, different measurement tools produce different modulus estimates.
2. LWD testing protocol must be followed to obtain useful results, since measurements vary significantly between successive tests.
3. Relatively good correlations were obtained between LWD and GeoGauge.
4. Relatively good correlations were obtained between DCP and CMV when deep DCP moduli were compared.
5. Both the LWD and GeoGauge are easy to use by a single person and provide repeatable measurements when properly seated.
6. The DCP is difficult to use by a single person, but easy to use if operated by two people. The DCP provides repeatable results and has the advantage of easily determining an estimated modulus profile with depth.

### 4.4 General Conclusions about Fieldwork Protocol

1. Elevation measurements collected from rover GPS ranged from 1085 ft to 1180 ft within the project area. Compactor GPS elevations ranged from 1131 ft to 1296 ft within the project area. Although the latitude and longitude readings from the compactor deviated very little from those measured by the rover, the elevation readings were higher than the rover by up to 100 ft at any particular location. Hence, this GPS technology is not adequate to distinguish between lifts.

## 5 Bibliography

Davich, P., Camargo, F., Larson, B., Roberson, R., Siekmeier, J., Validation of DCP and LWD Moisture Specifications for Granular Materials, LRRB Investigation 829, Mn/DOT, 2006.

DeBeer, M., Use of the Dynamic Cone Penetrometer (DCP) in the Design of Road Structures. Proceedings of the tenth regional conference for Africa on Soil Mechanics & Foundation Engineering and the third International Conference on Tropical & Residual Soils. Maseru. 23-27 September 1991.

Hoffmann, O., Guzina, B., and Drescher, A., Enhancements and Verification Tests for Portable Deflectometers, University of Minnesota, Mn/DOT Report 2003-10, May 2003

White, D.J., Jaselskis, E.J., Schafer, V.R. and Cackler, E.T., Real-Time Compaction Monitoring in Cohesive Soils from Machine Response. Transportation Research Board Record, Journal of the Transportation Research Board, No. 1936, Soil Mechanics, 2005.

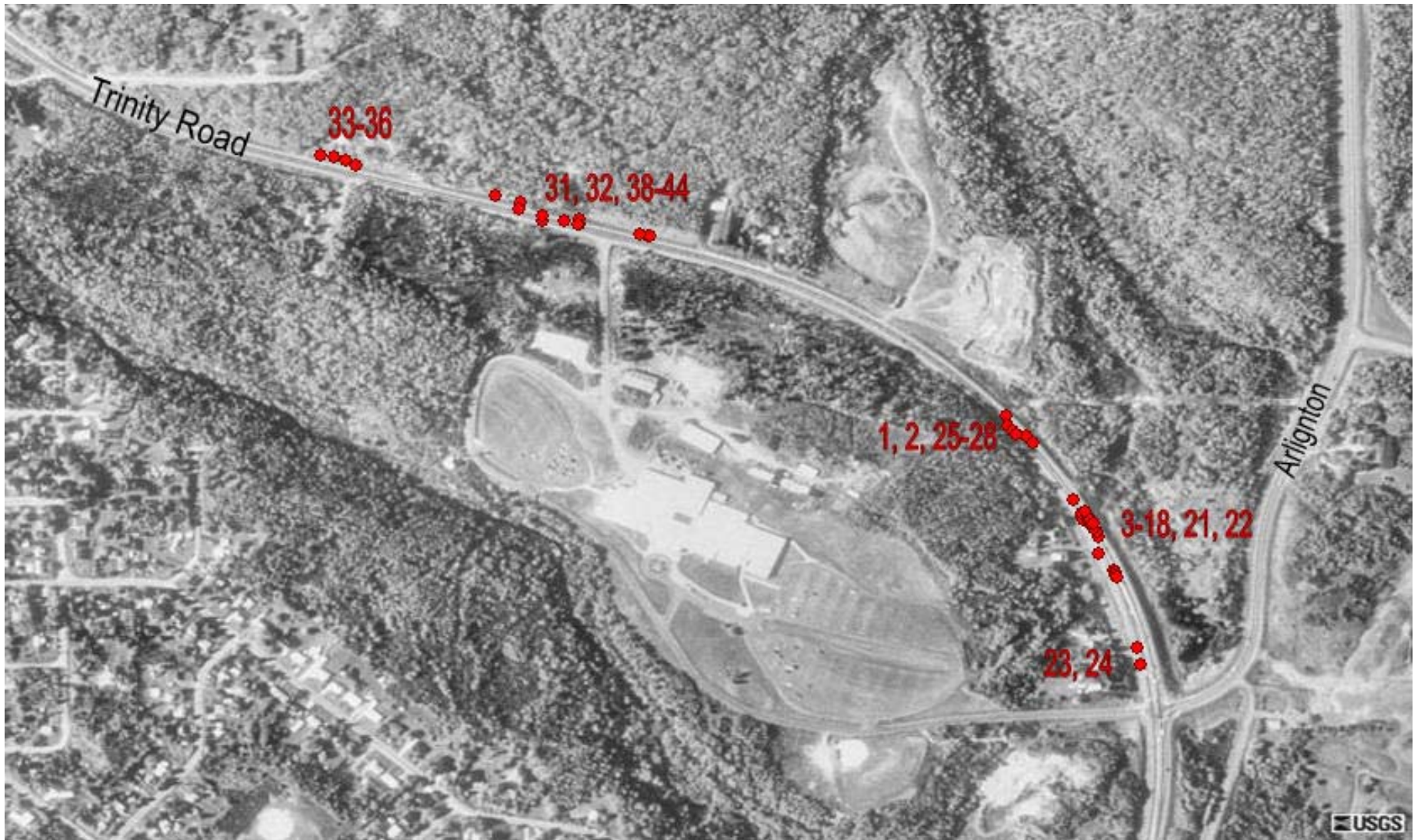


Figure 1

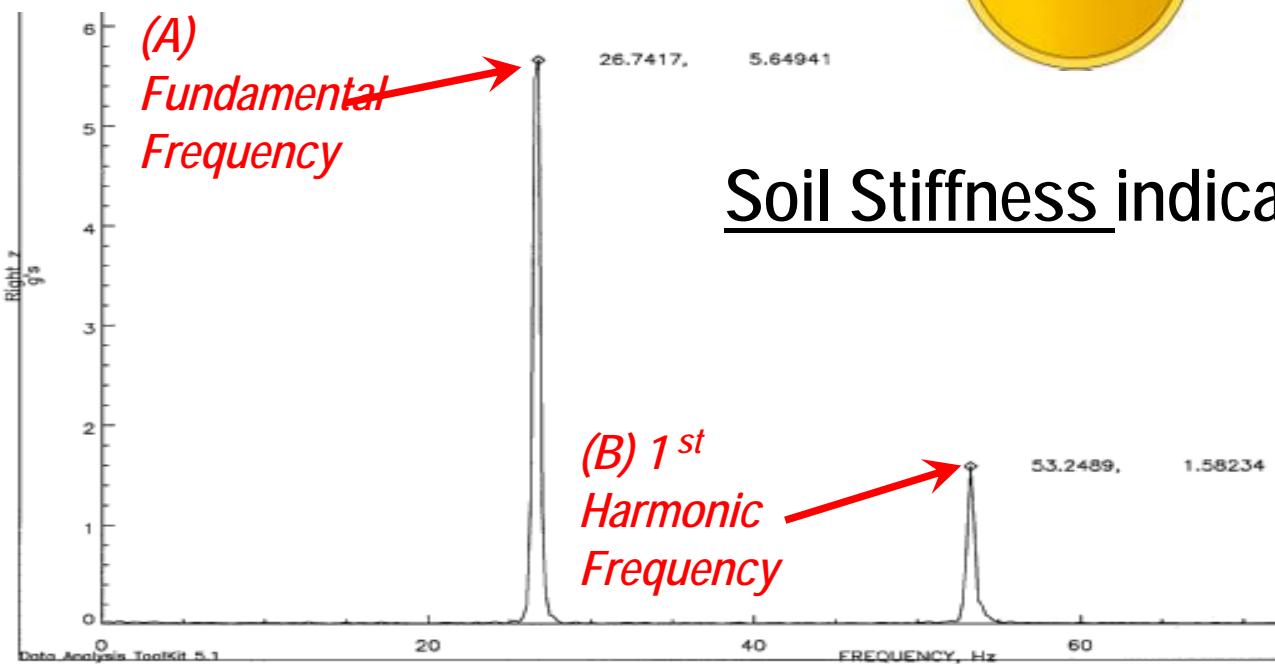
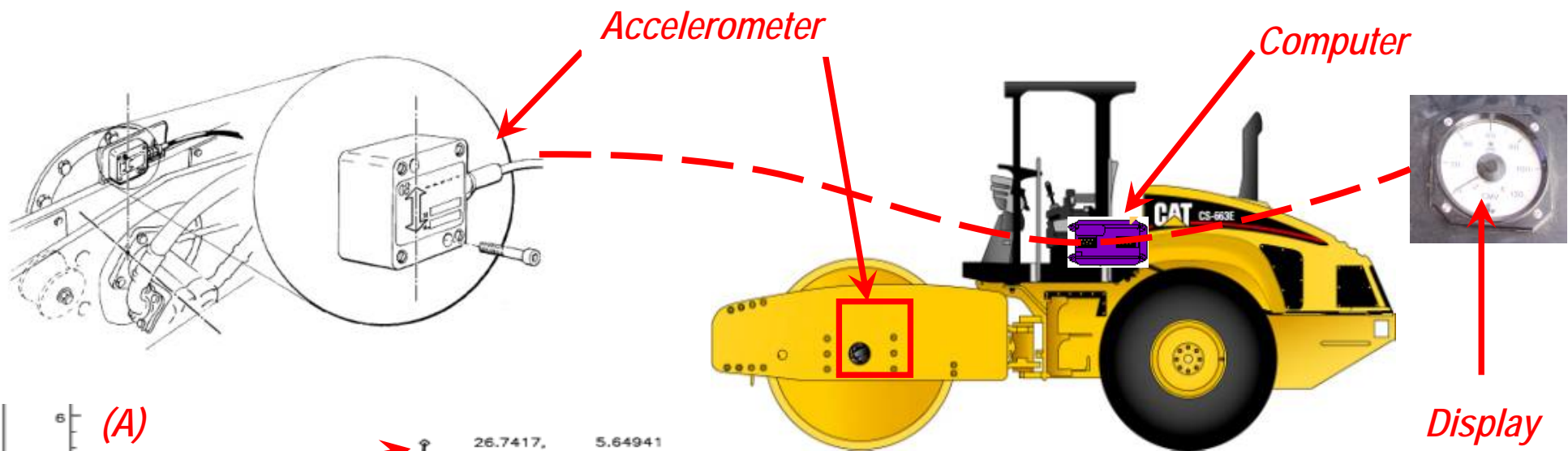
Aerial Photo of Site Illustrating Test Locations





Figure 2

### Intelligent Compaction Machine and GPS Base Station



Soil Stiffness indicated by Ratio of B to A

*Geodynamik (inventor of method)*  
*Caterpillar (user)*

Figure 3

Measuring Compaction via Compaction Meter Value



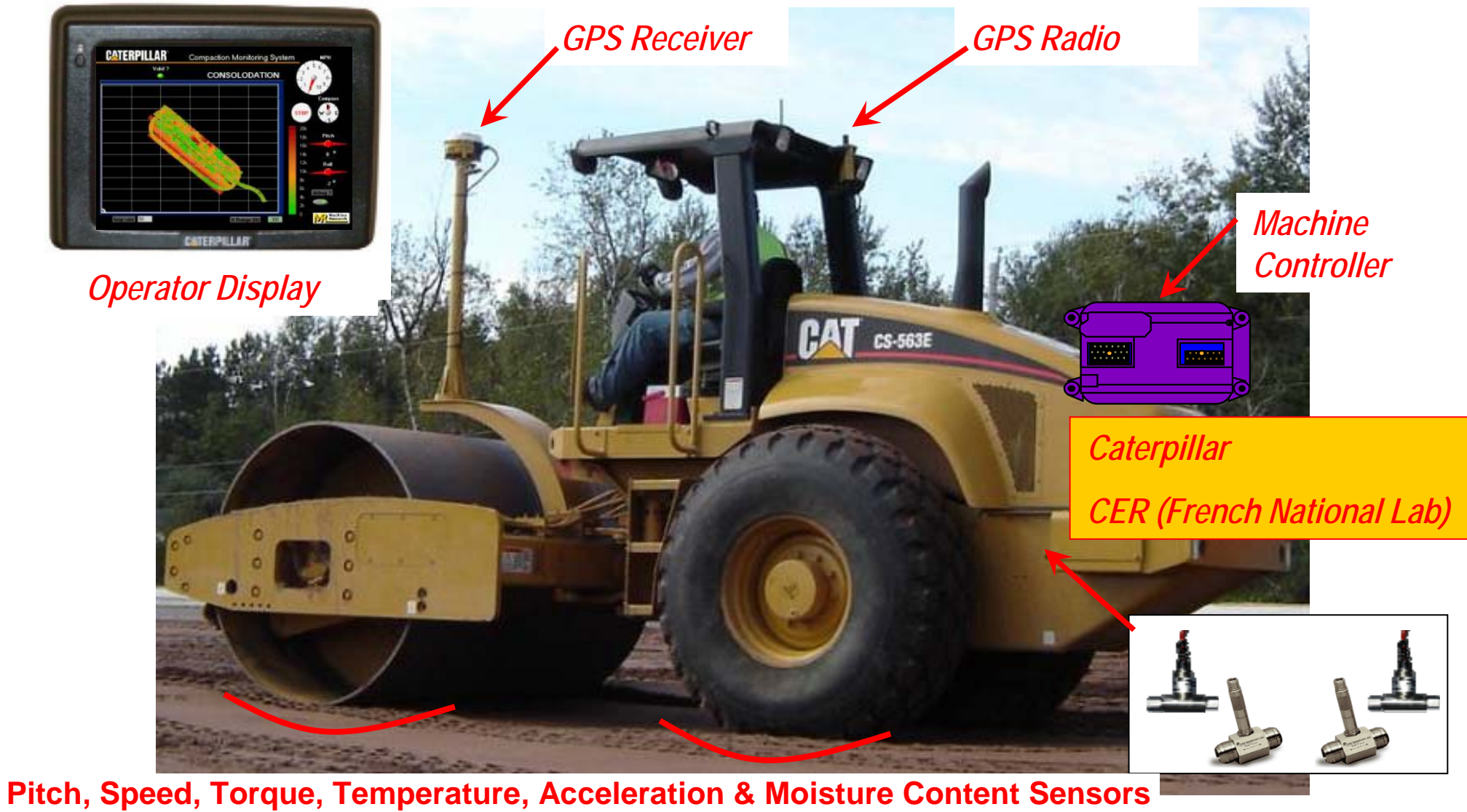


Figure 4

Measuring Compaction via Energy or Power Method



Dynamic Cone Penetrometer



Humboldt Geogauge



LWD

Figure 5

Photos of Select Companion Testing Devices

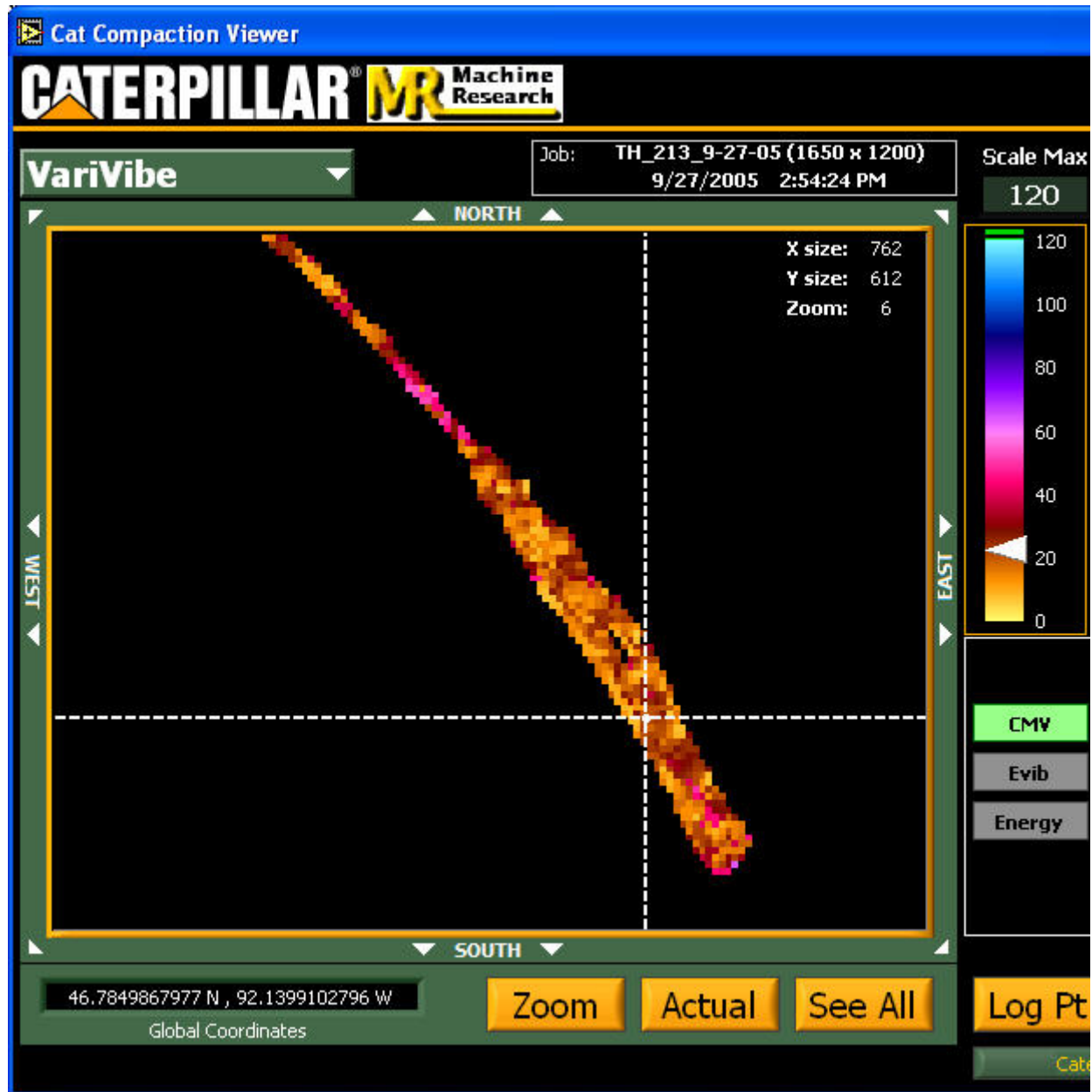


Figure 6

Caterpillar Compaction Viewer

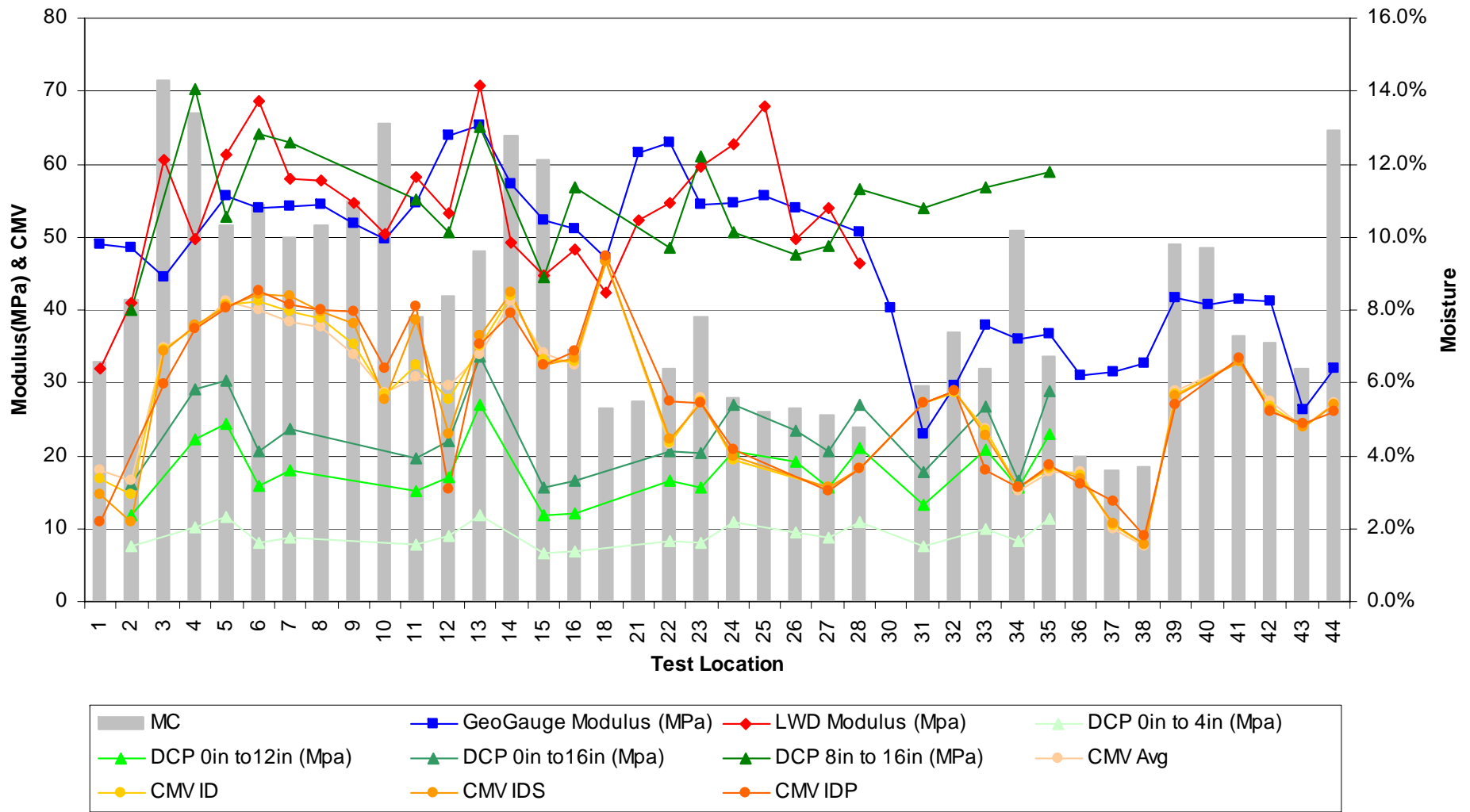
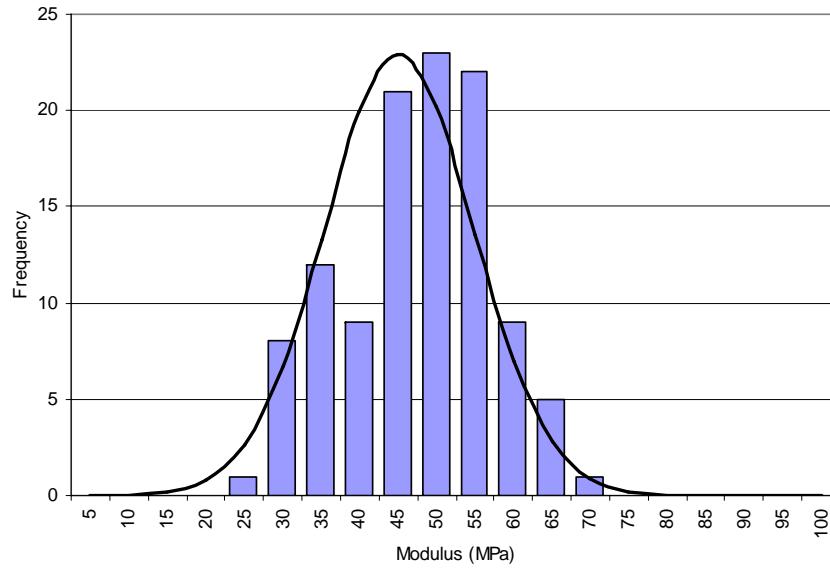


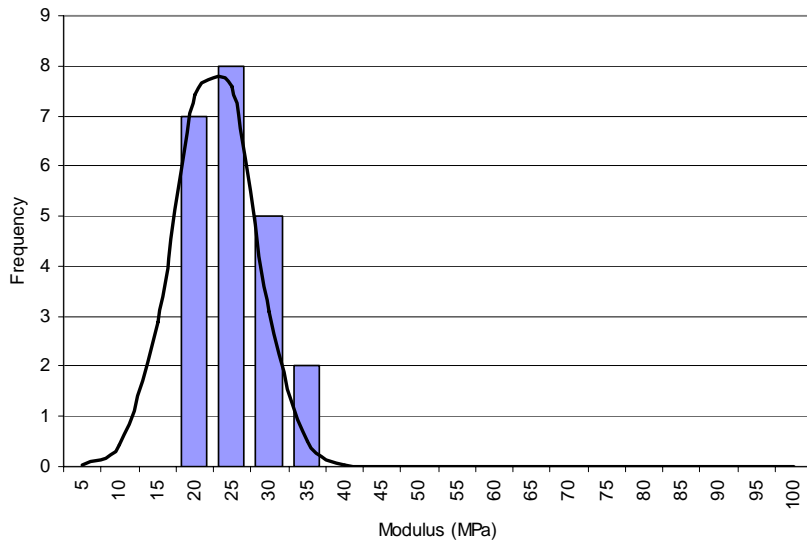
Figure 7

Test Results at all Locations (LWD Data is High Stress)

GeoGauge



DCP - 16"



CMV

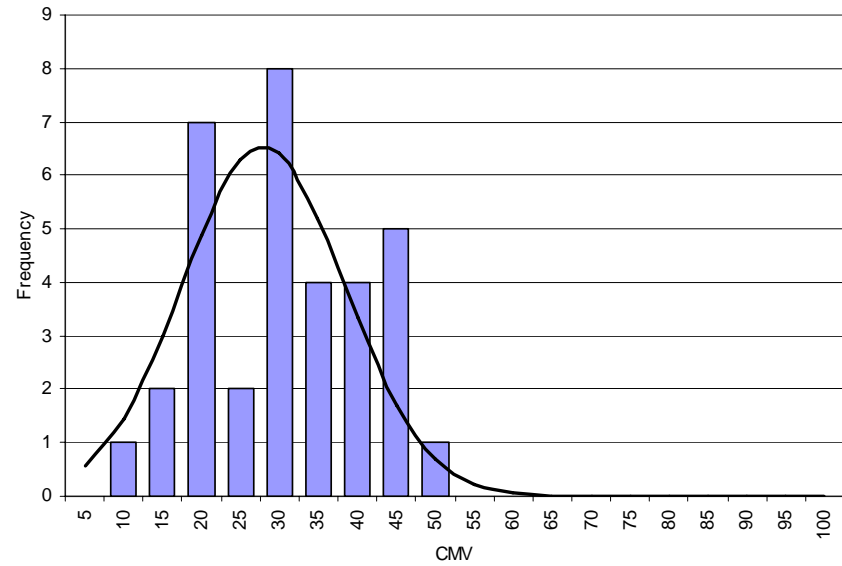


Figure 8

Histograms of Companion Tests



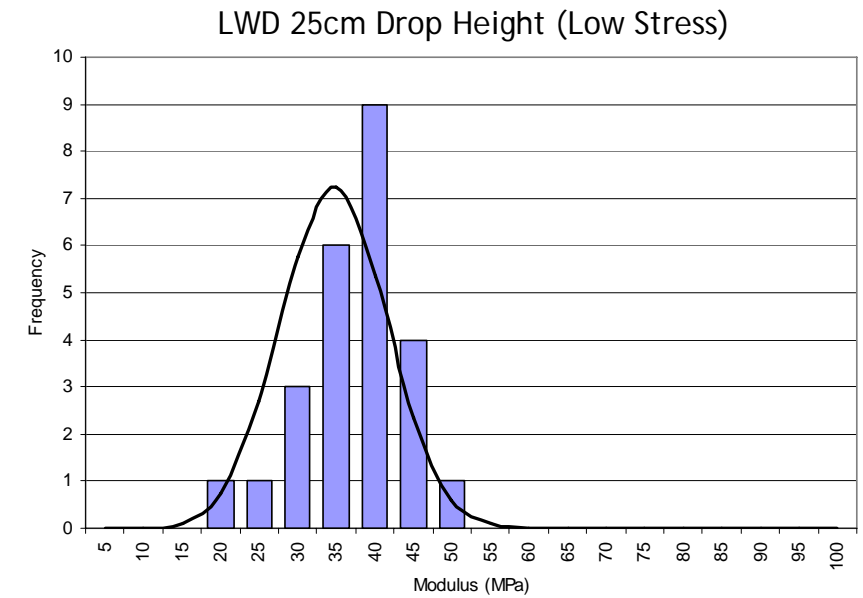
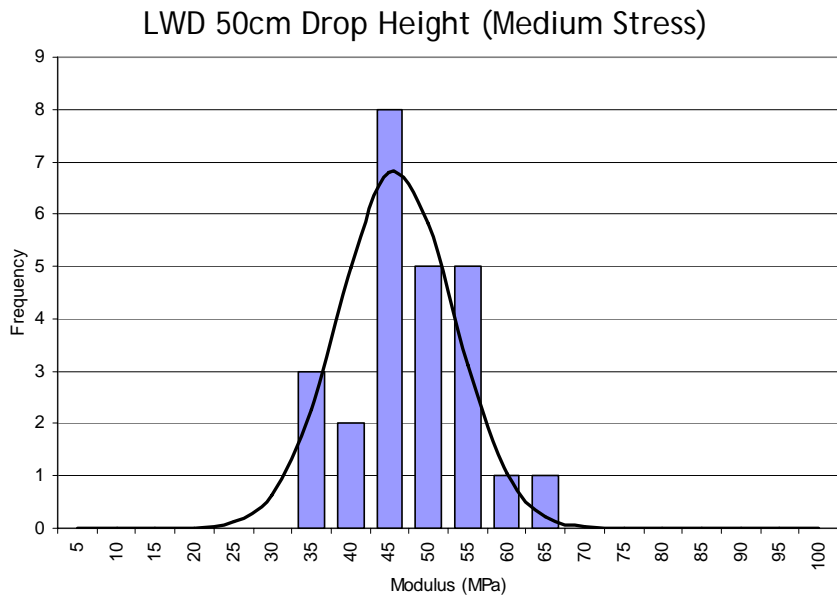
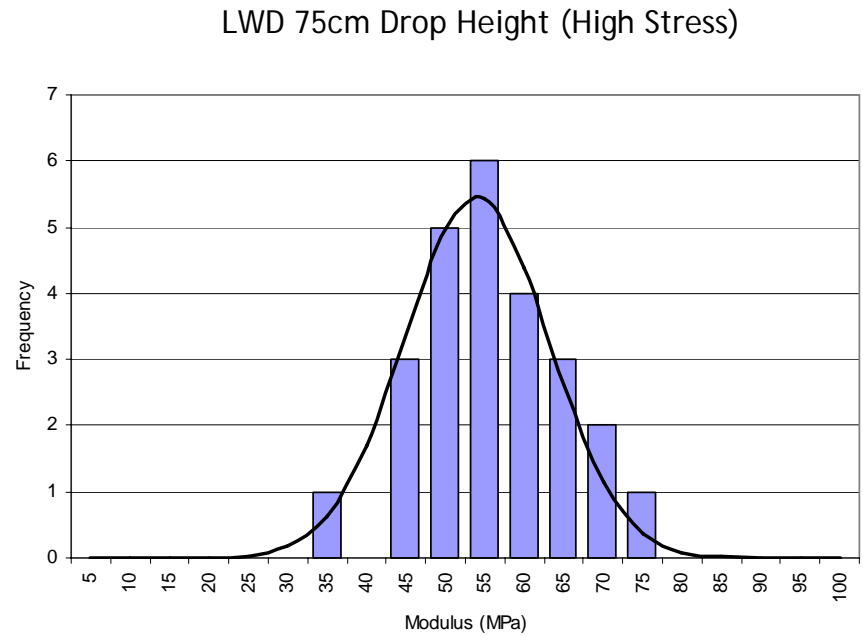
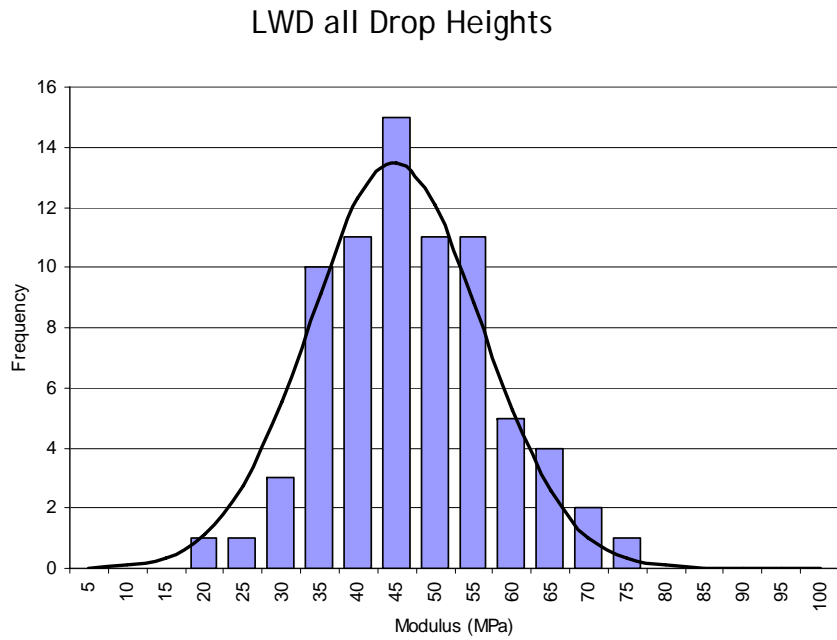
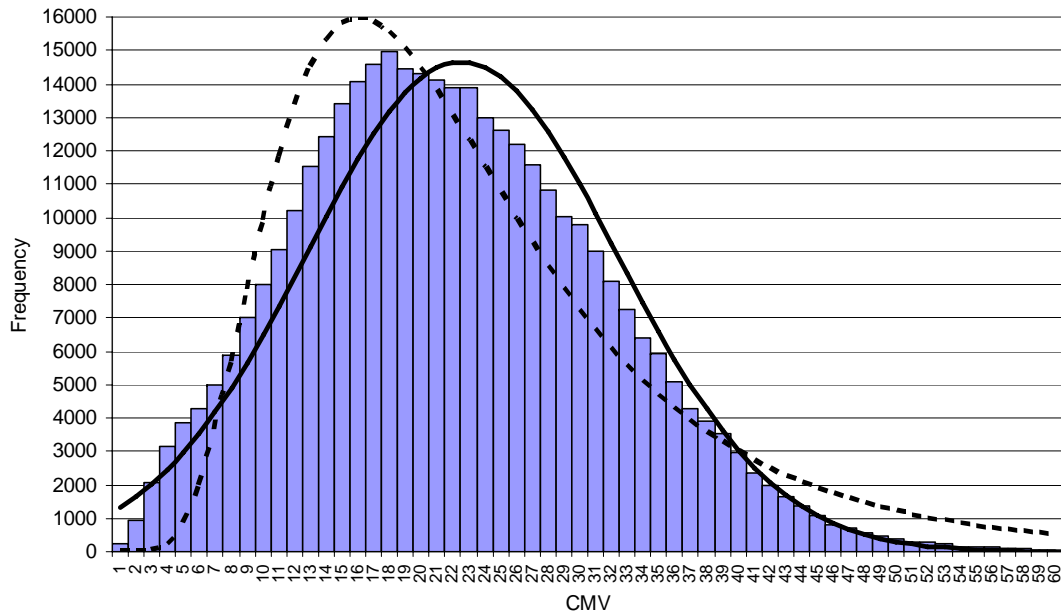
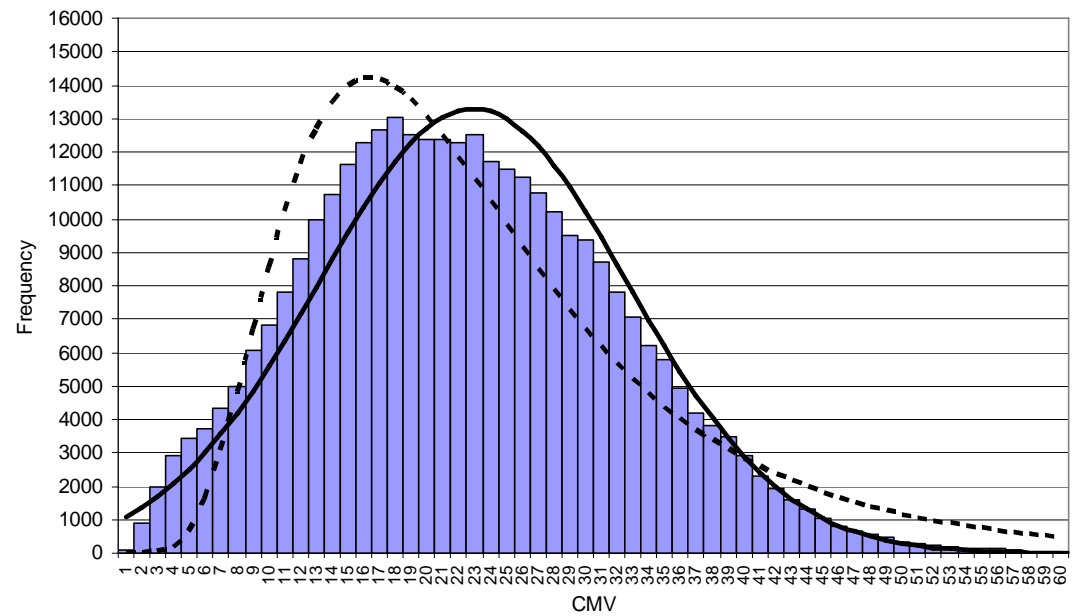
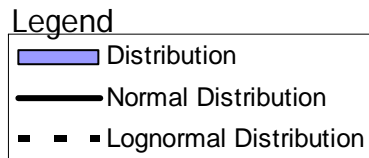


Figure 9

Histogram of LWD Tests at Various Drop Heights



CMV at all Amplitudes

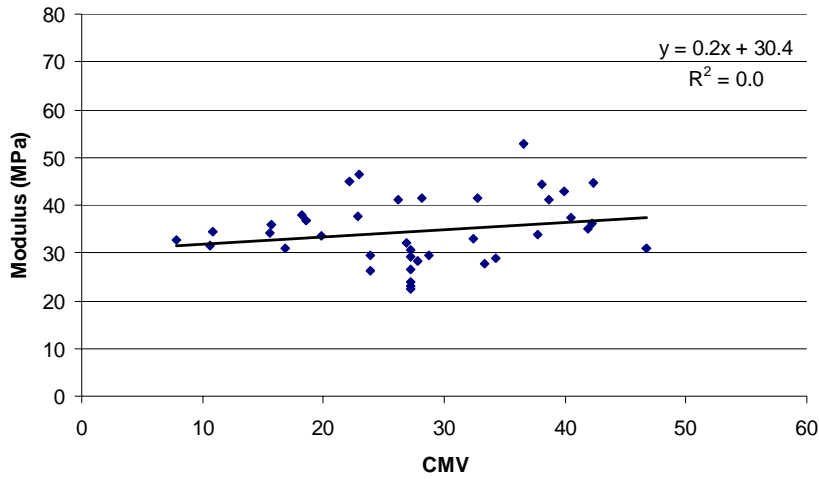


CMV at Amplitudes Greater Than 0.5mm

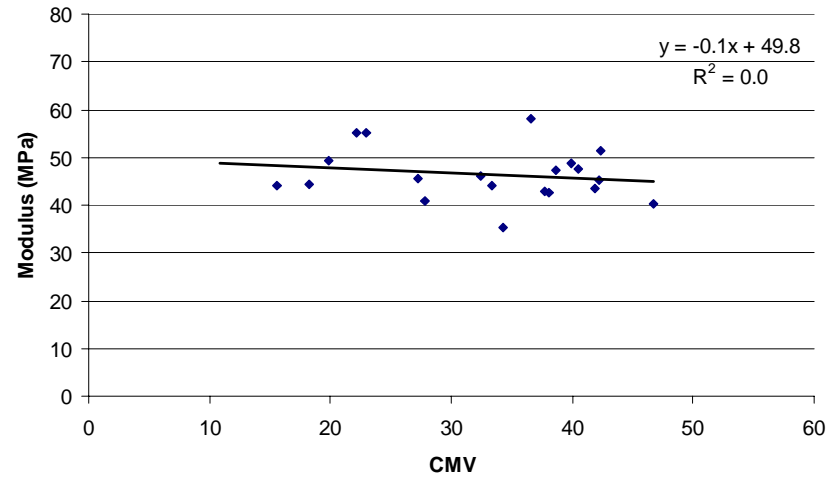
Figure 10

Histogram of CMV Tests for Seven Day Sample

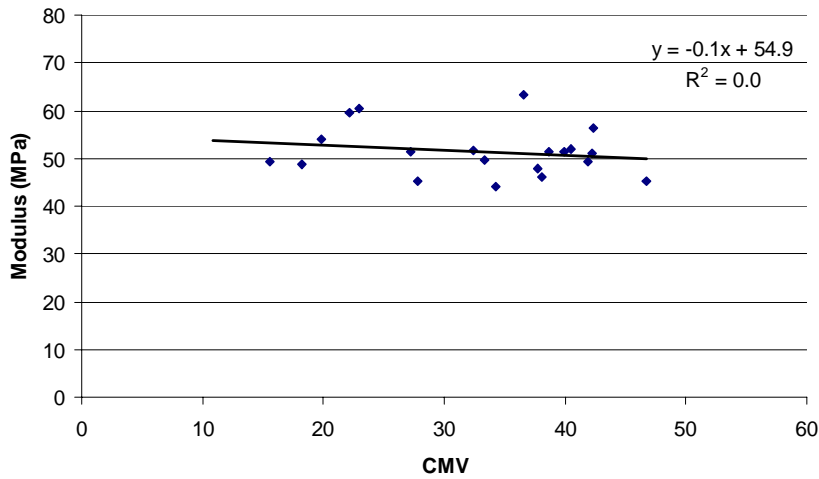
GeoGauge Measurement Before LWD Measurement



GeoGauge Measurement After First LWD Measurement



GeoGauge Measurement After Second LWD Measurement



GeoGauge Measurement After Final LWD Measurement

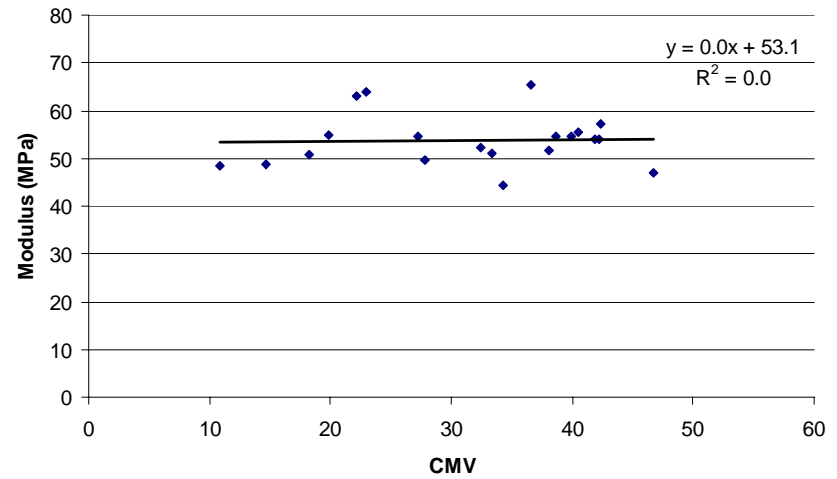
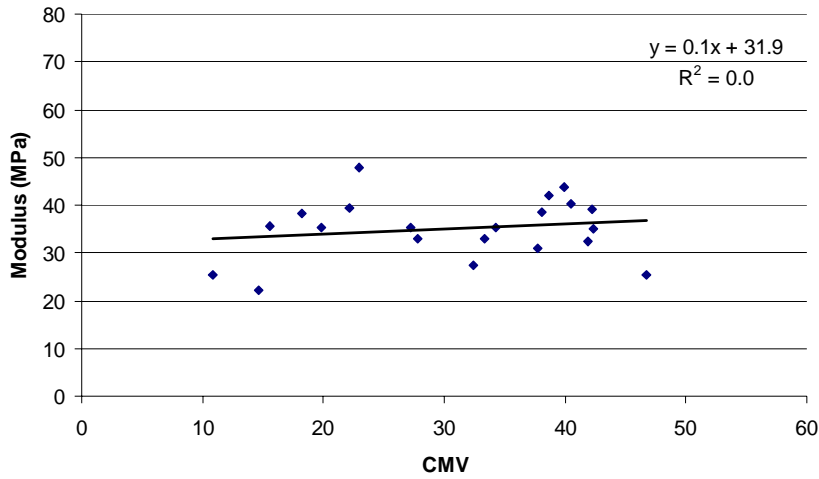


Figure 11

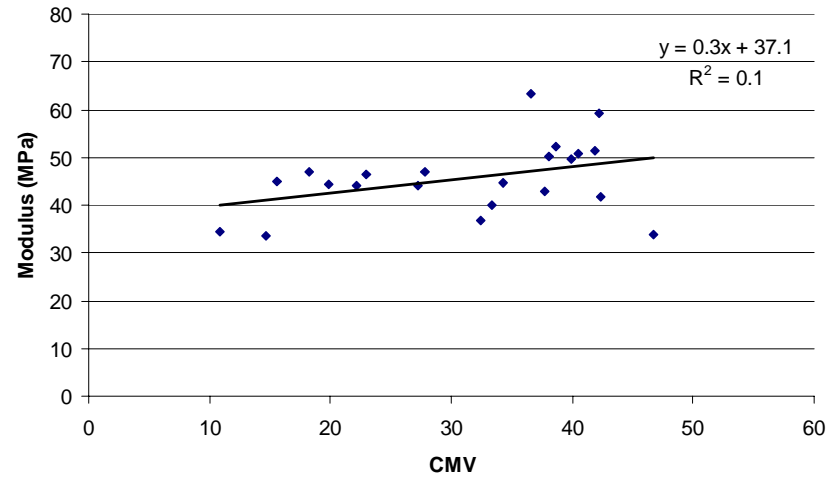
Comparison of CMV to GeoGauge



LWD Using Low Stress Measurement



LWD Using Medium Stress Measurement



LWD Using High Stress Measurement

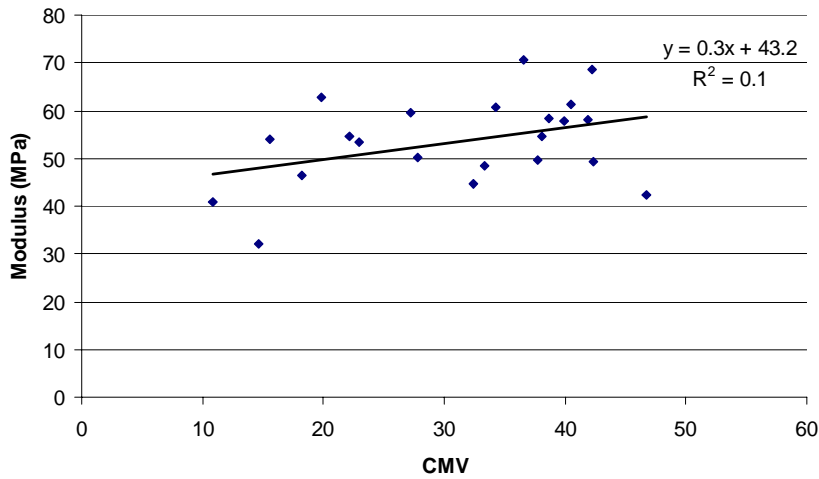


Figure 12

Comparison of CMV to LWD

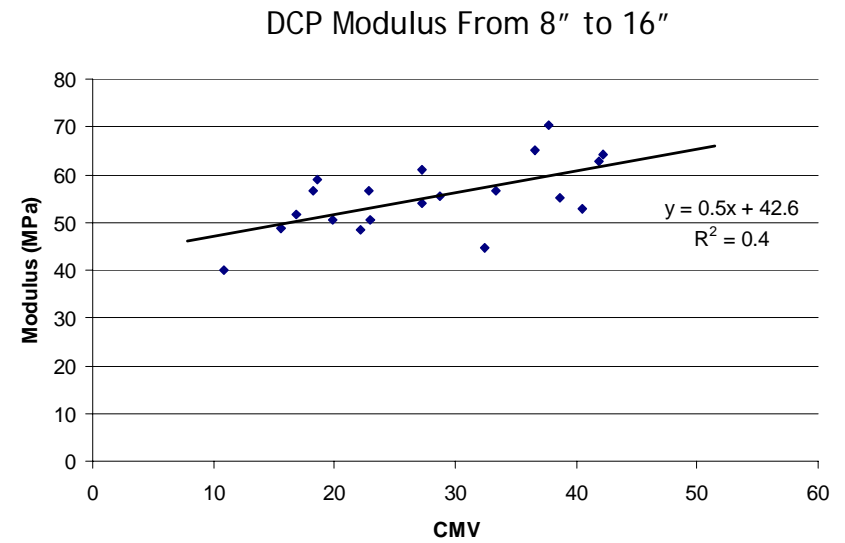
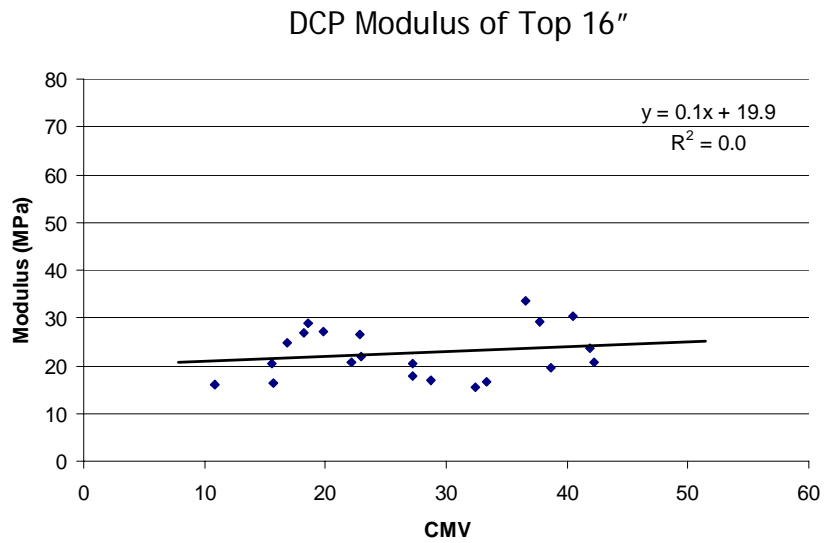
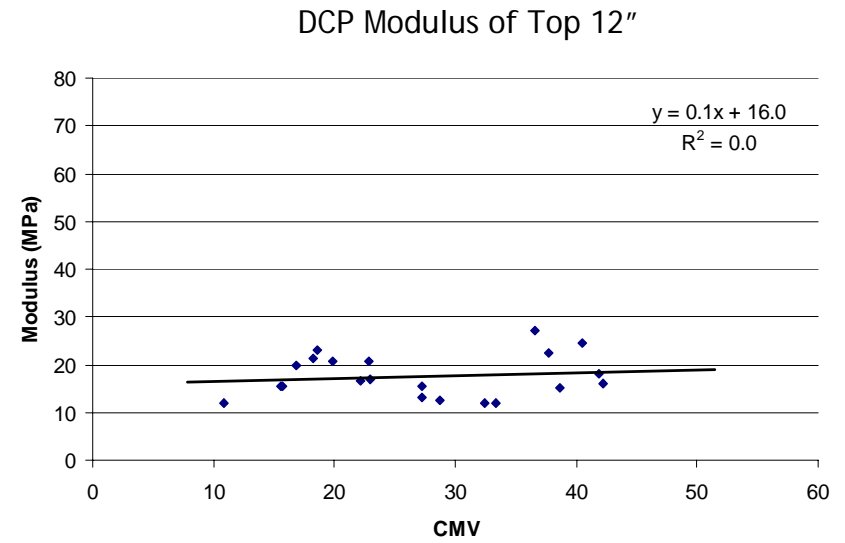
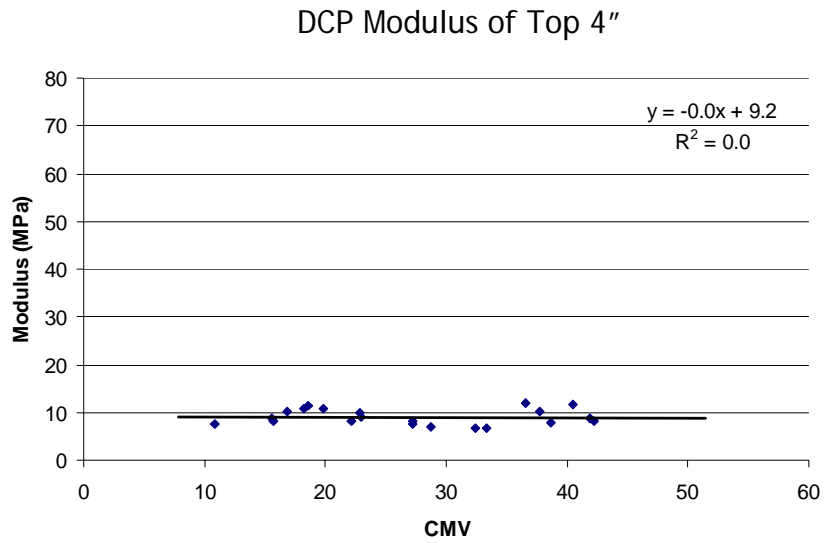


Figure 13

Comparison of CMV to DCP

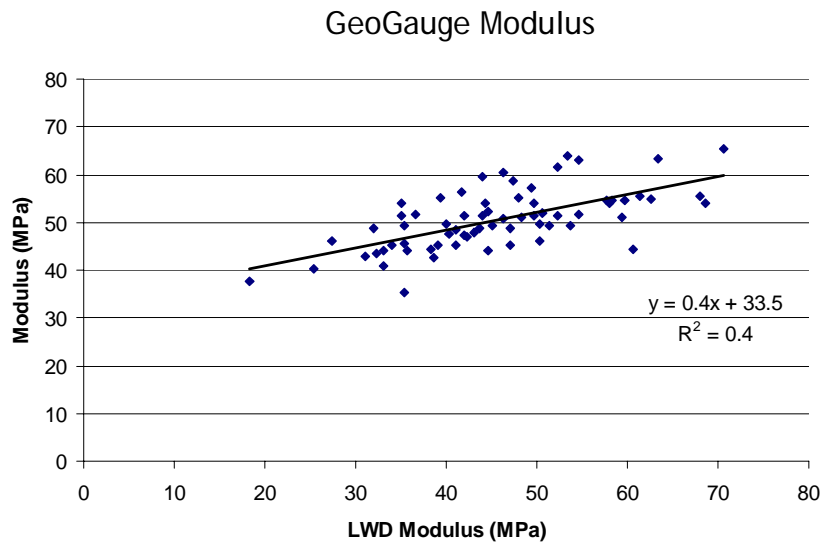
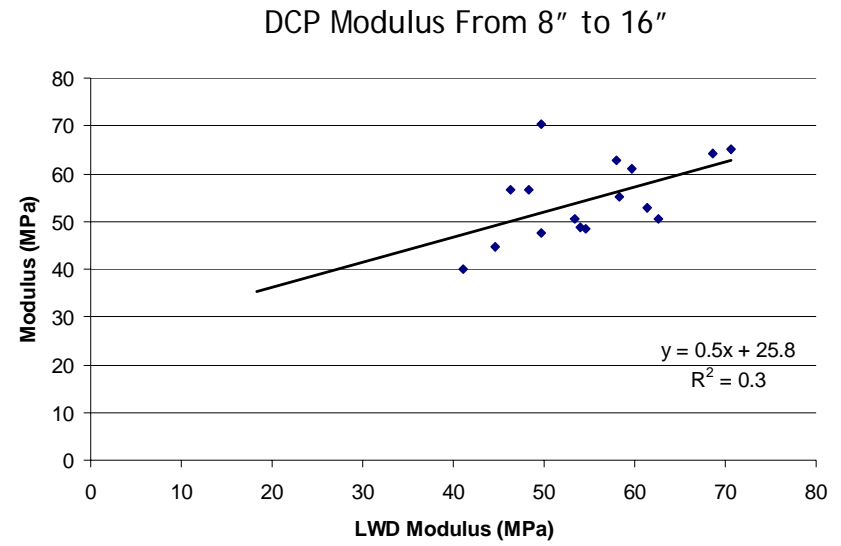
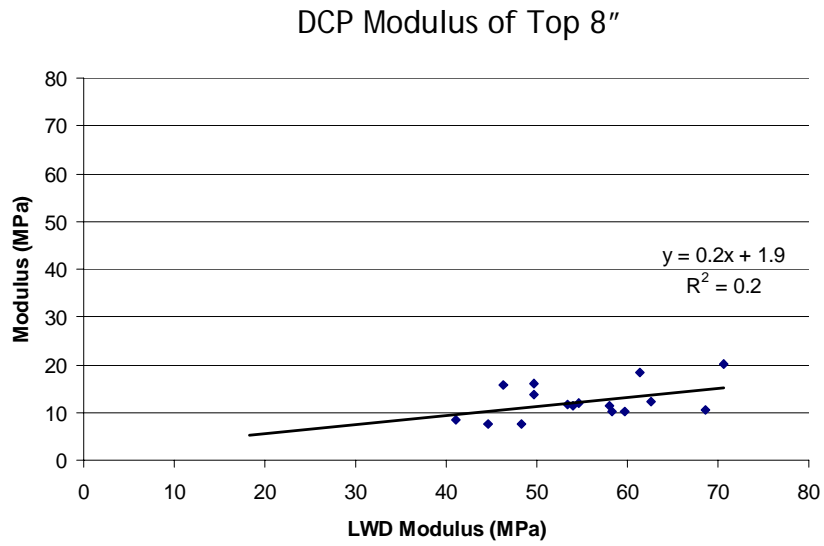


Figure 14

Comparison of LWD to DCP and GeoGauge

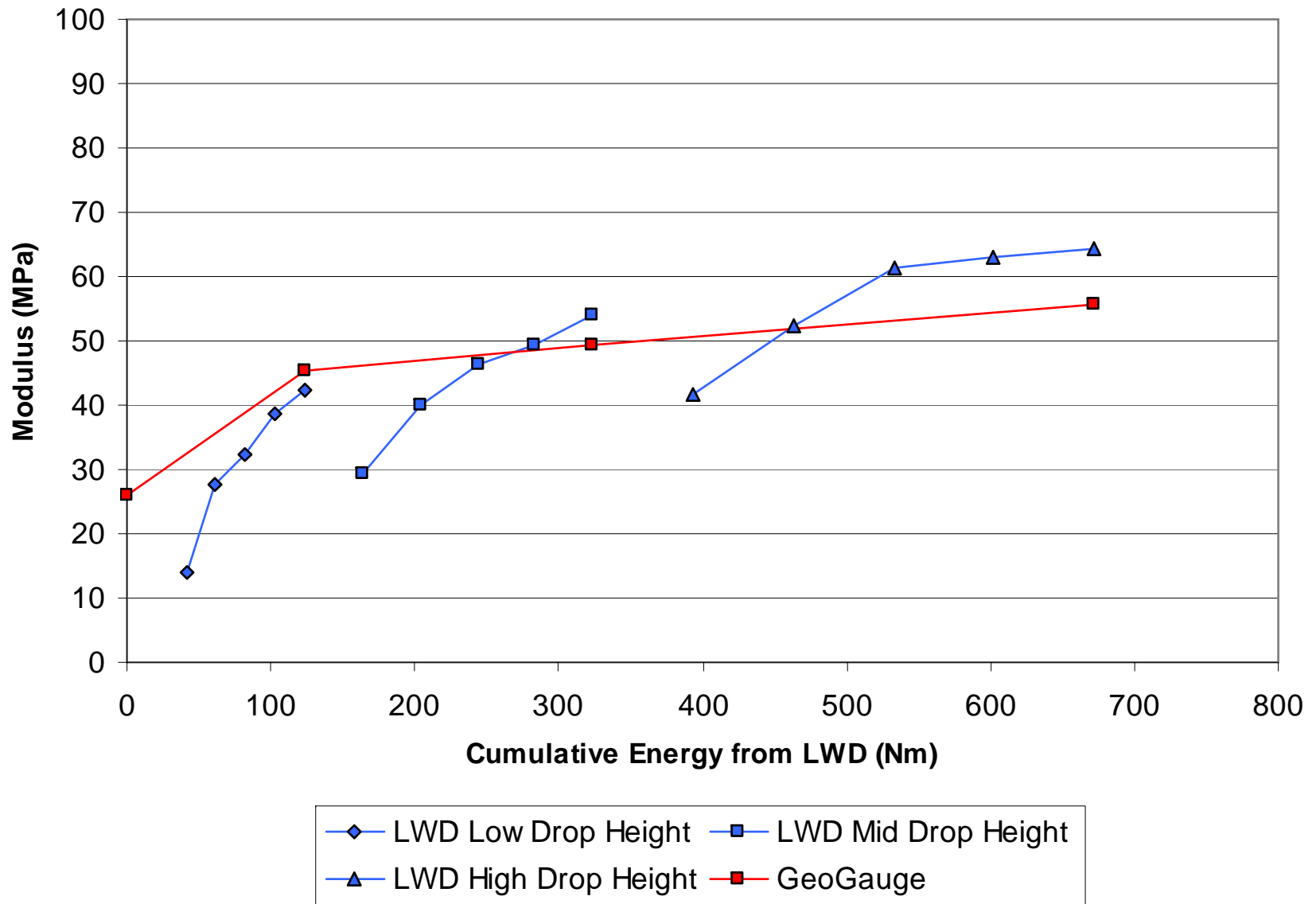


Figure 15

GeoGauge and LWD at Location 25



Figure 16

Cobbles Encountered at Location 17

## Appendix A

Moisture Content by Mn/DOT

SEP 28 2005

**STATE OF MINNESOTA**  
**DEPARTMENT OF TRANSPORTATION**  
**MATERIALS ENGINEERING AND RESEARCH**  
**TEST REPORT ON SAMPLE OF SUBSOIL**

PROJECT NO.	S.P.6915-125	DATE COMPLETED	9/28/2005
SOURCE	T.H.53	DATE RECEIVED	9/26/2005
TESTS REQUIRED	MOIST	SUBMITTED BY	J. SIEKMEIER
		PROJ. ENGINEER	

LAB NO: SS05202	DATE SAMPLED	9/22/2005	FIELD ID	1
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	6.6
LAB NO: SS05203	DATE SAMPLED	9/22/2005	FIELD ID	2
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	8.3
LAB NO: SS05204	DATE SAMPLED	9/22/2005	FIELD ID	3
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	14.3
LAB NO: SS05205	DATE SAMPLED	9/22/2005	FIELD ID	4
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	13.4
LAB NO: SS05206	DATE SAMPLED	9/22/2005	FIELD ID	5
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	10.3
LAB NO: SS05207	DATE SAMPLED	9/22/2005	FIELD ID	6
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	10.9
LAB NO: SS05208	DATE SAMPLED	9/22/2005	FIELD ID	7
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	10.0
LAB NO: SS05209	DATE SAMPLED	9/22/2005	FIELD ID	8
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	10.3
LAB NO: SS05210	DATE SAMPLED	9/22/2005	FIELD ID	9
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	11.0

*Siekmeier*

**STATE OF MINNESOTA  
DEPARTMENT OF TRANSPORTATION  
MATERIALS ENGINEERING AND RESEARCH  
TEST REPORT ON SAMPLE OF SUBSOIL**

PROJECT NO.	S.P.6915-125	DATE COMPLETED	9/28/2005
SOURCE	T.H.53	DATE RECEIVED	9/26/2005
TESTS REQUIRED	MOIST	SUBMITTED BY	J. SIEKMEIER
		PROJ. ENGINEER	

---

LAB NO: SS05211	DATE SAMPLED	9/22/2005	FIELD ID	10
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	13.1

---

LAB NO: SS05212	DATE SAMPLED	9/22/2005	FIELD ID	11
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	7.8

---

LAB NO: SS05213	DATE SAMPLED	9/22/2005	FIELD ID	12
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	8.4

---

LAB NO: SS05214	DATE SAMPLED	9/22/2005	FIELD ID	13
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	9.6

---

LAB NO: SS05215	DATE SAMPLED	9/22/2005	FIELD ID	14
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	12.8

---

LAB NO: SS05216	DATE SAMPLED	9/22/2005	FIELD ID	15
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	12.1

---

LAB NO: SS05217	DATE SAMPLED	9/22/2005	FIELD ID	16
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	6.9

---

LAB NO: SS05218	DATE SAMPLED	9/22/2005	FIELD ID	17
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	6.1

---

LAB NO: SS05219	DATE SAMPLED	9/22/2005	FIELD ID	18
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	5.3

---



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TEST REPORT ON SAMPLE OF SUBSOIL**

PROJECT NO.	S.P.6915-125	DATE COMPLETED	9/28/2005
SOURCE	T.H.53	DATE RECEIVED	9/26/2005
TESTS REQUIRED	MOIST	SUBMITTED BY	J. SIEKMEIER
		PROJ. ENGINEER	

LAB NO: SS05220	DATE SAMPLED	9/22/2005	FIELD ID	19
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	6.0
LAB NO: SS05221	DATE SAMPLED	9/22/2005	FIELD ID	20
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	5.4
LAB NO: SS05222	DATE SAMPLED	9/22/2005	FIELD ID	21
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	5.5
LAB NO: SS05223	DATE SAMPLED	9/22/2005	FIELD ID	22
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	6.4
LAB NO: SS05224	DATE SAMPLED	9/22/2005	FIELD ID	23
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	7.8
LAB NO: SS05225	DATE SAMPLED	9/22/2005	FIELD ID	24
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	5.6

COMMENTS

COPIES TO J. SIEKMEIER

~~XXXXXXXXXXXXXXXXXXXX~~

*Rod Patrin*

REVIEWED BY

CHARGE OUT: 1045-24

1283

OCT 07 2005

**STATE OF MINNESOTA  
DEPARTMENT OF TRANSPORTATION  
MATERIALS ENGINEERING AND RESEARCH**

**TEST REPORT ON SAMPLE OF SUBSOIL**

PROJECT NO.	S.P.6915-125	DATE COMPLETED	10/6/2005
SOURCE	T.H.53	DATE RECEIVED	10/4/2005
TESTS REQUIRED	MOIST	SUBMITTED BY	J. SIEKMEIER
		PROJ. ENGINEER	

LAB NO: SS05231	DATE SAMPLED	9/29/2005	FIELD ID	25
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	5.2
LAB NO: SS05232	DATE SAMPLED	9/29/2005	FIELD ID	26
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	5.3
LAB NO: SS05233	DATE SAMPLED	9/29/2005	FIELD ID	27
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	5.1
LAB NO: SS05234	DATE SAMPLED	9/29/2005	FIELD ID	28
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	4.8
LAB NO: SS05235	DATE SAMPLED	9/29/2005	FIELD ID	29
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	6.3
LAB NO: SS05236	DATE SAMPLED	9/29/2005	FIELD ID	31
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	5.9
LAB NO: SS05237	DATE SAMPLED	9/29/2005	FIELD ID	31A
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	4.0
LAB NO: SS05238	DATE SAMPLED	9/29/2005	FIELD ID	31B
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	3.3
LAB NO: SS05239	DATE SAMPLED	9/29/2005	FIELD ID	32
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	7.4

**STATE OF MINNESOTA  
DEPARTMENT OF TRANSPORTATION  
MATERIALS ENGINEERING AND RESEARCH  
TEST REPORT ON SAMPLE OF SUBSOIL**

PROJECT NO.	S.P.6915-125	DATE COMPLETED	10/6/2005
SOURCE	T.H.53	DATE RECEIVED	10/4/2005
TESTS REQUIRED	MOIST	SUBMITTED BY	J. SIEKMEIER
		PROJ. ENGINEER	

---

LAB NO: SS05240	DATE SAMPLED	9/29/2005	FIELD ID	32A
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LAB NO: SS05241	DATE SAMPLED	9/29/2005	FIELD ID	32B
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	4.8

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LAB NO: SS05242	DATE SAMPLED	9/29/2005	FIELD ID	33
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	6.4

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LAB NO: SS05243	DATE SAMPLED	9/29/2005	FIELD ID	34
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	10.2

---

LAB NO: SS05244	DATE SAMPLED	9/29/2005	FIELD ID	35
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	6.7

---

LAB NO: SS05245	DATE SAMPLED	9/29/2005	FIELD ID	36
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	4.0

---

LAB NO: SS05246	DATE SAMPLED	9/29/2005	FIELD ID	36B
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	8.0

---

LAB NO: SS05247	DATE SAMPLED	9/29/2005	FIELD ID	37
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	3.6

---

LAB NO: SS05248	DATE SAMPLED	9/29/2005	FIELD ID	38
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	3.7

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**STATE OF MINNESOTA  
DEPARTMENT OF TRANSPORTATION  
MATERIALS ENGINEERING AND RESEARCH  
TEST REPORT ON SAMPLE OF SUBSOIL**

PROJECT NO.	S.P.6915-125	DATE COMPLETED	10/6/2005
SOURCE	T.H.S3	DATE RECEIVED	10/4/2005
TESTS REQUIRED	MOIST	SUBMITTED BY	J. SIEKMEIER
		PROJ. ENGINEER	

---

LAB NO: SS05249	DATE SAMPLED	9/29/2005	FIELD ID	39
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	9.8

---

LAB NO: SS05250	DATE SAMPLED	9/29/2005	FIELD ID	40A
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	9.7

---

LAB NO: SS05251	DATE SAMPLED	9/29/2005	FIELD ID	41
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	7.3

---

LAB NO: SS05252	DATE SAMPLED	9/29/2005	FIELD ID	42A
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	7.1

---

LAB NO: SS05253	DATE SAMPLED	9/29/2005	FIELD ID	43A
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	6.4

---

LAB NO: SS05254	DATE SAMPLED	9/29/2005	FIELD ID	44
SAMPLE TAKEN FROM: TH53AJS			FIELD MOISTURE	12.9

---

**COMMENTS**

COPIES TO J. SIEKMEIER  
DAVE VAN DEUSEN

*Rock Patrusi*  
REVIEWED BY

CHARGE OUT: 1045-24

## Appendix B

Sand Cones by Mn/DOT



Minnesota Department of Transportation

*Tim Andersen*

Office of Materials and Road Research

Page No. 1

**Relative Density Test Grading & Base Construction**

S. P. No: T.H. 53 D-1 Research

Test Identification Data					
Date	9/29/05	9/29/05	9/29/05	9/29/05	
Test No.	33	34	35	36	
Soil Class or 3138 Class	SGB	SGB	SGB	SGB	
Station					
Roadway: Position to Center Line	Rt.	Rt.	Rt.	Rt.	
Depth Below Grade	0'	0'	0'	0'	
Volume Determination (sand cone)					
A. Wt. Sand & Container Before	2500	2500	2500	2500	
B. Wt. Sand & Container After	1068.8	1099.4	1022.4	967.8	
C. Wt. Sand In Funnel & Hole A-B	1431.2	1400.6	1477.6	1532.2	
D. Wt. Sand In Funnel (from Callb)	646.5	646.5	646.5	646.5	
E. Wt. Sand In In Hole C-D	784.7	754.1	831.1	885.7	
Inplace Dry Density Determination (Field Density Test)					
Container No.	23	13	12	11	
<b>- Burner Method -</b>					
F. Wt. Wet Soil + Pan	1165.5	1081.3	1173.1	1233.6	
G. Wt. Dry Soil + Pan	1103.7	1008.1	1103.6	1180.5	
H. Wt Moisture F-G	61.8	73.2	69.5	53.1	
J. Wt Pan	152.2	143.8	152.4	151.7	
K. Wt. Wet Soil F-J	1013.3	937.5	1020.7	1081.9	
<b>- Speedy Method -</b>					
M. Dial Reading					
N. Sample Size Factor					
P. % Moisture - Wet Wt. H/K*100 or M*N	6.1	7.8	6.8	4.9	
R. Total Wt. Wet Mat. From Hole	1013	938	1021	1082	
S. Wt. Molst. in Mat. from Hole R x P/100	62	73	70	53	
T. Dry Wt. of Mat. from Hole R - S	952	864	951	1029	
U. Unit Wt. of Sand kg/m <sup>3</sup>	93.6	93.6	93.6	93.6	
V. Dry Density kg/m <sup>3</sup> T/E x U	113.5	107.3	107.1	108.7	
Relative Density Determination					
W. Std Maximum Density	106.0	106.0	106.0	106.0	
Specs.	-----	-----	-----	-----	
Relative Density % V/W x 100	107	101	101	103	
Curve No.					
Inspector:					
Project Engineer					

## Appendix C

DCP Tests by Mn/DOT





## Appendix D

### Laboratory Tests by Mn/DOT

*Tim Andersen*

OCT 13 2005

LAB NO: SS05230

**STATE OF MINNESOTA**  
**DEPARTMENT OF TRANSPORTATION**  
**MATERIALS ENGINEERING AND RESEARCH**  
**TEST REPORT ON SAMPLE OF SUBSOIL**

PROJECT NO.	RESEARCH	DATE COMPLETED	10/13/2005
SOURCE		DATE RECEIVED	10/3/2005
TESTS REQUIRED	G,P	SUBMITTED BY	TIM ANDERSEN
		PROJ. ENGINEER	

---

DATE SAMPLED	9/29/2005	FIELD ID	53-1
SAMPLE TAKEN FROM: ROADWAY			

---


*Duluth  
IC Demo  
sampled  
9/29/2005*

% PASSING 2"	100.0	LIQUID LIMIT	
% PASSING 1"	<del>99.9</del> 99.1	PLASTIC LIMIT	
% PASSING 3/4"	98.5	PLASTICITY INDEX	
% PASSING 3/8"	96.6	% SILT	2.2
% PASSING #4	94.8	% CLAY	0
% PASSING #10	91.7	TEXTURAL CLASS	FS
% PASSING #20	87.4	RIBBON CLASS	S
% PASSING #40	71.5	AASHTO GROUP	<del>          </del>
% PASSING #60	34.0	GROUP INDEX	<del>          </del>
% PASSING #100	9.7	FIELD MOISTURE	
% PASSING #200	2.2	% ORGANIC	
		OPT# MOISTURE	9.3
		MAX# DENSITY	106
		R-VALUE (240 psi)	
		SPG	

TESTS METHODS: AASHTO T87 T88 T89 T90 T99 T100 T190

COMMENTS

COPIES TO TIM ANDERSEN

  
 \_\_\_\_\_  
 REVIEWED BY

CHARGE OUT: 1037 1038 ~~1042~~ 1042 ~~1040~~