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EVALUATION OF INTELLIGENT COMPACTION CONTROL IN THE M-189 RECONSTRUCTION PROJECT AT IRON RIVER, MICHIGAN

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EVALUATION OF INTELLIGENT COMPACTION CONTROL IN THE M-189 RECONSTRUCTION PROJECT AT IRON RIVER, MICHIGAN

By

Junhong Li

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

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This thesis has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Civil Engineering.

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Definitions and Abbreviations

CBR: California Bearing Ratio.

CCC: Continuous Compaction Control. The difference between CCC and Intelligent Compaction is that CCC cannot automatically adjust drum excitation in response to real-time feedback.

COV: Coefficient of Variance.

DCP: Dynamic Cone Penetrometer.

DPI: DCP Index.

IC: Intelligent Compaction.

ICMV: Intelligent Compaction Measurement Value. Also called CMV or CCV by different manufactures.

LWD: Light Weight Deflectometer.

MCH: Modified Clegg Hammer.

NDG: Nuclear Density Gauge.

QA: Quality Assurance.

QC: Quality Control.

Abstract

This research evaluated an Intelligent Compaction (IC) unit on the M-189 highway reconstruction project at Iron River, Michigan. The results from the IC unit were compared to several traditional compaction measurement devices including Nuclear Density Gauge (NDG), Geogauge, Light Weight Deflectometer (LWD), Dynamic Cone Penetrometer (DCP), and Modified Clegg Hammer (MCH). The research collected point measurements data on a test section in which 30 test locations on the final Class II sand base layer and the 22A gravel layer. These point measurements were compared with the IC measurements (ICMVs) on a point-to-point basis through a linear regression analysis. Poor correlations were obtained among different measurements points using simple regression analysis. When comparing the ICMV to the compaction measurements points. Factors attributing to the weak correlation include soil heterogeneity, variation in IC roller operation parameters, in-place moisture content, the narrow range of the compaction devices measurement ranges and support conditions of the support layers. After incorporating some of the affecting factors into a multiple regression analysis, the strength of correlation significantly improved, especially on the stiffer gravel layer. Measurements were also studied from an overall distribution perspective in terms of average, measurement range, standard deviation, and coefficient of variance. Based on data analysis, on-site project observation and literature review, conclusions were made on how IC performed in regards to compaction control on the M-189 reconstruction project.

1. Introduction

1.1 Research Background

In roadway construction, compaction is an essential process used to obtain high stiffness and uniformity of the subbase and base materials, which in turn provides for the long-term performance of the pavement material. Technically, subbase and base layers should be compacted properly to provide uniform support of the pavement layers. Desired compaction, however, is difficult to achieve due to soil heterogeneity, difficulty in maintaining a constant lift thickness, moisture content, and variability in the compaction process (Labuz, Guzina et al. 2008). Therefore, contractor quality control (QC) and agency quality assurance (QA) are critical during the compaction process. Typically, verification tests with nuclear or non-nuclear density devices are required for QC/QA. These traditional QC/QA procedures, as well as the way conventional compactor works, have had some shortcomings, which have resulted in under-compacted or over-compacted pavement products.

For traditional QC/QA practice, compaction measurements are taken on a predetermined basis such as one measurement per length or volume of material compacted. In general, most compaction requirements measure less that 1% of area of the roadway area (Mooney 2010). In some cases, compaction measurement tests (usually nuclear or non-nuclear density gauges) are performed at arbitrarily selected points in areas that might be suspected to be weak areas. Finally, judgment on quality of the entire section is made based on results of the in-situ tests conducted. This procedure, however, has some drawbacks. Firstly, measurements from a number of spot tests may not be representative of the entire section because quality of materials between these test spots remains unknown. Moreover, some conventional compaction test devices, such as NDG and Sand cone, measure the density rather than design-related mechanistic parameters such as stiffness, modulus or strength, which makes these conventional devices less straightforward and less effective in the mechanistic design of pavements. Finally, there are disadvantages in the conventional compaction process as well. Conventional compactors do not provide real-time feedback to the roller operator. In traditional compaction practice, the roller speed, vibration frequency and amplitude of the compactor drum are generally held constant, while a certain number of roller passes are applied to the base or subbase layer. Conventional QC/QA in-situ point tests are then conducted after the compaction process is finished. The problem with this approach is that the underlying conditions may vary. The same number of roller passes with constant vibratory frequency and amplitude does not necessarily lead to uniform compaction. Factors that control the compaction quality include support condition of sublayer, lift thickness, material type, in-situ moisture content, among others (Horan, Chang et al. 2012). So conventional compaction process can lead to either under-compacted or over-compacted sections.

Intelligent Compaction (IC) technology has been developed to address the foregoing shortcomings. The precursor of IC technology is known as Continuous Compaction Control (CCC). The difference between IC and CCC is that CCC cannot adjust roller vibration parameters in response to the real-time feedback. The introduction of automatic excitation adjustment feature was an attempt to improve compaction effectiveness. CCC was first introduced in European countries for road and embankment construction in the late 1970s. IC technology became available in the 1990s and has been accepted to be effective and reliable for compaction control in roadway constructions in Europe and Japan. But its introduction into the US has only been relatively recent. Research on IC has only been conducted by the Federal Highway Administration (FHWA) and state DOTs during the past few years. Research findings have shown, however, that IC technology can significantly improve the quality of compaction process.

The IC compactor is equipped with either a single or double self-propelled vibratory rollers with accelerometers mounted on the axle of the roller drums. Figure 1.1 shows the IC unit used in this project. The accelerometers measure response of the underlying material in real-time with 100% coverage of the operating section. The real-time mechanistic condition of the entire section is shown as a color-coded map on a displayer on the IC compactor. This feature helps the operator easily identify under-compacted area, avoid over-compaction and therefore attain higher uniformity.

Figure 1.1 IC Unit Utilized in The M-189 Reconstruction Project

As noted above, IC technology has been investigated by a number of states such as Minnesota, Iowa, Texas, among others. While it is still a relatively new technology it is now being used in Michigan. To investigate how well it will work on a standard MDOT construction project, a relatively small highway reconstruction project was selected in the Upper Peninsula. In May 2013, MDOT started the reconstruction of 1.2 miles of M-189 in Iron River Michigan. The reconstruction segment consisted of a 22A gravel base layer over a Class II sand subbase layer. The contract for this reconstruction required the use of an IC compaction unit. A test section within this 1.2-mile reconstruction was established to investigate how well the IC compactor compacted both the 22A aggregate and Class II sand layers. The investigation had two objectives. The first objective was to assess how well the IC unit compaction performed over the test section using a dense grid of nuclear density tests. The second objective was to assess four “non-nuclear” methods on the same dense grid by comparing both the IC unit values and the nuclear density measurements to the four non-nuclear test devices. These objectives are more fully described in the following section.

1.2 Research Introduction

As noted above, the M-189 pilot project involved reconstruction of a 1.2 miles long roadwork in which IC technology was utilized. Prior to and during construction, nuclear density gauge (NDG) tests were performed to establish the target ICMV for the subbase sand and base gravel respectively, based on correlation between ICMV and NDG density. The target ICMV was then used for QC during compaction. During the compaction process, the IC roller vibration frequency was held constant. After the section quality satisfied the requirements specified by the QC plan, the IC unit would finish the project segment. ICMVs were exported from the database after the compaction process finished.

This evaluation study on the IC trial specification of M-189 project at Iron River was conducted from May to November 2013. To conduct the evaluation, 30 measurement sites were established on a section of the reconstruction project, which was about 100 feet by 40 feet in dimension and located near north end of the project. Five different types of compaction measurement tests were conducted on the Class II sand subbase and 22A gravel base layer, respectively, after the final pass of the IC machine on each layer. The compaction measurement devices include NDG, Geogauge, LWD, DCP, and MCH. MDOT conducted the NDG tests while MTU conducted the four non-nuclear tests. Daniel VandenBerg, a former MTU graduate student, developed the Modified Clegg Hammer (MCH) in 2003. VandenBerg tested the MCH on 5 different types of sands in the laboratory, and found a very good correlation between integration value of the device with the sands' dry unit weight (Vanden Berge 2003). Therefore, MCH was also one of the four devices utilized in this research.

Before conducting field tests at Iron River, equipment evaluation tests were conducted at test sites in Hancock and Calumet in order to ensure the in-situ testing devices are working properly in the field and to see how these compaction tests measurements track each other.

As noted above, the test Section at Iron River is about 100 feet by 40 feet. Thirty test locations were selected on approximately eight feet spacing. In order to minimize the influence of various tests on the compacted material, non-destructive instruments (NDG, Geogauge and MCH) were performed first at each location followed by LWD and DCP tests. After field tests data collection, simple and multiple regression analyses were performed on the data to determine how did ICMVs correlate with point test measurements. Correlation among the point tests measurements was also investigated. Factors affecting the strength of correlation among different measurements are discussed. Some of the affecting factors such as in-place moisture content variation, roller speed, vibration frequency and amplitude were accounted for during the multiple regression analysis. Since NDG is the standard device used for QC/QA analysis, the NDG data was used as the primarily standard test data to which other measurements were compared. All measurements were also studied from an overall distribution perspective in terms of average, measurement range, standard deviation, and coefficient of variance. State of the art on IC technology is discussed in the literature review. Based on data analysis, on-site project observation and literature review, conclusions were made on how IC technology works for roadway compaction control.

2. Test Methods Summary

This chapter summarizes principles and test procedures involved in this research.

2.1 Intelligent Compaction (IC)

A). Fundamentals of IC Technology

The IC roller used in this project was a TEREX SP2010 with a single smooth drum. The roller weighs 10.11 tons, while the speed of the IC roller was 0 to 8.3 mph. The IC roller vibration frequency was maintained at 28.8 HZ, with a very slight fluctuation. The IC machine used in this project is shown in Figure 1.1. An IC unit typically includes the following components:

1. Either a single or double self-propelled vibratory rollers.
2. Accelerometer-based measurement system.
3. Onboard integrated documentation system to display, process and record data.
4. GPS system to monitor drum locations and number of roller passes.

The primary basis of the compaction determination made by the IC unit is based on vibration of the roller drum during compaction. The drum response is measured 30 to 60 times per second using an accelerometer. The response of the accelerometer is then used to determine an IC Measurement Value (ICMV). The ICMV is then related to nuclear density tests in the field to provide a correlation between ICMV & the compacted density.

ICMV should be viewed more as an index value than a stiffness value and is primarily used for comparison purposes(Labuz, Guzina et al. 2008).

There are mainly five suppliers for single drum IC roller. These vendors have various definition of ICMV because the methodology to calculate material response to the roller vibration is usually proprietary (Chang, Xu et al. 2011). A summary of manufactures for single drum IC rollers and their measurements is shown in Table 2.1. The primary assumption used with the IC unit is the ICMV result should be independent of which manufacture's unit is used. Effort may be made to standardize ICMVs from different vendors in the future. Currently, calibration is often performed to correlate the ICMV to other in-situ test measurements, density or stiffness. Target ICMV and optimum roller passes can also be determined from compaction curves from IC and in-situ test result during calibration process.

Table 2.1 A Summary for Single Drum IC Roller Vendors

Modified from (Chang, Xu et al. 2011)

Vendor	Ammann/ Case	Bomag	Caterpillar	Dynapac	Sakai
Model	ACEplus	VarioControl	NA	DCA-S (GPS)	CIS
Model Number	SV	BW213-4BVC	NA	CA 152–702	SV505/SV510
Measurement Value	Kb	E_{vib}	CMV	CMV	CCV
Measurement Unit	MN/m	MN/m^2	Unitless	Unitless	Unitless

ICMVs are linked with time and coordinate and recorded in the onboard documentation system. The documentation system includes an operator monitor that is capable of displaying real-time color-coded mapping of ICMVs, which include material stiffness measurements, number of roller passes, precise location of the roller, vibration frequency and amplitude of roller drums. The operator can view real-time response of the underlying material to roller vibration in the monitor while the IC machine is working. By comparing real-time ICMVs to the target ICMV, IC operator or project personnel can easily identify improperly compacted areas that need further compaction, or further QC/QA testing if desired. Real-time interaction between IC machine and operator is the key to reduce the variability of underlying material and to improve uniformity, which in turn guarantee better performance of the pavement. Therefore, IC technology provides the roller operator and project personnel unprecedented insight into the compaction process. In addition, it is possible to adjust the vibration frequency and amplitude of roller drums in response to real-time feedback. However, automatic adjustments of roller compaction parameters are not always available from some manufactures. In practice, however, the vibratory parameters are generally held constant during proof rolling or QA practice because ICMVs have been found to be highly dependent on roller speed, vibration frequency and amplitude.

The IC data is stored in the onboard computer, while it can also be sent to clouds and transferred to web-based storage. Therefore, IC data can be either downloaded from the onboard computer or exported from the web-based storage to Veda-compatible formats. Veda is the software, developed by the FHWA in which users can view and analyze IC data. This software is relatively straightforward, although the IC data from this project could not be downloaded into the Veda software. It is unclear as to why this happened but the main problem was that the Veda software would not accept the coordinate data from the IC unit.

B). Factors affecting ICMVs

As the above section mentioned, IC documentation systems of different vendors are proprietary. Thus the ICMV value is device dependent. In addition to this, factors affecting ICMVs include vibration frequency and amplitude, roller speed, roller driving directions, in-place moisture content, layer depth, and the support condition of sublift material. Mooney (2010) investigated how different factors affect ICMVs.

1). They found that the vibration amplitude dependence of ICMV is complicated and in some cases unpredictable, since both positive and negative amplitude dependence is possible.

2). ICMV was also found to decrease significantly with increased roller speed, as well as being influenced by both forward and backward driving modes.

3). ICMV usually increases with decreased moisture content.

4). Correlation between ICMV and spot test measurements would improve if the sublift material were stiffer, or if the layer beneath the compacting layer is more uniform.

C). IC specifications

IC specifications requires: 1) description of the equipment being used, 2) roller operation guideline, 3) records to be reported, 4) ground conditions, 5) IC calibration procedure, 6) QC/QA practice, 7) operator training, and so on.

Three categories of IC specifications for QC/QA practice are recommended by Mooney (2010):

1). IC technology is used in QA as an assist tool to identify weak areas where acceptance is based on traditional in-situ compaction test.

2). Acceptance is based on a target %ΔICMV and initial calibration of ICMVs is not required. This option determines the acceptance of a section based on the percentage change in ICMVs between two consecutive roller-passes over the same section.

3). A target ICMV is first determined on a test section based on density measurements generally using a nuclear density gauge. Acceptance is then based on achieving a percentage of the target ICMV over a specific proportion of the evaluated section. In the Minnesota DOT pilot specification, for example, it specifies that all segments shall be compacted so that at least 90% of the ICMVs are at least 90% of the target ICMV prior to placing the next lift.

Currently, four European countries (Austria, Germany, Sweden, and Switzerland) have IC QA specifications. Some US states are starting to implement preliminary specifications, such as Minnesota DOT pilot specification (2007). In European specifications, automatic changes in roller vibration amplitude and frequency in response to real-time feedback are permitted during the compaction process but are prohibited during roller-based QA. This is because ICMVs are highly dependent on roller vibration amplitude and frequency, in which this dependence is very difficult to predict.

2.2 Nuclear Density Gauge (NDG)

For this project, NDG tests were performed in accordance with ASTM_D6938-08a (2008), using a Troxler Model 3440, as shown in Figure 2.1. MDOT conducted all of the NDG tests taken at the Iron River site. NDG measures in-place density and water content of soil. When NDG is seated on a desired test location, a retractable rod of the gauge is lowered into a pre-drilled hole under the device. The device is moved slightly to ensure that the rod is in full contact with the hole. While taking measurement, gamma rays are emitted from the radioactive source located at the end of the retractable rod. These rays interact with the soil through absorption, scattering and photoelectric effect. A detector, which is located at the bottom of the gauge, counts the number of rays that reach it from the source. Finally, density is determined by correlation to the number of gamma rays received by the detector.

NDG gauge is also able to measures the moisture content of soils. To achieve this, the gauge emits neutrons that interact with hydrogen in the pore water. The hydrogen slows the rate of neutrons for the detector to pick up. The more slow-rate neutrons NDG receives, the higher moisture content soils will have.

Currently NDG is a widely accepted and standard device for QC/QA in roadway compaction. However, NDG is strictly regulated for storage, transportation and operation. Only licensed technicians are permitted to perform NDG tests, which makes the NDG less convenient to use. Moreover, comparing with stiffness/modulus measuring devices, NDG measurement (density) has less connection with the mechanistic design parameters, which are usually modulus, strength, and stiffness. Considering these facts, along with public’ s concerning about radioactive devices, engineers are investigating reliable non-nuclear alternatives to NDG, such as

Geogauge, LWD, etc.

Figure 2.1 Troxler Nuclear Density Gauge (NDG)

2.3 Sand Cone Test

Sand cone tests were performed at the Hancock test site in accordance with ASTM_D1556-07 (2007). The sand cone tests were conducted since no nuclear density gauge was available to compare to the other non-nuclear test devices that were being tested at he Hancock site. The device, as shown in Figure 2.2, consists of a jar, a metallic funnel, and a base plate.

Figure 2.2 Sand Cone Test Apparatus

2.4 Geogauge

Geogauge test was performed according to ASTM_D6758-08 (2008). The Humboldt Geogauge, shown in Figure 2.3, was used in this project. This hand-portable device weighs about 22 pounds. It measures the in-place stiffness of material at the ground surface by generating vibrations at 25 separate frequencies between 100 and 196 Hz. The Geogauge makes little or no penetration into the ground during testing, with a displacement less than 1.27×10^{-6}m or 0.0005 inch, making it a nondestructive test (Humbold Mfg. Co. 2007). Measurement typically takes about one minute with the average stiffness measured across the frequency range reported. Geogauge measures stiffness up to the depth of 0.7 to 1.0 feet into the ground. The Young's modulus can also be calculated from the measured stiffness if poison's ratio is assumed.

The Geogauge seats on the soil surface via a ring-shaped plate. Attached to a ring-shaped plate are a shaker that generates the vibration and a sensor that measures the response of the plate, which is a measure of the material's stiffness below the device. Before making a measurement, user must ensure 100% contact between the foot and the ground surface, since good seating is the key in making a good measurement. Prior to testing, generally, a slight rotation is applied to Geogauge to obtain good contact between the Geogauge and the soil. On particularly rough surfaces, however, user can use moist sand to assist in obtaining 100% contact. In this project, contact between the plate and the ground surface was sufficient for all the tests on Class II sand. For test on 22A gravel, however, moist sand was sometimes used to satisfy the 100% contact requirement.

Figure 2.3 Humboldt Geogauge

2.5 Light Weight Deflectometer

ZFG 3000 Light Weight Deflectometer, as shown in Figure 2.4, was used in this project. The LWD test was performed in accordance with ASTM_2835-11 (2011). LWD instrument consists of an electronic box, loading plate, loading mass and guiding rod. The loading mass is dropped on the loading plate at a fixed dropping height. A sensor, which is seated inside the load plate, measures the force and displacement. Settlement is then displayed on the electronic box that is connected to the loading plate. The loading mass is dropped three times for each test. After each of the first two drops, the electronic box will beep once to confirm that the drop is valid. After the third drop, a double beep confirms the end of the measurement. The electronic box will then average the three drops and report a final measurement value, called dynamic deflection modulus E_{vd}, MN/m^2.

Certain cautions should be paid to the test procedure. Before seating the base plate, user should level the soil surface to ensure full contact between plate and the ground. During test, the guiding rod must be held steady and vertical. Whenever moving the device to a new test location, user should do three pre-loading drops before performing a test. This is considered as conditioning of the base or subbase.

The reason is that the loading mass applies large force on the load plate to compact any loose soil beneath the plate. Measurement values may vary significantly between the first two or three drops(Petersen and Peterson 2006). Difference in measurements from the first five drops is shown in Figure 2.5. Applying three pre-loadings before each test can compact the loose soil near the surface and make measurements more consistent.

Figure 2.4 ZFG 3000 Light Weight Deflectometer (LWD)

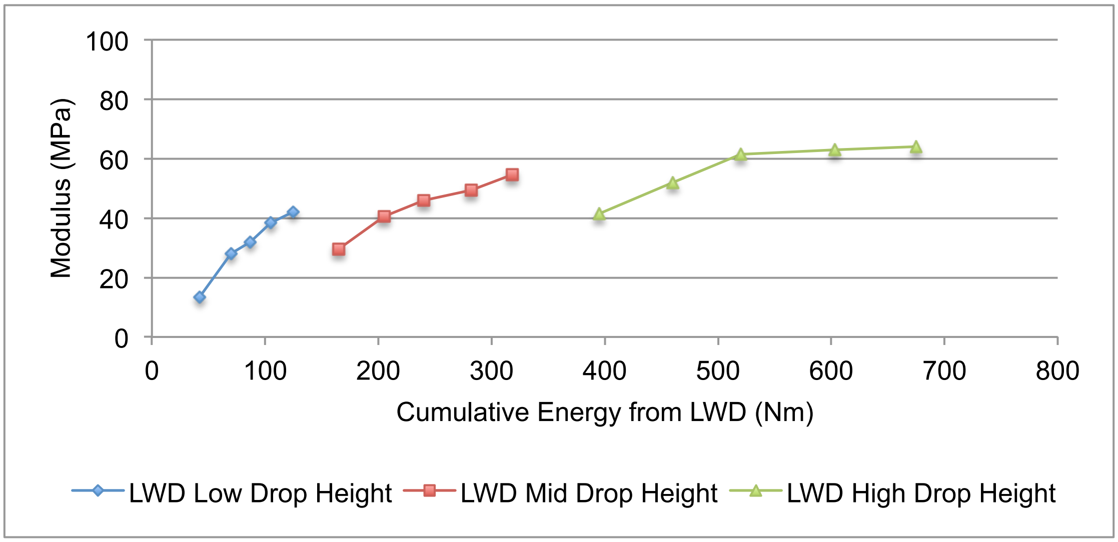

Figure 2.5 Differences in LWD Measurements From The First Five Drops

Modified from (Petersen and Peterson 2006)

2.6 Dynamic Cone Penetrometer

Dynamic Cone Penetrometer (DCP) test was performed in accordance with ASTM_D6951 (2009). The DCP device, as shown in Figure 2.6, is a hand-held device that determines strength of in-situ soil and boundary of soil layers by measuring penetration distance of a cone-tipped lower shaft into soils after each hammer blow. Soil resistance to penetration is considered as an indication of compaction level of the materials.

DCP device is easy to use and inexpensive to operate. The device is mainly comprised of a hammer, an upper shaft, a lower shaft, and a reading device. The hammer weighs 17.6 pounds. A 60-degree cone tip is attached to the lower end of the lower shaft, while an anvil connects the upper shaft and the lower shaft. During testing, the hammer is lifted to a fixed height (575mm) and freely dropped along the upper shaft onto the anvil. The momentum transmits downward and drives the lower shaft into soils. This operation is repeated until the desired depth is achieved. During the DCP test, operator records the penetration depth after each hammer blow. The measurement of DCP test is referred as the DCP penetration index (DPI) in unit of mm/blow.

The penetration index is often plotted with depth. In this way engineers are able to distinguish boundaries between different soil layers. DPI is also often used to estimate the California Bearing Ratio (CBR) value in order to better evaluate the mechanistic properties of subbase and base materials. The CBR test measures static penetration pressure required to drive a plunger with standard area into a soil a given distance. The CBR is expressed as a percentage that is determined by the ratio of the penetration resistance of a soil under test to the penetration resistance of a standard crushed rock at an equal penetration. Before performing an analysis of the DPI data, the DPIs were first converted to CBR values using a correlation equation from

(Webster, Grau et al. 1992), which is shown below:

$$\text{Log (CBR)} = 2.46 - 1.12 \log \text{(DPI)},$$

Where DPI is in mm/blow.

In this research, DCP test results are presented as a single CBR value. The single value is the weighted average CBR for a distance of 10 inches below the ground surface.

Figure 2.6 Dynamic Cone Penetrometer (DCP) Apparatus

2.7 Modified Clegg Hammer

The Modified Clegg Hammer (MCH) test was conducted in accordance with (ASTM_D5874-02 2002). Dr. Baden Clegg developed the Clegg hammer in the 1970's. The device consists of a hammer, a guiding tube, an accelerometer mounted in the hammer, and a data acquisition system connected to the accelerometer. The Clegg hammer measures the maximum deceleration as the hammer impacts the soil surface vertically. During testing, the data acquisition system records signals from the accelerometer. Typically, a standard hammer weighing 4.5Kg is used although a lighter weight PVC hammer is also available. The problem with this is that the hammer causes large penetration during testing, especially when testing on loose materials. In a research project that studied Clegg Hammer as an alternative to NDG, Farrag (2006), however, indicates that the Clegg hammer measurements are significantly adversely affected by moisture content.

In 2003, Dan Vandenberg developed the Modified Clegg Hammer (MCH), as shown in Figure 2.7. The modified Clegg hammer weighs only 0.5Kg. Another big difference of MCH from the standard Clegg Hammer is that a PVC handle was added to the hammer. The PVC handle will vibrate when the hammer hits the soil surface. A data acquisition software program named DasyLab was used to records this damping behavior, as shown in Figure 2.8. For the standard Clegg hammer, however, there is only one peak in the waveform collected. During a MCH test, a SciLab program, which was develop by Andy Hardyniec in 2007, processes the data collected by DasyLab almost simultaneously. An integration value, in the unit of m/s, will be reported to users at the end of each test.

Vanden Berge (2003) tested the device on five different types of sand with a wide range of density and moisture content in the laboratory. Vandenberg prepared test specimens with a range of moisture content in square wooden boxes by applying different compaction efforts. For each specimen, Vandenberg performed tests on each of four quadrants of the box. Each test consists of four drops of the hammer. Vandenberg collected the signals by Dasylab and analyzed the data using a Matlab program. During the data analysis, signals of the corresponding drops of the four quadrants were averaged. Finally the third and fourth averaged signals were averaged again. The final averaged waveform was used to assess the correlation with dry density of the sand. Vandenberg found that the integration value obtained from the first two peaks of the final averaged signal, as shown in Figure 2.8, had the best correlation with dry density.

In this research, MCH test was conducted following Vandenberg's procedure so that we could utilize the SciLab data analysis program. Each test obtained an integration value that is referred as the Clegg Impact Value (CIV).

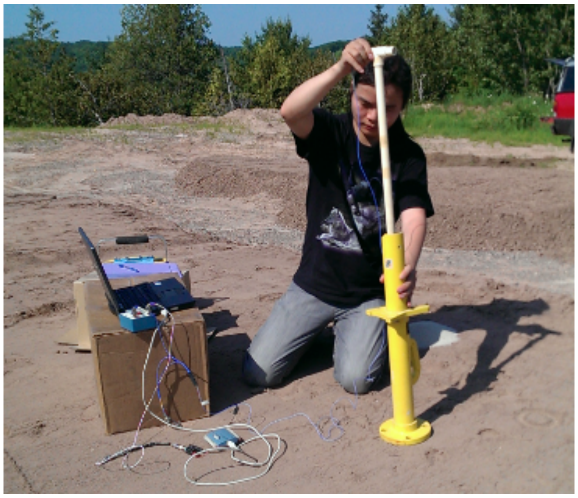

Figure 2.7 Modified Clegg Hammer (MCH) Device

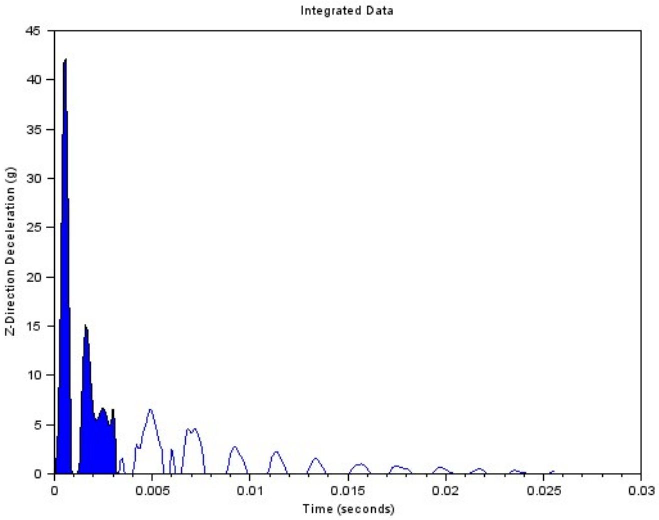

Figure 2.8 Illustration of The First Two Peak Integration of MCH Waveform
(From Test #2 on Sand at Iron River)

3. Review of Existing IC Research

Some recent researches on IC are discussed in this chapter. Main findings and conclusions of these researches are presented.

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

(Petersen and Peterson 2006)

This study focused on assessing the IC compaction data and point test measurement in a test section of the Mn/DOT TH 53 Trinity Road project. In-situ compaction tests including Geogauge, LWD and DCP were performed on 42 locations. Poor correlations were obtained between ICMVs and point tests measurements. The authors attributed this result to stress dependency of soil modulus and soil heterogeneity.

2). Intelligent Compaction Control of Highway Embankment Soil

(Rahman, Hossain et al. 2007)

This research evaluated ICMVs by comparing them with other conventional compaction measurements from Geogauge, LWD, Falling Weight Deflectometer (FWD) and DCP tests on compacted subgrade. Variation of ICMVs with the in-place moisture content and compaction level was also studied.

The following conclusions were made in this research:

1). IC roller stiffness measurement is sensitive to in-situ moisture content. Higher moisture content will result in lower stiffness value.

2). Low IC roller stiffness is obtained at both very high and very low percent compaction. Therefore, for IC compaction control, it is very necessary to develop a target stiffness value for a specific type of soil. Materials of the same density may exist for at least two different water contents (on either side of the Procter compaction curve). However, these materials with the same density have different mechanistic properties.

3). No universal correlation is observed between the IC roller stiffness and other in-situ point test measurements.

3). Intelligent Compaction Implementation: Research Assessment

(Labuz, Guzina et al. 2008)

This research aimed at providing a qualitative evaluation of the Mn/DOT IC Specifications by inspecting four construction sites and interviewing project personnel. This study integrated comments from the four construction sites and made the following recommendations:

1). Use the LWD for QA practice. A standard procedure for LWD should be developed and followed.

2). Establish a procedure to determine the target LWD value. Modulus estimate depends on boundary conditions as well as strain level. It is important to evaluate the stain level associated with IC and LWD tests, in order to develop a necessary basis for QC/QA specification.

3). ICMV is device and site dependent. Accordingly, the target ICMV should be site specific. It is thus necessary to re-calibrate the ICMV for different soils or site conditions. This report recommended eliminating calibration and increasing frequency of LWD testing.

4). IC is recommended for uniformity control and not for measuring stiffness.

5). Simplify IC data evaluation.

6). Support development of alternative IC methodologies. Considering IC data interpretation algorithms are proprietary in nature and thus cannot be verified. It may be worthwhile to develop an alternative methodology for compaction control, e.g., considering a continuous mapping of rutting depth for the test roller, which is a widely accepted QA device. At least the alternative methodology can work as an independent device to verify the IC values.

7) Simplify or eliminate moisture corrections. Although moisture is known to affect stiffness and strength, it may be more efficient to allow a range of in-place moisture content on condition that the target stiffness or strength measurement is satisfied.

4). Intelligent Soil Compaction Systems

(Mooney 2010)

This research was conducted by the Colorado School of Mines and Iowa State University to assess the reliability and effectiveness of IC technology in different soil types, and to develop preliminary generic specifications for the application of IC in QA of soil and aggregate base material compaction. To achieve this goal, Mooney et al. (2010) collected and compared IC and traditional compaction data from five active state DOT construction projects. Further analysis determined a few important factors that affected the accuracy of IC system, such as moisture content, layer depth, and supporting from the sublift material. This study also summarized the current state of practice of IC through literature review and interviews with compaction equipment manufacturers and international research.

Main achievements obtained in this study are summarized below:

1). This study developed six roller-integrated QA options to accommodate different earthwork site conditions. These recommended specifications were evaluated and compared with each other on full-width test beds with various conditions, such as different testing materials, single lift with different depths, multiple lifts and layered system with different depths, and IC machine from different vendors.

2). In this research, field tests revealed that ICMVs varied with roller parameters such as vibration amplitude and frequency, roller speed, and roller travel direction. Dependence of ICMVs on vibration amplitude was found to be unpredictable.

Amplitude dependence is influence by material type, layer thickness, relative stiffness of layers, and drum/soil interaction. Both positive and negative dependence are therefore possible. This is why IC roller parameters must be held constant during roller-base QA for a given soil & moisture condition.

3). Field tests were conducted on 17 different materials to assess the correlation of ICMVs to spot test measurements. Test results indicated that correlations were possible between ICMVs with constant operating parameters and spot test measurements, such as dry density, modulus, and CBR. Further analyses determined the correlations depended on various factors including soil heterogeneity, moisture content, limited measurement range, and variation in roller vibration parameters.

5). Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, And Asphalt Pavement Materials

(Chang, Xu et al. 2011)

This research was sponsored under a Transportation Pooled Fund project, in which 12 participating State DOTs participated. The main purpose of this project was to extend implementation of IC technology, to assist State DOTs in developing IC compaction control specifications, and to identify further research needs for IC.

This study summarized the benefit of IC technology as follows:

1). IC mapping is effective in identifying weak zones for corrective effort being applied prior to placement of the next lift or layer.

2). IC technology can be very helpful under low visibility conditions by maintaining consistent compaction patterns.

3). IC will significantly reduce variability of various stages of pavement constructions and thus will produce pavement products with high quality.

Findings of IC technology implementing on soils were also presented:

1). Influence depths associated with various devices and in-place moisture content are the primary factors affecting correlations between ICMV and other in-situ test measurements.

2). A linear correlation was found between ICMV and back-calculated stiffness from deflections, e.g., LWD and FWD.

3). A poorer correlations was found between ICMV and DCP test.

4). The least desirable correlations were found between ICMV and density measurements.

5). Optimum roller passes can be determined to avoid under and over compaction by using the compaction curve of IC data on a test section.

This study also made suggestions on future research needs for IC. First, Correlations between ICMV and in-situ test measurements could be improved if a better ICMV model is developed to decouple stiffness for each layer. Second, real-time in-place moisture content mapping was recommended and should be accounted for in an improved ICMV model. Finally, the authors recommended standardizing IC data management and analysis tool, although the IC systems of different manufactures are proprietary.

4. Field Studies and Test Results

4.1 Hancock Test Site

Hancock test site was located at the Superior Sand & Gravel Quarry in Hancock, Michigan, as shown in Figure 4.1. On July 05th, five compaction tests (including Sand Cone test, Geogauge, LWD, DCP and MCH test) were performed on two soil pads, which were Class II sand and 22A gravel, respectively. Material of these two test sections, as shown in Figure 4.2, was laid uncompacted. These two pads had a dimension of approximately 50 feet by 15 feet, with a thickness of about 10 inches. The field test at Hancock site aimed at ensuring that these point test devices were working properly and investigating how different measurements track each other.

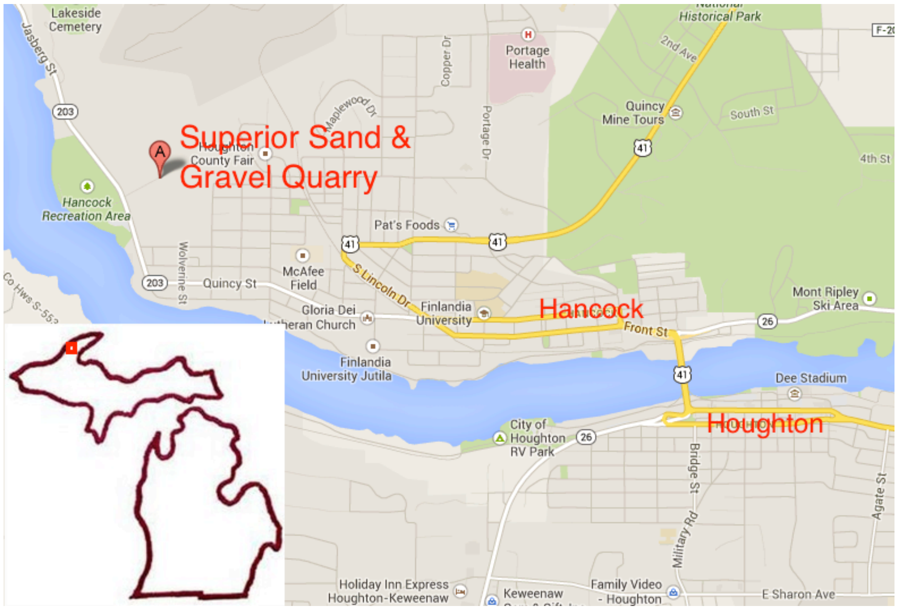

Figure 4.1 Location of the Hancock Test Site

(Created by the author from Google map.)

Figure 4.2 Hancock Test Site

Two test spots were arbitrarily selected on each of the Class II sand and 22A gravel test pad. Sand Cone test, LWD, and MCH tests were performed at each location. Geogauge and DCP were performed four times at each location and these measurements were averaged to provide a single value. Soil samples at all locations were collected to determine the moisture content by oven drying. Grain size analysis tests were also conducted in the laboratory in accordance with ASTM-D422 (2007) and located in Appendix A, which includes all of the test data from the Hancock test site.

4.2 Calumet Test Site

Calumet test site was located at Laurium in Calumet Township, MI. The purpose of the field tests at Calumet site was to test the compaction testing equipment on fully compacted gravel. In-situ tests were performed on the compacted gravel base layer on July 24th. This section was compacted by traditional compactor. Compaction test equipment included the NDG, Geogauge, LWD, DCP and MCH test. Four locations were arbitrarily selected. All tests were performed once at each location. Non-destructive in-situ tests were followed by destructive tests. Please refer to

Appendix B for detailed test data at Calumet test site.

4.3 Iron River Test Site

Iron River test section was located near the north end of the M-189 reconstruction project in Iron River, Michigan, as shown in Figure 4.3. The test section was approximately 100 feet by 40 feet. Thirty test locations were surveyed in on both sand and gravel layers, after the final IC roller pass for each layer. The test locations on sand differed slightly from those on gravel. Figure 4.4 and Figure 4.6 are photos of the sand and gravel layers, respectively. Figure 4.5 and Figure 4.7 illustrate the distribution and location of point test locations on sand and gravel layers, respectively. Non-destructive point tests (NDG, Geogauge and MCH) were performed first at each test location, followed by the LWD and DCP tests. MDOT conducted the NDG tests. For DCP test at Iron River site, the weighted average from surface to a depth of 10 inches was used to calculate a single CBR value for comparison with other measurements. Grain size analysis tests were also conducted in the laboratory in accordance with ASTM-D422 (2007). A hand-held GPS receiver was used to collect coordinates of all test locations, as shown in Table 4.1 and Table 4.2.

Figure 4.3 Location of the Iron River Test Site

(Created by the author from Google map.)

Figure 4.4 Subbase Sand Test Section at Iron River Site

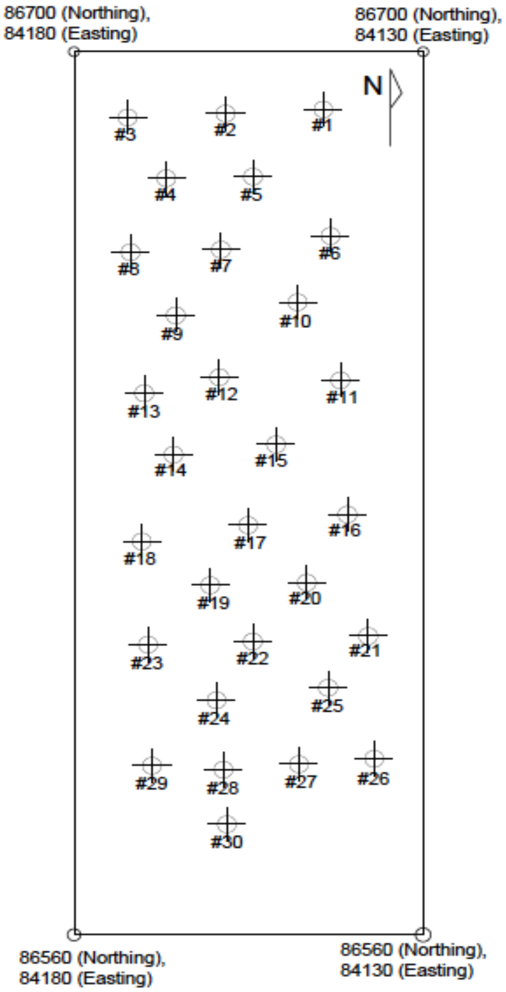

Figure 4.5 Illustration of Point Tests Location on the Class II Sand Section

Figure 4.6 Base Gravel Test Section at Iron River Site

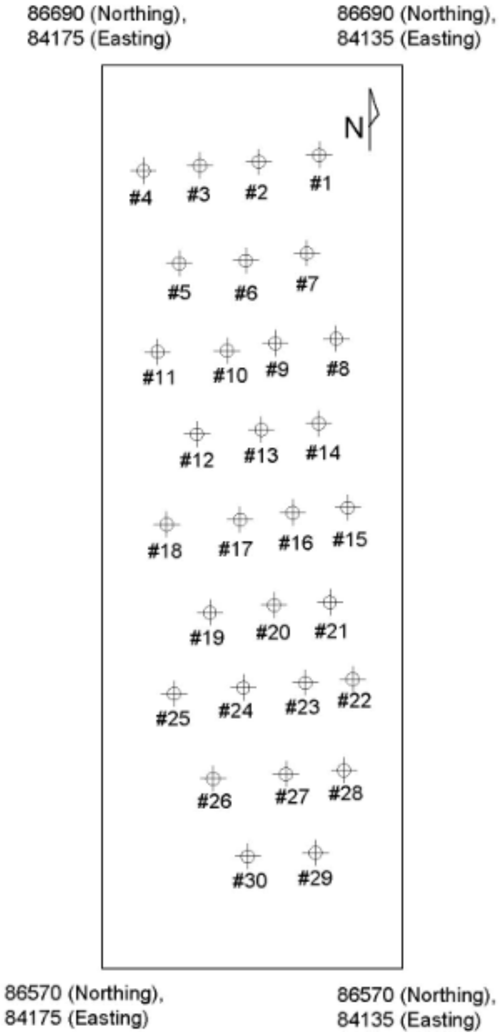

Figure 4.7 Illustration of Point Tests Location on the 22A Gravel Section

Table 4.1 Point Test Locations on the Class II Sand Layer at Iron River

Test Number	Northing	Easting	Elevation
1	86690.832	84144.312	1505.69
2	86690.206	84158.316	1505.22
3	86689.580	84172.320	1504.74
4	86679.918	84166.782	1504.86
5	86680.182	84154.362	1505.26
6	86670.796	84143.285	1505.81
7	86668.620	84158.947	1505.21
8	86668.234	84171.917	1504.87
9	86658.212	84165.431	1505.20
10	86660.306	84147.982	1505.66
11	86647.915	84141.851	1505.87
12	86648.385	84159.191	1505.46
13	86645.857	84169.945	1505.19
14	86636.145	84165.746	1505.35
15	86637.746	84151.076	1505.66
16	86626.643	84140.846	1506.10
17	86624.932	84155.077	1505.81
18	86622.370	84170.303	1505.52
19	86615.415	84160.499	1505.84
20	86615.862	84146.649	1506.04
21	86607.372	84137.878	1506.34
22	86606.488	84154.380	1506.03
23	86605.998	84169.378	1505.72
24	86597.224	84159.629	1505.99
25	86599.146	84143.590	1506.22
26	86587.932	84137.007	1506.54
27	86587.054	84147.804	1506.38
28	86586.175	84158.600	1506.22
29	86586.802	84168.850	1506.00
30	86577.520	84158.107	1506.20

Table 4.2 Point Test Locations on the 22 A Gravel Layer at Iron River

Test Number	Northing	Easting	Elevation
1	86678.115	84146.084	1506.63
2	86677.219	84154.128	1506.29
3	86676.698	84161.939	1506.11
4	86676.014	84169.466	1505.87
5	86663.701	84164.686	1506.09
6	86664.066	84155.842	1506.45
7	86665.028	84147.712	1506.62
8	86653.671	84143.808	1506.74
9	86653.095	84151.894	1506.58
10	86652.085	84158.331	1506.38
11	86651.928	84167.611	1506.16
12	86640.946	84162.352	1506.33
13	86641.574	84153.748	1506.58
14	86642.438	84146.143	1506.83
15	86631.235	84142.260	1507.10
16	86630.551	84149.610	1506.90
17	86629.644	84156.615	1506.74
18	86629.011	84166.335	1506.48
19	86617.282	84160.615	1506.74
20	86618.259	84152.066	1506.98
21	86618.666	84144.652	1507.17
22	86608.434	84141.607	1507.28
23	86607.957	84147.925	1507.13
24	86607.300	84156.168	1506.96
25	86606.487	84165.357	1506.74
26	86595.216	84160.151	1506.93
27	86595.805	84150.536	1507.20
28	86596.339	84142.799	1507.32
29	86585.340	84146.560	1507.34
30	86584.886	84155.575	1507.16

A). Class II Sand

Measurement tests on sand were performed on August 13th, after the subbase sand layer was shown to meet the QC plan specification by the IC compactor. Each of the five point tests was conducted once at each of the 30 test locations. Thirty ICMVs with corresponding coordinates were extracted from the IC database on August 12th, which was the latest record for our test section prior to our in-situ point test. Please refer to Appendix C for detailed test data on sand at Iron River.

B). 22A Gravel

Two sets of point compaction tests were performed on the gravel layer. The first set was conducted on Sep. 12th and 13th. On Sep. 12th, NDG, Geogauge and LWD tests were conducted once at each of the 30 locations. DCP was conducted once at each of the first 18 locations. Due to a technical issue, the MCH test was unable to be conducted until Sep. 13th. MCH test was conducted once at each of the 30 spots. However, the contractor conducted their final grade operations, which included one additional pass of the IC compactor on Sep.13th, the morning before the MCH test. That means additional compaction was applied to the gravel section between MCH test and other tests performed on the previous day. That is the primary reason why a second set of tests were performed on the gravel. However, the regression analyses for both sets of measurements used the same IC data, which was extracted from the IC database on Sep. 3rd. This is because that the IC data on Sep. 3rd is the up-to-date record for the gravel test section. The additional effort applied to the gavel layer, which was witnessed by the author after the first set of field test on gravel on September 13th, could not be found in the database due to some technical reason. This is one potential problem with the regression analysis result. It should also be mentioned that 25 ICMV out of 30 locations on the gravel section were available. Please refer to Appendix D for the 1st set of test data on gravel at Iron River site.

The second set of tests was performed on September 16th. All point compaction tests except DCP was conducted once at each of the 30 test locations. DCP test was conducted once at each of the last 10 spots (from #21 to #30). Please refer to Appendix E for the 2nd set of test data on gravel at Iron River site.

5. Comparison and Discussion of Test Results

Testing was conducted at three sites. The first site was at the Superior Sand & Gravel Quarry in Hancock. The second site was on a MDOT pavement project in Calumet, Michigan. And the third site was in Iron River, Michigan. The Hancock site was the site in which the equipment was tested to make sure their performance and that we understand the operation of the equipment. The Calumet site was used to test the equipment on compacted gravel. While only a limited number of tests were conducted, the test results are reported below. Following the Hancock and Calumet sites results, the Iron River results will be presented and discussed.

5.1 Hancock Test Site

Based on data collected, simple regression analysis was performed to evaluate correlations among different compaction testing measurements on a point-to-point basis at the Hancock site. Figure A.3 in Appendix A presents the regression analysis results for the R^2 parameter. Table 5.1 below also summarizes the coefficient of determination among different measurements. It should be noted that the purpose of these measurements was made to test out the equipment. In addition, both the sand and gravel layers were in a very loose state with compaction.

Table 5.1 shows the correlation between each two devices. In general, poor correlations were obtained at Hancock site. There are at least three reasons accounting for this result:

1). The test pads at Hancock site were laid down in a totally uncompacted state.

2). Limited number of tests (only 4) was conducted.

3). Most of the devices were originally developed for compaction control on dense material.

Table 5.1 Coefficient of Determination (R^2) Among Different Measurements at Hancock

R^2	Sand Cone	Geogauge	LWD	DCP	MCH
Sand Cone	1.0	0.2646	0.0193	0.2246	0.0100
Geogauge		1.0	0.1928	0.0589	0.0116
LWD			1.0	0.8770	0.5788
DCP				1.0	0.4611
MCH					1.0

5.2 Calumet Test Site

At the Calumet site, simple regression analyses were performed to evaluate correlations among different measurements on a point-to-point basis on a 22A gravel layer. Again, only four data points were collected representing a very small data set. Figure B.1 in Appendix B shows the regression analysis results. Table 5.2 below also summarizes the R^2 parameter among different measurements. Since MDOT uses the NDG for QC/QA, it is used as the standard test data to which other measurements were compared.

Table 5.2 shows that fairly good correlations were obtained. All of the other four test results correlated with the NDG measurements. Coefficient of determination between NDG and Geogauge reaches as high as 0.977. Poor correlations only occur between MCH & LWD and MCH & DCP. Soil heterogeneity and limited number of tests conducted may be responsible for the poor correlations. Although generally good correlations were obtained at Calumet site for the Geogauge & NDG results, these analysis results may not be very representative because only four measurements of each device were taken as noted above.

Table 5.2 Coefficient of Determination (R^2) Among Different Measurements at Calumet

R^2	NDG	Geogauge	LWD	DCP	MCH
NDG	1.0	0.9766	0.4119	0.6979	0.7029
Geogauge		1.0	0.3556	0.8018	0.7184
LWD			1.0	0.0404	0.0149
DCP				1.0	0.8460
MCH					1.0

5.3 Iron River Test Site

A). Class II Sand

The test data on the Class II sand is provided in Appendix C. NDG data is used as the standard test data to which other measurements were compared since NDG is the accepted compaction test method for QA. All 30 NDG values meet the MDOT compaction criteria. Figure 5.1 and Figure 5.2 summarize different measurements. As these figures indicate, MCH and DCP measurements track the NDG measurements trend well. However, there were lower ICMVs obtained for both high and low dry densities measured by the NDG, as shown in Figure 5.3. This indicates that it would be worthwhile to develop a target "stiffness" for granular pavement layers for compaction control. The QC/QA practice would then not only depend on in-place dry density alone, because the same density can be obtained at two different moisture contents. However, same density does not necessarily indicate equal stiffness.

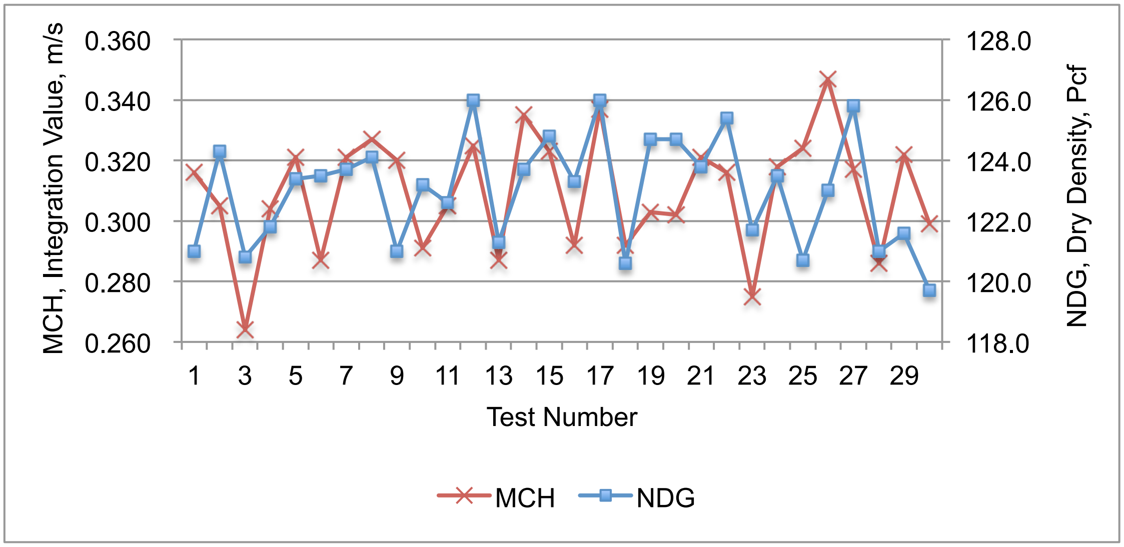

Figure 5.1 NDG and MCH Test Results on Class II Sand at Iron River

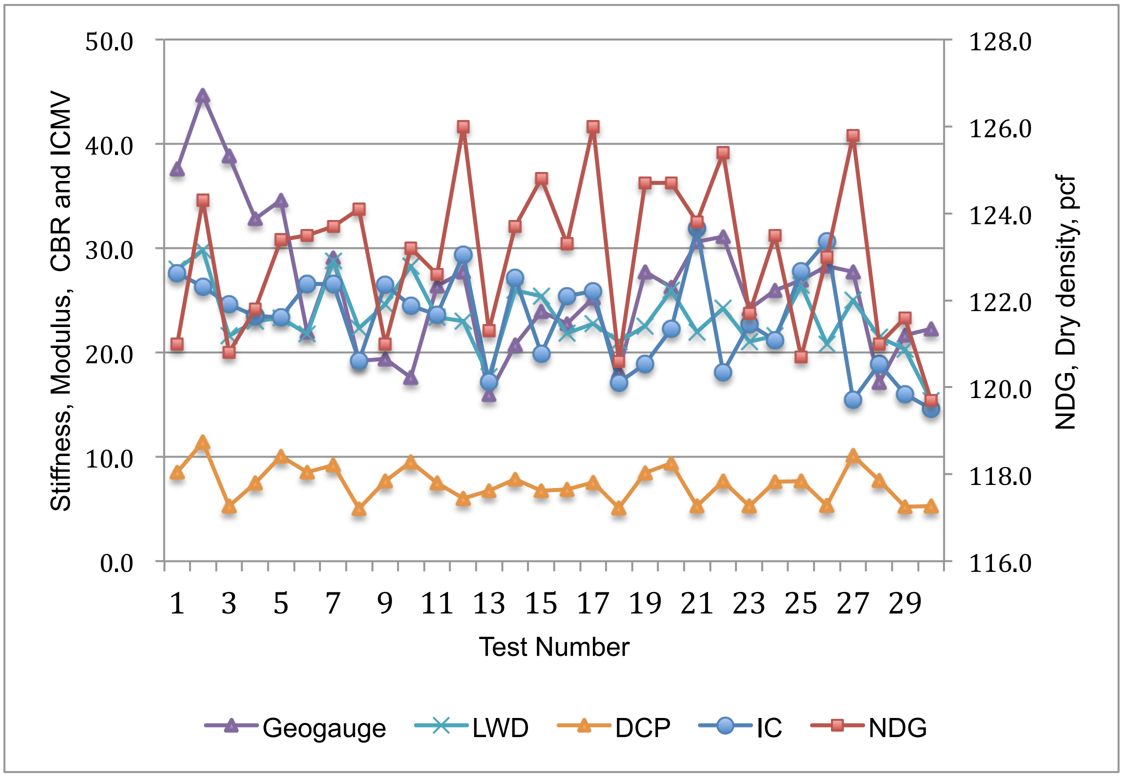

Figure 5.2 NDG, Geogauge, LWD and DCP Test Results on Class II Sand at Iron River

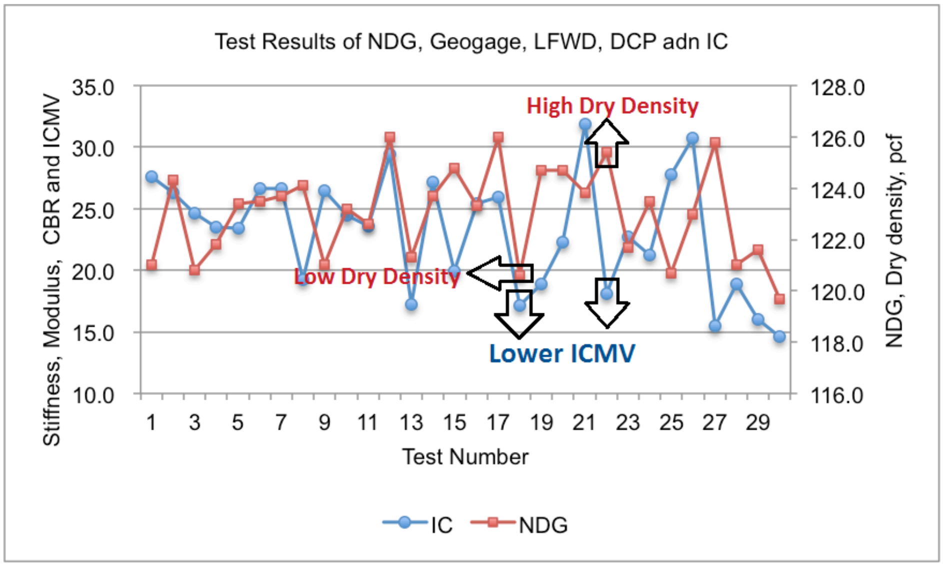

Figure 5.3 Illustration of Lower ICMV Obtained at Both Low and High Dry Density

Next, measurements were studied on an overall distribution basis, using statistical measures including average, standard deviation, coefficient of variance (COV), and minimum & maximum values. The values are summarized in Table 5.3. Figure C.2 and Figure C.3 in Appendix C compare histograms of different testing measurements. Theoretically equivalent normal distribution curves were added to these figures for comparison with the actual histograms. As these plots indicate, a normal distribution roughly fit the IC and MCH results.

Table 5.3 Statistical Measures for Different Tests on the Class II Sand at Iron River

Test	Mean	Standard Deviation	COV (%)	Minimum	Maximum	Number of Tests
NDG	123.0	1.79	1.45	119.7	126.0	30
IC	23.10	4.7	20.33	14.6	31.9	30
Geogauge	26.22	6.78	25.87	15.93	44.65	30
LWD	23.31	3.16	13.57	15.40	29.84	30
DCP	7.41	1.74	23.54	5.03	11.43	30
MCH	0.309	0.02	6.2	0.264	0.347	30

In order to have a better understanding of the measurements overall distribution in the compacted state, the minimum and maximum values of the X-axis of each histogram represent the approximate values of different measurements at the loose state and very dense state. The approximate values of different measurements at the loose state were obtained from the Hancock test site because the test sections at Hancock were laid fully uncompacted. The max dry densities developed for QC/QA at the Iron River test site were used as dry density at the very dense state. Maximum measurement values other than NDG density were determined together by their overall distribution and the preliminary relationships between NDG density and corresponding measurements. Table 5.4 summarizes the approximate values for different measurements on sand at the loose state and very dense state. Note that the minimum and maximum values of various measurements are very approximate.

Table 5.4 Summary of Approximate Value for Different Measurements on the Class II Sand at Loose and Dense State at Iron River

	Minimum (Loose)	Maximum (dense)	Range
ICMV	8.0	45.0	37.0
NDG	92.2	128.5	36.3
Geogauge	10	50	40
LWD	10	33	23
DCP	2	13	11
MCH	0.21	0.38	0.17

For the M-189 project, the "*target pass number*" guideline of five passes was generally exceeded during compaction on the subbase sand. The roller passes in many areas on the sand layer exceeded 15, which is much higher than the target pass number of 5 estimated for the sand section. This over-compaction is demonstrated in the compaction curve of IC data at several arbitrarily selected points and shown in Figure 5.4. Please note that a roller speed variation existed among different roller passes and that this variation in roller speed is not accounted for in Figure 5.4. In Figure 5.4, three arbitrarily locations point 2, 8, 23 were inspected. An approximate parabolic best-fit line was placed through each of the three sets of data. It can be seen in Figure 5.4 that after the 5th pass the ICMVs tend to decrease, indicating over-compaction. During the compaction on the base grave section in the M-189 project, however, the target roller pass guideline was followed much closer.

Finally, different measurements were compared with each other on a point-to-point basis. Simple regression analysis and multiple regression analysis were performed to assess correlations among different measurements and reported below.

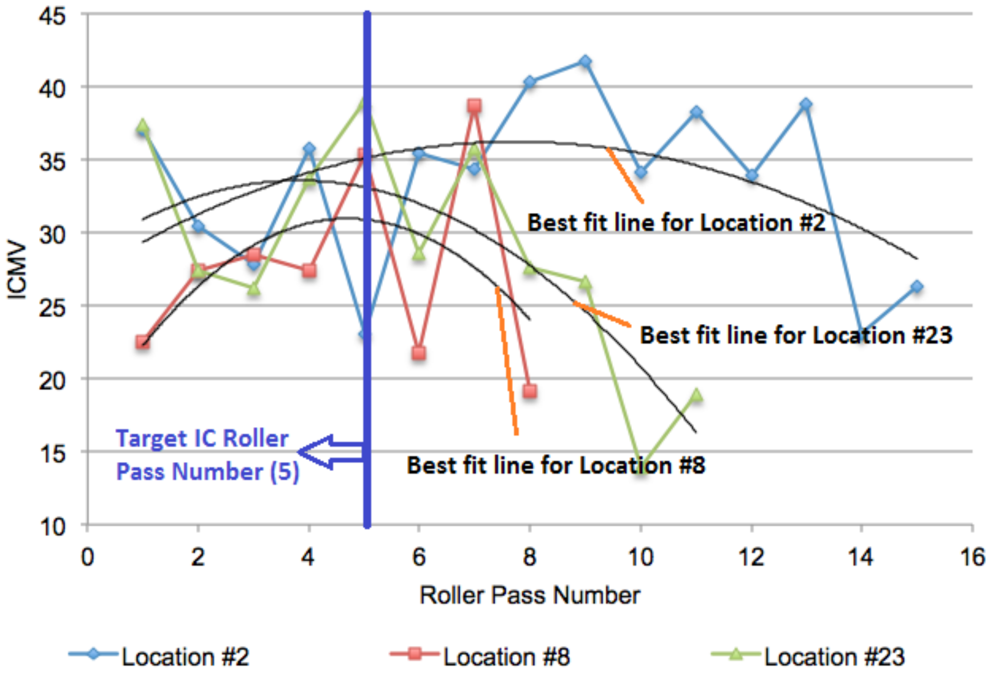

Figure 5.4 Compaction Curve of IC Compactor for Three Arbitrarily Selected Locations On the Class II Sand at Iron River

a). Simple Regression Analysis

Figures C.4 & C.9 in Appendix C present the simple regression analysis results. Table 5.5 below also summarizes the coefficient of determination among different measurements for simple regression analysis. For reference, a R^2 value of greater than 0.5 is considered to be acceptable based on European IC specifications (Mooney 2010). As shown in Table 5.5, generally poor correlations were obtained among different measurements. The following factors may account for this result:

1). Soil Heterogeneity.

It is widely accepted that soil is very homogeneous. During field tests, it was not practical to conduct each of the compaction tests at the same location. Therefore, tests at the same locations were performed at spots within a distance of 10 inches from the marked points, the coordinates of which are shown in Table 4.1 and Table 4.2. Therefore, the slight difference in test locations of various devices with the same test number is an addictive factor affecting the correlation between different measurements. In addition, the stiffness of the support from layers beneath the compaction layer also has an influence on the correlation. This is discussed in detail in the fourth factor below.

2). Moisture Content Variation.

The modulus/stiffness value can vary depending on the moisture content at the time of measurement being taken for a given density. Fernandez (2010) conducted research to evaluate the influence of compaction moisture content and density on the stiffness, modulus and strength of different materials. He found that the changes in modulus at the time of QA test could vary by a factor of five for materials compacted to the maximum dry density but with 2% to 3% variation in compaction moisture content.

3). Narrow Range of Measurements taken on the final compacted layer.

All compaction tests were performed after the final pass of each layer, i.e., the test section was already compacted when compaction tests were conducted. Narrow range of measurement values is unfavorable for correlation. Over a wider range of stiffness, a better correlation might be obtained if IC and point tests were performed after each roller pass or every other roller pass, thus providing a wider range of densities and stiffness.

4). Supporting from sublift material.

Heterogeneity in support conditions of sublift material can adversely affect the correlation between ICMV and point measurements. This is mainly due to the different measurement depths of various testing devices. The IC roller can sense a much larger volume of soil than other devices such as LWD, NDG, Geogauge and MDH. Typically, an ICMV can be representative of soil condition to a depth of four feet, while the LWD, Geogauge or NDG can measure soil properties to a depth of only about one foot.

In addition, the strength of correlation between different measurements is related to the overall stiffness of the sublift material. Mooney et al. (2003) conducted research to study the correlation between ICMV and spot test measurements for sand subgrade soil and crushed rock base material. They found that strength of the correlation would improve if the sublift material was stiffer, or more uniform.

Table 5.5 Coefficient of Determination (R^2) Among Different Measurements on the Class II Sand at Iron River (Simple Regression Analysis)

R^2	NDG	IC	Geogauge	LWD	DCP	MCH
NDG	1.0	0.0202	0.0321	0.1302	0.1358	0.1896
IC		1.0	0.1320	0.1752	0.0089	0.0884
Geogauge			1.0	0.1668	0.1178	0.0050
LWD				1.0	0.4913	0.0634
DCP					1.0	0.0026
MCH						1.0

b). Multiple Regression Analysis

Multiple regression analysis between ICMV and other measurements were performed to incorporate available affecting factors such as the in-place moisture content, roller speed, vibration frequency and amplitude. The significance of the influence of these affecting factors on ICMVs was assessed. The multiple regression analysis model is built as shown in the equation below:

$$\text{ICMV} = B_0 + B_1*(\text{Point measurement}) + B_2*w\% + B_3*V + B_4*f + B_5*A$$

Where B_0 = intercept; B_1, B_2, B_3, B_4 and B_5 = regression coefficients; W% is in-place moisture content; V = roller speed; f = frequency; and A = amplitude.

The significance of incorporating these parameters into a multiple regression analysis is assessed by the t-value and p-value. In this analysis, the criteria to identify the significance of a variable is based on the following criteria: a $p\text{-value} < 0.05$ indicates significance, an absolute value of $t\text{-value} > 1$ indicates significance. Parameters including w%, V, f and A were initially incorporated in the multiple regression analysis to assess the significance of each variable. Parameters in the initial analysis shown as not significant were eliminated from the final analysis. Parameters with a t-value near the edge of the selecting criteria were still kept in the model. In the initial multiple regression analysis for measurements on sand, vibration frequency and amplitude were shown as insignificant and were thus removed from the final analysis. The model for the final multiple regression analysis is shown below:

$$\text{ICMV} = B_0 + B_1 * (\text{Point measurement}) + B_2 * w\% + B_3 * V$$

The final analysis results are shown in Table 5.7. For the multiple regression analysis, the reported R^2 was adjusted for the number of parameters in the model. The adjusted coefficients of determination R^2_{adj} were compared with R^2 from simple regression analysis, which is summarized in Table 5.6. Figure C.10 in Appendix C also shows the multiple regression analysis results. Although the strength of correlation is still weak, it is greatly improved in the multiple regression analysis after incorporating moisture content variation and roller speed.

Table 5.6 Coefficient of Determination (R^2) Between ICMV and Point Measurements on the Class II Sand at Iron River (Multiple Regression Analysis)

	IC & NDG	IC & Geogauge	IC & LWD	IC & DCP	IC & MCH
R^2 (Simple Regression)	0.0202	0.1320	0.1752	0.0089	0.0884
R^2_{adj} (Multiple Regression)	0.1152	0.1429	0.2241	0.1155	0.1200

Table 5.7 Results of Multiple Regression Analysis for Different Measurements on the Class II Sand at Iron River

Test Device	Model	Term	Coefficient Value	Standard Error	t-Value	P-value	R^2	R^2_{adj}
NDG	$ICMV=B_0+B_1*\gamma_d+B_2*V+B_3*W$	B_0	37.90	63.47	0.60	0.56	0.2067	0.1152
		B_1	-0.11	0.53	-0.20	0.84		
		B_2	-4.24	2.27	-1.86	0.07		
		B_3	1.97	0.99	1.99	0.06		
Geogauge	$ICMV=B_0+B_1*(stiffness)+B_2*V+B_3*W$	B_0	23.33	7.37	3.17	0.00	0.2316	0.1429
		B_1	0.14	0.15	0.94	0.36		
		B_2	-3.76	2.29	-1.65	0.11		
		B_3	1.32	1.03	1.28	0.21		
LWD	$ICMV=B_0+B_1*Evd+B_2*V+B_3*W$	B_0	19.09	7.46	2.56	0.02	0.3044	0.2241
		B_1	0.68	0.35	1.92	0.07		
		B_2	-4.70	2.14	-2.19	0.04		
		B_3	0.36	1.12	0.32	0.75		
DCP	$ICMV=B_0+B_1*CBR+B_2*V+B_3*W$	B_0	24.96	7.30	3.42	0.00	0.2070	0.1155
		B_1	-0.15	0.66	-0.22	0.83		
		B_2	-4.04	2.41	-1.67	0.11		
		B_3	2.03	1.09	1.85	0.08		
MCH	$ICMV=B_0+B_1*(Integration)+B_2*V+B_3*W$	B_0	18.24	17.78	1.03	0.31	0.2111	0.1200
		B_1	21.36	49.77	0.43	0.67		
		B_2	-3.76	2.50	-1.51	0.14		
		B_3	1.70	0.95	1.80	0.08		

B). 22A Gravel

As noted above, two sets of data were obtained from the final compaction of the 22A gravel base layer at the Iron River site. The situation developed that an equipment malfunction caused us to not finish testing the final compacted layer, which was on September 12th & 13th. Upon returning to the site the following Monday September 16th, the contractor had conducted a final grading and single-pass of compaction roller prior to paving this section of the project. Thus, additional compaction (one pass) was applied to the 22A base layer. We re-established an additional 30 locations at approximately the same locations as the day before using the previous day's coordinates. The locations were re-established by the contractor's surveyor. NDG tests were again conducted at each location as well as all four of the non-nuclear devices with the exception that the DCP unit broke after testing 12 locations. The two sets of data were analyzed separately.

1). 1st set – September 12th & 13th 22A test Results

Figures 5.5 & 5.6 below summarize all of the measurements obtained during September 12th & 13th. NDG data is used as the standard test data to which other measurements were compared. As Figures 5.5 & 5.6 indicate, LWD measurements have a similar trend with NDG measurements. Lower ICMVs were obtained for both high and low dry densities.

Next, measurements are studied on an overall distribution basis. Statistical measures are summarized in Table 5.8. Stiffness/modulus measurements from devices such as Geogauge, LWD and MCH have similar COV with ICMV while NDG shows a much lower COV value. Figures D.2 & D.3 compare histograms of different testing measurements. Theoretical normal distribution curves were added to these figures for comparison with the actual histograms. As these plots indicate, a normal distribution generally fit the NDG and Geogauge relatively well.

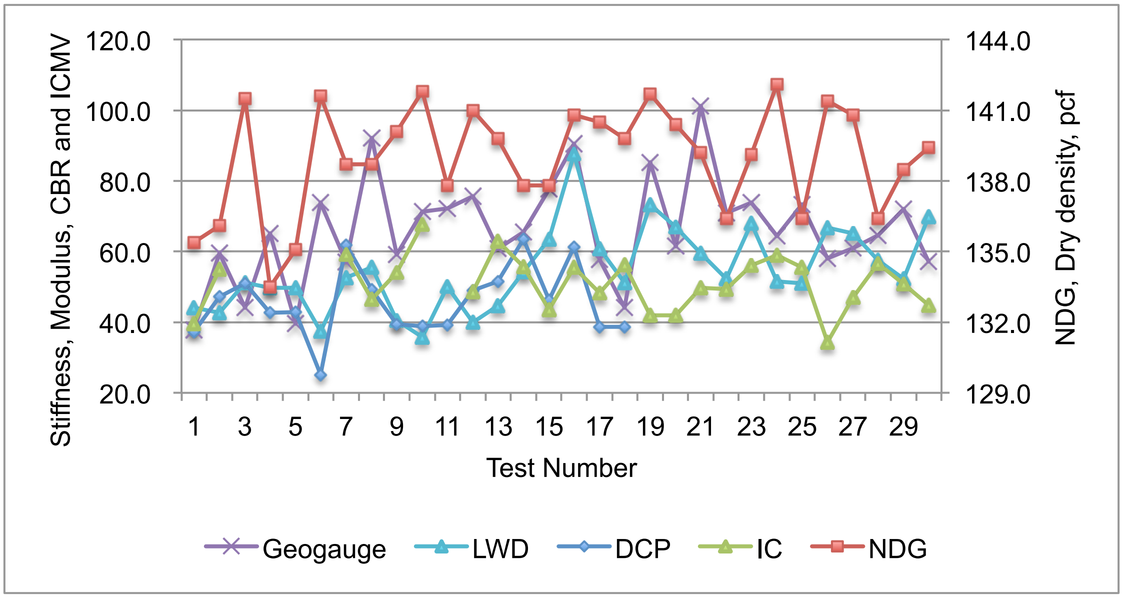

Figure 5.6 NDG and IC, Geogauge, LWD and DCP Test Results on 22A Gravel (1st Set)

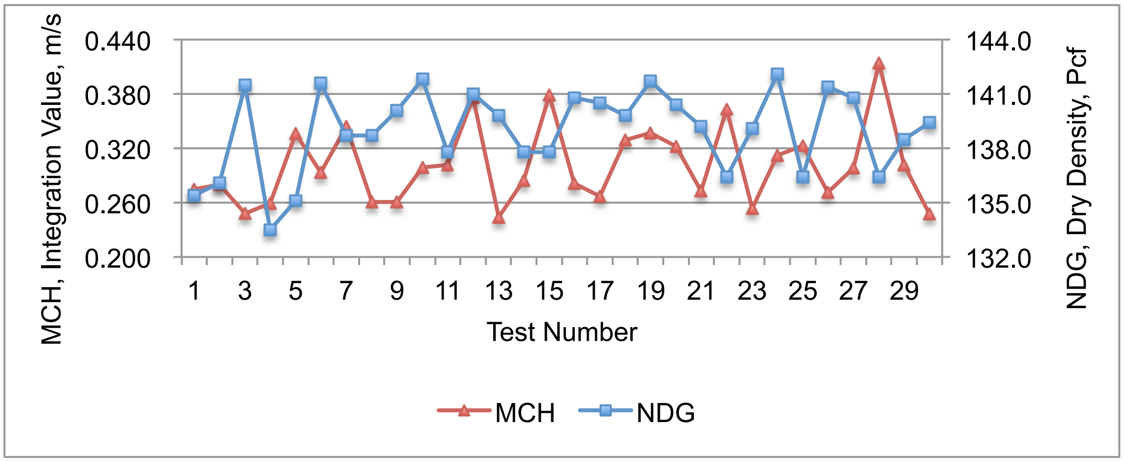

Figure 5.5 NDG and MCH Test Results on 22A Gravel (1st Set) at Iron River

In order to have a better understanding of the measurements overall distribution and the compacted state, the minimum and maximum values of the X-axis of each histogram represent the approximate values for different measurements at the loose state and very dense state. The method used to obtain the measurement value range is the same as that used for sand. Table 5.9 summarizes the approximate values for different measurements on sand at the loose state and very dense state.

Table 5.8 Statistical Measures for Different Test Methods (1st Set) on Gravel at Iron River

Test	Mean	Standard Deviation	COV (%)	Minimum	Maximum	Number Of Tests
NDG	139.0	2.3	1.65	133.5	142.1	30
IC	51.2	7.74	15.12	34.3	67.6	25
Geogauge	66.26	14.78	22.31	37.82	101.15	30
LWD	54.85	11.68	21.29	35.71	87.55	30
DCP	45.80	9.85	21.51	25.18	63.54	18
MCH	0.301	0.044	14.51	0.240	0.410	30

Table 5.9 Summary of Approximate Value for Different Measurements on Gravel at Loose and Dense State at Iron River

	Minimum (Loose)	Maximum (dense)	Range
IC	17.0	70.0	53.0
NDG	93.1	145.0	47.5
Geogauge	21.9	115	93.1
LWD	11.6	100	98.4
DCP	2.1	75	72.9
MCH	0.22	0.43	0.24

Finally, different measurements were compared to each other on a point-to-point basis. Simple regression analysis and multiple regression analysis were performed to assess correlations among different measurements.

a). Simple Regression Analysis

Figure D.4 & D.9 in Appendix D present the simple regression analysis results. Table 6.10 below also summarizes the coefficient of determination (R^2) among different measurements for simple regression analysis. As shown in Table 5.10, generally poor correlations were obtained among different measurements mainly due to soil heterogeneity, narrow range of measurements and support condition of sublift material.

Table 5.10 Coefficient of Determination (R^2) Among Different Measurements on Gravel (1st Set) at Iron River (Simple Regression Analysis)

R^2	NDG	IC	Geogauge	LWD	DCP	MCH
NDG	1.0	0.0008	0.0376	0.0345	0.0004	0.0241
IC		1.0	0.0010	0.1712	0.0600	0.0001
Geogauge			1.0	0.0952	0.0414	0.0048
LWD				1.0	0.2742	0.0009
DCP					1.0	0.0022
MCH						1.0

b). Multiple Regression Analysis

Multiple regression analysis between ICMV and other measurements were performed to incorporate available affecting factors such as the in-place moisture content, roller speed, vibration frequency and amplitude. The significance of the influence of these affecting factors on ICMVs was assessed. The multiple regression analysis model is built as shown in the equation below:

$$\text{ICMV} = B_0 + B_1\text{*(Point measurement)} + B_2\text{*w\%} + B_3\text{*V} + B_4\text{*f} + B_5\text{*A}$$

In the initial multiple regression analysis for measurements on gravel, moisture content was shown not to be significant and was thus removed from the final analysis. This analysis also indicated that the moisture content variation was not significant for the gravel test section. The model for the final multiple regression analysis is shown below:

$$\text{ICMV} = B_0 + B_1\text{*(Point measurement)} + B_3\text{*V} + B_4\text{*f} + B_5\text{*A}$$

The final analysis results are shown in Table 5.12. For the multiple regression analysis, the reported R^2 was adjusted for the number of parameters in the model. The adjusted coefficients of determination R^2_{adj} were compared with R^2 from simple regression analysis, which is summarized in Table 5.11. Figure D.10 in Appendix D also shows the analysis results. As Table 5.11 shows, the strength of correlation is significantly improved in the multiple regression analysis after incorporating roller compaction parameters.

Table 5.11 Coefficient of Determination (R^2) Between ICMV and Point Measurements on Gravel (1st Set) at Iron River (Multiple Regression Analysis)

	IC & NDG	IC & Geogauge	IC & LWD	IC & DCP	IC & MCH
R^2 (Simple Regression)	0.0008	0.0010	0.1712	0.0600	0.0001
R^2_{adj} (Multiple Regression)	0.6336	0.6129	0.6269	0.7622	0.6124

2). 2nd set – September 16th 22A test Results

Figures 5.7 & 5.8 below summarize the measurement results on September 16th. The NDG data again is used as the standard test data to which other measurements were compared. As Figures 5.7 & 5.8 show, the Geogauge and LWD measurements tracked the trend of NDG measurements relatively well. Lower ICMVs were obtained for both high and low dry densities.

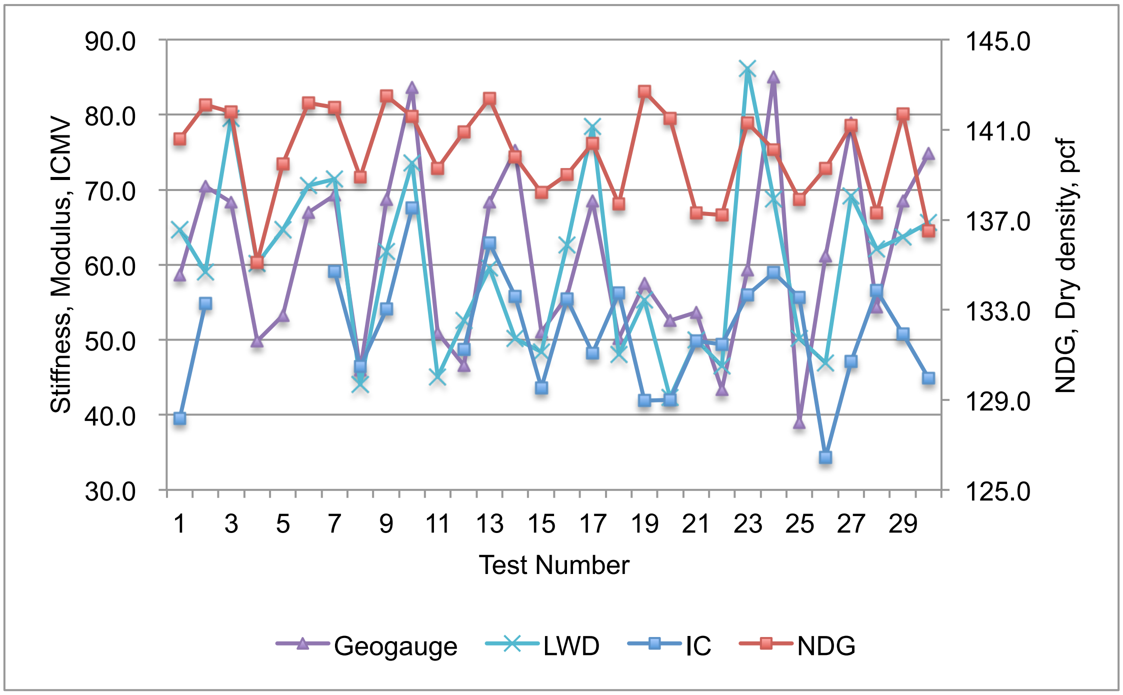

Figure 5.7 NDG and IC, Geogauge and LWD Test Results on Gravel (2nd Set)

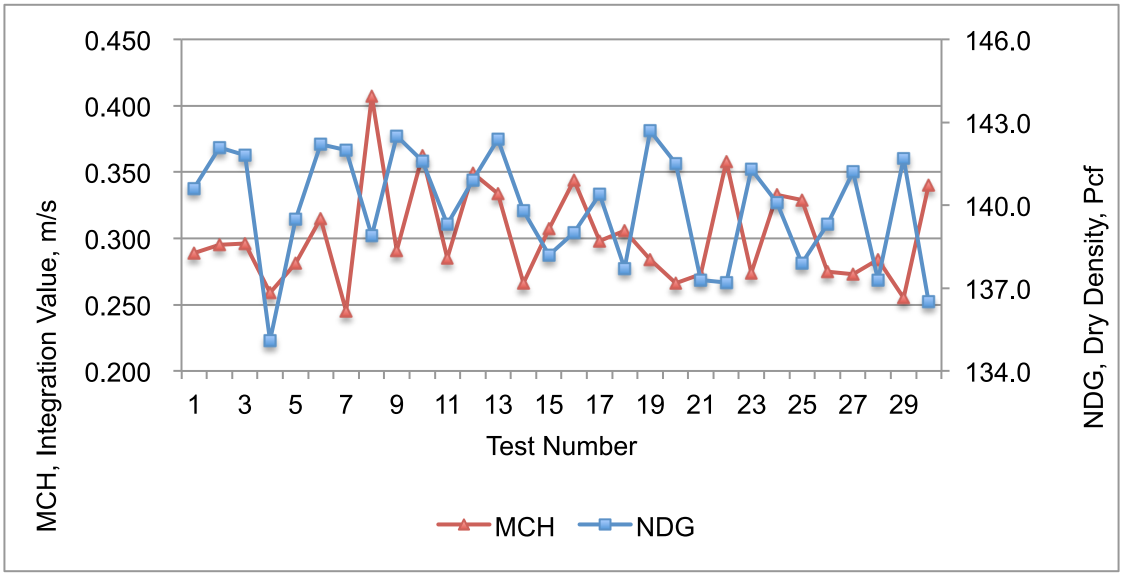

Figure 5.8 NDG and MCH Test Results on Gravel (2nd Set) at Iron River

Next, measurements are studied on an overall distribution basis. Statistical measures are summarized in Table 5.12. Again, IC, Geogauge, LWD, and MCH measurements have similar COV that are significantly different from the NDG measurement. Figure E.1 and Figure E.2 compare histograms of different testing measurements. Theoretical normal distribution curves were added to these figures for comparison with the actual histograms. As these plots indicate, a normal distribution generally fit the NDG and MCH relatively well.

Table 5.12 Statistical Measures for Different Tests (2nd Set) on Gravel at Iron River

Test	Mean	Standard Deviation	COV (%)	Minimum	Maximum	Number of Tests
NDG	139.9	2.06	1.5	135.1	142.7	30
IC	51.2	7.74	15.1	34.3	67.6	25
Geogauge	61	12.08	19.8	39.01	85.03	30
LWD	60.04	11.58	19.3	42.29	86.21	30
DCP	33.1	6.29	19.0	20.71	43.81	9
MCH	0.302	0.38	12.4	0.245	0.407	30

Finally, different measurements were compared to each other on a point-to-point basis. Simple regression analysis and multiple regression analysis were performed to assess correlations among different measurements.

a). Simple Regression Analysis

Figures E.3 & E.4 in Appendix E present the simple regression analysis results. Table 5.13 below also summarizes the coefficient of determination (R^2) among different measurements for simple regression analysis. Generally poor correlations were obtained among different measurements.

Table 5.13. Coefficient of Determination (R^2) Among Different Measurements on Gravel (2nd Set) at Iron River (Simple Regression Analysis)

R^2	NDG	IC	Geogauge	LWD	DCP	MCH
NDG	1.0	0.0262	0.2348	0.1441	0.0497	0.0202
IC		1.0	0.1131	0.1573	0.0797	0.0316
Geogauge			1.0	0.3505	0.4340	0.0169
LWD				1.0	0.2383	0.0224
DCP					1.0	0.0072
MCH						1.0

b). Multiple Regression Analysis

Multiple regression analysis between ICMV and other measurements were performed to incorporate available affecting factors. The multiple regression analysis model is the same as that used in the 1st set of data analysis. As in the 1st set of data analysis, in-place moisture content was shown as insignificant and was thus removed from the final analysis. The final analysis results are shown in Tables 5.15 & 5.16. The adjusted coefficients of determination R^2_{adj} were compared with R^2 from simple regression analysis, which is summarized in Table 5.14. Figure E.7 in Appendix E also shows the analysis results. As Table 5.14 shows, the strength of correlation is significantly improved in the multiple regression analysis after incorporating roller compaction parameters.

Table 5.14 Coefficient of Determination (R^2) Between ICMV and Point Measurements on Gravel (1st Set) at Iron River (Multiple Regression Analysis)

	IC & NDG	IC & Geogauge	IC & LWD	IC & DCP	IC & MCH
R^2 (Simple Regression)	0.0262	0.1131	0.1573	0.0797	0.0316
R^2_{adj} (Multiple Regression)	0.6226	0.6508	0.7692	0.9006	0.6158

Table 5.15 Results of Multiple Regression Analysis for Different Measurements on Gravel (1st Set) at Iron River

Test Device	Model	Term	Coefficient Value	Standard Error	t Value	P-value	R^2	R^2_{adj}
NDG	ICMV=B_0+B_1*γ_d+B_2*V+B_3*f+B_4*A	B_0	801.63	392.75	2.04	0.05	0.6947	0.6336
		B_1	-0.68	0.57	-1.19	0.25		
		B_2	-3.52	1.83	-1.92	0.07		
		B_3	-26.69	12.19	-2.19	0.04		
		B_4	62.61	16.67	3.76	0.00		
Geogauge	ICMV=B_0+B_1*(stiffness)+B_2*V+B_3*f+B_4*A	B_0	658.05	382.12	1.72	0.10	0.6774	0.6129
		B_1	-0.04	0.07	-0.51	0.61		
		B_2	-4.30	1.78	-2.41	0.03		
		B_3	-24.93	12.72	-1.96	0.06		
		B_4	64.63	17.10	3.78	0.00		
LWD	ICMV=B_0+B_1*Evd+B_2*V+B_3*f+B_4*A	B_0	613.49	356.10	1.72	0.10	0.6891	0.6269
		B_1	-0.09	0.09	-1.01	0.32		
		B_2	-4.08	1.75	-2.33	0.03		
		B_3	-23.05	11.88	-1.94	0.07		
		B_4	60.60	17.42	3.48	0.00		
DCP	ICMV=B_0+B_1*CBR+B_2*V+B_3*f+B_4*A	B_0	242.43	423.08	0.57	0.58	0.8415	0.7622
		B_1	0.16	0.13	1.24	0.25		
		B_2	-2.36	2.19	-1.08	0.31		
		B_3	-10.78	13.96	-0.77	0.46		
		B_4	63.78	20.77	3.07	0.02		
MCH	ICMV=B_0+B_1*(Integration)+B_2*V+B_3*f+B_4*A	B_0	525.93	389.68	1.35	0.19	0.6770	0.6124
		B_1	11.68	23.96	0.49	0.63		
		B_2	-4.01	1.84	-2.18	0.04		
		B_3	-20.76	12.89	-1.61	0.12		
		B_4	68.31	17.50	3.90	0.00		

Table 5.16 Results of Multiple Regression Analysis for Different Measurements on Gravel (2^{nd} Set) at Iron River

Test Device	Model	Term	Coefficient Value	Standard Error	t Value	P-value	R^2	R^2_{adj}
NDG	$ICMV=B_0+B_1*\gamma_d+B_2*V+B_3*f+B_4*A$	B_0	454.82	382.36	1.19	0.25	0.6889	0.6226
		B_1	0.58	0.58	1.01	0.33		
		B_2	-5.03	1.92	-2.63	0.02		
		B_3	-20.98	12.04	-1.74	0.10		
		B_4	69.79	16.98	4.11	0.00		
Geogauge	$ICMV=B_0+B_1*(stiffness)+B_2*V+B_3*f+B_4*A$	B_0	663.56	346.76	1.91	0.07	0.7090	0.6508
		B_1	0.14	0.09	1.57	0.13		
		B_2	-5.41	1.85	-2.93	0.01		
		B_3	-25.25	11.59	-2.18	0.04		
		B_4	62.12	16.22	3.83	0.00		
LWD	$ICMV=B_0+B_1*Evd+B_2*V+B_3*f+B_4*A$	B_0	691.23	280.88	2.46	0.02	0.8077	0.7692
		B_1	0.28	0.07	3.74	0.00		
		B_2	-6.35	1.49	-4.28	0.00		
		B_3	-26.58	9.39	-2.83	0.01		
		B_4	64.85	13.03	4.98	0.00		
DCP	$ICMV=B_0+B_1*CBR+B_2*V+B_3*f+B_4*A$	B_0	2279.53	339.14	6.72	0.00	0.9503	0.9006
		B_1	-0.07	0.15	-0.49	0.65		
		B_2	-4.14	1.73	-2.40	0.07		
		B_3	-86.87	12.30	-7.06	0.00		
		B_4	144.43	22.45	6.43	0.00		
MCH	$ICMV=B_0+B_1*(Integration)+B_2*V+B_3*f+B_4*A$	B_0	611.99	361.78	1.69	0.11	0.6798	0.6158
		B_1	-16.93	26.18	-0.65	0.53		
		B_2	-4.24	1.77	-2.39	0.03		
		B_3	-23.44	12.08	-1.94	0.07		
		B_4	68.08	17.09	3.98	0.00		

6. Conclusions and Future Work

6.1 Conclusions and Recommendations

A) Hancock Site Field Study

In general, poor correlations between the devices tested at the Hancock site were obtained. This was due to soil heterogeneity, a limited number of tests (only four locations were tested), and the uncompacted soil pads on which the in-situ tests were performed. However, the LWD and DCP did have the best correlation (R^2) with each other (R^2=0.877).

B) Calumet Site Field Study

Good correlations were obtained among different measurements in general on the compacted 22A layer. All of the other four tests correlate well with NDG density. However, these analysis results may not be very representative since only four measurements for each device were taken. Therefore, correlations among different devices would need further evaluation.

C) Iron River Test Site

Conclusions on how the IC technology works for compaction control are based on data analysis, on-site project observation and literature review.

1. The traditional QC/QA practice, as well as the conventional compaction procedure, has some shortcomings. The IC technology, however, addresses these disadvantages well.

2. The QC/QA practice cannot depend on in-place dry density alone, since the same density can be obtained at two different moisture contents. In addition, the same density does not necessarily indicate equal stiffness. Also, lower ICMV was obtained for both high and low dry densities.

3. It was found a target stiffness for soil type and layer would assist in better compaction since the ICMV depends on many factors such as material type, lift

thickness, in-place moisture content, support condition of sublift layers, roller compaction parameters, and so on. In addition, the documentation systems used to calculate the ICMV from different vendors are proprietary. Therefore, a target ICMV would be site dependent as well as equipment dependent.

4. Measurements were studied on an overall normal distribution basis in terms of average value, standard deviation, COV, minimum and maximum values. The statistical analysis shows that the stiffness/modulus measuring devices such as Geogauge and LWD capture the variation of ICMVs (which also measures stiffness of underlying material) much better than NDG density. It is also shown that the IC, MCH and DCP measurements track the NDG measurements trend well on the sand section. While on the gravel section, the Geogauge and LWD measurements track the NDG dry density trend well. An equivalent normal distribution curve seems to fit the NDG, MCH and IC relatively well.

5. Simple regression analysis and multiple regression analysis were performed to assess correlations among different measurements. For both the simple regression analyses on sand and gravel, generally poor correlations were obtained among different measurements mainly due to soil heterogeneity, moisture content variation, narrow range of measurements and support condition of sublift material. However, the strength of correlation in multiple regression analysis improved greatly after incorporating some of the affecting factors such as the in-place moisture content, roller speed, vibration frequency and amplitude.

6. Optimum or target roller pass number guideline should be followed to improve effectiveness and uniformity of the compaction product. In the M-189 project, the target pass number guideline were exceeded during compaction on the subbase sand. The roller passes in many areas even exceeded 20, which is much higher than the target pass number of five determined for the sand section. Therefore, This appears to

have resulted in over-compaction, which was demonstrated in the compaction curve of IC data at several arbitrarily selected points.

7. Observations on the IC technology used at the Iron River site:

a). IC system is designed to measure the real-time stiffness of underlying material with 100% coverage of compacted section area. IC mapping was found to be effective in identifying weak areas for corrective effort being applied prior to placement of the next lift or layer. Therefore, accelerating application of IC technology to roadway construction could improve uniformity of compacted section, and thus improve long-term performance of the pavement.

b). The IC operator found the real-time feedback continuously from IC system was useful and thus was able to easily identify uncompacted areas. This feature helps improve effectiveness greatly.

c). The IC compactor was easy to operate according to the feedback from the IC operator.

8. Troubles were encountered, however, during importing IC data into FHWA Veda software. Coordinates of the M-189 project were on a MDOT local datum and needed to be converted to the Michigan State Plane Cooordinate system before importing to Veda. However, the IC data could still not be imported successfully after conversion possibly due to incompatibility. It was found that the IC data processing software was not as user-friendly as it should have been. Therefore, there needs to be an effort to improve the compatibility of the data analysis software with IC data of various format from different vendors.

9. The roller compaction parameters have a significant influence on ICMV and therefore must be held constant during proof rolling or roller-based QA. In the M-189 project, there was a significant variation in the roller speed throughout the project.

6.2 Future Research Needs

A): For research on IC technology:

1. It was found that additional factors such as compactor speed and frequency could be incorporated in a multiple regression analysis to produce better correlations between ICMV and point test measurements. For example, the point compaction tests can be performed after each IC roller pass or every other roller pass in order to increase the measurement value range. Parameters representing the support condition of sublift layers can also be accounted for during the regression analysis. Future research should therefore be conducted to better understand how these factors affect the measurement values for stiffness since this parameter will be central in the design of pavement structure as well as the QA/QC techniques to assess stiffness.

2. The ICMV has been successfully correlated with the plate loading test measurement in Europe, possibly because these two measuring devices sense a similar volume of soil. Plate loading tests can be performed in an effort to get a better correlation between ICMV and modulus measurement. Future research should be conducted to evaluate the volume of material each test device can measure and to determine if the volume of material beyond this tested volume is consistent with measured volume. This would possibly allow other non-nuclear testing devices to be used.

3. There is a need to better develop IC QA specifications. Currently, four European countries (Austria, Germany, Sweden, and Switzerland) have IC QA specifications. Some US states are starting to implement preliminary specifications, such as Minnesota DOT pilot specification (2007).

B): On the manufacture side

1. A more compatible and standardized data analysis software should be developed to make the data process more convenient.

2. Stiffness is sensitive to in-place moisture content. So moisture content control is critical during roadway compaction. A feature should be added to the IC machine in the future to measure the real-time compaction moisture content during intelligent compaction. In such a manner, project personnel could easily monitor the in-place moisture content during compaction and maintain the in-place moisture content within the prescribed range of optimum moisture content. In addition, the compaction moisture content has a significant impact on modulus measurements and thus affects the strength of correlation between different measurements.

3. The documentation system of different vendors is proprietary, and thus ICMVs are device dependent. Effort should be made to standardize ICMVs from different vendors in the future.

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Appendix A: Data Analysis For Hancock Site

Table A.1 Sand Cone Calibration for Hancock Site

Apparatus weight (Before filling the cone & base plate)	6347.0	g
Apparatus weight (After filling the cone & base plate)	4524.2	g
Weight of sand required to fill the cone and base plate	1822.8	g
Apparatus weight (Before filling the cone & base plate & mold)	6347.3	g
Apparatus weight (After filling the cone & base plate & mold)	1642.0	g
Weight of Sand required to fill the cone, base plate & mold	4705.3	g
Calibration mold diameter	6.0	inches
Calibration mold height	4.5	inches
Calibration mold volume	0.074	ft^3
Weight of Sand required to fill the calibration mold	2882.5	g
Unit weight of calibration sand	**86.3**	**pcf**
Volume of Cone & base plate	**0.047**	**ft^3**

Table A.2 Moisture Content Tests for Samples From Hancock Site

Test Number	Wt. before drying (Soil + pan, g)	Wt. after drying (Soil + pan, g)	Moisture Content (%)
1	241.9	235.1	2.89
2	203.3	197.5	2.94
3	167.9	163.4	2.75
4	174.1	168.6	3.26

Table A.3 Sand Cone Tests at Hancock Site

Test Number	1	2	3	4
Wt. of apparatus before testing, (g)	6088.6	5786.0	5919.9	5793.1
Wt. of apparatus after testing, (g)	2176.0	1876.9	2057.0	1504.7
Wt. of Calibration Sand required to fill the cone, base plate & hole, (g)	3912.6	3909.1	3862.9	4288.4
Wt. of testing material (sand/gravel, g)	2303.9	2247.2	2431.7	2492.3
Volume of cone, base plate & hole, (ft^3)	0.099	0.099	0.098	0.109
Volume of hole, (ft^3)	0.053	0.053	0.052	0.062
Unit Wt. of testing material (sand/gravel, pcf)	**96.0**	**93.8**	**103.8**	**87.9**
Moisture content (%)	2.89	2.94	2.75	3.26
Dry Unit Wt. of testing material (sand/gravel, pcf)	**93.3**	**91.1**	**101.0**	**85.2**

Table A.4 Summary of Compaction Test Data at Hancock Site

Test Number		Sand Cone	Geogauge	LWD	DCP	MCH
		Dry Density pcf	Stiffness (klbs/in)	Dynamic deflection module E_{vd}, MN/m^2	CBR, %	Integration Value (m/s)
Gravel	1	93.3	25.7	18.73	2.09	0.295
	2	91.1	22.4	18.6	3.11	0.336
Sand	3	101.0	20.4	12.68	5.74	0.290
	4	85.2	23.4	10.45	10.85	0.274

Table A.5 Grain Size Analysis of Sand Sample From Hancock Site

Sieve		Wt. without soil	Wt. with soil	Soil Retained	Percentage on each sieve	Cumulative percentage retained	% Finer
No. (US std)	Size (mm)						
5/8"	15.88	562.3	573.2	10.9	2.9	2.9	**97.1**
1/2"	12.70	807.3	816.3	9.0	2.4	5.2	**94.8**
4	4.75	718.3	741.3	23.0	6.0	11.3	**88.7**
10	2.00	432.5	482.1	49.6	13.0	24.3	**75.7**
40	0.425	388.3	518.0	129.7	34.0	58.3	**41.7**
60	0.250	315.4	387.7	72.3	19.0	77.3	**22.7**
100	0.150	352.3	396.2	43.9	11.5	88.8	**11.2**
140	0.106	331.3	347.1	15.8	4.1	92.9	**7.1**
200	0.075	291.5	303.5	12.0	3.1	96.1	**3.9**
Pan	--	278.4	293.3	14.9	3.9	100.0	**0.0**

W total= 381.1

Error Reporting

W Initial (g)	Winitial - Wtotal (g)	(n+2)*balance sensitivity	**Checked**
382.1	1.0	1.1	

1. Percentage passing #4 (1/4 in) sieve)	88.7
Percentage passing #40 (0.425 mm) sieve)	41.7
Percentage passing #200 (0.075 mm) sieve)	3.9

2. From the grain size distribution, determine D10, D30 and D60, *grain size that corresponds to 10%, 30% and 60% passing*

D10 =	0.14
D30 =	0.30
D60 =	0.93

3. Calculate the Coefficient of Uniformity (Cu) and Curvature (Cc)

Cc =	0.69
Cu =	6.64

4. Classify the soil by the Unified methods.

Poorly-graded sand

Table A.6 Grain Size Analysis of Gravel Sample From Hancock Site

Sieve		Wt. without soil	Wt. with soil	Soil Retained	Percentage on each sieve	Cumulative percentage retained	% Finer
No. (US std)	Size (mm)						
5/8"	15.88	562.3	762.3	200.0	24.6	24.6	**75.4**
1/2"	12.70	810.6	929.3	118.7	14.6	39.2	**60.8**
4	4.75	718.6	844.4	125.8	15.5	54.7	**45.3**
10	2.00	432.7	498.8	66.1	8.1	62.8	**37.2**
40	0.425	388.3	521.6	133.3	16.4	79.2	**20.8**
60	0.250	315.5	406.4	90.9	11.2	90.4	**9.6**
100	0.150	352.3	397.1	44.8	5.5	95.9	**4.1**
140	0.106	331.3	344.0	12.7	1.6	97.4	**2.6**
200	0.075	291.5	300.5	9.0	1.1	98.5	**1.5**
pan	--	278.3	290.2	11.9	1.5	100.0	**0.0**
			W total=	813.2			

Error Reporting

W Initial (g)	Winitial - Wtotal (g)	(n+2)*balance sensitivity	**Checked**
813.8	0.6	1.1	

1. Percentage passing #4 (1/4 in) sieve)	45.3
Percentage passing #40 (0.425 mm) sieve)	20.8
Percentage passing #200 (0.075 mm) sieve)	1.5

2. From the grain size distribution, determine D10, D30 and D60, *grain size that corresponds to 10%, 30% and 60% passing*

D10 = 0.26

D30 = 0.97

D60 = 12.30

3. Calculate the Coefficient of Uniformity (Cu) and Curvature (Cc)

Cc = 0.29

Cu = 47.31

4. Classify the soil by the Unified methods.

Poorly-graded gravel with sand

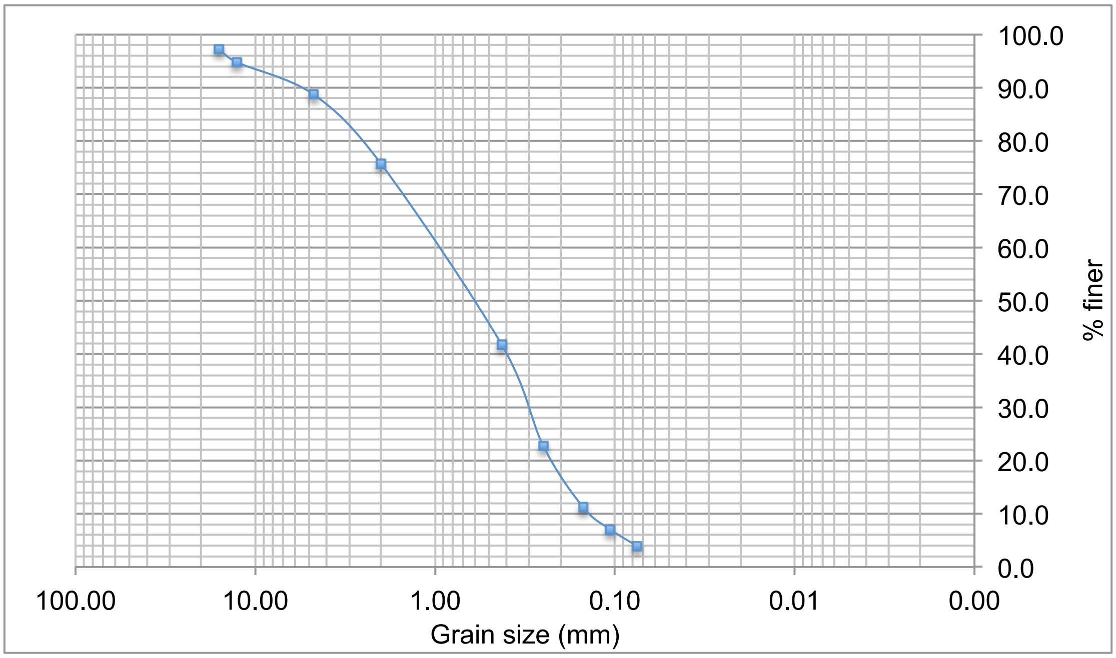

Figure A.1 Grain Size Distribution Curve For Sand Sample From Hancock Site

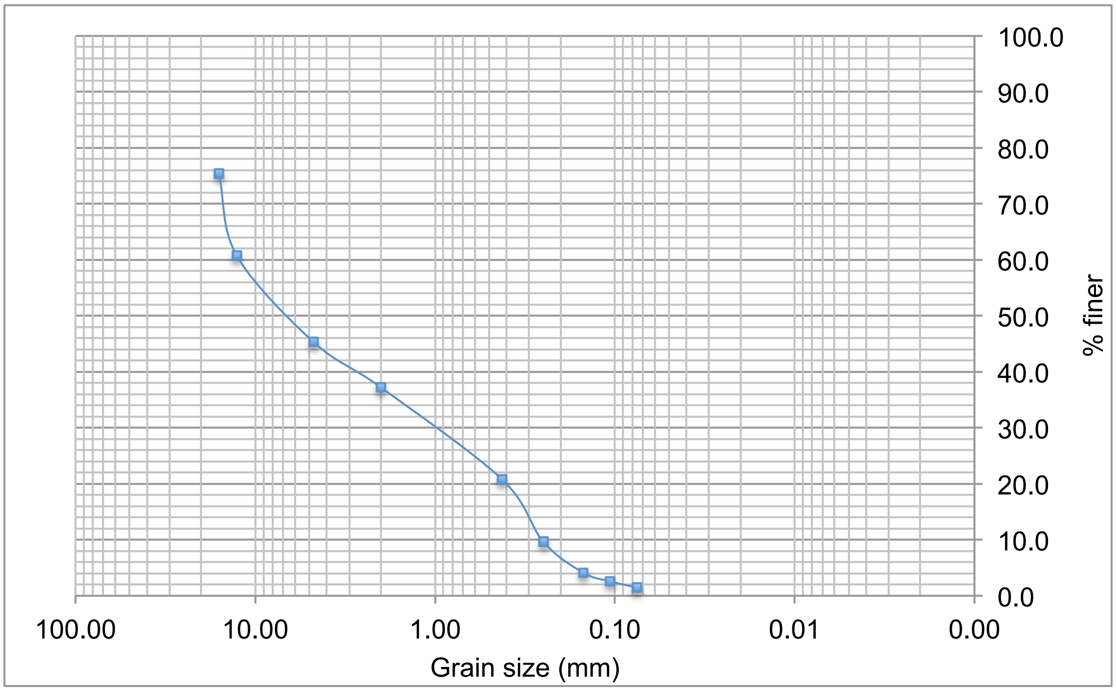

Figure A.2 Grain Size Distribution Curve For Gravel Sample From Hancock Site

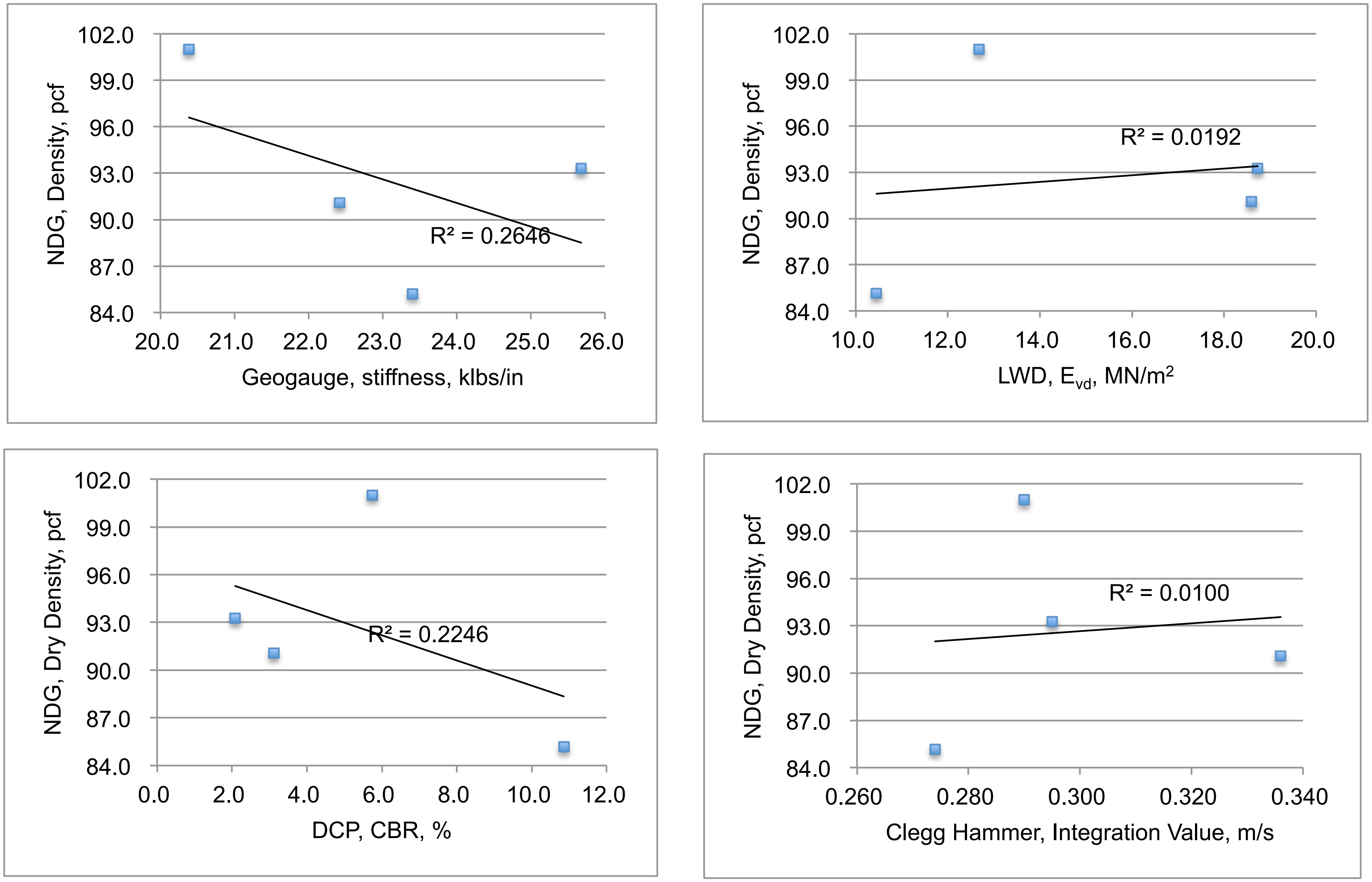

Figure A.3 Comparison of NDG to Geogauge, LWD, DCP and MCH at Hancock Site

Appendix B: Data Analysis For Calumet Site

Table B.1 Summary of Test Data at Calumet Site

Test Number	NDG	Geogauge	LWD	DCP	MCH	Moisture Content
	Dry Density (pcf)	Stiffness (klbs/in)	Dynamic deflection module E_{vd}, MN/m^2	CBR %	Integration Value (m/s)	%
1	132.7	70.40	41.06	27.82	0.273	5.7
2	131.4	68.97	24.17	30.98	0.303	5.6
3	137.7	98.88	47.47	34.67	0.348	5.1
4	137.2	93.34	34.94	34.32	0.388	4.9

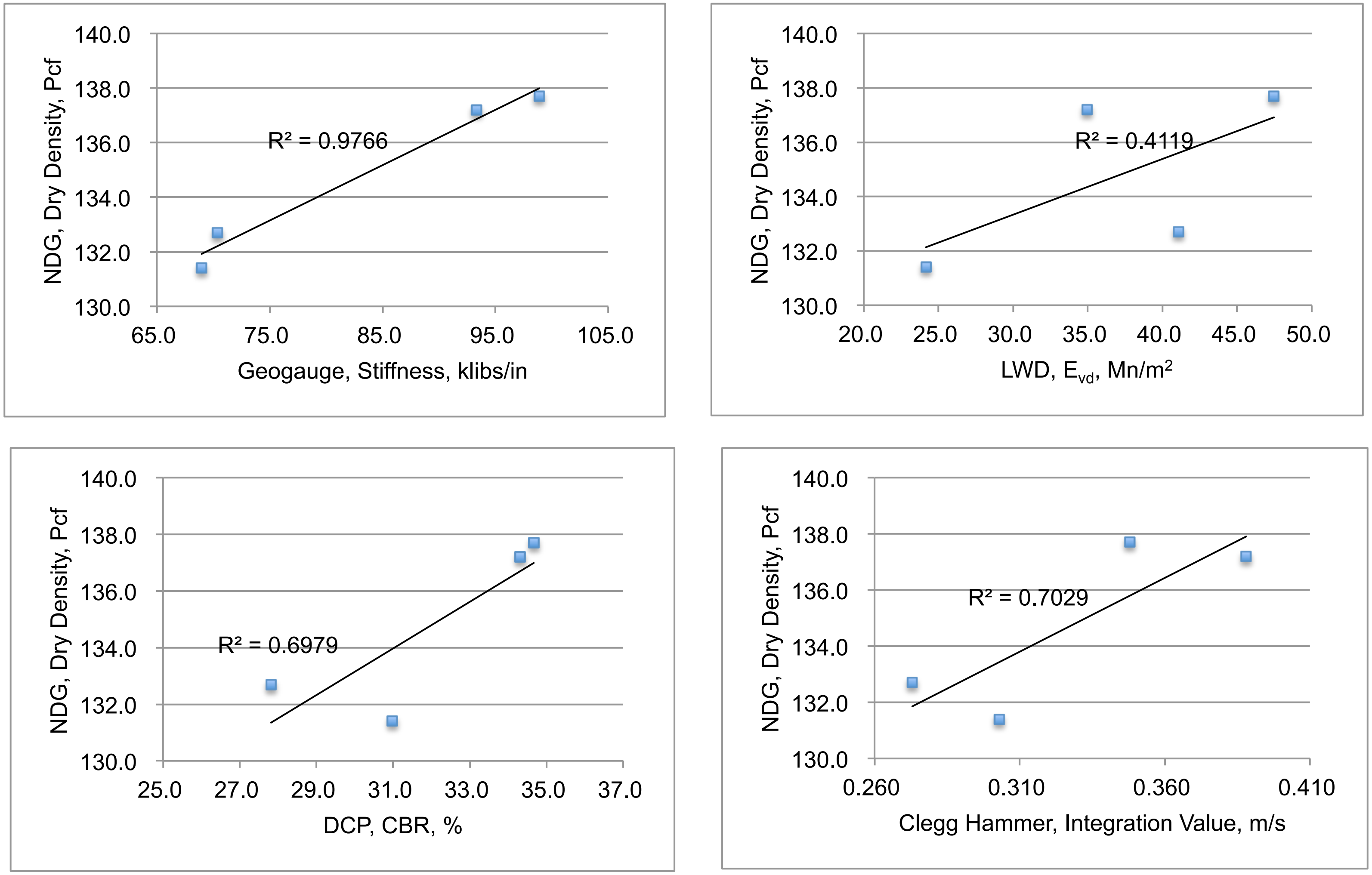

Figure B.1 Comparison of NDG to Geogauge, LWD, DCP and MCH at Calumet Site

Appendix C: Data Analysis For Sand at Iron River

Table C.1 Grain Size Analysis of Sand Sample From Iron River Site

Sieve		Wt. without soil	Wt. with soil	Soil Retained	Percentage on each sieve	Cumulative percentage retained	% Finer
No. (US std)	Size (mm)						
5/8"	15.88	562.20	562.18	-0.02	0.0	0.0	100.0
3/8"	9.50	800.74	810.92	10.18	0.8	0.8	99.2
4	4.75	466.42	557.70	91.28	6.9	7.6	92.4
10	2.00	487.23	606.83	119.60	9.0	16.6	83.4
40	0.425	328.52	1062.6	734.08	55.3	71.9	28.1
60	0.250	369.24	629.50	260.26	19.6	91.5	8.5
100	0.150	346.63	416.30	69.67	5.2	96.8	3.2
140	0.106	339.06	349.90	10.84	0.8	97.6	2.4
200	0.075	327.91	336.55	8.64	0.7	98.2	1.8
pan	--	374.96	398.51	23.55	1.8	100.0	0.0
			W total=	1328.08			

Error Reporting

W Initial (g)	Winitial - Wtotal (g)	(n+2)*balance sensitivity	**Checked**
1328.05	-0.03	0.11	

1. Percentage passing #4 (1/4 in) sieve)	92.4
Percentage passing #40 (0.425 mm) sieve)	28.1
Percentage passing #200 (0.075 mm) sieve)	1.8

2. From the grain size distribution, determine D10, D30 and D60, *grain size that corresponds to 10%, 30% and 60% passing*

D10 =	0.24
D30 =	0.43
D60 =	1.00

3. Calculate the Coefficient of Uniformity (Cu) and Curvature (Cc)

Cc =	0.77
Cu =	4.17

4. Classify the soil by the Unified methods.

Poorly-graded sand

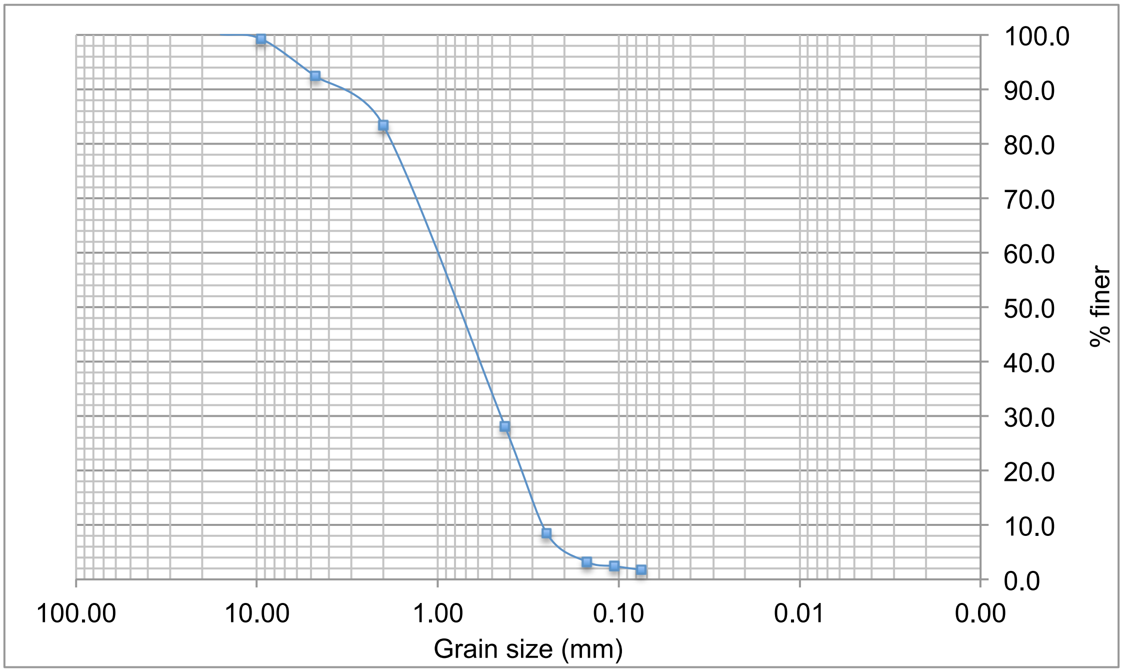

Figure C.1 Grain Size Distribution Curve For Sand Sample From Iron River Site

Table C.2 Summary of Test Data on Class II Sand at Iron River Site

Test #	NDG		IC	MCH	Geogauge	LWD	DCP	W%
	Dry Unit Wt. (pcf)	% Max r_d	ICMV	Integration Value (m/s)	Stiffness (klbs/in)	E_{vd} MN/m^2	CBR %	%
1	121.0	96.0	27.6	0.316	37.60	27.99	8.53	7.1
2	124.3	98.7	26.3	0.305	44.65	29.84	11.43	6.4
3	120.8	95.9	24.6	0.264	38.83	21.59	5.26	5.1
4	121.8	96.7	23.5	0.304	32.83	23.03	7.50	5.9
5	123.4	97.9	23.4	0.321	34.62	23.34	10.07	6.1
6	123.5	98.0	26.6	0.287	22.00	21.76	8.53	5.0
7	123.7	98.2	26.6	0.321	29.09	28.81	9.20	5.9
8	124.1	98.5	19.2	0.327	19.19	22.32	5.03	4.3
9	121.0	96.0	26.5	0.320	19.42	24.59	7.67	5.7
10	123.2	97.8	24.5	0.291	17.64	28.27	9.53	5.7
11	122.6	97.3	23.6	0.305	26.42	23.36	7.50	5.6
12	126.0	96.0	29.4	0.325	27.77	23.01	6.05	6.0
13	121.3	96.3	17.2	0.287	15.93	17.70	6.73	3.7
14	123.7	98.2	27.2	0.335	20.77	25.95	7.84	5.1
15	124.8	99.0	19.9	0.323	23.91	25.40	6.75	6.9
16	123.3	97.9	25.4	0.292	22.74	21.87	6.91	5.2
17	126.0	100.0	25.9	0.337	25.25	22.75	7.57	6.1
18	120.6	95.7	17.1	0.292	18.15	21.03	5.08	4.0
19	124.7	99.0	18.9	0.303	27.72	22.52	8.46	5.8
20	124.7	96.0	22.3	0.302	26.29	25.98	9.40	6.6
21	123.8	98.3	31.9	0.321	30.61	21.99	5.26	5.7
22	125.4	99.5	18.1	0.316	31.10	24.22	7.67	6.5
23	121.7	96.6	22.7	0.275	24.16	21.03	5.26	3.4
24	123.5	98.0	21.2	0.318	25.96	21.59	7.60	5.3
25	120.7	95.8	27.8	0.324	26.94	26.44	7.67	6.0
26	123.0	96.0	30.7	0.347	28.28	20.81	5.33	4.5
27	125.8	99.8	15.5	0.317	27.76	25.03	10.16	6.4
28	121.0	96.0	18.9	0.286	17.13	21.49	7.74	4.8
29	121.6	96.5	16.0	0.322	21.67	20.33	5.23	3.7
30	119.7	95.0	14.6	0.299	22.28	15.40	5.28	4.3

Table C.3 ICMV and IC Roller Compaction Parameters on Class II Sand

Test Number	ICMV	IC Roller Speed (mph)	Roller Vibration Frequency (Hz)	Roller Vibration Amplitude (mm)
1	27.6	3.0	28.4	1.52
2	26.3	3.1	28.4	1.65
3	24.6	2.8	28.2	1.66
4	23.5	3.4	28.3	1.64
5	23.4	2.7	28.3	1.66
6	26.6	3.4	28.3	1.59
7	26.6	2.9	28.3	1.69
8	19.2	2.9	28.2	1.67
9	26.5	3.1	28.3	1.69
10	24.5	3.0	27.9	1.68
11	23.6	3.0	28.4	1.58
12	29.4	3.1	28.4	1.52
13	17.2	2.8	28.2	1.69
14	27.2	3.2	28.3	1.66
15	19.9	3.0	28.3	1.63
16	25.4	2.9	28.4	1.67
17	25.9	2.7	28.4	1.60
18	17.1	2.5	28.6	1.71
19	18.9	3.0	28.4	1.53
20	22.3	3.3	28.2	1.65
21	31.9	2.3	28.3	1.64
22	18.1	2.9	28.2	1.69
23	22.7	3.0	28.5	1.71
24	21.2	3.3	28.5	1.51
25	27.8	2.8	28.4	1.64
26	30.7	1.4	28.4	1.59
27	15.5	3.0	28.4	1.62
28	18.9	3.0	28.4	1.52
29	16.0	3.0	28.4	1.65
30	14.6	2.9	28.2	1.66

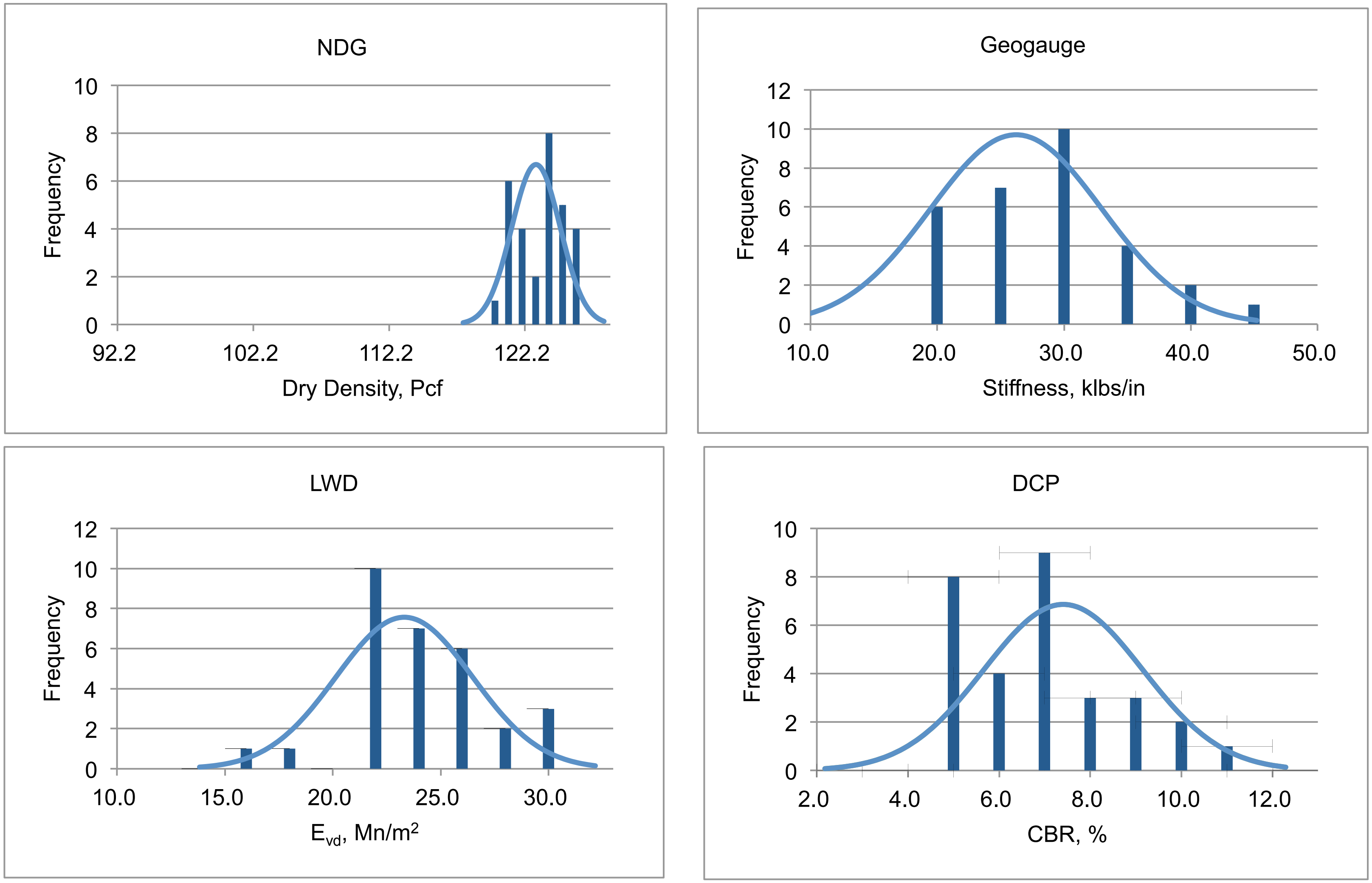

Figure C.2 Histograms of NDG, Geogauge, LWD, and DCP Test on Sand at Iron River

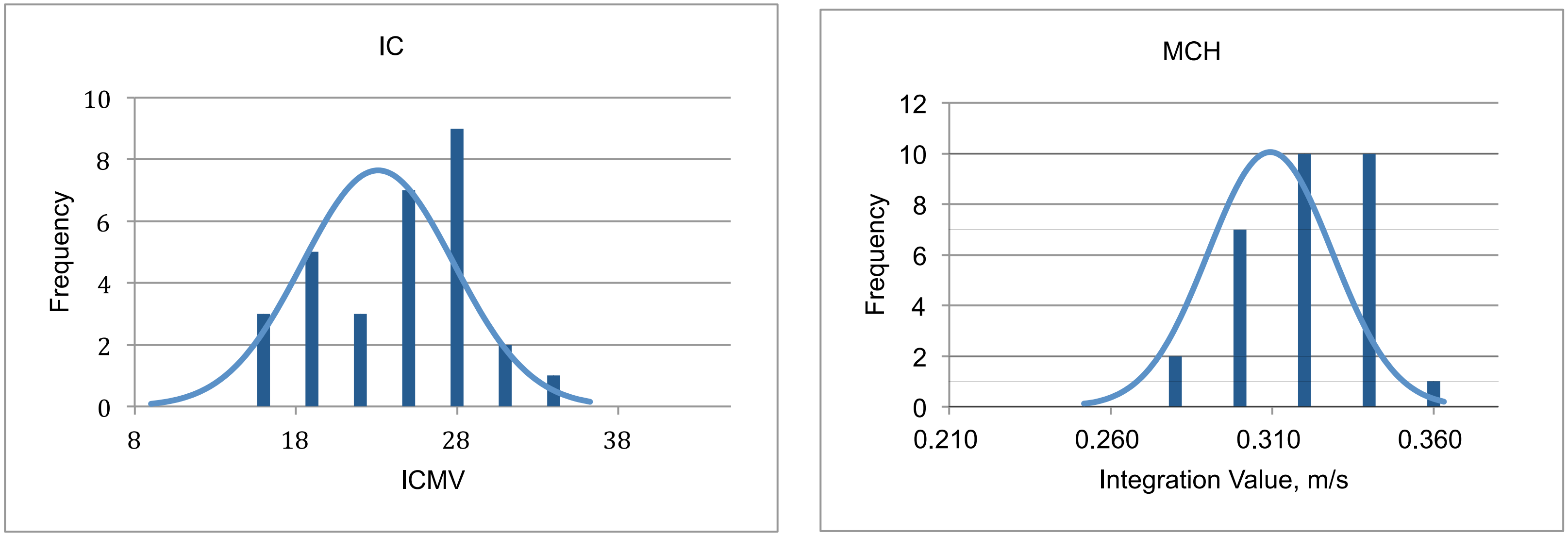

Figure C.3 Histograms of IC and MCH Test on Sand at Iron River

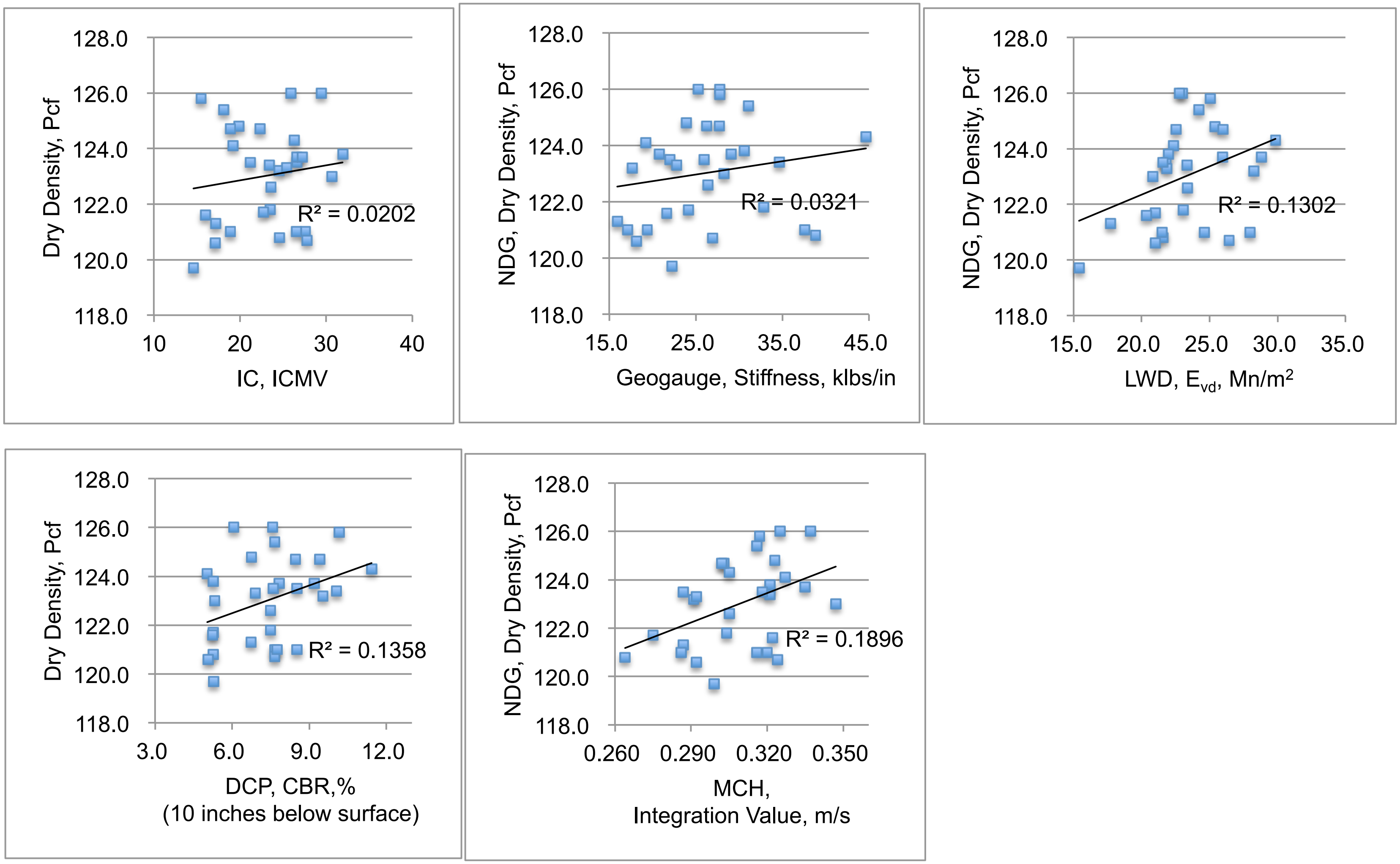

Figure C.4 Comparison of NDG to IC, Geogauge, LWD, DCP and MCH on Sand at Iron River (Simple Regression)

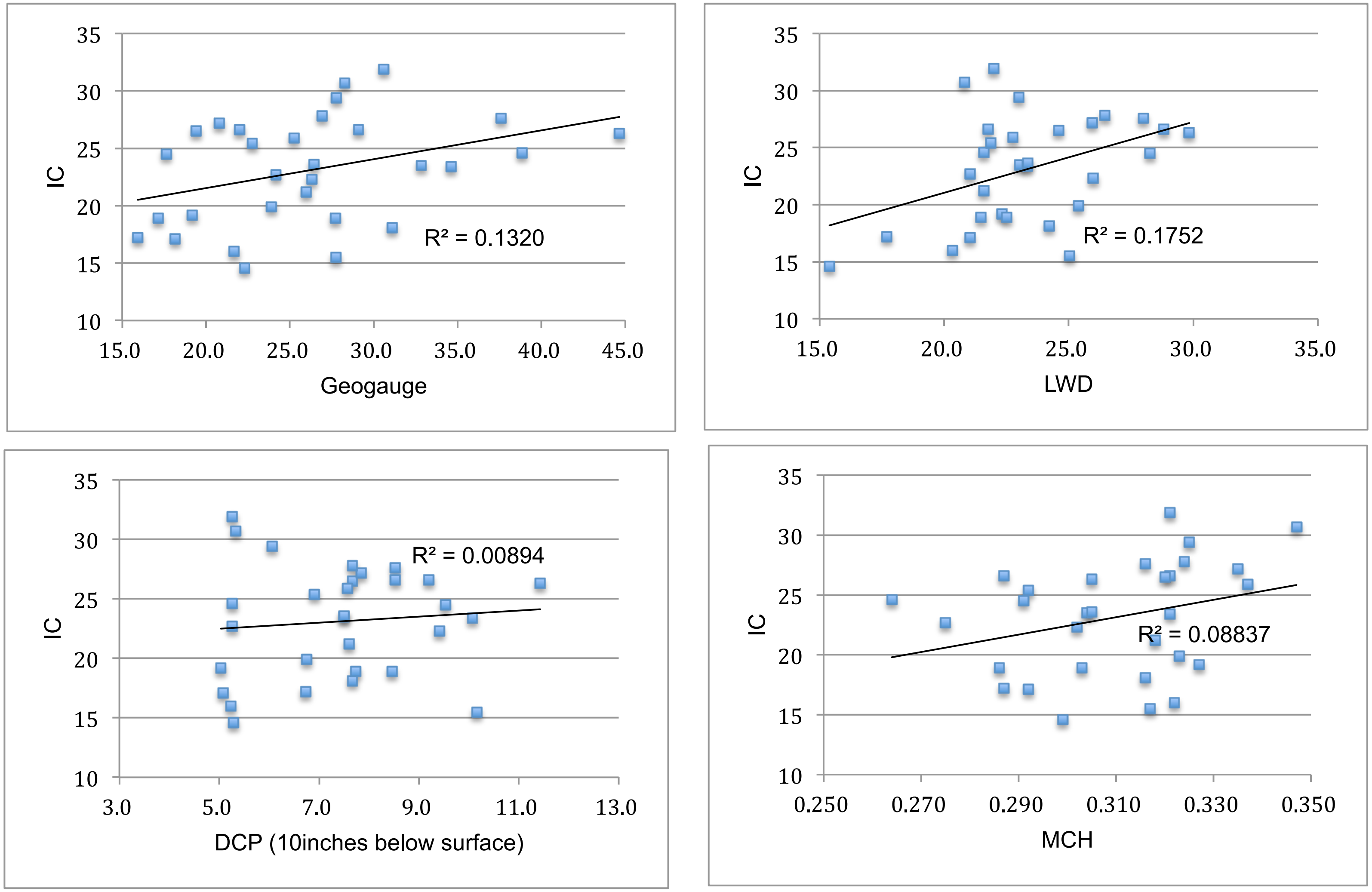

Figure C.5 Comparison of IC to Geogauge, LWD, DCP and MCH on Sand at Iron River (Simple Regression)

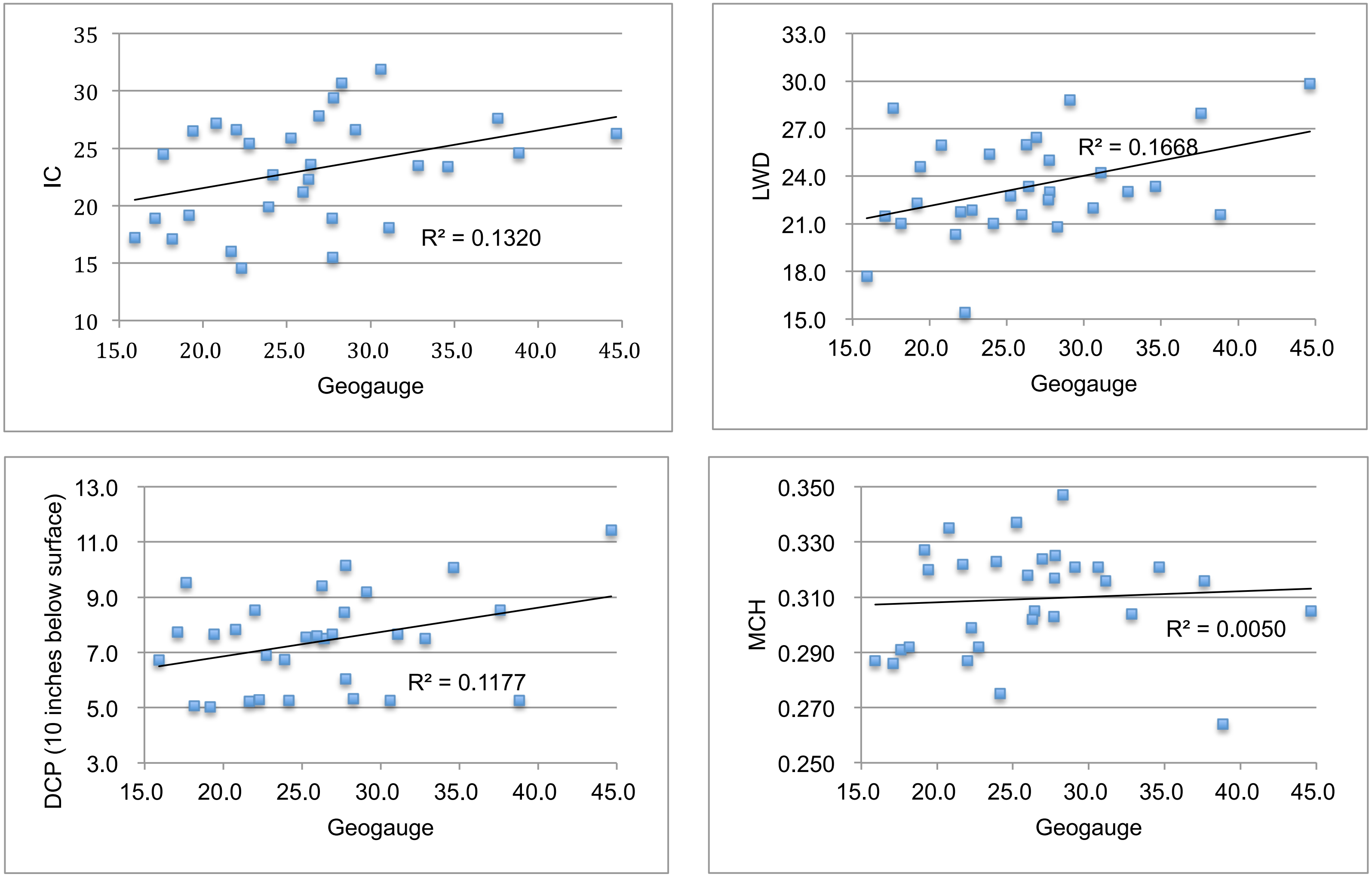

Figure C.6 Comparison of Geogauge to IC, LWD, DCP and MCH on Sand at Iron River (Simple Regression)

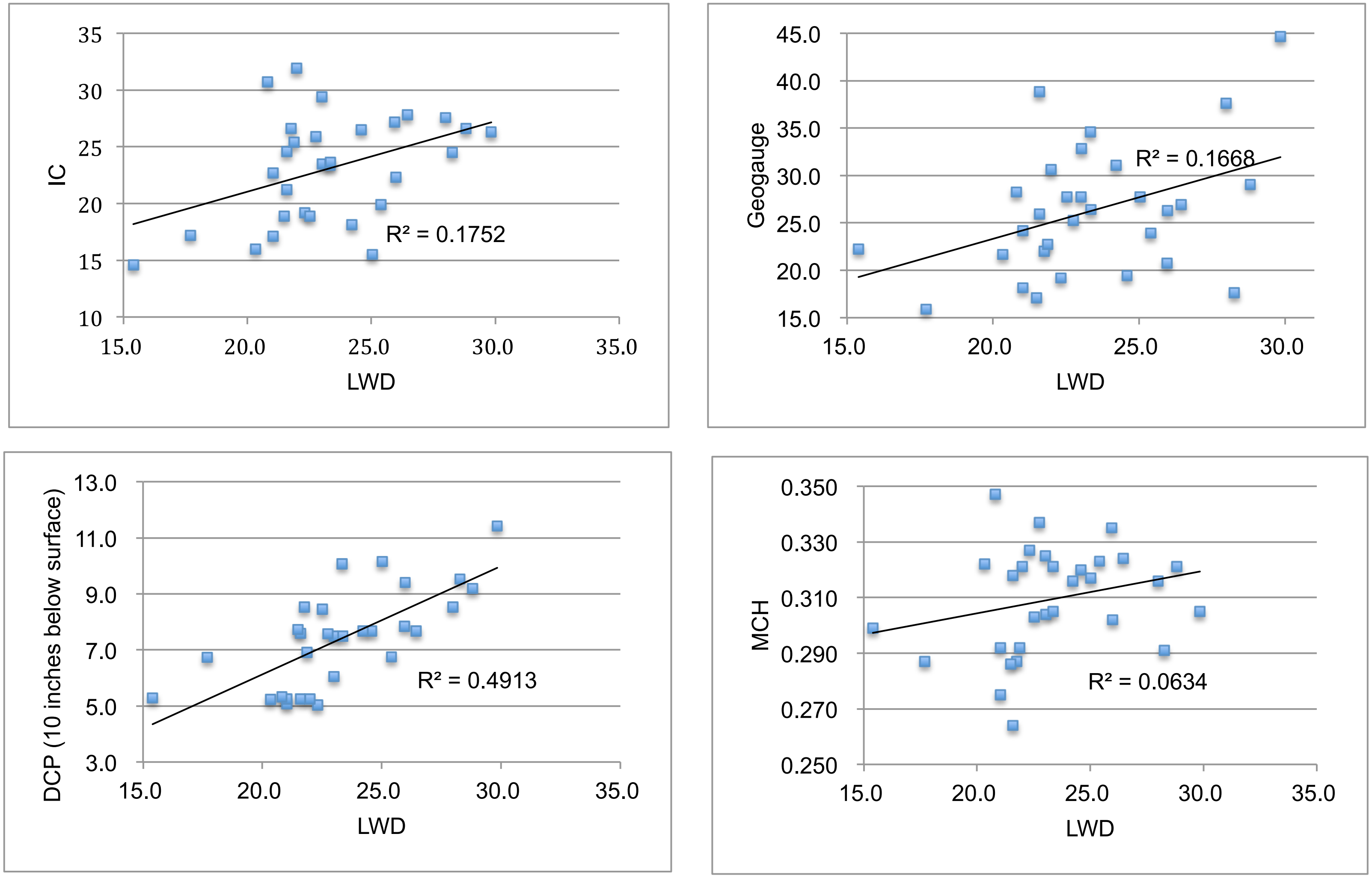

Figure C.7 Comparison of LWD to IC, Geogauge, DCP and MCH on Sand at Iron River (Simple Regression)

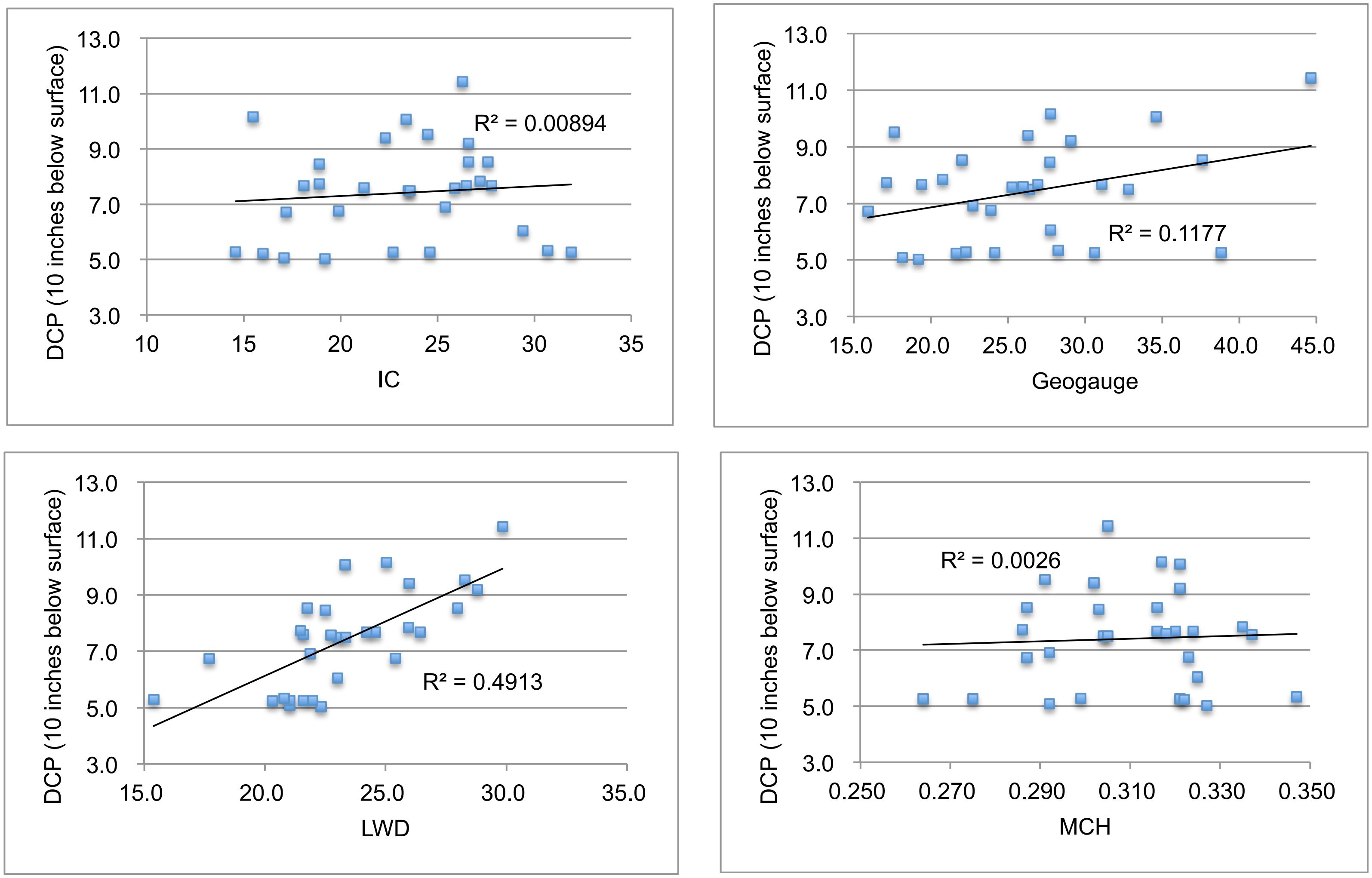

Figure C.8 Comparison of DCP to IC, Geogauge, LWD and MCH on Sand at Iron River (Simple Regression)

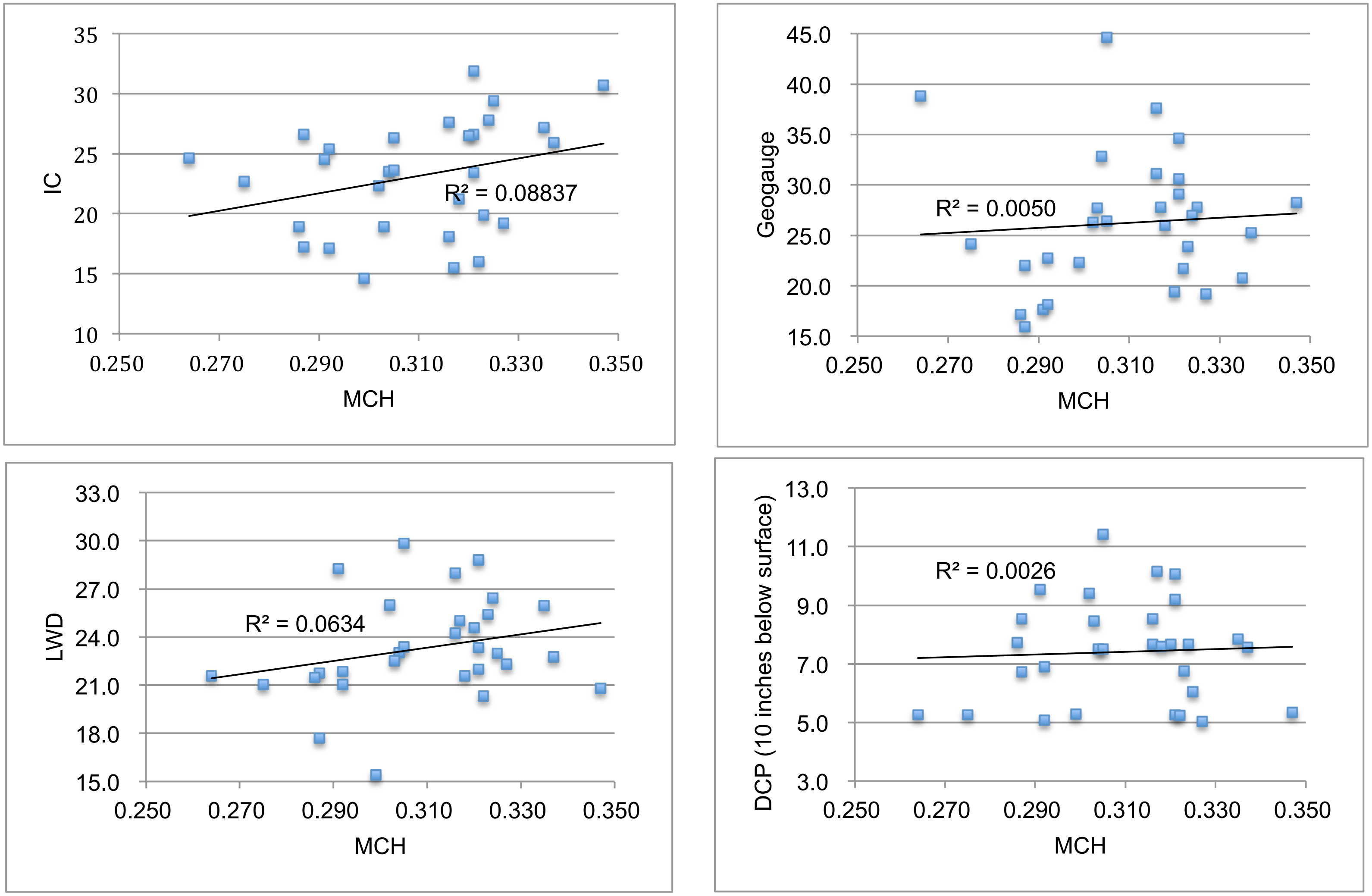

Figure C.9 Comparison of MCH to IC, Geogauge, LWD and DCP on Sand at Iron River (Simple Regression)

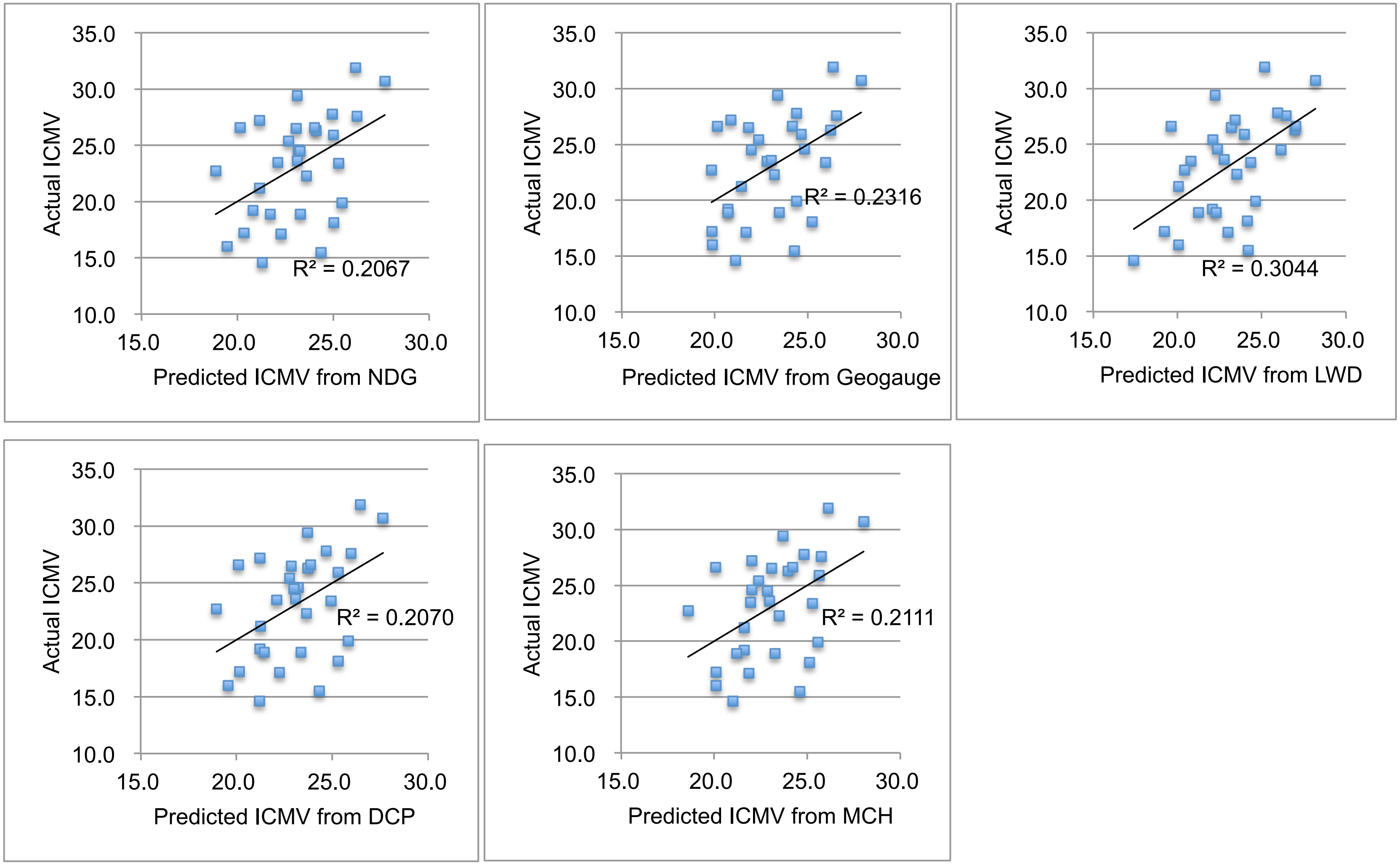

Figure C.10 Correlation of IC to NDG, Geogauge, LWD, DCP and MCH on Sand at Iron River (Multiple Regression)

Appendix D: Data Analysis for Gravel (1st Set) at Iron River

Table D.1 Grain Size Analysis of Gravel Sample From Iron River Site

Sieve		Wt. without soil	Wt. with soil	Soil Retained	Percentage on each sieve	Cumulative percentage retained	% Finer
No. (US std)	Size (mm)						
5/8"	15.88	562.18	611.41	49.23	3.8	3.8	**96.2**
3/8"	9.50	800.75	1053.6	252.85	19.8	23.6	**76.4**
4	4.75	466.42	675.21	208.79	16.3	39.9	**60.1**
10	2.00	487.25	638.31	151.06	11.8	51.7	**48.3**
40	0.425	329.13	790.81	461.68	36.1	87.8	**12.2**
60	0.250	369.33	469.73	100.40	7.8	95.7	**4.3**
100	0.150	346.62	371.31	24.69	1.9	97.6	**2.4**
140	0.106	339.08	344.78	5.70	0.4	98.0	**2.0**
200	0.075	327.89	333.90	6.01	0.5	98.5	**1.5**
pan	--	374.96	394.19	19.23	1.5	100.0	**0.0**

W total= 1279.64

Error Reporting

W Initial (g)	Winitial - Wtotal (g)	(n+2)*balance sensitivity	**Checked**
1279.73	0.09	0.11	

1. Percentage passing #4 (1/4 in) sieve)	60.1
Percentage passing #40 (0.425 mm) sieve)	12.2
Percentage passing #200 (0.075 mm) sieve)	1.5

2. From the grain size distribution, determine D10, D30 and D60, *grain size that corresponds to 10%, 30% and 60% passing*

D10 = 0.37

D30 = 0.90

D60 = 4.55

3. Calculate the Coefficient of Uniformity (Cu) and Curvature (Cc)

Cc = 0.48

Cu = 12.30

4. Classify the soil by the Unified methods.

Poorly-graded Gravel with Sand

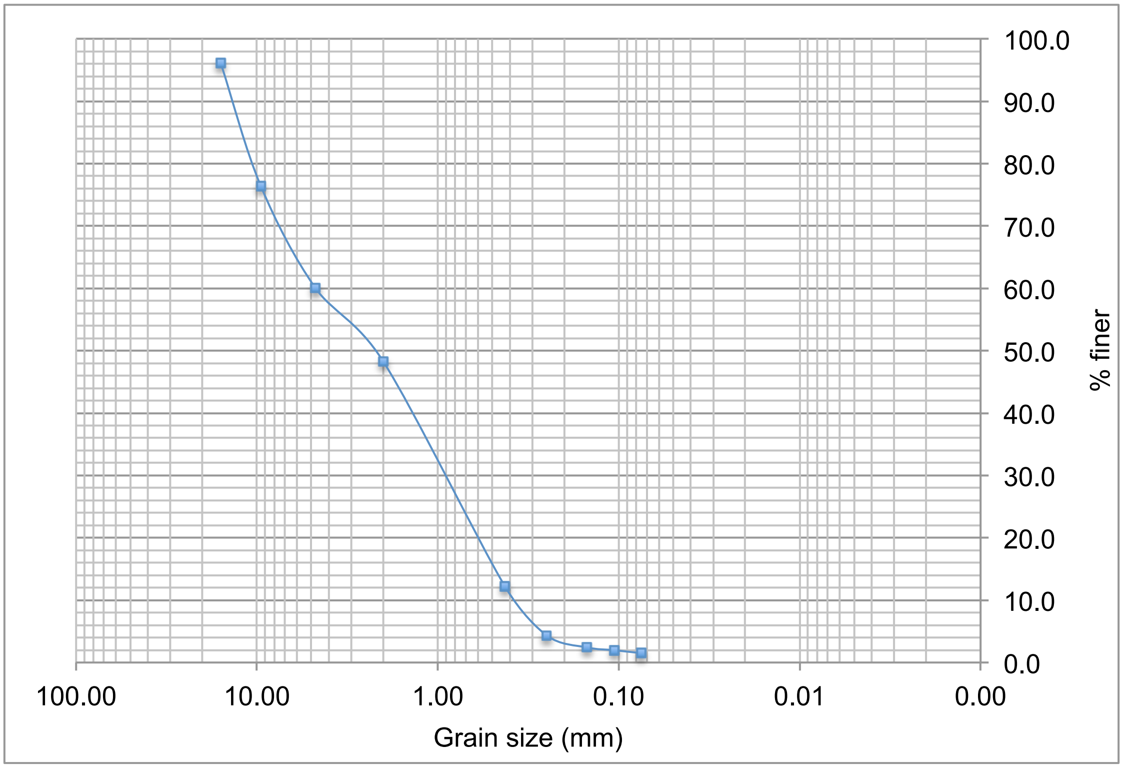

Figure D.1 Grain Size Distribution Curve for Gravel Sample From Iron River Site

Table D.2 Summary of Test Data (1st set) on 22A Gravel at Iron River Site

Test #	NDG		IC	MCH	Geogauge	LWD	DCP	W%
	Dry Unit Wt. (pcf)	% Max r_d	ICMV	Integration Value (m/s)	Stiffness (klbs/in)	E_{vd} MN/m^2	CBR %	%
1	135.4	96.3	39.5	0.275	37.82	44.20	37.24	3.1
2	136.1	96.8	54.9	0.280	59.50	42.61	47.23	3.4
3	141.5	100.6	/	0.248	44.13	51.14	51.08	3.3
4	133.5	95.0	/	0.259	65.20	49.67	42.74	3.5
5	135.1	96.1	/	0.336	39.54	49.78	42.82	2.9
6	141.6	100.7	/	0.293	73.91	37.38	25.18	3.4
7	138.7	98.6	59.1	0.344	57.05	52.69	61.92	3.2
8	138.7	98.6	46.4	0.261	92.17	55.61	49.20	3.2
9	140.1	99.6	54.1	0.261	59.20	40.54	39.43	3.3
10	141.8	100.9	67.6	0.299	71.35	35.71	38.91	3.1
11	137.8	98.0	/	0.302	72.27	50.11	39.21	3.1
12	141.0	100.3	48.7	0.376	75.68	39.96	49.09	3.2
13	139.8	99.4	62.9	0.244	60.83	44.73	51.58	3.2
14	137.8	98.0	55.8	0.285	65.56	54.35	63.54	3.3
15	137.8	98.0	43.6	0.379	77.67	63.56	46.30	3.0
16	140.8	100.1	55.5	0.281	90.55	87.55	61.39	3.1
17	140.5	99.9	48.2	0.267	57.70	60.81	38.77	3.4
18	139.8	99.4	56.2	0.329	44.15	51.14	38.77	3.0
19	141.7	100.8	41.9	0.337	85.33	73.29		3.0
20	140.4	99.9	42.0	0.322	61.42	66.96		3.0
21	139.2	99.0	49.8	0.273	101.15	59.52		2.8
22	136.4	97.0	49.4	0.363	71.01	52.20		2.8
23	139.1	98.9	56.0	0.254	73.85	67.98		2.7
24	142.1	101.1	59.0	0.312	64.48	51.49		3.1
25	136.4	97.0	55.6	0.323	73.34	51.02		3.6
26	141.4	100.6	34.3	0.271	58.14	66.77		3.2
27	140.8	100.1	47.1	0.298	60.95	65.22		3.2
28	136.4	97.0	56.6	0.414	64.54	57.54		3.2
29	138.5	98.5	50.8	0.302	71.93	52.20		3.1
30	139.4	99.1	44.9	0.247	57.24	69.88		3.0

Table D.3 ICMV and IC Roller Compaction Parameters on 22A Gravel

Test Number	ICMV	IC Roller Speed (mph)	Roller Vibration Frequency (Hz)	Roller Vibration Amplitude (mm)
1	39.5	2.4	28.7	1.69
2	54.9	3.1	28.4	1.76
7	59.1	2.3	28.5	1.81
8	46.4	2.4	28.4	1.76
9	54.1	3.2	28.5	1.87
10	67.6	5.5	28.0	2.11
12	48.7	2.8	28.4	1.76
13	62.9	2.8	28.3	1.96
14	55.8	2.1	28.4	1.83
15	43.6	2.6	28.5	1.75
16	55.5	3.2	28.4	1.83
17	48.2	2.8	28.4	1.76
18	56.2	1.9	28.4	1.80
19	41.9	2.8	28.4	1.70
20	42.0	3.0	28.4	1.81
21	49.8	2.0	28.5	1.79
22	49.4	2.6	28.5	1.77
23	56.0	3.2	28.4	1.79
24	59.0	2.9	28.4	1.80
25	55.6	1.7	28.4	1.82
26	34.3	2.8	28.5	1.69
27	47.1	2.7	28.4	1.73
28	56.6	1.9	28.4	1.76
29	50.8	3.4	28.4	1.78
30	44.9	3.0	28.6	1.84

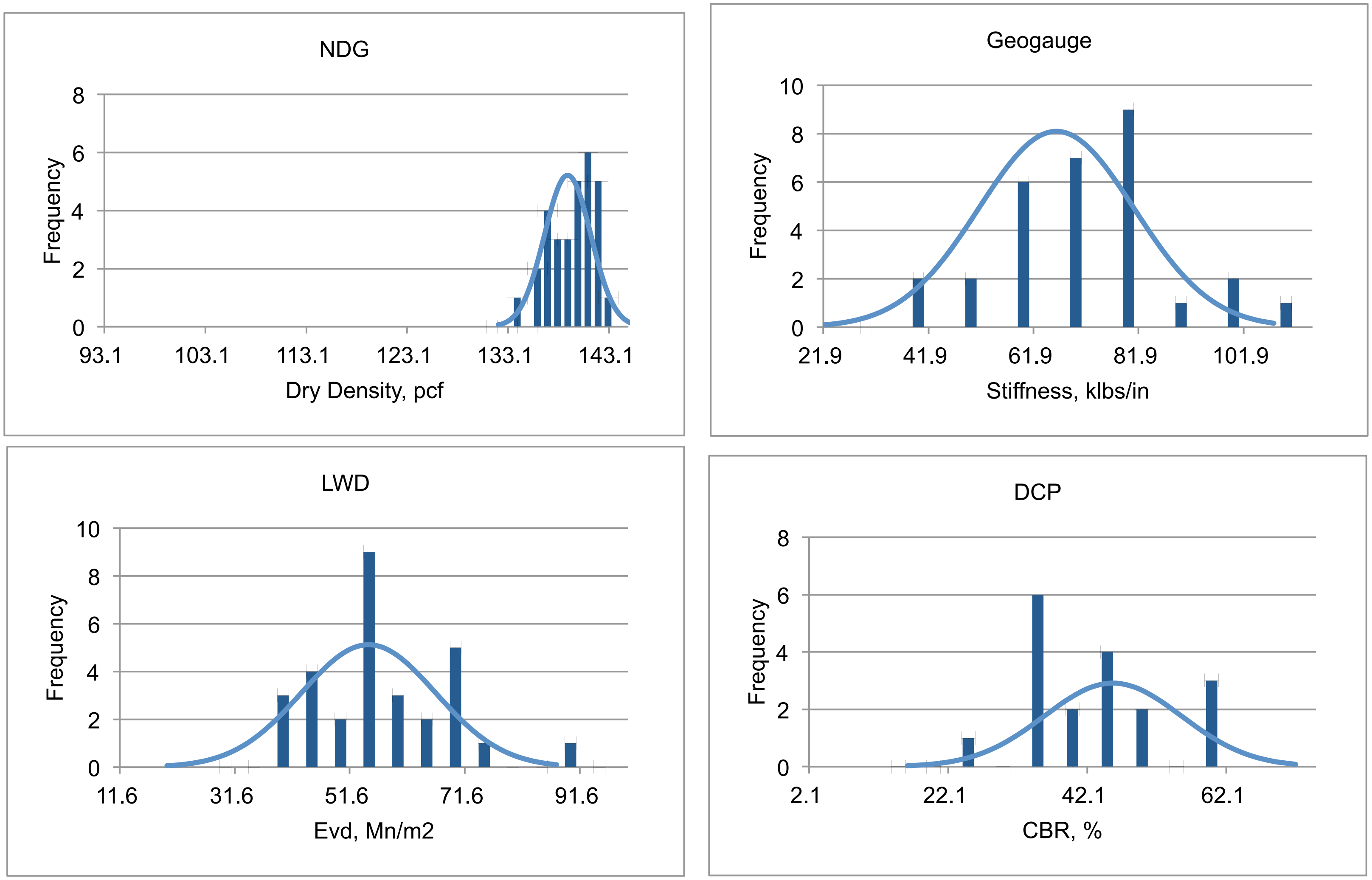

Figure D.2 Histograms of NDG, Geogauge, LWD, and DCP Test (1st Set) on Gravel at Iron River

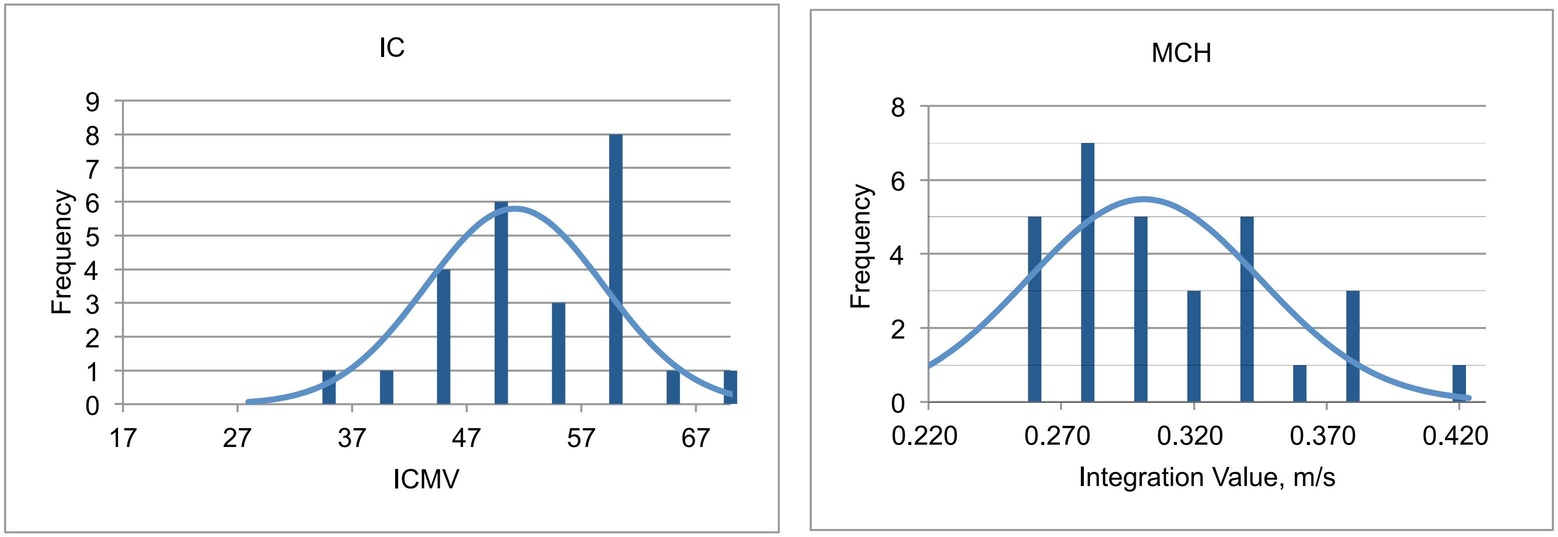

Figure D.3 Histograms of IC and MCH Test (1st Set) on Gravel at Iron River

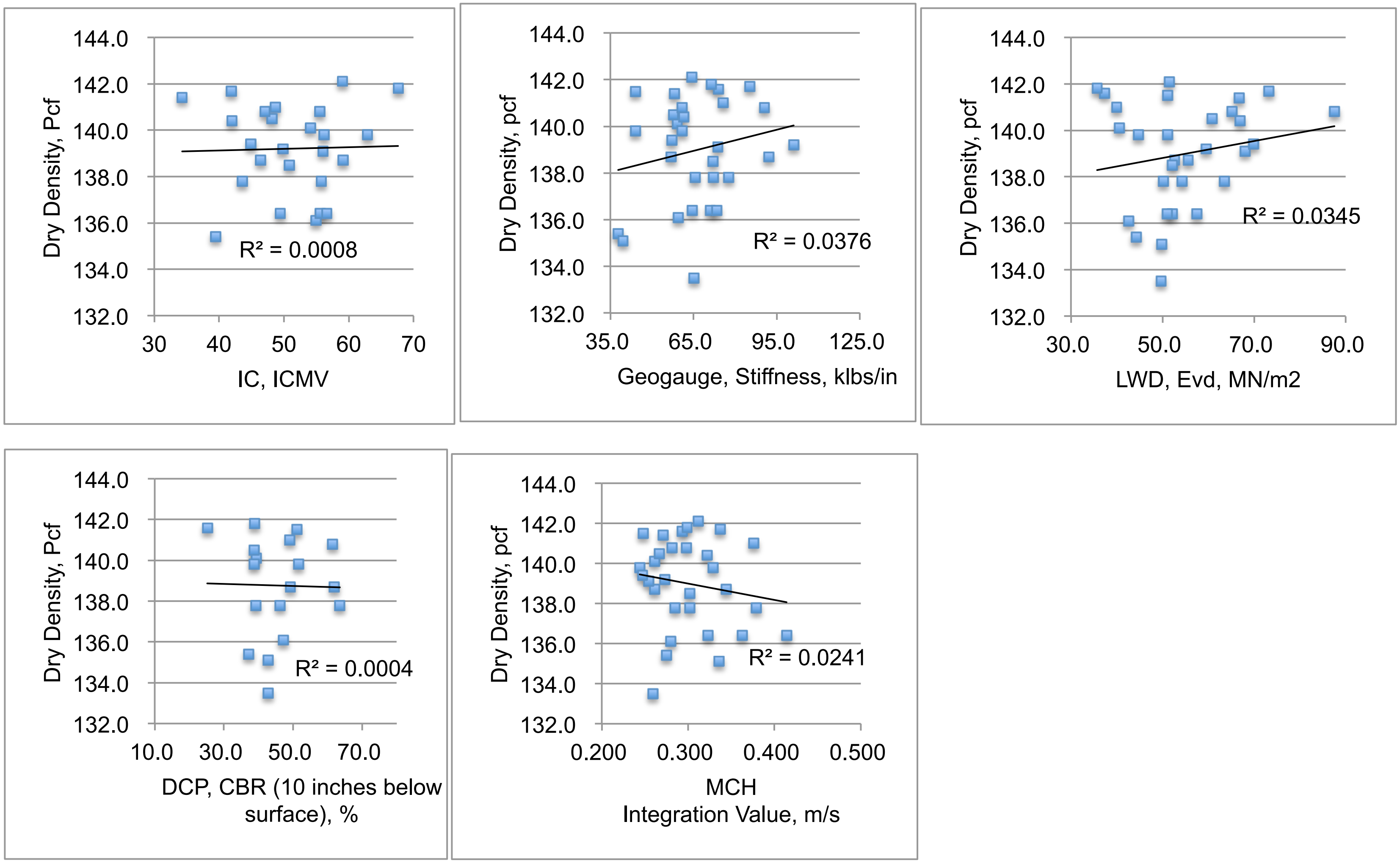

Figure D.4 Comparison of NDG to IC, Geogauge, LWD, DCP and MCH (1st Set) on Gravel at Iron River (Simple Regression)

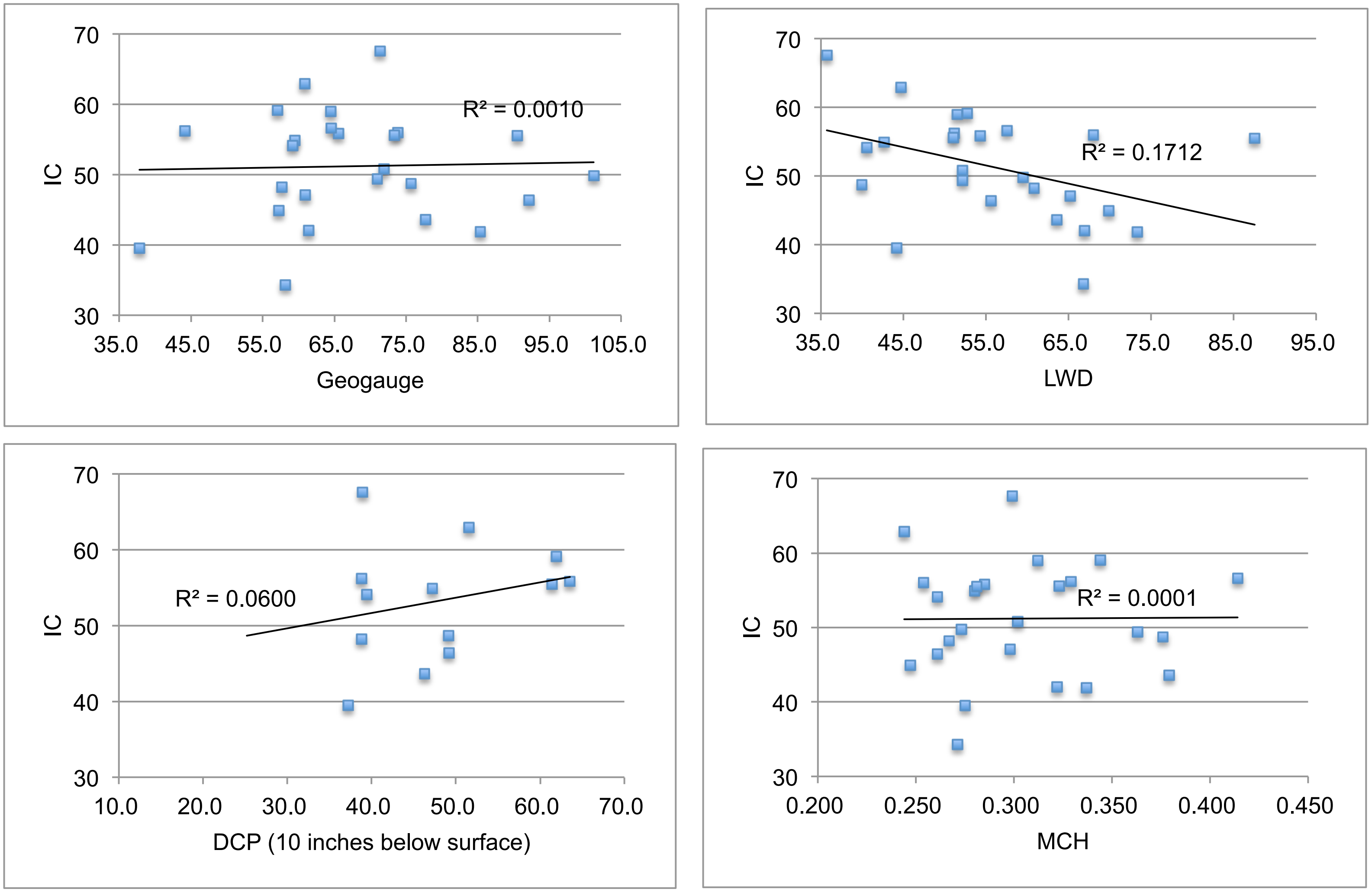

Figure D.5 Comparison of IC to Geogauge, LWD, DCP and MCH (1st Set) on Gravel at Iron River (Simple Regression)

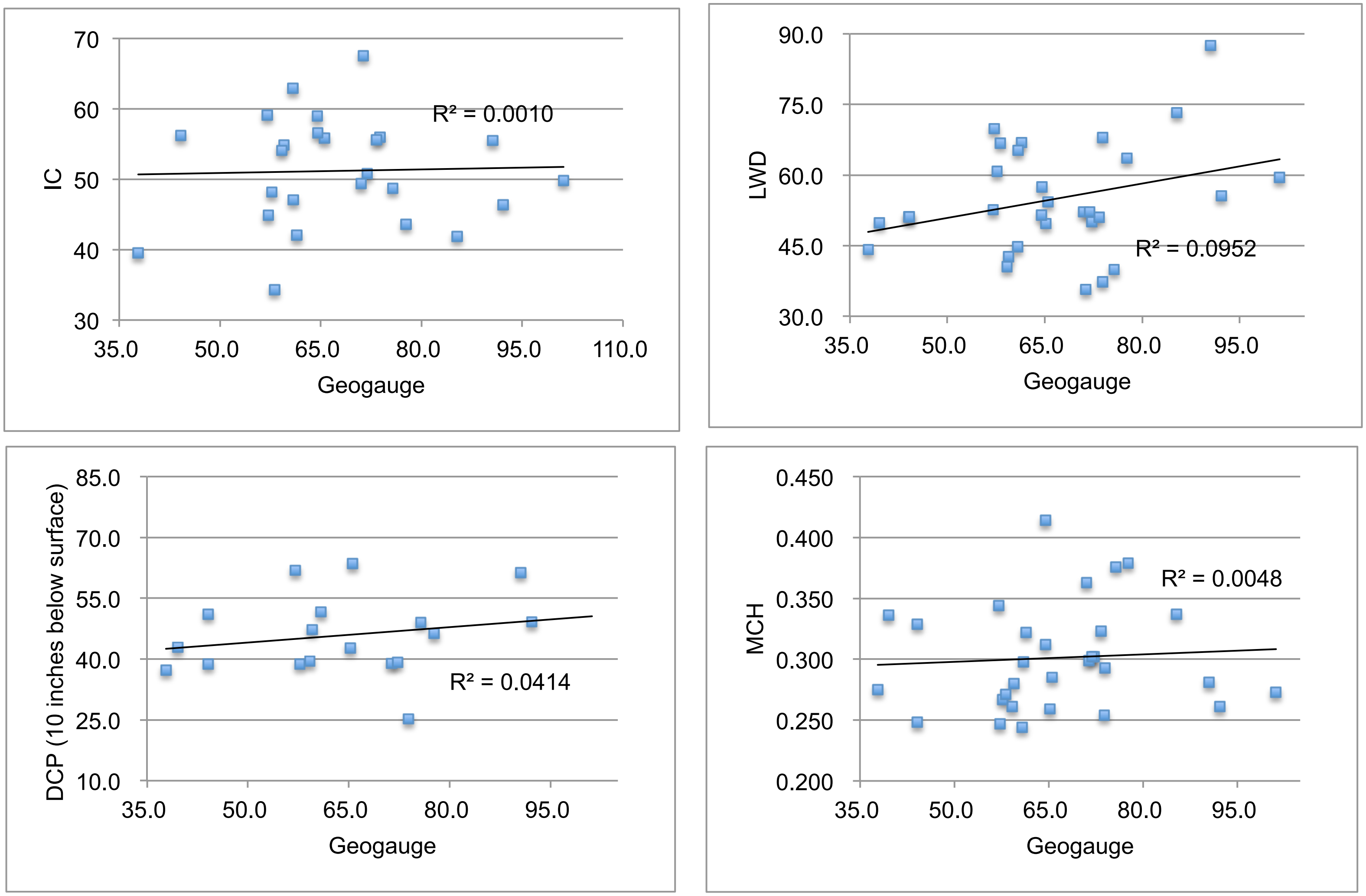

Figure D.6 Comparison of Geogauge to IC, LWD, DCP and MCH (1st Set) on Gravel at Iron River (Simple Regression)

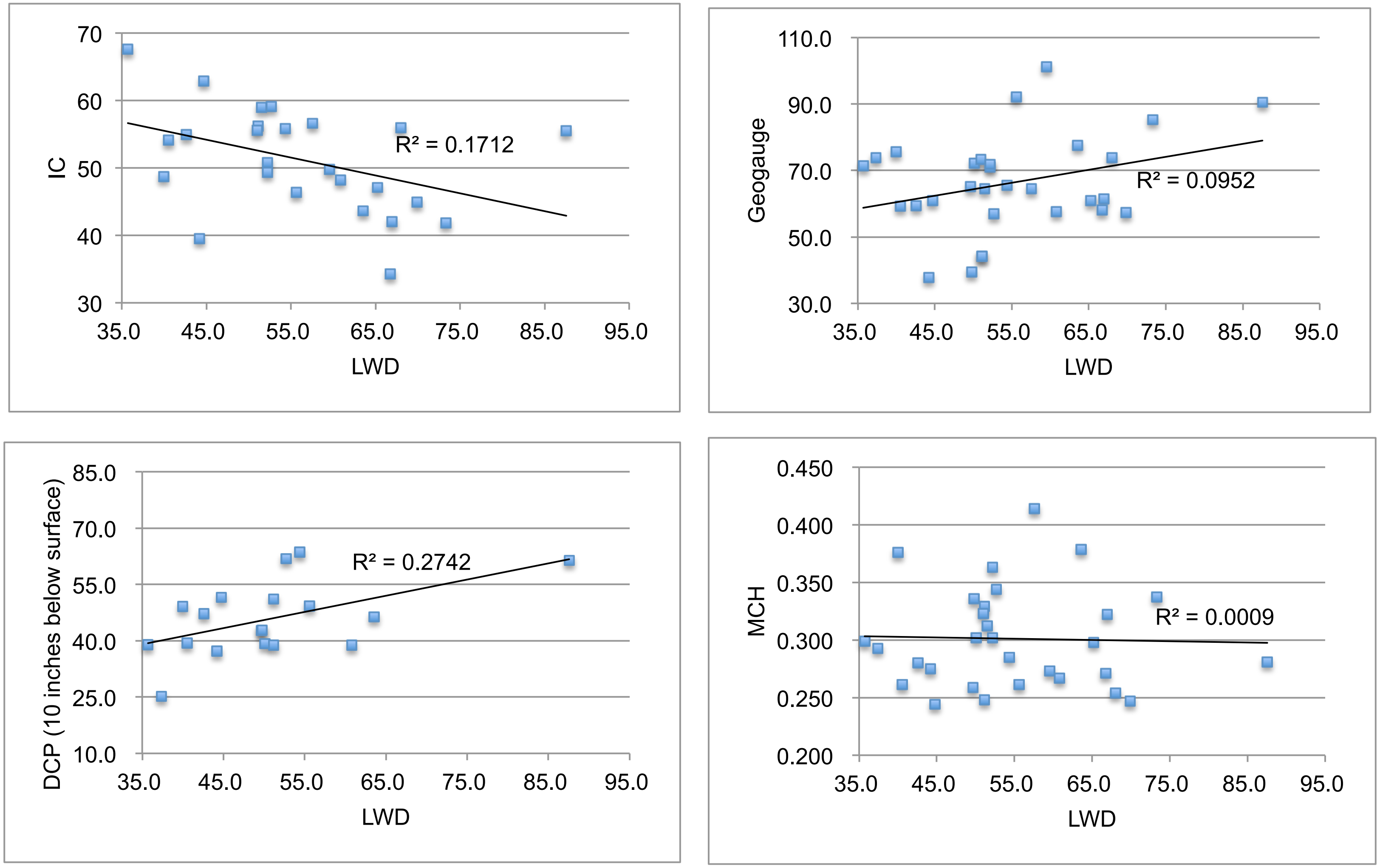

Figure D.7 Comparison of LWD to IC, Geogauge, DCP and MCH (1st Set) on Gravel at Iron River (Simple Regression)

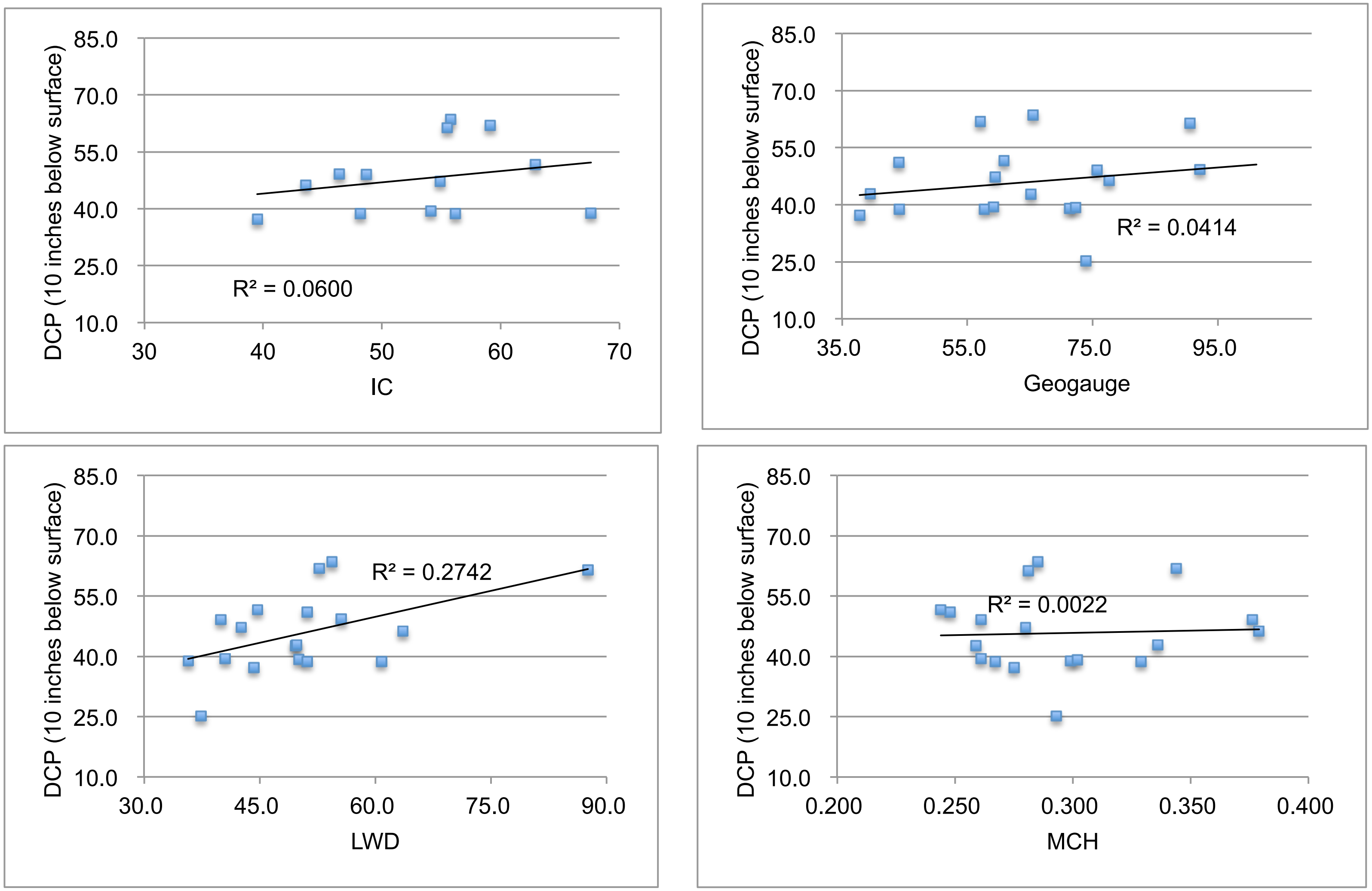

Figure D.8 Comparison of DCP to IC, Geogauge, LWD and MCH (1st Set) on Gravel at Iron River (Simple Regression)

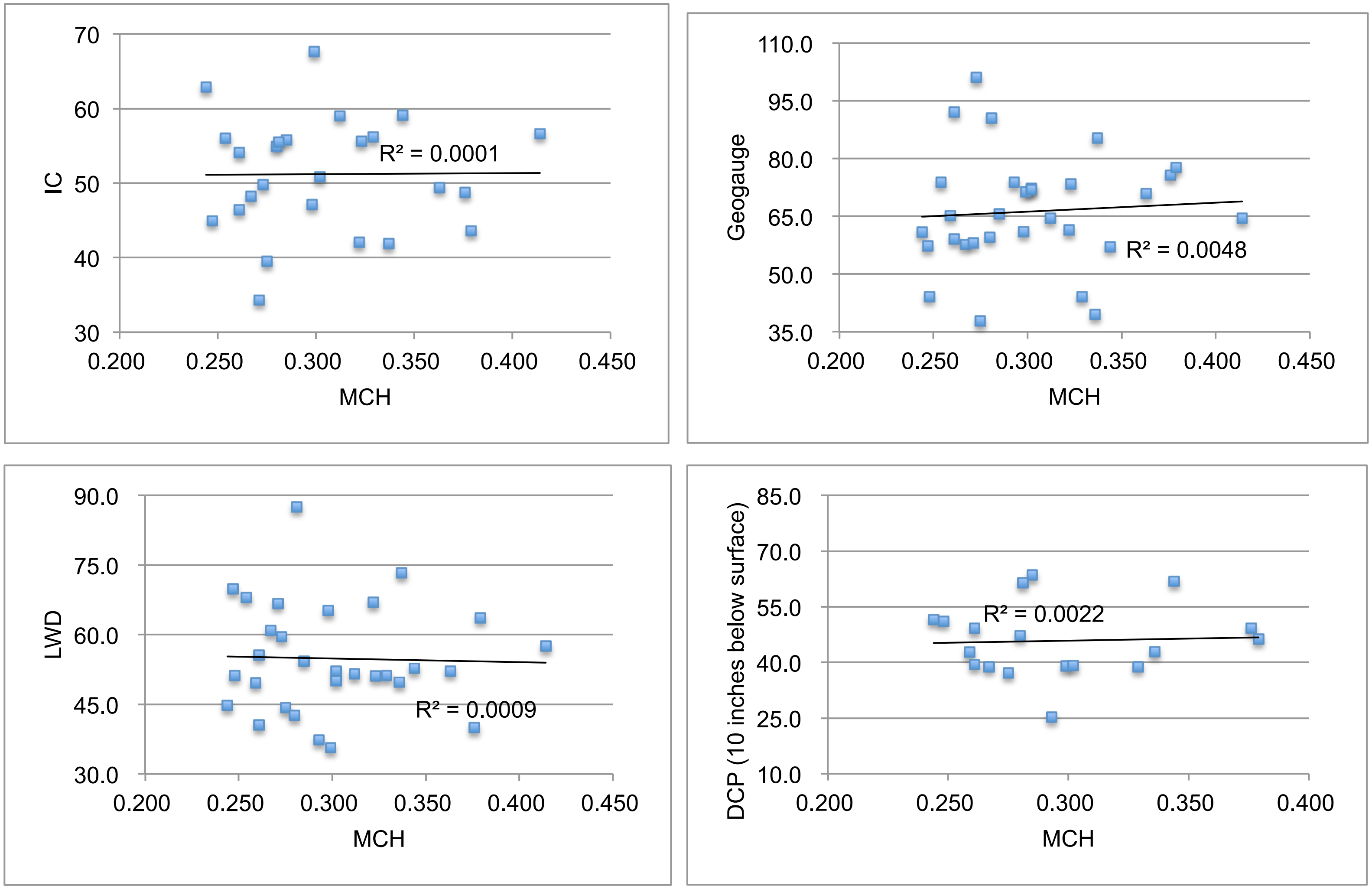

Figure D.9 Comparison of MCH to IC, Geogauge, LWD and DCP (1st Set) on Gravel at Iron River (Simple Regression)

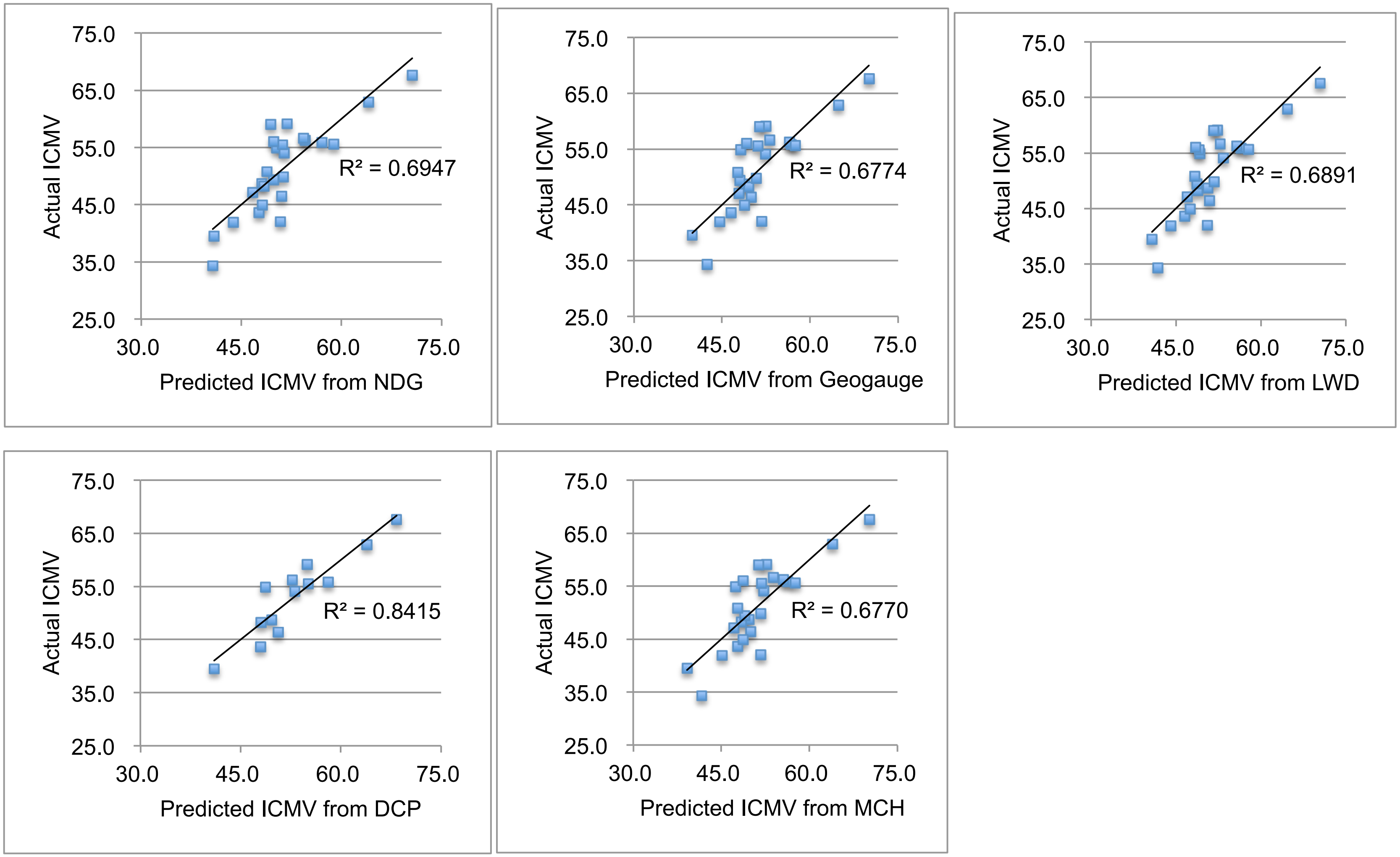

Figure D.10 Correlation of IC to NDG, Geogauge, LWD, DCP and MCH (1st Set) on Gravel at Iron River (Multiple Regression)

Appendix E: Data Analysis for Gravel (2nd Set) at Iron River

Table E.1 Summary of Test Data (2^{nd} set) on 22A Gravel at Iron River Site

	NDG		IC	MCH	Geogauge	LWD	DCP	W%
Test #	Dry Unit Wt. (pcf)	% Max r_d	CMV	Integration Value(m/s)	Stiffness (klbs/in)	E_{vd} MN/m^2	CBR %	%
1	140.6	100.0	39.5	0.289	58.60	64.66		3.8
2	142.1	101.1	54.9	0.295	70.51	59.06		3.7
3	141.8	100.9	/	0.296	68.35	79.51		3.5
4	135.1	96.1	/	0.259	49.84	60.16		3.8
5	139.5	99.2	/	0.281	53.21	64.66		3.7
6	142.2	101.1	/	0.315	66.99	70.53		3.6
7	142.0	101.0	59.1	0.245	69.32	71.43		3.5
8	138.9	98.8	46.4	0.407	45.96	44.03		3.7
9	142.5	101.4	54.1	0.291	68.67	61.81		3.4
10	141.6	100.7	67.6	0.362	83.62	73.53		3.2
11	139.3	99.1	/	0.285	50.95	45.09		3.8
12	140.9	100.2	48.7	0.349	46.60	52.57		3.8
13	142.4	101.3	62.9	0.334	68.34	59.52		3.5
14	139.8	99.4	55.8	0.266	75.28	50.22		3.5
15	138.2	98.3	43.6	0.307	51.01	48.39		4.0
16	139.0	98.9	55.5	0.344	55.79	62.67		3.3
17	140.4	99.9	48.2	0.298	68.56	78.40		3.7
18	137.7	97.9	56.2	0.306	50.17	48.08		4.1
19	142.7	101.5	41.9	0.284	57.52	55.28		3.6
20	141.5	100.6	42.0	0.266	52.58	42.29		3.3
21	137.3	97.7	49.8	0.273	53.65	50.00	33.043	3.6
22	137.2	97.6	49.4	0.358	43.32	46.49	20.714	3.5
23	141.3	100.5	56.0	0.274	59.27	86.21	36.128	3.3
24	140.1	99.6	59.0	0.333	85.03	68.81	43.805	3.1
25	137.9	98.1	55.6	0.329	39.01	50.22		4.4
26	139.3	99.1	34.3	0.275	61.16	46.97	33.367	3.8
27	141.2	100.4	47.1	0.273	78.90	69.23	28.287	3.2
28	137.3	97.7	56.6	0.284	54.34	62.15	32.157	3.9
29	141.7	100.8	50.8	0.255	68.50	63.74	33.367	3.3
30	136.5	97.1	44.9	0.340	74.82	65.60	37.035	3.3

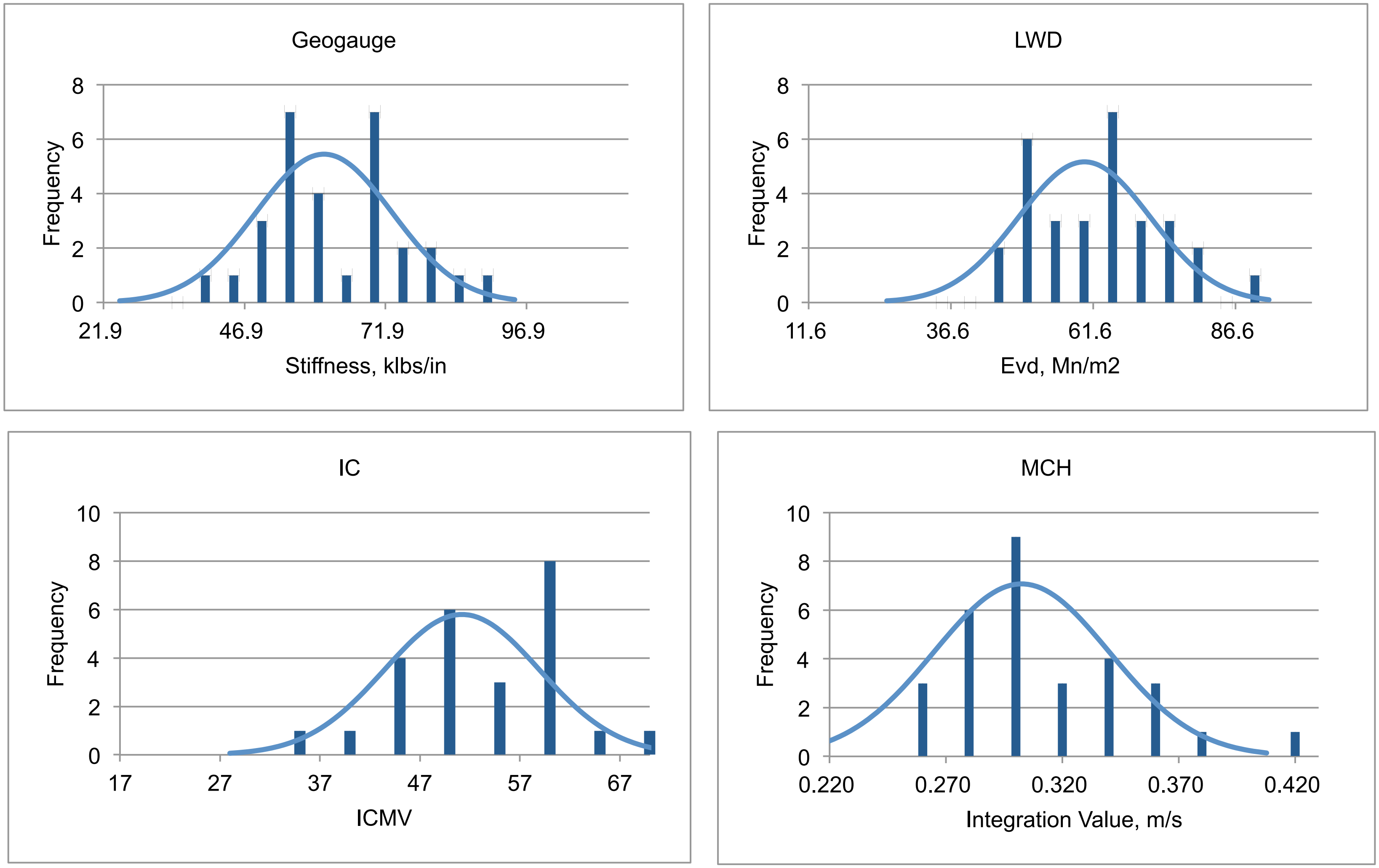

Figure E.1 Histograms of Geogauge, LWD, IC and MCH Test (2nd Set) on Gravel at Iron River

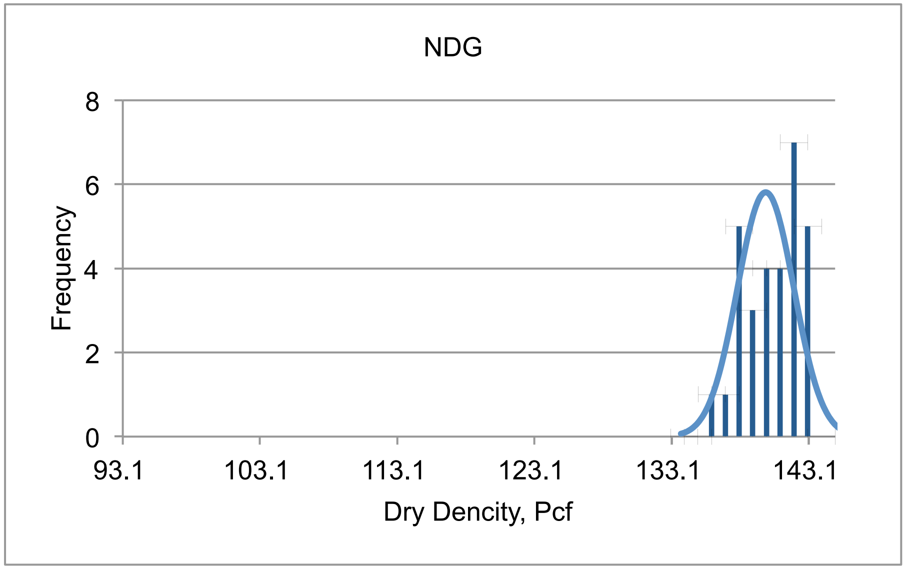

Figure E.2 Histograms of NDG Test (2nd Set) on Gravel at Iron River

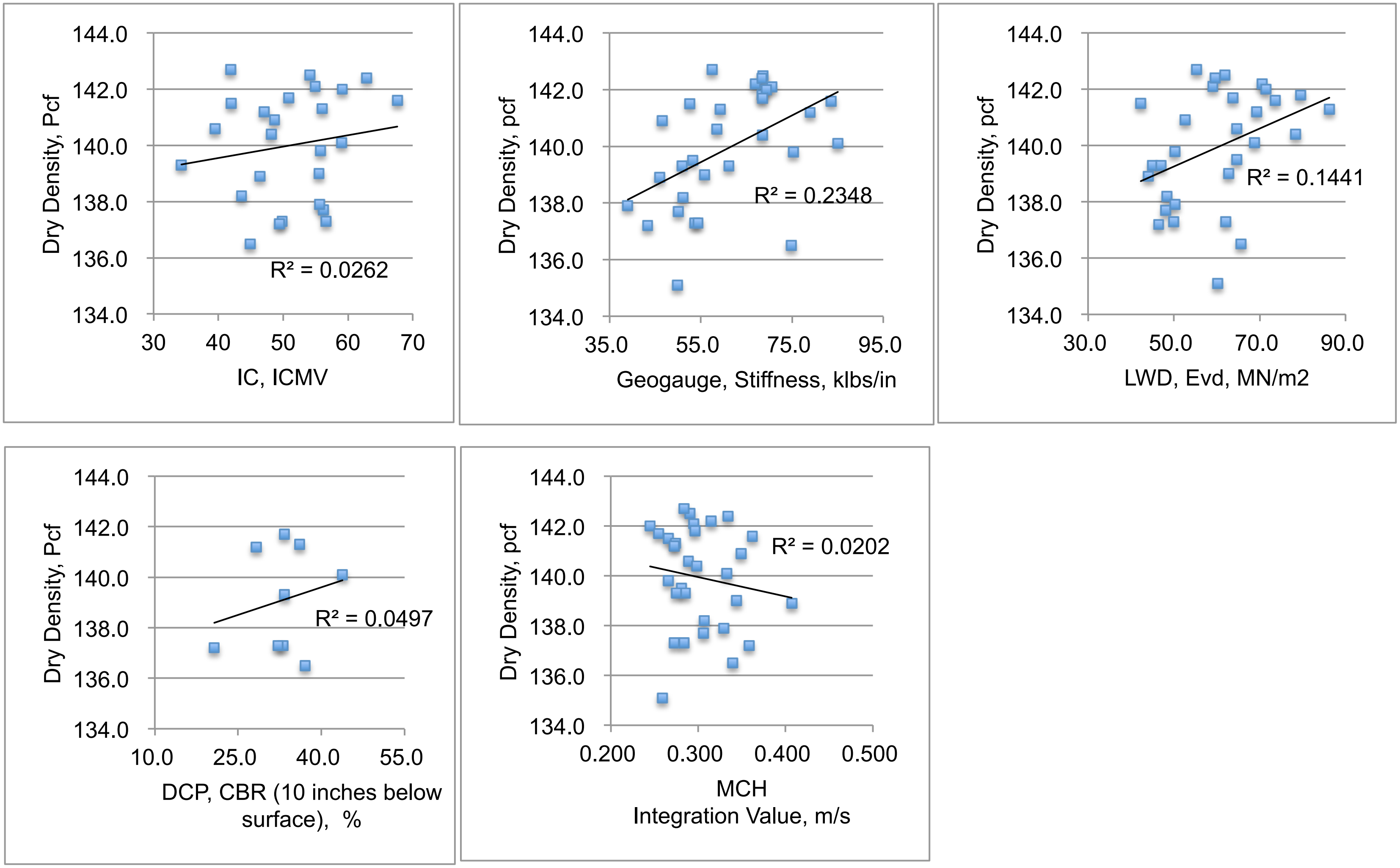

Figure E.3 Comparison of NDG to IC, Geogauge, LWD, DCP and MCH (2nd Set) on Gravel at Iron River (Simple Regression)

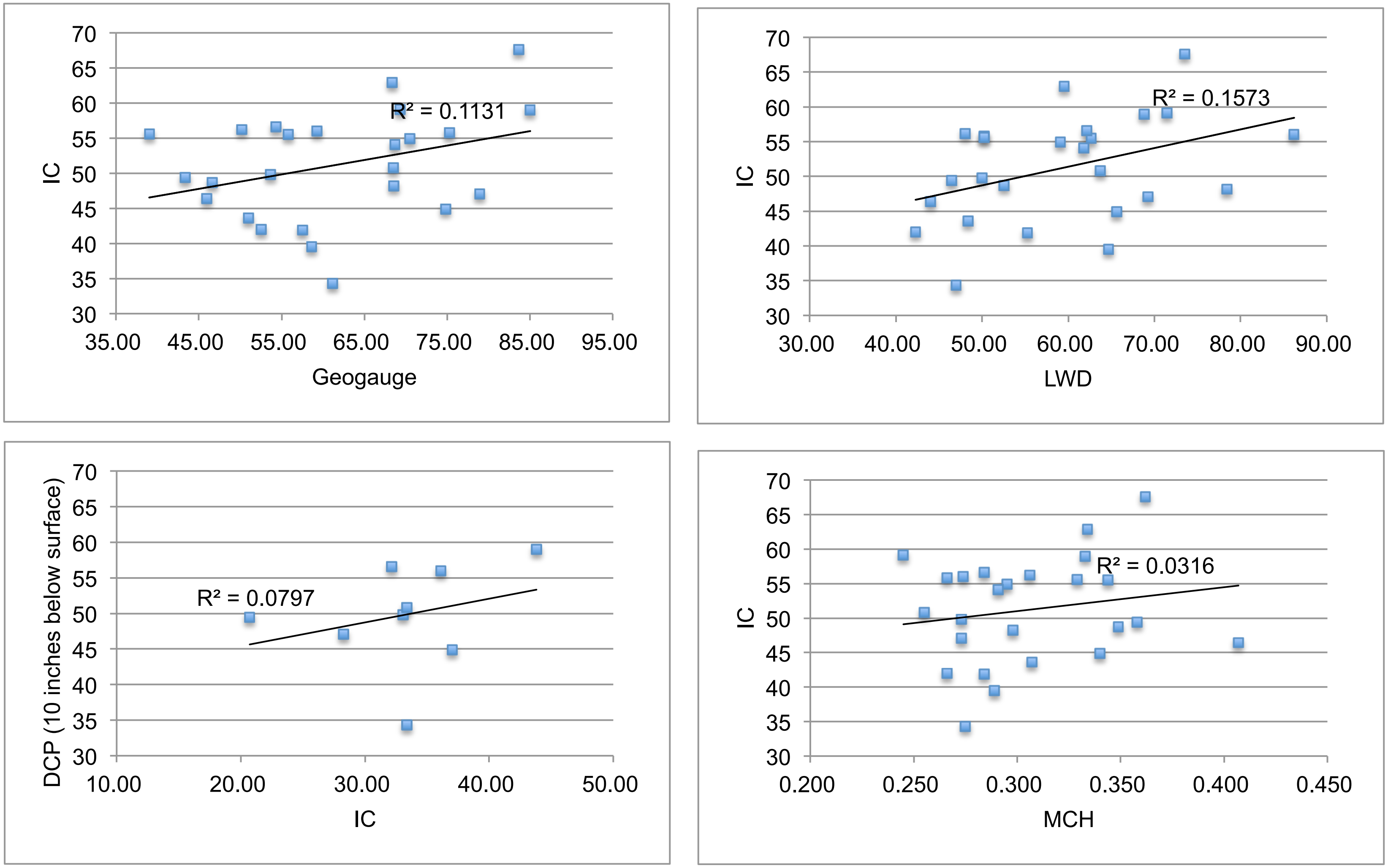

Figure E.4 Comparison of IC to Geogauge, LWD, DCP and MCH (2nd Set) on Gravel at Iron River (Simple Regression)

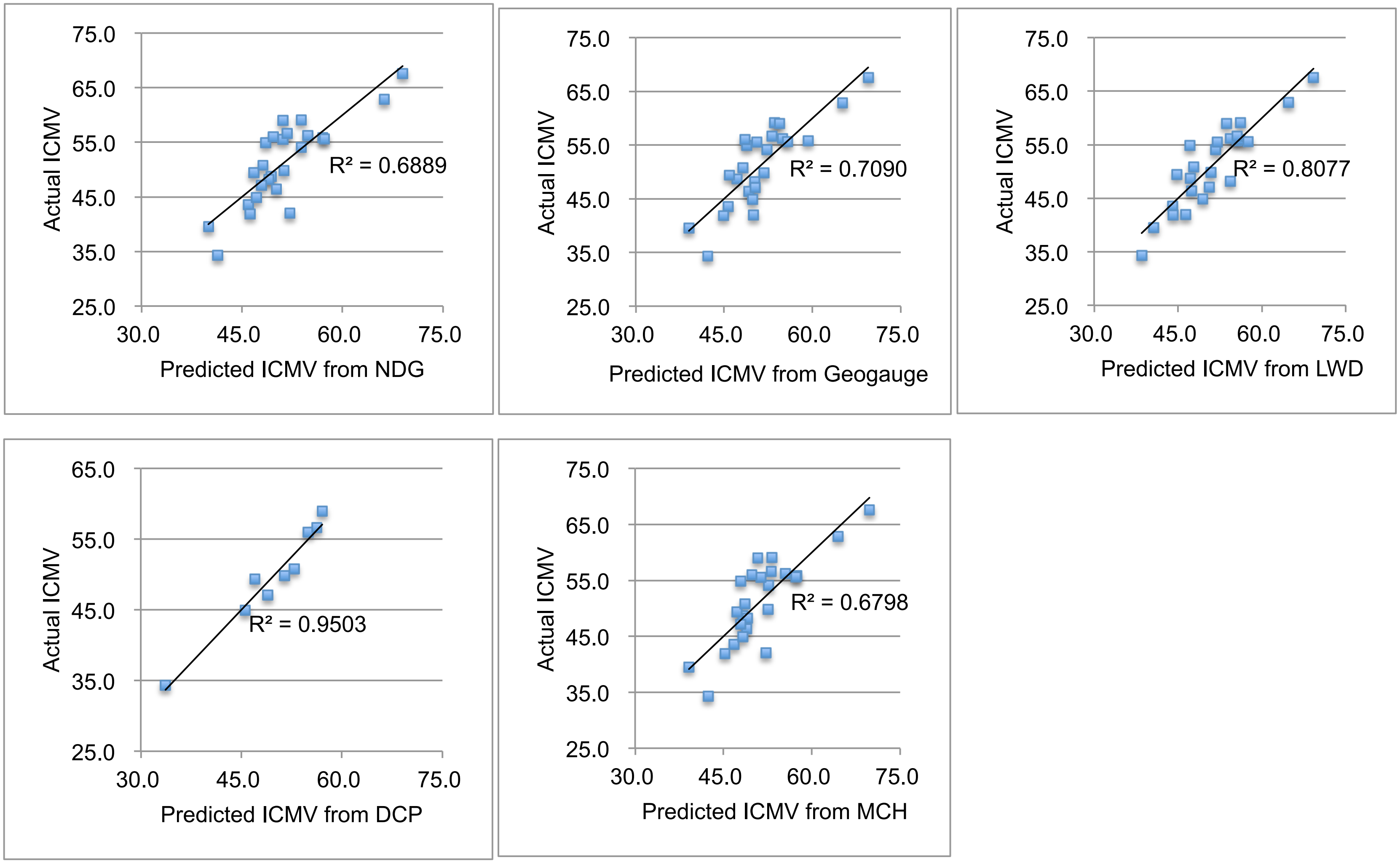

Figure E.5 Correlation of IC to NDG, Geogauge, LWD, DCP and MCH (2nd Set) on Gravel at Iron River (Multiple Regression)