Intelligent Compaction: A Minnesota Case History

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ABSTRACT: Intelligent Compaction (IC) uses an instrumented roller to provide continuous, real time verification of in situ soil properties over the entire compaction area. Ammann, Bomag and Caterpillar compactors were used on three trunk highway projects in Minnesota during 2005. The objective of this study was to compare quality control data from an IC roller with quality assurance data collected from several hand-held field-testing devices. The results demonstrate the potential of IC technology for use as quality control during construction. This case history discusses the field study results and makes recommendations for IC implementation in 2006.

1 INTRODUCTION

The Minnesota Department of Transportation (Mn/DOT) is participating in a series of national studies investigating new technologies that improve the grading and base compaction process. However, because these studies will not be completed for several years, Mn/DOT is also pursuing its own implementation strategy and has been conducting field and laboratory investigations that will aid in the implementation of these new technologies. One of the most promising tools that was identified in 2004 for improving the subgrade compaction process is Intelligent Compaction (IC) (Petersen, 2005). IC is defined as continuous calculation of modulus, or related parameters, with a real-time feedback mechanism and automatic adjustment. Intelligent compaction involves the use of rollers that are equipped with a control system that can automatically adjust compactive effort in response to a material's modulus during the compaction process. The roller is equipped with a documentation system that allows continuous data recordation in the form of a plan-view, color-coded plot of roller stiffness and roller pass number measurements. The output enhances the ability of the roller operator and project inspection personnel to make real-time corrections in the compaction process (NCHRP, 2005). A series of IC field trials, conducted in Minnesota during 2005, included equipment manufactured by Ammann, Bomag, and Caterpillar. This case history documents those field trials and has the following objectives:

- Assess the ability of the roller to accurately measure in situ soil properties by comparing the measurements provided by the roller with measurements provided from portable field devices.
- Identify devices that show promise as quality assurance (QA) tools in conjunction with the intelligent compactors.
- Validate the light weight deflectometer quality assurance procedures developed in Mn/DOT report INV 829.
- Make recommendations for implementation of IC technology on future projects.

1.1 *Overview*

Intelligent compaction was developed in Europe in the late 1970's and early 1980's. The primary European equipment manufacturers that currently have equipment in the US are Ammann, Bomag, Dynapac and Geodynamik. US construction manufacturers are also developing similar IC technology. Caterpillar has developed IC rollers that will be available through Caterpillar's "field follow" program in 2006, with full production by 2007.

Intelligent compaction rollers use either accelerometers and/or machine energy to calculate an index parameter related to modulus, stiffness, or bearing capacity. This information is then used by the roller's control systems to determine whether to increase or decrease compaction energy by automatically adjusting the internal, mechanical parameters of the roller. All IC rollers essentially use a combination of three different parameters: amplitude, frequency, and speed, to modify the compactive energy delivered by a roller of specific mass and diameter.

1.1.1 *Amplitude*

Amplitude is a nonnegative scalar measure of the magnitude of oscillation (Fig. 1). The amplitude of the roller is dictated by the position of the eccentric masses inside the roller. The amplitude can be increased and decreased by altering the unbalanced force generated by the moving the masses inside the drum.

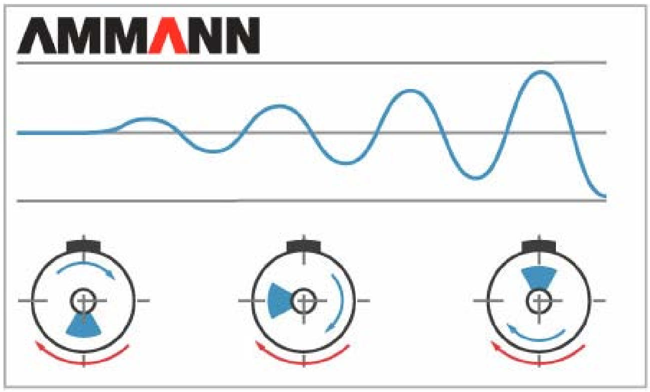


Fig. 1 Amplitude of Drum Vibration (Amman, 2003)

1.1.2 *Frequency*

Frequency is the number of oscillations per unit time (Fig.2). The frequency of the drum can be adjusted to optimize compaction of a specific soil type. Matching the frequency of the drum with that of the underlying soil increases the efficiency of compactions (Anderegg and Kaufmann, 2004). However, others believe that altering drum frequency may lead to increased maintenance and a reduced operational life for the roller.

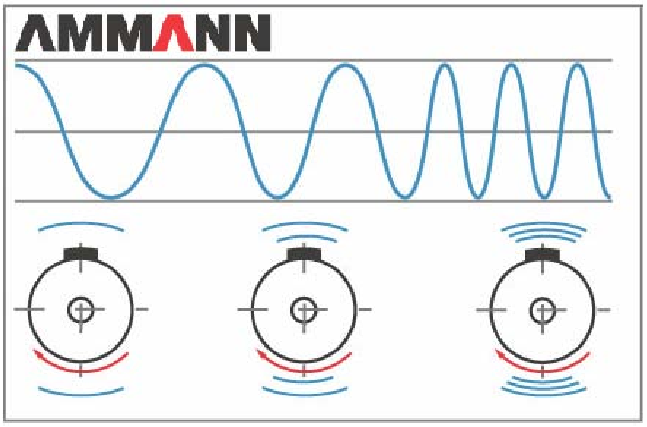


Fig. 2. Frequency of Drum Vibration (Amman, 2003)

1.1.3 *Speed*

Speed of the roller dictates how much energy, per unit length of soil, is delivered to the underlying soil layer (Fig.3). If the roller travels slowly, more energy is delivered per unit area; conversely, the faster the roller travels, the less energy is delivered per unit area of soil. It is usually recommended that an optimum speed be determined and maintained for the materials at the job site.

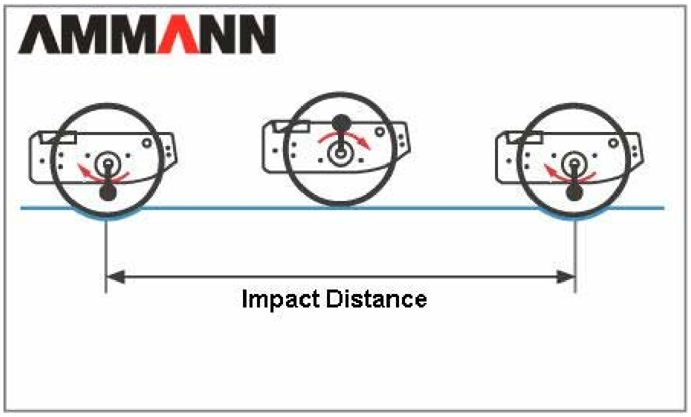


Fig. 3 Speed of Roller Drum (Amman, 2003)

1.2 *IC Implementation*

IC produces a more uniform product than standard compaction methods since the roller continuously alters the amount of energy being transferred to the soil based upon a target value for the roller specific compaction-related parameter. In addition, research has shown that thicker lifts of material can be more efficiently compacted using IC technology (McVay and Ko, 2005). These factors contribute to IC's ability to streamline the compaction process, which has the potential to translate into significant cost savings for the contractor.

Real-time geospatial location combined with verification of lift compaction makes it possible to assure complete coverage of the compaction area throughout the construction process. The roller's measurement / control systems help to attain a more uniform subgrade which contributes to increased pavement service life. This also helps to eliminate the chance of over compaction, which can lead to costly damage to the roller and aggregate fracture.

In addition, the roller output of in situ subgrade modulus provides a vital link to mechanistic pavement design. IC roller data can be easily mapped and stored for later use in forensic analysis and used during long-term pavement management.

Finally one of the important benefits of IC is that it will make it possible to eliminate sand cone testing. Newer mechanistic tests such as the DCP and LWD are far better suited for quality assurance in conjunction with IC. Furthermore, mechanistic tests can be conducted in a fraction of the time required for sand cones. Mechanistic testing, in conjunction with IC, has the potential to greatly improve the efficiency of quality control / quality assurance (QC/QA) for construction projects. Even more significantly, these new test devices increase jobsite safety. Testing personnel will no longer be required to subject themselves to the dangers of conducting sand cones. Tests can be conducted quickly with minimal danger to personnel and construction delays will be lessened as mechanistic test results are available immediately and are less affected by the vibrations of passing heavy equipment traffic.

2 MATERIALS AND METHODS

2.1 *Moisture Meters*

These devices estimate the volumetric moisture content by measuring the electrical properties of the soil. The electrical properties of the soil have been shown to directly correspond to the amount of water per unit volume of soil (Topp,1980). A simple conversion is required to obtain gravimetric moisture content of the sample based upon an assumed density for the material.

2.1.1 *Percometer*

The Percometer (Fig. 4) is a device that estimates a soil's moisture content by measuring the dielectric permittivity and conductivity. This instrument, manufactured in Estonia by ADEK, consists of a 6-cm.-diameter probe attached to a small computer. When the surface of the probe is pressed against the material to be tested the device emits a small electrical current. Dielectric permittivity and conductivity values are calculated as the current moves through the soil between electrodes on the probe. The measured values of dielectric permittivity are proportional to the soil's volumetric moisture content (Roadscanners, 2006).

Fig. 4 Percometer

2.1.2 *Trident*

The Trident (Fig. 5) is a device that estimates a soil's moisture content from dielectric permittivity. This instrument, manufactured in Illinois by James Instruments Inc., consists of a set of five stainless steel prongs approximately 9 cm in length. When the prongs are pressed into the material to be tested, the device emits a small electrical current. An analog-digital converter then combines the complex dielectric constant into a unitless parameter with values ranging from 0 - 4095. This value can then be correlated to a specific moisture content by performing a calibration procedure for the specific soil type. Mn/DOT has developed a preliminary procedure to utilize these moisture devices in the field (Mn/DOT Grading and Base Office, 2006).

Fig. 5 Trident T-90 Moisture Meter

2.2 *Modulus Measurement Devices*

Hand-held field devices are capable of estimating the modulus of a soil layer by applying a load and then measuring the soils response. While such devices can be used to estimate a value for the elastic modulus of the soil layer, which is in theory an independent soil parameter, factors such as stress, moisture content and spatial unknowns influence the measurement. The effects of stress are primarily due to differences in the applied mean and deviator stress levels, the applied strain level, and the applied strain rate. These factors vary from device to device and they greatly affect the estimation of soil modulus (Briaud and Seo, 2003). This complicates comparative analysis of field devices and characterization of subgrade spatial variability. These problems are well documented (Petersen, 2005) and further research is required to resolve these issues (Petersen et al, 2006a).

2.2.1 *Light Weight Deflectometer*

The light weight deflectometer (LWD, Fig. 6) induces a soil response by dropping a weight onto a plate resting on the test layer. A load cell within the instrument measures the time history of the load pulse and a geophone in contact with the test layer measures the time history of the soil’s velocity. The velocity is then which is integrated to determine displacement. The time history files are automatically exported wirelessly to a data acquisition system, where the peak load and displacement values are used to calculate modulus values. Time history files can also be analyzed using a fast Fourier transform for a more accurate modulus calculation (Hoffmann et al, 2003). Mn/DOT has developed a specification for pilot projects in which the LWD will be used. A pilot LWD performance specification was also developed in 2006 (Davich et al, 2006). This specification is modeled after the DCP specification, with the acceptance criteria being minimum LWD modulus for the given grading number and moisture content (Fig. 7).

Fig. 6 Light Weight Deflectometer

LWD Quality Assurance Procedure							
Test	**Soil**	**Test Parameters**			**LWD**		**P/F**
		Barrel Density	**Oven Dry Moisture Content**	**Grading Number**	**Target Modulus**	**Test Modulus**	
		(kg/m^3)	**(Percent)**		**(MPa)**	**(MPa)**	
23	DN	1987	5.1	5.1	40	40	**PASS**
1	DN	-	5.1	5.1	40	13	**FAIL**
24	DN	2043	6.4	5.1	40	38	**FAIL**
2	DN	1951	7.2	5.1	40	18	**FAIL**
6	DN	2076*	9.2	5.1	36	6	**FAIL**
5	DN	1985	9.7	5.1	36	10	**FAIL**
4	DN	1976	10.0	5.1	High MC	10	**HIGH**
3	DN	1999	10.0	5.1	High MC	8	**HIGH**
21	FHJ	1820	7.5	6.1	35	59	**PASS**
7	FHJ	1764	7.8	6.1	35	46	**PASS**
18	FHJ	1945*	8.0	6.1	35	54	**PASS**
16	FHJ	1839	8.1	6.1	35	74	**PASS**
8	FHJ	1791	9.5	6.1	35	55	**PASS**
9	FHJ	1802	10.7	6.1	High MC	32	**HIGH**
15	FHJ	1773	11.4	6.1	High MC	49	**HIGH**
10	FHJ	1790	12.8	6.1	High MC	7	**HIGH**
11	KLO	1847	7.1	5.4	40	38	**FAIL**
22	KLO	1937	7.1	5.4	40	47	**PASS**
17	KLO	1963	8.1	5.4	36	59	**PASS**
12	KLO	1881	8.9	5.4	36	40	**PASS**
19	KLO	1882	8.9	5.4	36	44	**PASS**
20	KLO	1916	10.3	5.4	High MC	32	**HIGH**
14	KLO	1916	10.5	5.4	High MC	26	**HIGH**
13	KLO	1869	12.0	5.4	High MC	7	**HIGH**

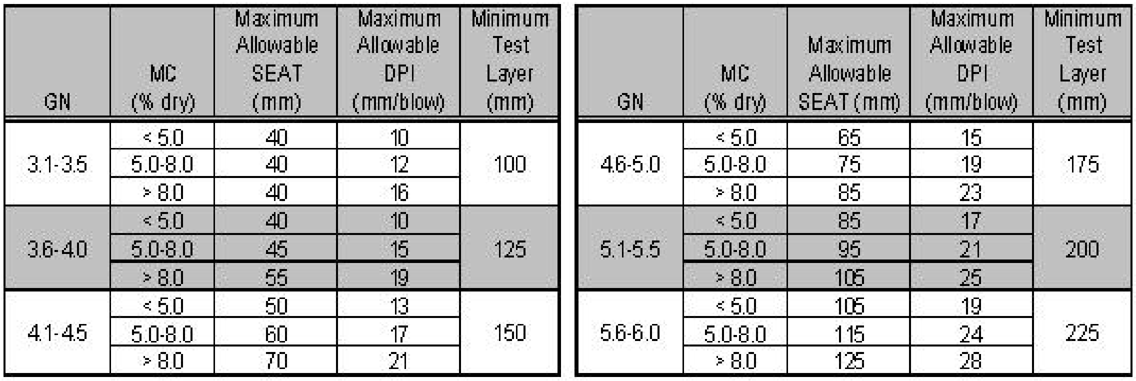
Fig. 7. LWD Pilot Specification

2.2.2 *Dynamic Cone Penetrometer*

The dynamic cone penetrometer (DCP, Fig. 8) uses the impact force generated by a falling mass to drive a shaft with a conical point into a compacted material. The conical point is sloped at 60°, the falling mass is 8 kg (17.64 lbs), and the drop height is 575 mm (22.64 in). The shaft's penetration into the soil is measured following every blow, and the resulting penetration per blow measurements can be related to modulus values using the method outlined in section 3.3. Mn/DOT currently has a specification that makes use of the DCP for the quality assurance of aggregate base material. This specification requires that the tip of the DCP penetrate the soil no further than 1.57" during two seating blows or 1.2" during three subsequent blows. Mn/DOT has developed a pilot specification for use with the DCP test, which uses the grading number (GN) (Eq.1) and moisture content to determine acceptable penetration indexes for the lift (Oman, 2004). This procedure was recently validated for select granular materials (Davich et al, 2006).

$$\mathrm{GN}(\%\mathrm{Passing}) = \frac{25mm + 19mm + 9.5mm + 4.75mm + 2.00mm + 425\mu m + 75\mu m}{100} \qquad \text{Eq. 1}$$

Fig. 8 Dynamic Cone Penetrometer



GN	MC (% dry)	Maximum Allowable SEAT (mm)	Maximum Allowable DPI (mm/blow)	Minimum Test Layer (mm)
3.1-3.5	< 5.0	40	10	100
	5.0-8.0	40	12	
	> 8.0	40	16	
3.6-4.0	< 5.0	40	10	125
	5.0-8.0	45	15	
	> 8.0	55	19	
4.1-4.5	< 5.0	50	13	150
	5.0-8.0	60	17	
	> 8.0	70	21	

GN	MC (% dry)	Maximum Allowable SEAT (mm)	Maximum Allowable DPI (mm/blow)	Minimum Test Layer (mm)
4.6-5.0	< 5.0	65	15	175
	5.0-8.0	75	19	
	> 8.0	85	23	
5.1-5.5	< 5.0	85	17	200
	5.0-8.0	95	21	
	> 8.0	105	25	
5.6-6.0	< 5.0	105	19	225
	5.0-8.0	115	24	
	> 8.0	125	28	

Fig. 9 DCP Pilot Specification for Grading and Base Materials

2.2.3 *GeoGauge*

The GeoGauge (Fig. 10) produced by Humboldt Manufacturing, directly measures stiffness of the underlying material by measuring the response of the soil when subject to an applied force at a range of frequencies from 100 - 200 Hz. The device can also calculate the Young's modulus if an estimate of the soil's Poisson's ratio is entered into the device. Mn/DOT has developed a specification for pilot projects where the GeoGauge has been used (Main Associates, 2005).

Fig. 10 Humboldt Geogauge

3 ATWATER TEST SITE

3.1 *Description*

State Project 3404-52 involved an 11.9-mile long mill and overlay on TH 12 from Willmar to Atwater. A 1-mile long full depth bituminous structure constructed in 1989 was replaced with this project. During June and July 2005, the reconstruction involved removal of the existing bituminous surface and the subgrade to accommodate a 30” aggregate base/HMA design. The work involved a 6” subgrade preparation of the clay loam material. The pavement structure consisted of 10” HMA, 6” class 5 aggregate base, and 14” select granular subbase. The final acceptance of the compacted material for this project was sand cone testing.

3.2 *Bomag IC Roller*

The VARIO Control roller developed by Bomag (Fig. 11) was used on the TH 12 project. The Bomag roller is a single drum vibratory roller, equipped with a GPS system. This roller determines the underlying soil modulus using the Evib measurement system. The roller continuously monitors the stiffness of the soil using an accelerometer mounted at the side of the drum. The energy of compaction is automatically adjusted based upon the data obtained from the accelerometer by varying the vertical component of the drum vibrations. This is achieved by altering the position of the two internal counter-rotating weights. The applied energy is thus increased or decreased by changing the direction of vibrations, while maintaining a constant frequency. The information collected by the roller’s instruments is then displayed to the operator on the in-cab screen in real time. The data is provided in the form of computerized gages (Fig. 11) and color-coded maps that document number of roller passes as well as estimated modulus. In addition, paper strips that document Evib modulus vs. position can be printed on demand and electronic data files can be exported for use in other software applications.

Fig. 11 Bomag Variocontrol Roller

3.3 *Field Data Collection*

Data was collected in two separate trips to the site. The first set of data was collected June 23, 2005 on the east embankment approach to the bridge. An area was selected where production compaction had already been completed. The IC roller measured the in situ modulus for three side-by-side passes, 100 ft in length. Using the data from the roller, the area of greatest uniformity was selected for testing. A test grid was then established for comparative testing. The three by four grid (Fig. 12) consisted of three separate roller lanes (A, B and C) and four rows spaced 5 feet apart.

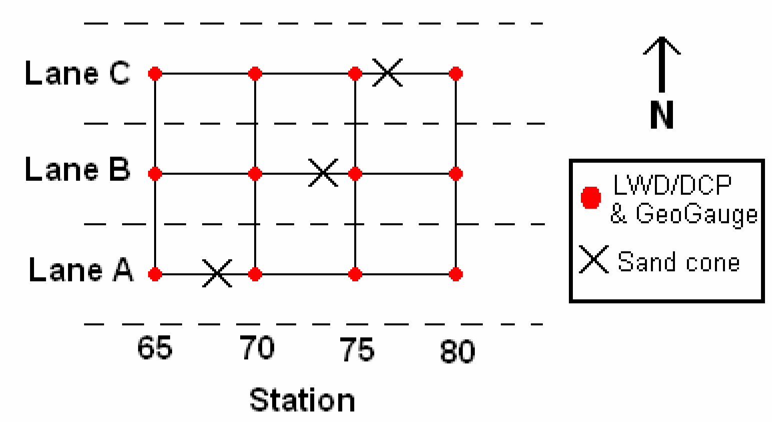


Fig. 12 Test Grid Layout

Each test was marked and GPS data was obtained for later use. The tests were conducted in order of increasing destructiveness at each test node. The first test performed at each node was the LWD. Two seating drops were performed followed by three data readings obtained for three different heights of 25, 50 and 75 centimeters. Two GeoGauge readings were taken subsequently at the same spot. After the first GeoGauge test was completed, the device was reseated to ensure a more accurate reading for the second test. Next, a DCP test was conducted, driving the tip to a depth of approximately 300 mm into the lift. Finally, material was collected and placed in sealed containers for the later determination of the oven dry moisture content for each node. Three sand cone tests were also performed at the locations indicated in the figure by a skilled technician. Additional material was collected at each sand cone test location for Proctor and gradation testing.

The second trip to the project occurred June 28, 2005 and consisted of testing on the west embankment to the bridge. Four areas were observed and selected for testing. The selection process consisted of choosing two areas that were expected to pass the inspection, one area that would not pass and was clearly rutting, and one area where geofabric had been installed. The roller compacted two side-by-side lanes in the selected areas and two tests were performed at each location in the center of each roller pass. The same sequence of testing was performed as described above.

4 DULUTH TEST SITE

4.1 *Description*

State Project 6915-125 involved the reconstruction of a 2.25 mile long segment of TH 53 in Duluth into a four-lane section with 12-foot lanes, a 13-foot continuous left turn lane, curb and gutter, retaining walls and 5-foot sidewalks. The pavement structure consisted of 8” HMA, 6” Class 6 aggregate base, and 36” subcut backfilled with select granular borrow. For this project, the acceptance criterion of the compacted material was based on super quality compaction and test rolling, with the option of performing sand cones and moisture testing (Horan, 2005).

4.2 *Caterpillar IC Roller*

The Caterpillar IC roller (Fig. 13) was used on the TH 53 project. This roller is a single drum vibratory roller, equipped with a GPS. This roller calculates two index parameters called compaction meter value (CMV) and machine power. These can be used to estimate in situ modulus by relating these index parameters to other in situ modulus tests (Cackler et al, 2005). An accelerometer is used to measure the movement of the drum in response to the soil and this information is used to continuously alter the compaction energy. The Caterpillar roller increases and decreases the applied load by altering the amplitude of drum vibrations. This is achieved by positioning eccentric masses about the roller’s axle. The roller data is also displayed in the form of color-coded maps to the operator (Fig. 13). The roller documents this entire process storing all relevant time, position, and compaction data for later use.

Fig. 13 Caterpillar IC Roller

4.3 *Field Data Collection*

An area isolated from the active construction project was chosen for testing and the Caterpillar IC roller was made available for the comparative testing. An area was selected where production compaction had already been completed and the roller was used to measure the stiffness for a single 100 ft pass. Three locations were selected and the same test sequence conducted at the Atwater project was performed at each of these locations. Material from each location was collected for determination of oven dry moisture content. Moisture testing was also conducted in the field using Percometer and Trident moisture meters. CNA Consulting Engineers conducted additional field verification testing at this project (Petersen et al, 2006b).

5 JANESVILLE TEST SITE

5.1 *Description*

State project 8103-47 involves the reconstruction of 12.4 miles of TH 14 between Waseca and Janesville beginning in 2004 and continuing through 2006. Work is also occurring on several county roads within the project limits. The pavement structure consists of 8.5” non-reinforced, doweled concrete pavement, 4” open graded aggregate base, 4” class 5 aggregate base, and 3.5’ select grading materials typically fine grained cohesive soils.

5.2 *Ammann IC roller*

Both the Ammann and Caterpillar rollers were used on the TH 14 project. The Caterpillar rollers were used on the site July 18th to 22nd and the Ammann roller was used on the site October 28th to November 7th. The Ammann roller is a single drum vibratory roller (Fig. 14) that was not equipped with GPS. The Ammann roller utilized the ACE measurement system to measure in-situ stiffness. An accelerometer is used to determine underlying soil stiffness and this information is used to automatically adjust compaction energy. The ACE system automatically adjusts the compaction energy imparted to the soil by altering the roller amplitude and frequency of the drum vibrations. The measurements are displayed in the cab in real time on a series of gages that display roller amplitude, stiffness, and roller speed (Fig. 14).

Fig. 14 Ammann IC Roller

5.3 *IC Field Trial*

Dr. White and his research team from Iowa State University conducted these IC evaluation trials in cooperation with Ammann, Caterpillar, Mathowitz construction, and Mn/DOT district personnel. Results of this field trial can be found in two project reports produced by Iowa State (White et al, 2006a and White et al, 2006b)

6 RESULTS

6.1 *Atwater Test Site*

Four gradation tests were conducted on material collected from the test grid. Three samples were tested at the District 8 soil laboratory and used a limited number of sieves. Testing on the final sample was conducted according to ASTM procedures at the Office of Materials lab. The results of tests A, B, C, and the Maplewood test (Table 1 and Fig 17) show the material is fairly uniform in gradation. For this paper the gradation of the select granular present at the testing area will be assumed to be consistent with the gradation determined by the Maplewood lab.

Table 1. Gradation for Select Granular material

Sieve Size	**Percent Passing [%]**			
	District Lab Test A	**District Lab Test B**	**District Lab Test C**	**Maplewood Lab**
50 mm (2 in)	100	100	100	
37.5 mm (1 1/2 in)	100	100	100	
31.5 mm (1 1/4 in)	100	100	100	100
25.0 mm (1 in)	100	100	100	100
19.0 mm (3/4 in)	100	100	100	99.9
16.0 mm (5/8 in)				99.7
12.5 mm (1/2 in)				99.1
9.5 mm (3/8 in)	96	96.7	84.2	96.1
4.75 mm (#4)	80.9	81.7	69.9	80.5
2.36 mm (#8)				66.7
2.00 mm (#10)				63
1.18 mm (#16)				51.8
600 um (#30)				34.6
425 um (#40)				25.8
300 um (#50)				16.8
150 um (#100)				8.1
75 um (#200)				5.4

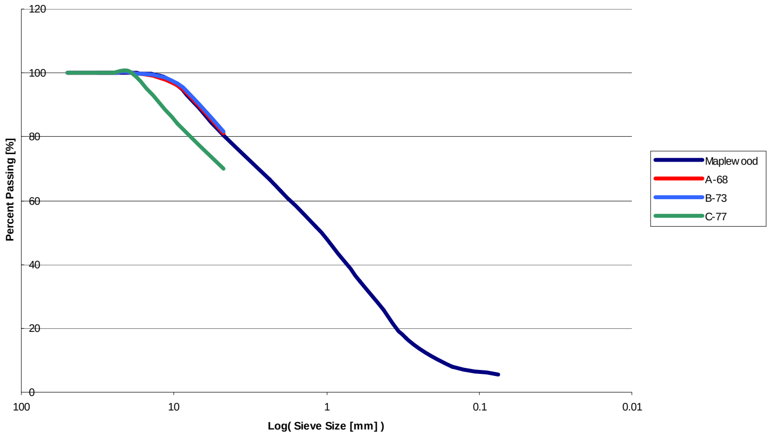


Figure 15. Gradation Curve for Select Granular Material

Four Proctor tests were conducted on the same samples used for the gradation testing. Once again, three tests were conducted at the District 8 lab and one test was conducted at the Office of Materials lab. The results of the Proctor tests (Table 2) suggest that the material is fairly uniform. There is however a noticeable difference between the values determined at the district lab and that determined at the Mn/DOT lab.

Table 2. Standard Proctor Results

Test	Location	Optimum	Optimum
		Density	MC
		[lb/ft^3]	[%]
1	A 68	126.4	9.3
2	B 73	127.4	9.9
3	C 77	126.4	9.1
4	ABC	124.8	7.0

Bomag, DCP, LWD, and Geogauge tests were conducted on the test grid. The results of these tests are presented in Table 3 and Table 4. The statistical analysis of this data shows that there is a similar amount of precision among all the devices, which suggests that the attempts to select a uniform area succeeded.

Table 3. Device Modulus Measurements

Station	Lane		Modulus					
		DCP	DCP	LWD			GeoGauge	Bomag Avg
65,70,75,80	A,B,C	DPI	Top 200 mm	25cm	50 cm	75cm		
[ft]		[mm/blow]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]
65	A	27	35	36	37	42	54	36
70	A	20	44	38	41	48	57	49
75	A	21	42	43	41	49	60	54
80	A	22	40	43	43	48	58	42
65	B	17	63	60	58	61	73	49
70	B	18	55	48	47	54	61	34
75	B	24	46	42	45	49	59	42
80	B	20	59	46	50	55	55	44
65	C	17	59	65	59	61	69	41
70	C	18	59	35	36	43	65	34
75	C	19	59	41	40	44	62	33
80	C	16	63	44	44	48	61	28

Table 4. Statistical Analysis of Device Modulus Measurements

Device	Mean Modulus [MPa]	Standard Deviation [MPa]	Coefficient of Variation
DCP	52	9.4	0.18
LWD 25	45	8.5	0.19
LWD 50	45	7.0	0.16
LWD 75	50	6.1	0.12
GEO	61	5.3	0.09
BOMAG	40	6.9	0.18

Comparative statistical analysis (SAS, 2005) was used to determine whether the device measurements of modulus were significantly different from the Bomag modulus measurements. The test was preformed at α 0.05. The results of this analysis (Table 5) show that the device measurements are not significantly different than the Bomag measurements. This means that the QA device measurements do not statistically differ from the Bomag measure of modulus and it implies that all of these devices can be used as QA tools in conjunction with the Bomag IC roller. However, differences in modulus values may have practical significance. The GeoGauge proved to consistently measure higher modulus values than the Bomag roller on the order of 20 MPa.

Table 5. Two Tail F-Test Results

Device	P-Value
DCP	0.104
LWD 25	0.950
LWD 50	0.883
LWD 75	0.560
GEO	0.552

Despite having established that the measurements from each QA device have trends that are reasonably similar to the Bomag modulus measurements; there are no strong statistically significant correlations between the QA device measurements and the Bomag measurements due to the uniformity of the area tested(Table 6).

Table 6. Linear Regression with Bomag Measurements

Device	R^2 Value
DCP	0.242
LWD 25	0.000
LWD 50	0.002
LWD 75	0.035
GeoGauge	0.036

The narrow range of observed modulus values in the testing grid and the different influence depths associated with each device may explain these weak correlations. Full depth DCP tests were conducted within the test grid to illustrate the variability of layer modulus with depth (Fig.18).

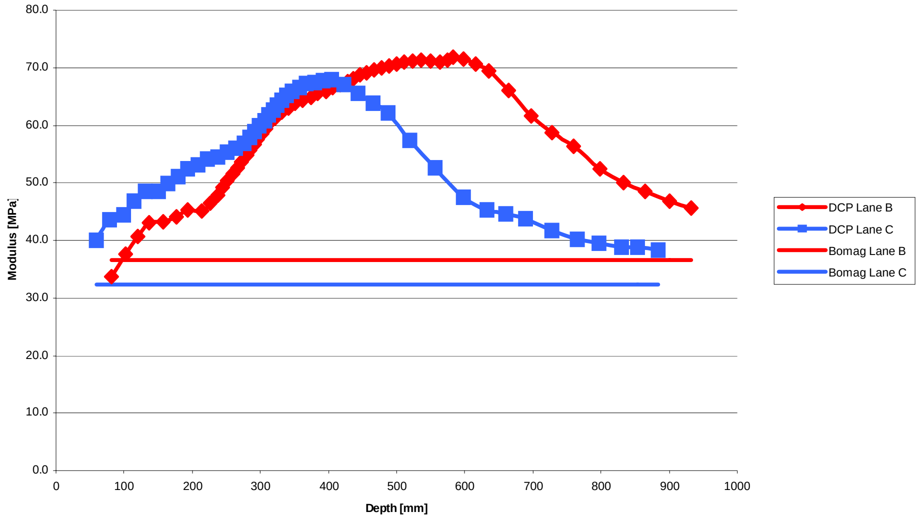


Fig. 16 Depth Effect of Layer at Station 72

The above graph illustrates the variable nature of the test grid modulus vs. depth. Each QA device estimates the composite modulus of the layer to a depth no greater then its influence depth and since the influence depth for each device ranges from a few centimeters to nearly a meter, it makes sense that the data is not strongly correlated.

Applying the currently accepted QA procedure, the sand cone test, to the data obtained from the test grid (Table 7 & 8) shows that 100% of the sand cone tests pass for the lowest determined optimum density. This optimum density corresponds to the Proctor test conducted at the Office of Materials lab. Using the highest determined optimum density from one of the District 8 lab tests shows that 67% pass; however the one observed failure was only 0.5% relative density below meeting the acceptance criteria. Even using the highest optimum density these tests suggest that the lift meets current specifications. It is also interesting to note the variability of the relative densities for the sand cone tests conducted in the test grid. Tables 7 and 8 illustrate the dramatic effect that small changes in optimum Proctor density can have on the sand cone test. The tests show that there is as much as 5% difference in the relative densities for the tests using the minimum and maximum determined Proctor densities. This 5% density difference would correspond to a much greater change in strength (Proctor, 1945, 1948). Therefore strength-based tests such as the DCP, LWD and GeoGauge will often seem more variable than sand cones.

Table. 7 Sand cone Quality Control of Testing Grid at the Assumed Optimum Density of 124.8 lb/ft^2

Test Location		**Sand cone**	**Optimum**	**Relative**	**Test**
Lane	**Station**	**Density**	**Density**	**Density**	**Pass/Fail**
	[ft]	**[lb/ft3]**	**[lb/ft3]**	**[%]**	
A	68	127.0	124.8	102.0	Pass
B	73	127.2	124.8	102.0	Pass
C	77	130.3	124.8	104.5	Pass

Table 8. Sand cone Quality Control of Testing Grid at the Assumed Optimum Density of 127.4lb/ft^2

Test Location		**Sand cone**	**Optimum**	**Relative**	**Test**
Lane	**Station**	**Density**	**Density**	**Density**	**Pass/Fail**
	[ft]	**[lb/ft3]**	**[lb/ft3]**	**[%]**	
A	68	127.0	127.4	99.5	Fail
B	73	127.2	127.4	100.0	Pass
C	77	130.3	127.4	102.5	Pass

Applying the DCP pilot specification to the DCP data obtained from the test grid (Table 8) shows that only 50% of the DCP tests would pass. This lift would therefore not meet the DCP pilot specifications. However it is important to note that half of these failures have DPI’s within 2mm/blow of the allowable penetration index. In addition the pilot specification will likely be modified based upon new data collected on select granular samples in 2005 (Davich et al, 2006).

Table 9. Application of DCP Pilot Specification to Test Grid DCP Data

X	**Y**		**Oven**			**DCP SPEC**			
Station	**Offset**	**GN**	**Dry**	**Allowable**	**Allowable**	**Measured**	**Measured**	**SEAT**	**DPI**
65,70,75,80	**A,B,C**		**MC**	**Seat**	**DPI**	**Seat**	**DPI**	**Pass/Fail**	**Pass/Fail**
[ft]			**[%]**	**[mm]**	**[mm/blow]**	**[mm]**	**[mm/blow]**		
65	A	4.7	7.0	75	19	83	27	Fail	Fail
70	A	4.7	7.4	75	19	85	20	Fail	Fail
75	A	4.7	6.9	75	19	94	21	Fail	Fail
80	A	4.7	7.7	75	19	88	22	Fail	Fail
65	B	4.7	6.7	75	19	52	17	Pass	Pass
70	B	4.7	7.8	75	19	64	18	Pass	Pass
75	B	4.7	7.3	75	19	63	24	Pass	Fail
80	B	4.7	7.0	75	19	78	20	Fail	Fail
65	C	4.7	6.6	75	19	49	17	Pass	Pass
70	C	4.7	7.4	75	19	49	18	Pass	Pass
75	C	4.7	7.4	75	19	49	19	Pass	Pass
80	C	4.7	7.2	75	19	42	16	Pass	Pass

Applying the LWD pilot specification to the data collected from the test grid using the LWD 50 modulus measurements (Table 8), show that 58% of the LWD 50 tests pass. These results are very similar to the results found applying the DCP pilot specification.

Table 8 LWD Pilot Specification

Station	**Lane**	**Test Parameters**		**Target**	**LWD**	**Pass/Fail**
		Oven Dry MC	**Grading Number**	**Young's Modulus**	**Young's Modulus**	
		[%]		**[MPa]**	**[MPa]**	
65	A	7.0	4.7	42	37	Fail
70	A	7.2	4.7	42	41	Fail
75	A	7.4	4.7	42	41	Fail
80	A	7.4	4.7	42	43	Pass
65	B	6.6	4.7	42	58	Pass
70	B	7.4	4.7	42	48	Pass
75	B	6.9	4.7	42	45	Pass
80	B	6.9	4.7	42	45	Pass
65	C	6.7	4.7	42	59	Pass
70	C	7.2	4.7	42	36	Fail
75	C	7.3	4.7	42	40	Fail
80	C	7.3	4.7	42	44	Pass

7 CONCLUSIONS

The statistical analysis of the data showed that the modulus measurements from the QA devices were not significantly different from the Bomag IC estimated modulus. This suggests that the Bomag roller is capable of classifying the modulus for the entire lift. Furthermore, the IC roller provides 100% verification of this lift area. This is a dramatic improvement over sand cone testing, which covers less than 1% of the compacted volume. The data from the IC roller also provides a record that can be used for decision making during future rehabilitation and pavement maintenance activities.

The QA devices showed promise and are similarly precise, but additional testing, covering a wider range of material types is required to demonstrate a strong statistical correlation with the Bomag modulus measurement. Additional research is also required to classify each device’s measurement depth.

The results of the field-testing showed that the LWD pilot specification has the potential to be implemented. The LWD specification preformed on par with the DCP specification and it seems that given the LWD’s ability to track Bomag modulus measurements, further research to refine the target modulus values for the specification could prove very beneficial.

One of the most challenging aspects of implementing IC technology on future construction projects will be handling the massive amounts of data that are generated and converting them to usable formats for field inspectors. Mn/DOT has developed a preliminary plan for achieving this. First, the roadway alignment data for a project is imported to ArcMap (Fig. 17). ArcMap is a geospatial mapping tool that allows the overlaying of alignment data as a layer of a geographical information system.

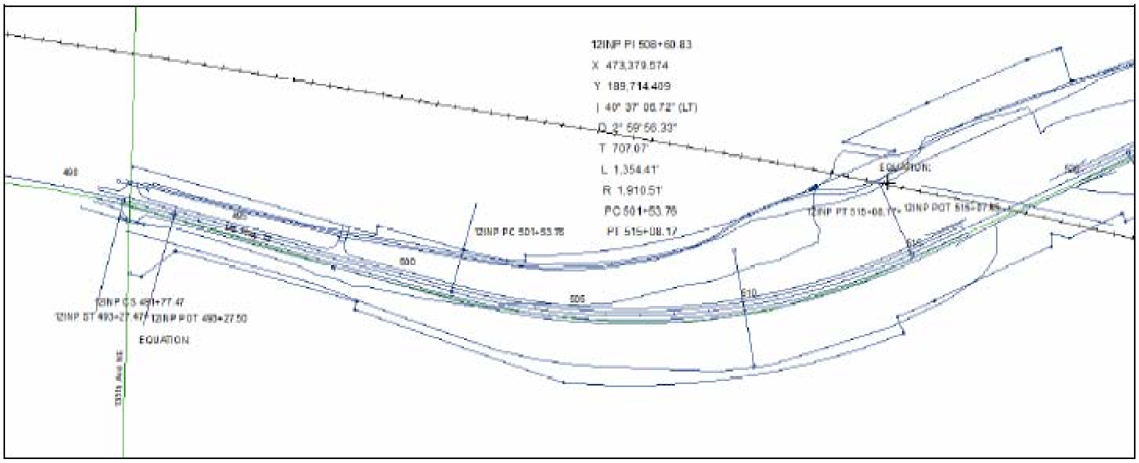


Fig. 17 ArcMap file of Road Alignment

Second, an aerial photograph of the site is imported into ArcMap to provide a visual reference for Mn/DOT field inspectors (Fig. 18).

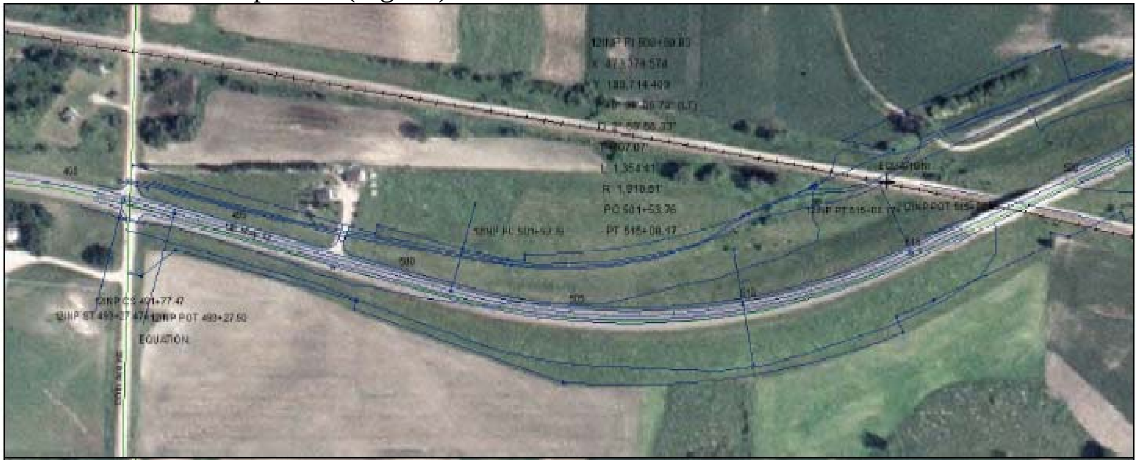


Fig. 18 Arcmap Road Alignment atop Aerial Photograph of the Atwater Project

Third, the Bomag modulus data are imported. This map is used to identify problem areas during the construction process and decide how to properly address them.

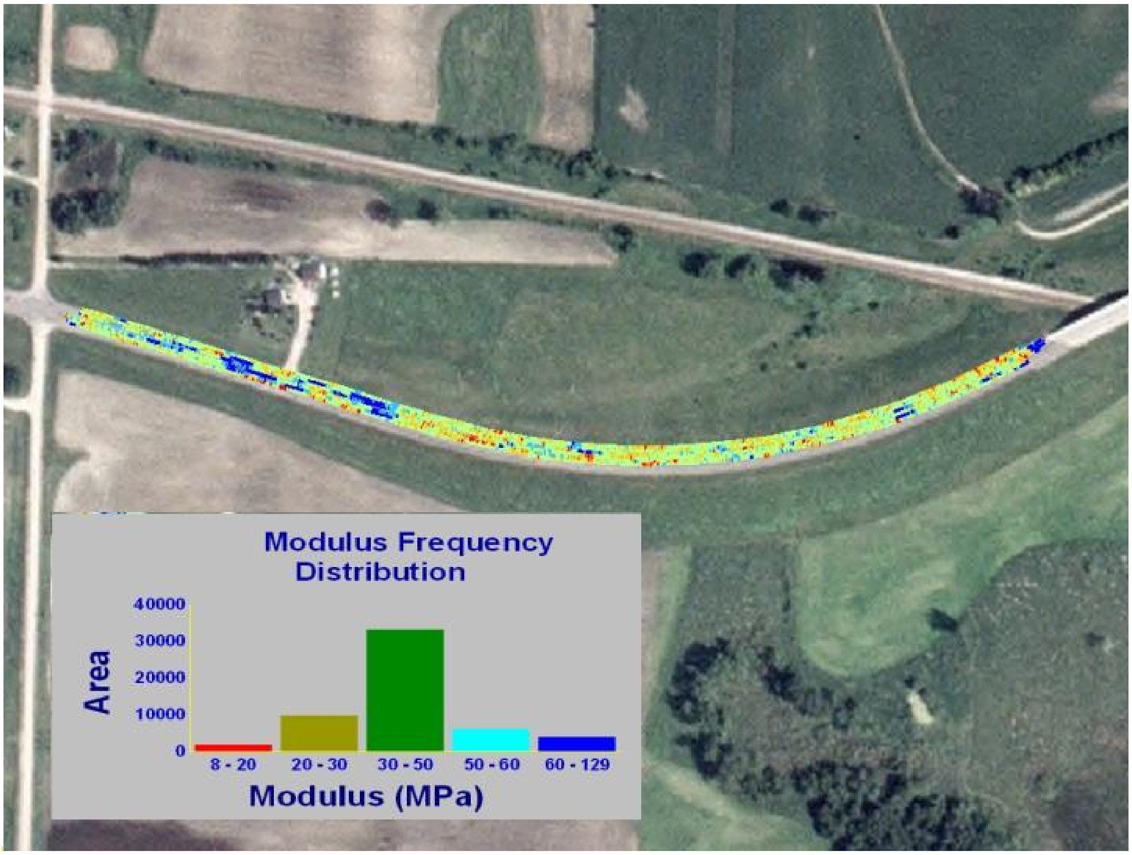


Fig. 19 Aerial Reference Photo with Bomag Modulus Data of Atwater Project

Finally, once compaction has been completed, the reference photo (Fig. 19) coupled with geostatistical methods can be used to determine locations for QA testing.

The field studies helped identify that some rollers require alterations to their data recordation software. Ideally all roller manufacturers will adopt a standardized data format so that roller data can be exported and analyzed in an expeditious manner. In order to accomplish this the authors suggests that the roller manufacturers provide all of the following data in a comma delimited ASCII format:

- Roller parameters including width, diameter, static drum mass, maximum vertical dynamic force and horsepower
- Frequency, amplitude, and acceleration of the drum
- Modulus, stiffness, or compaction index parameter
- Position data that includes x,y,and z coordinates for each side of the drum in UTM NAD 1983 zone 15N format
- Time stamp for each data point accurate to the frequency of the drum.

Some difficulties were experienced, from site to site, dealing with GPS data because there was no current standard for GPS. However, the roller data collected from the Atwater site was recovered from the Bomag roller successfully and was uploaded to Mn/DOT standard GIS software. This demonstrates that the Bomag roller is capable of meeting the requirements of the implementation plan developed by Mn/DOT.

The intelligent compaction rollers all exhibited tremendous promise for use as QC tools on project sites. These trials showed that the technology is field-functional and that implementation is feasible for the 2006 construction season. The portable field-testing devices such as the DCP, LWD, and GeoGauge were found to show great potential for QA. Despite continued challenges with direct comparisons between each device, the results of this study suggest that the modulus estimates from each device are similarly precise and more relevant to performance than the currently accepted QA test, the sand cone. Furthermore, given that the portable field device tests can be conducted more quickly, are safer, and are better suited for use with IC technology; it is strongly recommended that these newer tests be considered as a replacement for the sand cone test.

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