# Suitability of Intelligent Compaction for Relatively Smaller-Scale Projects in Vermont

**Final Report**

**Project Number: SPR-RSCH018-744**

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Report Submitted on: 01/31/2017

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| 4. Title and Subtitle<br><br>Suitability of Intelligent Compaction for Relatively Smaller-Scale Projects in Vermont | | 5. Report Date<br>November 28, 2016<br><br>6. Performing Organization Code |
| 7. Author(s)<br><br>Kamali-Asl, Arash, Ghazanfari, Ehsan, and Dewoolkar, Mandar M. | | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address<br><br>Department of Civil and Environmental Engineering<br>The University of Vermont<br>213 Votey Hall<br>33 Colchester Ave.<br>Burlington, VT 05405 | | 10. Work Unit No.<br><br>11. Contract or Grant No.<br>744 |
| 12. Sponsoring Agency Name and Address<br><br>Vermont Agency of Transportation<br>Materials and Research Section<br>One National Life Drive<br>Montpelier, VT 05633 | | 13. Type of Report and Period Covered<br>Final<br>(2015-2016)<br><br>14. Sponsoring Agency Code |
| 15. Supplementary Notes | | |

| 16. Abstract | | | |
|---|---|---|---|


Intelligent Compaction (IC) is considered to be an innovative technology intended to address some of the problems associated with conventional compaction methods of earthwork (e.g. stiffness-based measurements instead of density-based measurements). IC typically refers to an improved compaction process using rollers equipped with an integrated measurement system that consists of a global positioning system (GPS), accelerometers, onboard computer reporting system, and infrared thermometers IC determines the compacted material's stiffness/modulus simultaneously while compacting based on measured frequency and amplitude of excitation.

The overarching objective of this research was to investigate the suitability of IC technology for comparatively smaller-scale embankment, subgrade, and base material construction that are typical for Vermont. The specific objectives were to: perform a literature review of IC technology; assess the accuracy and reliability of IC measured values (e.g. stiffness); investigate the influence of relevant parameters (i.e. density, soil type, moisture content, etc.) on these measurements; investigate different options for quality control (QC) and quality assurance (QA) specifications for IC; and make specific recommendations to the Agency.

The literature review suggests that: (i) IC stiffness measurements near the surface are less reliable compared to deeper measurements; (ii) correlations between IC measured stiffness and modulus of spot-test measurements vary considerably in layer and layered soil structures; and (iii) for asphalt, IC measured stiffness correlates well with nuclear density gauge measurements, only when the asphalt mix is hot. In addition, the existing quality control (QC) and quality assurance (QA) specifications for implementing IC need further improvements.

It is suggested that to better investigate the reliability of implementing IC for both earthwork construction and asphalt pavement in Vermont's harsh winter conditions, it would be necessary to conduct field experiments. In addition, preparing a new set of QC/QA specifications is an important step toward implementation of IC in Vermont projects, which can be accomplished in collaboration with other states and as some local experience in IC is gained. Also, it is recommended to evaluate the correlation between IC stiffness measurements and in-situ stiffness measurements in different seasons in Vermont.


| 17. Key Words | | 18. Distribution Statement | |
|---|---|---|---|
| Intelligent Compaction<br>In-situ Testing<br>Measurement Values<br>Spot-test Measurements<br>Stiffness Measurements | | No Restrictions | |
| 19. Security Classif. (of this report)<br>Unclassified | 20. Security Classif. (of this page)<br>Unclassified | 21. No. Pages<br>49 | 22. Price |

## ACKNOWLEDGMENTS

This work was funded by the Vermont Agency of Transportation (VTrans). The authors would like to thank VTrans for supporting this project. Initial feedback on the project objectives provided by Mr. Chris Benda and Mark Woolaver of VTrans is greatly appreciated.

## ORGANIZATION OF THE REPORT

It should be noted that most of the material summarized in this report is a synthesis of information gathered from the following sources: MN/RC 2009-14 report (White et al., 2009); Mooney and Rinehart (2009); Rinehart et al. (2009); NCHRP report 676 (Mooney et al., 2010); FHWA-IF-12-002 report (Chang et al., 2011); FHWA-HIF-14-017 report (Chang et al., 2014); and MPC 15-281 report (Savan et al., 2015). This report is structured as follows: Chapter 1 gives an introduction about intelligent compaction. Chapter 2 includes the literature review on earthwork construction, asphalt pavement and cost-benefit analysis. Chapter 3 provides conclusions, and Chapter 4 provides recommendations

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# CHAPTER 1 –INTRODUCTION

## 1.1 Different Components of IC

Effective compaction of embankments, subgrades, and base materials is critical to the performance of pavements and other earth structures. Current quality-control (QC) and quality-assurance (QA) testing devices (e.g. nuclear density tests) are typically used to assess less than 1% of the actual compacted area (NCHRP report 676 [Mooney et al., 2010]); they provide only spot checks and are unable to provide a wide measure of adequate compaction. In addition, from the QA-QC perspective, it is highly desirable to transition from the current density-based acceptance practice to stiffness-based inspection practice.

Intelligent Compaction (IC) is an innovative technology intended to address some of these problems associated with conventional compaction methods (NCHRP report 676 [Mooney et al., 2010]). IC refers to an improved compaction process using rollers equipped with an integrated measurement system that consists of a GPS (global positioning system), accelerometers, onboard computer reporting system, and infrared thermometers for hot mix asphalt (HMA)/warm mix asphalt (WMA) feedback control (FHWA-IF-12-002 report [Chang et al., 2011]) as depicted in Figure 1.

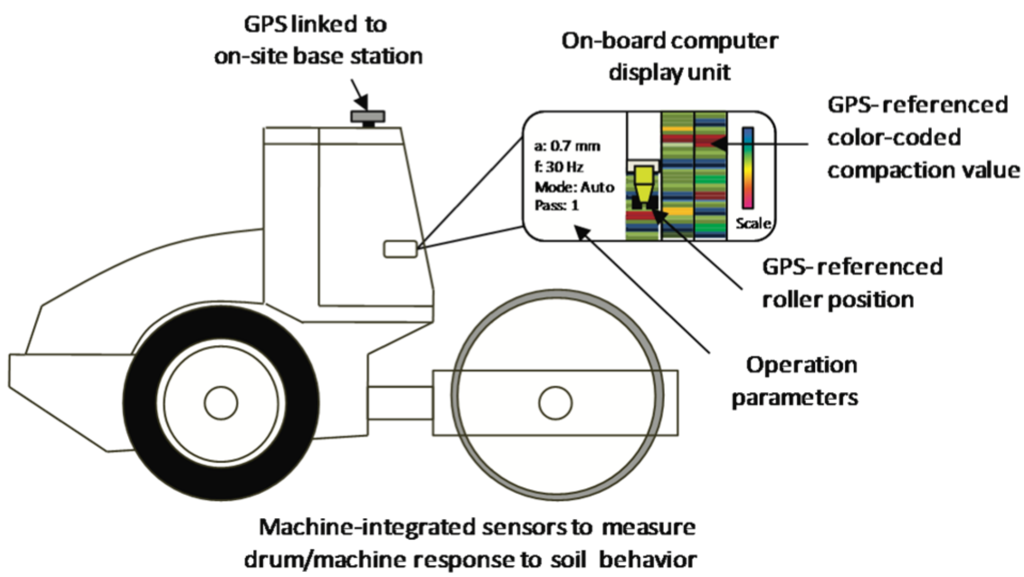


**Figure 1.** Schematic showing different components of IC rollers (Source: FHWA-IF-12-002 report [Chang et al., 2011])

NCHRP report 676 (Mooney et al., 2010) suggests that IC has the following capabilities:

1. Extraction of mechanical characteristics of soil, including stiffness;
2. Automatic adjustment of frequency and amplitude of excitation; and
3. Creation of a comprehensive map of the roller paths.

Each soil/asphalt layer is compacted using IC rollers, which are fitted with accelerometers to measure stiffness of the soil/asphalt layer (NCHRP report 676 [Mooney et al., 2010]). Values of various parameters such as the drum length, drum radius, static mass, static linear load, excitation frequency and excitation force of some typical rollers used in IC are reported in Table 1.

**Table 1.** Characteristics of some of the rollers (Source: NCHRP report 676 [Mooney et al., 2010])

| Roller | MV | Drum Length, m (ft) | Drum Radius, m (ft) | Static Mass, kg (lb) | Static Linear Load, kN/m (kip/ft) | Excitation Frequency, Hz | Excitation Force, kN (kip) |
|---|---|---|---|---|---|---|---|
| Ammann/Case AC110/SV212 | $k_s$ | 2.20 (7.22) | 0.75 (2.46) | 11,500 (25,350) | 31.5 (2.2) | 20–34 | 0–277 (0–62) |
| Bomag BW113-BVC | $E_{vib}$ | 2.13 (7.00) | 0.75 (2.46) | 14,900 (32,850) | 42.4 (2.9) | 28 | 0–365 (0–82) |
| Caterpillar CS563 | $CMV_C$ MDP | 2.13 (7.00) | 0.76 (2.49) | 11,100 (24,500) | 26.9 (1.8) | 32 | 133, 266 (30, 60) |
| Dynapac CA362 | $CMV_D$ | 2.13 (7.00) | 0.77 (2.53) | 13,200 (29,100) | 37.3 (2.6) | 32 | 0–260 (0–58) |
| Sakai SV510 | CCV | 2.13 (7.00) | 0.75 (2.46) | 12,500 (27,600) | 32.2 (2.2) | 37, 28 | 186, 245 (42, 55) |

By integrating measurement (e.g. acceleration, temperature), documentation, and control systems, the IC technology allows for real-time monitoring and corrections in the compaction process (NCHRP report 676 [Mooney et al., 2010]). Color-coded plots can provide the number of roller passes, compaction level, temperature measurements as well as exact location of the roller drum (Gallivan et al., 2011).

Figure 2 shows a Sakai IC roller, which is equipped with an on-board display, accelerometer, documentation system and infrared thermometers. Figure 3 shows examples of accelerometers for both soil and asphalt compaction mounted on Caterpillar and Bomag rollers, respectively.


**Figure 2.** Sakai roller (Source: Naras et al., 2015)


**Figure 3.** Accelerometers mounted on the rollers (Source: Naras et al., 2015)

Figure 4 shows different GPS elements, which are implemented during earthwork construction based on IC. Figure 5 shows the Sakai onboard display unit, which is used for showing the routes to be compacted and the level of achieved compaction during IC.


**Figure 4.** GPS system for the IC earthwork constructions (Source: Naras et al., 2015)

**Figure 5.** Sakai IC onboard display unit (Source: Naras et al., 2015)

The capability of IC technology to improve the compaction process for roadway construction is well documented from projects in Europe, Asia, and the United States (Xu et al. 2012). The most significant improvement is the substantial reduction in variability of measured properties as reported by Xu et al. (2012).

The more uniform material properties obtained by the IC technology helps ensure higher quality pavements that provide the desired performance and intended service life (MN/RC 2009-14 report [White et al., 2009]). NCHRP report 676 (Mooney et al., 2010) has identified IC as a viable alternative that could lead to a stiffness-based specification. IC techniques provide a number of benefits for roadway construction over the conventional compaction processes. In addition to reducing the compaction variability of road building materials, these include: (i) optimization of labor work; (ii) reduction of material variability; (iii) less need for compaction and maintenance; (iv) spotting hard-to-compact areas; (v) corrections during the process of earthwork compaction; (vi) documentation of construction records; (vii) generation of IC base map; and (viii) possibility of retrofitting existing equipment (NCHRP report 676 [Mooney et al., 2010]).

## 1.2 Correlations for Roller Measurement Values

IC provides measures of material's compaction state as well as stiffness. Thurner and Sandstorm (1980) indicated that the ratio of the amplitude of the first harmonic to that of the excitation frequency could be considered as a measure of compaction state as well as the soil stiffness. The compactometer and compaction meter value (CMV) were introduced by Thurner and Sandstorm (1980). Compaction Control Value (CCV) is implemented to identify weak spots for evaluation via a static plate load test (PLT), a lightweight deflectometer (LWD) or density spot testing (NCHRP report 676 [Mooney et al., 2010]).

Roller measurement values (MVs) are correlated to PLT modulus, LWD modulus or density for QA (NCHRP report 676 [Mooney et al., 2010]). Automatic adjustment of frequency and amplitude of vibration to rollers, thanks to the servo-controlled eccentric excitation, is a unique feature of IC (NCHRP report 676 [Mooney et al., 2010]). It is important to consider the interaction between roller and soil/rock in IC as it contains nonlinear and chaotic behavior (Adam and Kopf, 2004).

Automatic feedback control of the centrifugal force is implemented in order to prevent chaotic motion in IC rollers (Anderegg and Kaufmann, 2004). Figure 6 shows the possible modes of vibration in the IC compaction of soils.

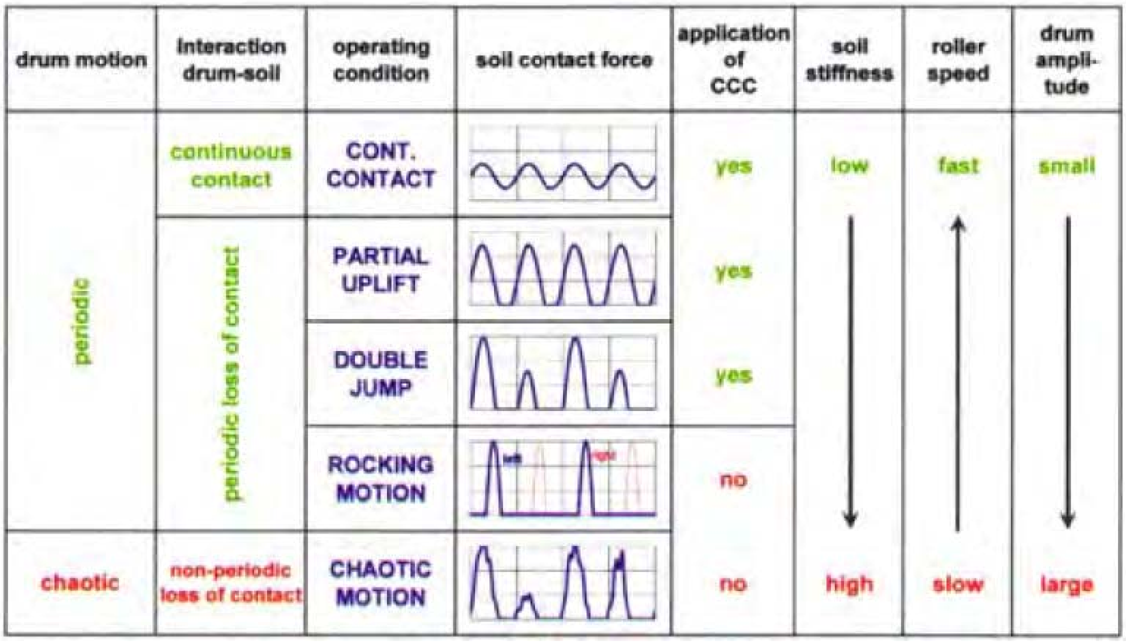


**Figure 6.** The modes of vibration during compaction of soils (Source: Adam and Kopf, 2004)

The underlying soil has a direct influence on sensitivity of roller MVs (Mooney et al., 2003). Correlations between CMV and PLT moduli $E_{V1}$ and $E_{V2}$ and also CMV and density were reported by Floss et al. (1991) concluding that the correlation between CMV and density is not as promising as that of CMV and PLT. The correlation between Bomag (roller manufacturer) $E_{vib}$ and PLT for silty gravel was investigated and reported to have a strong correlation (Krober et al., 2001).

Classified regression relationships to correlate the roller MV to spot-test measurements in earthworks were performed by Brau et al. (2004), which considered different soil types, layered and homogenous soils, and different roller vibration amplitude. The study concluded that this approach is feasible; however, it entails significant uncertainties. Mooney et al. (2003 and 2005) reported that given the stiffer sub-lift material, CMV and CCV correlate better with spot-test measurements.

Long-term performance of pavements strongly depends on effective compaction of embankments, subgrades, and base materials. The conventional rolling equipment and techniques for achieving the target levels of compaction have worked reasonably well over the years; however, they are not free of deficiencies. The typical problems associated with traditional methods include non-uniformity derived from variability in the materials (particularly in the natural soil), poor control of moisture content in the underlying layers, low or non-uniform temperatures in the hot-mix asphalt (HMA) or warm-mix asphalt (WMA) layer, poorly compacted longitudinal joints, and a lack of tools that provide feedback to the roller operator so that the roller pattern can be continuously achieved (NCHRP report 676 [Mooney et al., 2010]).

These problems have, in turn, resulted in lower productivity and higher costs during construction as well as reduced pavement performance, shorter pavement lives, and higher maintenance and rehabilitation costs as reported in the literature (NCHRP report 676 [Mooney et al., 2010]; FHWA-HIF-14-017 report [Chang et al., 2014]; and MPC 15-281 report [Savan et al., 2015]). In addition, current QC and QA testing devices (e.g. nuclear density tests) can only provide spot measurements and are unable to provide a system-wide measure of proper compaction (NCHRP report 676 [Mooney et al., 2010]). From QA-QC perspective, it is highly desirable to transition from the current density-based acceptance practice to stiffness-based inspection practice (NCHRP report 676 [Mooney et al., 2010]).

One of the important parameters in IC is the measurement depth, which determines the accuracy of the stiffness/moduli estimations for different layers in the earthwork (NCHRP report 676 [Mooney et al., 2010]). Several experimental studies (e.g. Floss et al., 1991; Brandl and Adam, 2000) and numerical studies (e.g. Brandl et al., 2005) proposed measurement depth based on the weight of rollers. There are limited studies on the use of in-ground instrumentation to monitor soil response (e.g. D'Appolonia et al., 1969; Brandl and Adam, 2000; Brandl et al., 2005; Ping et al., 2002). Several researchers have also worked on geostatistical aspects of roller MVs (e.g. Grabe, 1994; Petersen et al., 2007).

The roller-integrated measurement systems, feedback control and GPS-based documentation for each manufacturer's IC rollers are described in NCHRP report 676 (Mooney et al., 2010). The specifications for roller-based Continuous Compaction Control (CCC) have been provided in the aforementioned report, which includes the specifications from Austria (1990), Germany (1994), Sweden (1994) and Minnesota in the United States (2008). The German specifications introduced weak areas for spot testing, and the Austrian specifications use percentage change of MVs as an alternative to a calibration method (NCHRP report 676 [Mooney et al., 2010]). In the Swedish specifications, the use of roller-integrated CCC to identify weak spots for PLT is permissible. For determination of intelligent compaction target values (IC-TVs), the implementation of QC by the contractor, and QA by the engineer and control strips are mandated by the Minnesota Department of Transportation (Mn/DoT) (NCHRP report 676 [Mooney et al., 2010]).

Introduction of variable excitation force amplitude and variable excitation force frequency has enabled inclusion of automatic feedback control (AFC) of the applied excitation force (NCHRP report 676 [Mooney et al., 2010]). Since the specifications for QA using current CCC technology requires roller operation with constant operational parameters, CCC-based QA should not be performed during automatic feedback control operation. Manufacturers such as Bomag, Case/Ammann and Dynapac offer commercially available AFC of excitation force (NCHRP report 676 [Mooney et al., 2010]).

Manufacturers aim at preventing excessive vertical excitation force amplitude in order to avoid unstable jump mode vibration (NCHRP report 676 [Mooney et al., 2010]). Different manufacturers have developed their AFC mode with a specific criterion (NCHRP report 676 [Mooney et al., 2010]). AFC-based IC aims at providing improved compaction efficiency as well as more uniform compaction (FHWA-IF-12-002 report [Chang et al., 2011]). Since the roller measurement values depend on the frequency and amplitude of the roller, evaluation of AFC-based IC requires independent assessment of compaction (NCHRP report 676 [Mooney et al., 2010]).

## 1.3 Objectives

The overarching objective of this research was to investigate the suitability of IC technology for comparatively smaller-scale embankment, subgrade, and base material construction that are typical for Vermont. The specific objectives were to: perform a literature review; assess the accuracy and reliability of IC measured values (e.g. stiffness); investigate the influence of different parameters (i.e. density, soil type, moisture content, etc.) on these measurements; investigate different options for quality control (QC) and quality assurance (QA) specifications for IC; and make specific recommendations to the Agency.

# CHAPTER 2 - LITERATURE REVIEW

## 2.1 Benefits and Shortcomings of IC

The traditional methods of compaction do not provide continuous assessment of the achieved density, and more importantly, desired material properties. In addition, these methods are unable to evaluate the compaction level at all regions of the earthwork, rather, some spot measurements are made corresponding to a limited proportion of the earthwork (FHWA-IF-12-002 report [Chang et al., 2011]). To address these shortcomings, Continuous Compaction Control (CCC)-based methods and the concept of Intelligent Compaction (IC) was introduced (NCHRP report 676 [Mooney et al., 2010]). In CCC, sensors are installed on rollers and by using GPS the roller route is recorded to ensure that all regions of the earthwork are covered. The sensors are used to measure acceleration corresponding to the vibratory rollers, and then, the stiffness is computed based on acceleration signals. IC was introduced as a modification to CCC in which a feedback control system is implemented such that amplitude and frequency of excitation are modified to achieve optimum level of compaction (NCHRP report 676 [Mooney et al., 2010]).

On the other hand, implementation of IC requires operators and officials that are educated and experienced on IC. In addition, application of AFC mode in IC for QA/QC is not allowed since the earthwork is not homogenous. The capital cost associated with IC is another limitation, although it could be compensated over the lifetime of the constructed facility. Limited research and field work regarding the application of IC for asphalt makes it more challenging compared to soils. Finally, it should be noted that a comprehensive cost analysis was not found for the implementation of IC in roadways for both soils and asphalt.

## 2.2 IC Implementation for Soil

NCHRP report 676 (Mooney et al., 2010) provided a comprehensive investigation on IC for soil embankments. Minnesota, Colorado, Maryland, Florida and North Carolina were selected to conduct field-testing on intelligent soil compaction. Figure 7 shows photographs of these test beds.

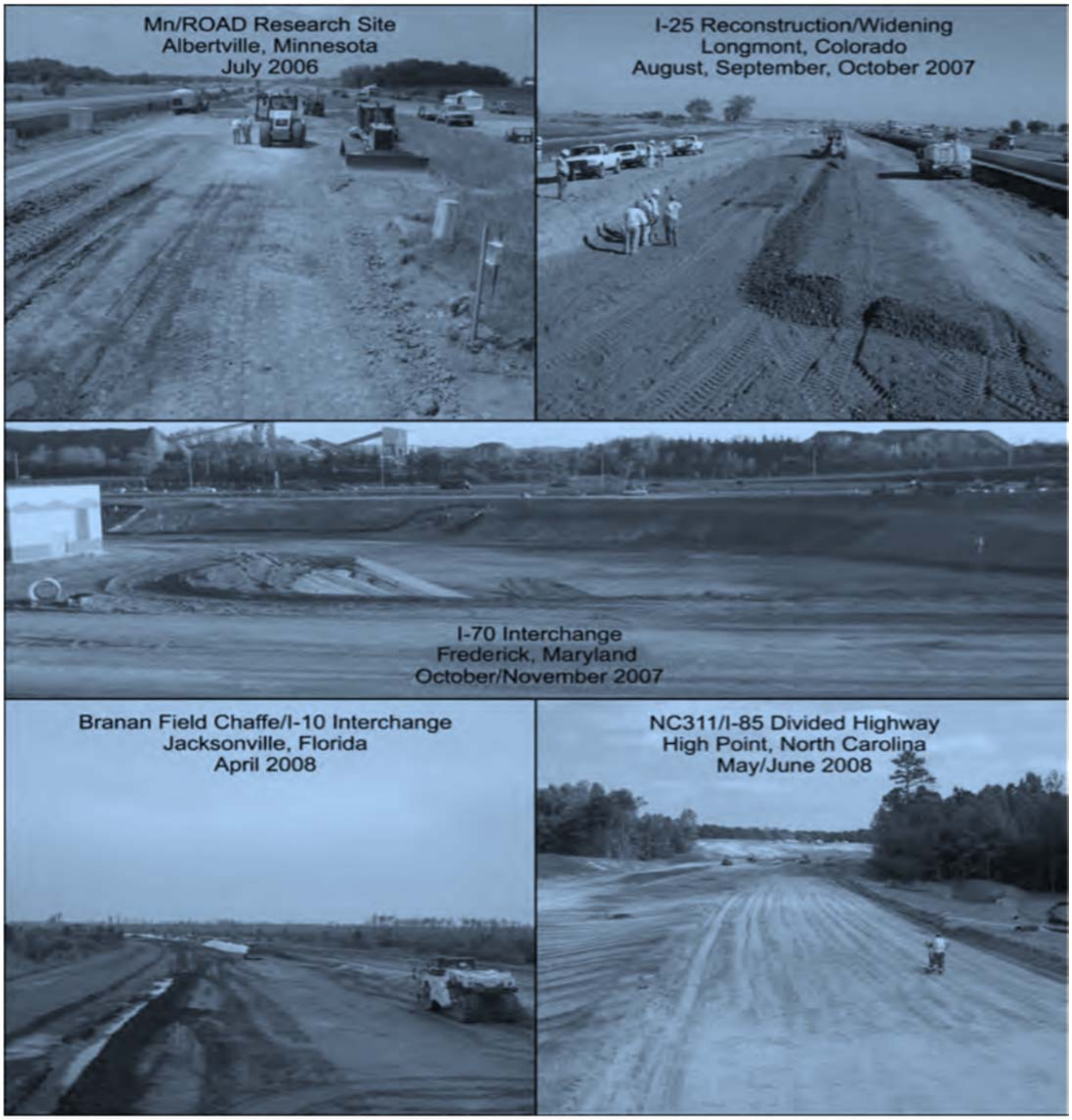


**Figure 7.** Picture of the earthwork of different sites for NCHRP project (Source: NCHRP report 676 (Mooney et al., 2010))

The materials used in the study included granular soils, fine-grained soils and aggregate base material. A summary of the rollers used in the abovementioned project and their relevant information are included in Table 2.

**Table 2**. Summary of the characteristics of the rollers used in the NCHRP project (Source: NCHRP report 676 [Mooney et al., 2010])

| | Intelligent Compaction Features | | |
|---|---|---|---|
| **Roller Manufacturer** | **Roller-Integrated Measurement** | **Automatic Feedback Control of:** | **GPS-Based Documentation** |
| Ammann/Case | Stiffness $k_s$ | Eccentric force, amplitude, and frequency | Yes |
| Bomag | Stiffness $E_{vib}$ | Vertical eccentric force amplitude | Yes |
| Caterpillar | MDP, $CMV_C$ | None | Yes |
| Dynapac US | $CMV_D$ | Eccentric force amplitude | Yes |
| Volvo | $CMV_V$ | None | No |
| Sakai America | CCV | None | Yes |

The researchers identified more than 200 test beds across the five sites. The test beds involved "single lifts of subgrade, subbase and base course materials ranging in thickness from 15 to 30 cm (6 to 12 in) and, in some cases, multiple lifts and layered systems to depths greater than 1.5 m (4.9ft)" (NCHRP report 676 [Mooney et al., 2010]). Although the study suggests avoiding IC during QA, it can be used during the compaction process. The study used static PLT, dynamic cone penetrometer (DCP), LWD, and nuclear density gauge (NDG) for spot-test measurements.

One of the main issues to be addressed for transition from the current density-based acceptance practice to stiffness-based inspection practice using IC is whether intelligent compaction measurement values (ICMVs) in terms of stiffness can be directly correlated to in-situ measurements (e.g., moduli, density, and California bearing ratio) using conventional methods (NCHRP report 676 [Mooney et al., 2010]). ICMVs are a composite reflection of typical base, sub-base, and subgrade structures (NCHRP report 676 [Mooney et al., 2010]). Layer thickness, relative stiffness of the layers, vibration amplitude, and drum/soil interaction issues (contact area, dynamics) are the contributing factors to roller MVs (NCHRP report 676 [Mooney et al., 2010]). Different parameters including layer interaction, drum/soil contact mechanics, and stress-dependent soil modulus contribute to the amplitude dependence of roller MVs (FHWA-IF-12-002 report [Chang et al., 2011]).

Roller measurements can be used for development of mechanistic–empirical–based design (e.g., AASHTO 2007 Pavement Design Guide) of pavements through extraction of mechanistic material properties (NCHRP report 676 [Mooney et al., 2010]).

The method for the characterization of the level of the layer compaction used by different manufacturers is different. For example, CMV, as an indication of layer stiffness/modulus; or CCV, as layer stiffness for Sakai IC asphalt rollers, can be used as ICMV (NCHRP report 676 [Mooney et al., 2010]).

A number of studies were performed over the past two decades to relate roller MVs to spot-test measurements (e.g., density, PLT modulus, LWD modulus). Krober et al. (2001) investigated correlations between ICMV and PLT moduli $E_{V1}$ and $E_{V2}$ (vibration modulus), and the correlations between ICMV and density during field-testing on a silty gravel and reported a strong linear correlation between $E_{vib}$ and both $E_{V1}$ and $E_{V2}$ ($R^2 > 0.9$). Developed regression relationships using ICMVs and spot-test measurement data from several sites by Brau et al. (2004) show significant scatter. Mooney et al. (2003, 2005) considered sand subgrade soil and crushed rock base material for correlation studies between ICMVs and dry density as well as DCP, and concluded that if the sub-lift material was stiffer the strength of the correlation and sensitivity of the ICMVs improved significantly. White and Thompson (2008) developed reasonable correlations of ICMVs to spot test measurements for different cohesionless base materials using linear regression analysis.

Another aspect of IC development is the evaluation of the surface area reflected in individual MVs, spatial resolution in MV records and uncertainty in roller MVs. According to NCHRP report 676 (Mooney et al., 2010), some of the important parameters that affect the performance of IC are:

(i) The influence of vibration amplitude and frequency,

(ii) Roller speed, and forward/reverse driving mode on roller MVs, and

(iii) Effects of soil heterogeneity on roller MVs.

Also, the main reasons for roller MV position error (see Figure 8) include (NCHRP report 676 [Mooney et al., 2010]):

(i) Physical offset of the GPS receiver from the drum center

(ii) Movement of roller which results in data averaging during the calculation of roller MVs

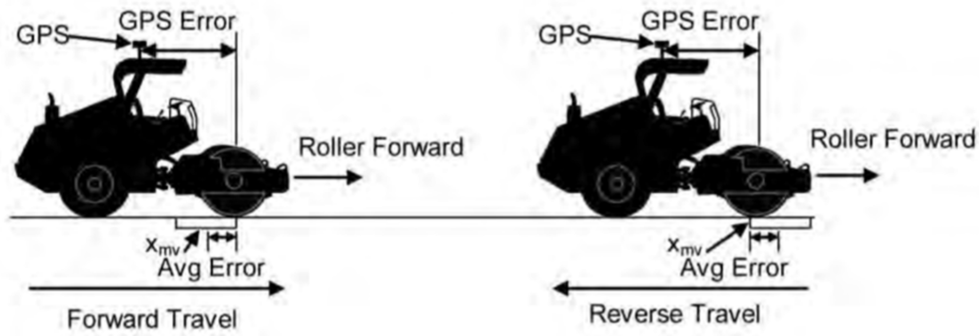


**Figure 8.** A Schematic showing sources of error during the compaction of earthwork using IC (Source: NCHRP report 676 [Mooney et al., 2010])

### 2.2.1 Uncertainties in IC measurement values

To verify the uncertainty associated with IC, tests were repeated to examine the appropriate functioning of the roller measurement systems (NCHRP report 676 [Mooney et al., 2010]). According to FHWA-IF-12-002 report (Chang et al., 2011), the roller MVs are based on variation of soil stiffness and soil damping. An independent evaluation of MVs was taken into account to examine roller MV trends (NCHRP report 676 [Mooney et al., 2010]). Independently computed MVs were compared with those introduced by the companies and in all of them minor differences were noticed (NCHRP report 676 [Mooney et al., 2010]). The study also performed light weight deflectometer (LWD) tests to investigate the directional dependence of roller MVs across the drum lane. Regarding directional dependence, the report suggests that consecutive passes should follow similar paths if pass-to-pass analysis is to be performed (NCHRP report 676 [Mooney et al., 2010]).

### 2.2.2 Roller measurement depth

It is critical to investigate the roller measurement depth for IC implementation. NCHRP report 676 (Mooney et al., 2010) found that the compaction of thin lifts of stiff soil layers over a softer material does not influence MVs in field experiments. The underlying subgrade material was reported to have no influence on roller-measured stiffness for depths greater than the measurement depth; however, for depths less than that the base thickness-to-subgrade thickness ratio has a direct influence on roller-measured stiffness NCHRP report 676 [Mooney et al., 2010]). In addition, it is reported that the measurement depth is a function of stress and strain decay in soil profiles (NCHRP report 676 [Mooney et al., 2010]).

Roller-based stiffness is derived from cyclic drum deformation and is indirectly influenced by the soil response in both directions (FHWA-IF-12-002 report [Chang et al., 2011]). Roller MVs were found to significantly depend on the structure of the layered system (NCHRP report 676 [Mooney et al., 2010]). Several layered test beds were constructed to investigate roller measurements in different sub-layers. Table 3 summarizes the key observations made in test beds (NCHRP report 676 [Mooney et al., 201])).

**Table 3.** Key observations made in different test beds (Source: NCHRP report 676 [Mooney et al., 201])

| # | Observation | Potential Reasoning |
|---|---|---|
| 1 | Base-to-subgrade stiffness does not alter measurement depth, while it can be moderately influenced by excitation force. | The measurement depth is computed based on the ratio between value of maximum strain and 10% of maximum strain, hence, increasing excitation force causes relative increase in the ratio between these two stresses. Therefore, the measurement depth increases. |
| 2 | Both roller-measured stiffness and soil modulus decrease as excitation force increases in the case of homogeneous soils. | The increase in excitation force causes higher shear stresses on the soil elements and also stress-softening in the soil, and therefore the roller-measured soil stiffness and in-situ soil modulus increase. |
| 3 | Roller MVs cannot well represent the soil immediately beneath the drum. The correlation between ICMVs and in-situ test measurements are not in fair agreement. | -- |
| 4 | In layered structures, the soil modulus decreases as the excitation force increases, while roller-measured stiffness increases with increase in the excitation force. | Increasing the excitation force in layered structures causes the increased contribution of the stiffer layer in the soil stiffness measurements, and consequently, the roller-measured stiffness increases. However, any increase in excitation force leads to decrease in soil modulus due to increased shear stresses on soil element. |
| 5 | Placing crushed rock base atop stiffer subgrade compared to a softer subgrade will result in higher sensitivity of roller MVs. | -- |

### 2.2.3 Relationship between MVs and soil moduli – QA perspective

It is important to understand the relationship between roller-measured soil stiffness and soil modulus, for performing appropriate QA (NCHRP report 676 [Mooney et al., 2010]). Results from low-vibration amplitude roller passes over two different soils (clayey sand subgrade A-6(1) and granular subbase A-1-b) are discussed in NCHRP report 676 [Mooney et al., 2010]). It was found that: (i) the measurement depth linearly increases by 3 cm for each 0.1 mm increase in the vibration amplitude, and (ii) granular soils show positive relationship between MVs and amplitude of the roller; hence, the report suggests the use of constant amplitude for QA. In addition, the study found that if the ratio of lift stiffness to sub-lift stiffness is less than 50%, the soil stiffness measurements are not reliable. NCHRP report 676 (Mooney et al., 2010) suggested six QA options as summarized in Table 4.

**Table 4:** QA options (Source: NCHRP report 676 [Mooney et al., 2010]).

| Option | Description |
|---|---|
| 1 | "Includes point measurements on the weakest areas based on MVs". |
| 2a | "Compares percent change in the mean MV between consecutive passes". |
| 2b | "Same as option 2a, with the exception that percent change of MV at a location is evaluated between consecutive passes. In addition, it requires that a certain percentage of locations must have a percent change lower than a threshold". |
| 3a | "Establishes an acceptable correlation between measurement values and spot-test measurements to create target values". |
| 3b | "Establishes a target value (TV) based on the mean MV when the percent difference of measurement values for consecutive passes does not exceed 5% for 90% of the entire area". |
| 3c | "A target value is created based on the correlation of lab-determined properties and measurement values". |

### 2.2.4 Case studies on QA for soil compaction using IC

NCHRP report 676 (Mooney et al., 2010) presented a number of case studies regarding QA for soil compaction using intelligent compaction and the results are summarized in Table 5.

**Table 5:** Case studies on QA (Source: NCHRP report 676 [Mooney et al., 2010])

| Case | Description |
|---|---|
| 1 | Test bed CO34 in Colorado, which took place on a 4-foot wide by 1000-foot long granular subbase. QA options a, 2a, 2b, and 3a were implemented among which 2a, and 2b met the QA standards. |
| 2 | Test bed FL15 in Florida on a 40-foot wide by 200-foot long evaluation area consisting of granular subgrade. QA options 1, 2a, and 2b were implemented and the latter two met the QA criteria. |
| 3 | Test bed FL19 again in Florida with aggregate base took place on a 30-foot by 917-foot evaluation area. QA option 3a was implemented and it did not meet the criteria |
| 4 | Test bed FL23 on a 36-foot by 825-foot evaluation area of granular subgrade material took place in Florida. QA options 1, 2a, 2b, 3a, and 3b were used and options 1, 2a, and 2b got accepted. |
| 5 | Test bed NC20 in North Carolina took place on a 60-foot by 1640-foot evaluation area with granular subgrade. QA options 1, and 3a were implemented. It was found that the former option should be used with additional caution. |
| 6 | Test bed MN10 in Minnesota on a non-granular subgrade was performed to evaluate QA option 3c, leading to unsatisfactory results and therefore, it was not accepted. |
| 7 | Test bed 1 located in West Lafayette, Indiana was used to investigate "the effect of the roller's vibration amplitude on soil density, modulus, and strength". |
| 8 | Texas DOT performed compaction projects on seven test beds. Various spot-test measurements were conducted including LWD, PLT, dry unit weight, CBR and FWD. FWD and PLT correlated better with MVs than LWD. |

### 2.2.5 Relationship between stress-strain and roller measurements

The relationship between stiffness and in-situ stress-strain modulus is another important factor to be evaluated in IC. In a series of projects performed and presented in NCHRP report 676 (Mooney et al., 2010), in-situ behavior during static and vibratory roller passes was captured at multiple levels using vertically homogeneous embankments and layered subgrade/subbase/base. The vibration amplitude was found to be dependent on roller MVs and measurement depth of the instrumented roller (NCHRP report 676 [Mooney et al., 2010]. Figure 9 shows a series of photographs from different sensors installed at the depth of the earthwork to measure stress/strain.

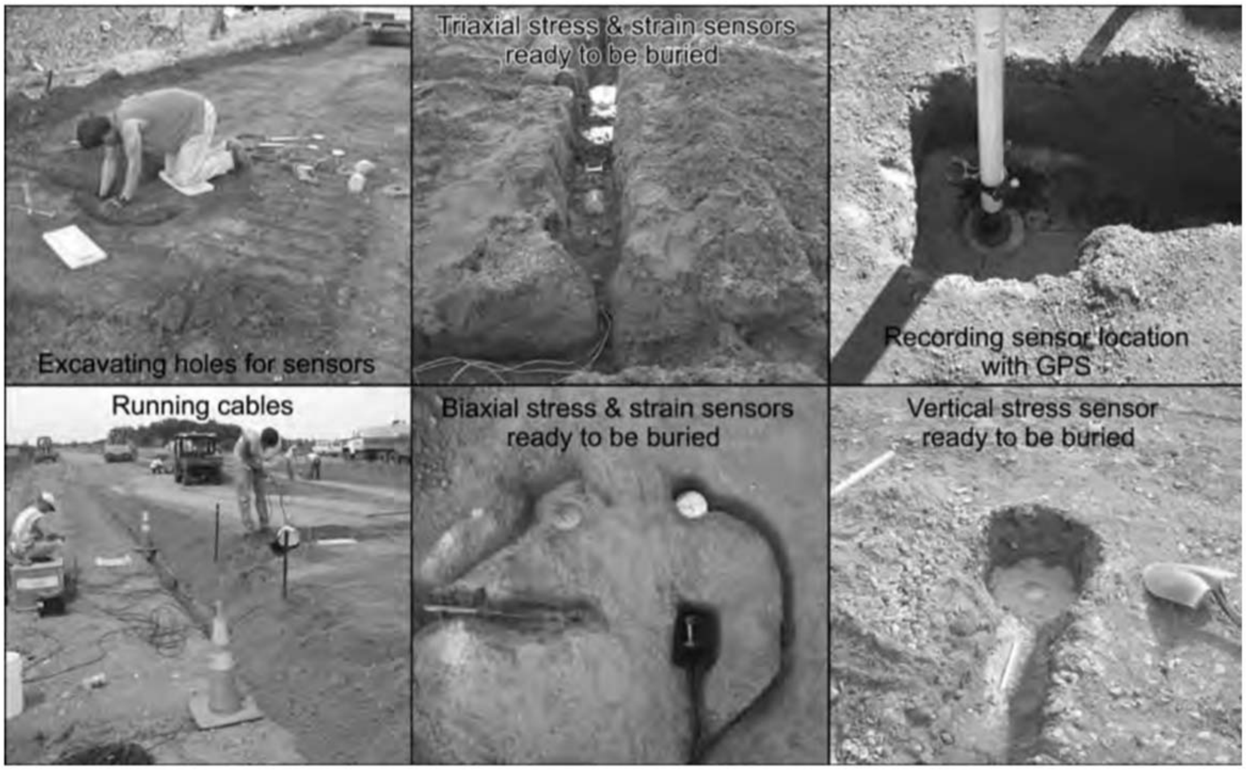


**Figure 9.** Photographs showing different stress/strain sensors employed to capture the soil behavior (Source: NCHRP report 676 [Mooney et al., 2010])

Low-amplitude vibration and static roller passes are recommended toward the end of compaction since near surface release of locked in stresses and strains and/or loosening of soil is commonly observed in compacted soils (Mooney and Rinehart, 2009). Bow effect (i.e. the change in the pattern of surrounding soil as a result of the waves formed at the bow of a roller) may cause vertical extension and longitudinal compression in front of the drum, which in turn, leads to asymmetric conditions (Mooney and Rinehart, 2009). The stress/strain state in the center of the drum is another issue studied by Mooney and Rinehart (2009), which follows the plane strain conditions and varies over the length of the drum.

For clayey sand, the levels of strain $\varepsilon_z$ and $\varepsilon_x$ during vibratory loading are higher than those in static tests; which could be attributed to the generation of pore air and/or pore water leading to modulus degradation (Mooney and Rinehart, 2009). For clayey sand, the soil modulus decreases with increasing excitation force (Mooney and Rinehart, 2009).

### 2.2.6 Other considerations for IC development

Rocking is another common phenomenon in rollers when soil stiffness beneath the drum is heterogeneous (Facas et al., 2010). Direction of compaction has influence on stiffness measurements and leads to different values for stiffness (Facas et al., 2010). This difference is attributed to a rocking motion of the soil beneath the drum, and in turn, shows the stiffness heterogeneity of the soil. Placing a sensor on the drum's center of gravity provides a directionally independent stiffness measurement, however, it is practically difficult to install sensors at the center of gravity (Facas et al., 2010). Instead, two vertical accelerometers are placed at the two ends of the drum; or equivalently one vertical accelerometer and one rotational accelerometer, can be installed to capture the parameters of rocking motion (Facas et al., 2010).

The effects of different stress states and paths on ICMVs are studied by Rinehart et al. (2009). Plane-strain conditions exist under the center of the drum to a depth of approximately 0.5 m (Rinehart et al., 2009). In subgrade materials, the laboratory values for the deviatoric stress are generally lower than the values of deviatoric stress in the field, however, the median stress values in the field are less than those of the laboratory experiments (Rinehart et al., 2009). In addition, resilient modulus in the field is less than values measured in the laboratory as stated by Rinehart et al. (2009). In base materials, the laboratory values for the deviatoric stress are generally lower than the values of deviatoric stress in the field, however, the median stress values in the field are less than those of the laboratory experiments (Rinehart et al., 2009).

## 2.3. Roller MVs and spot measurements

Implementation of roller-integrated compaction monitoring technologies into earthwork specifications requires an understanding of relationships between roller MVs and soil compaction measurements (NCHRP report 676 [Mooney et al., 2010]). Five roller-integrated measurement systems, each with a unique MV and 17 different soil types were evaluated in a series of projects performed by NCHRP report 676 (Mooney et al., 2010). The report found that it is possible to develop a simple linear correlation between roller MVs and in situ point measurements for a compaction layer underlain by relatively homogenous and stiff/stable supporting layer. The primary factors that affect roller MVs and spot measurements relationships include: (i) sampling disturbance, (ii) differences in the stress states between the laboratory specimen and in-place pavement material, (iii) non-representative materials, and (iv) inherent errors in the field and laboratory test procedures (NCHRP report 676 [Mooney et al., 2010]).

### 2.4. Field Tests for IC Implementation

An extensive IC project was conducted in Minnesota at four different sites and LWD technologies were used for QA/QC during compaction of the soil (MN/RC 2009-14 report [White et al., 2009]). ICMVs were compared with point measurement values and the effects of the roller operating conditions were investigated (MN/RC 2009-14 report [White et al., 2009]). Both granular and non-granular soils were considered in the project (MN/RC 2009-14 report [White et al., 2009]).

A statistical framework was created for the development of future specifications to be used as QA/QC in IC projects (MN/RC 2009-14 report [White et al., 2009]). They recommended the evaluation of multiple soil types and various IC rollers to be incorporated in this statistical analysis. The report also suggested implementing a real-time data analysis external to the IC manufacturer’s software (MN/RC 2009-14 report [White et al., 2009]). There are three different roller-integrated measurement values used in this study including compaction meter value (CMV), resonant meter value (RMV) and machine drive power (MDP). The study used different in-situ testing methods as summarized in Table 6.

**Table 6.** Different in-situ testing techniques used in the study (Source: (MN/RC 2009-14 report [White et al., 2009])

| Test | Description |
|---|---|
| Heavy Test Rolling | This test was performed using a pneumatic tire two-wheeled trailer, which is towed by a tractor. |
| Light Weight Deflectometers (LWD) | Zorn, Keros and Dynatest LWDs are used in this study and the modulus can be determined from the measurements. |
| Falling Weight Deflectometer (FWD) | FWD test was performed by applying three seating drops using a nominal force followed by three test drops. |
| Dynamic Cone Penetrometer (DCP) | DCP tests were performed at the depth of 1 m using typical DCP setup and 2 m using extension rods. |
| Cone Penetration Test (CPT) | Tip resistance, sleeve friction, and pore pressure can be measured during penetration. |
| Nuclear Gauge (NG) | Test was used for measurement of the soil dry unit weight and its moisture content. |
| Shelby Tube Sampling | Unconfined compressive strength, resilient modulus, unconsolidated-undrained testing were performed on samples. |
| Static Plate Load Test (PLT) | Loading is applied on a 20-30 cm plate and the deformation is measured. Initial and reloading moduli can be found using these data. |
| Clegg Hammer | This device has a 20-kg hammer with a drop height of 450 mm. "The Clegg impact value is derived from the peak deceleration of the free falling drop hammer in a guide sleeve for four consecutive drops". |
| Soil Stiffness Gauge (SSG) | The device applies small dynamic force and measures the soil deflection. Using this data, modulus can be calculated. |
| Earth Pressure Cells (EPC) | Using this device, the horizontal and vertical stresses in the pavement foundation can be measured. |

Figure 10 shows photographs of these in-situ testing measurements used in this study (MN/RC 2009-14 report [White et al., 2009]).

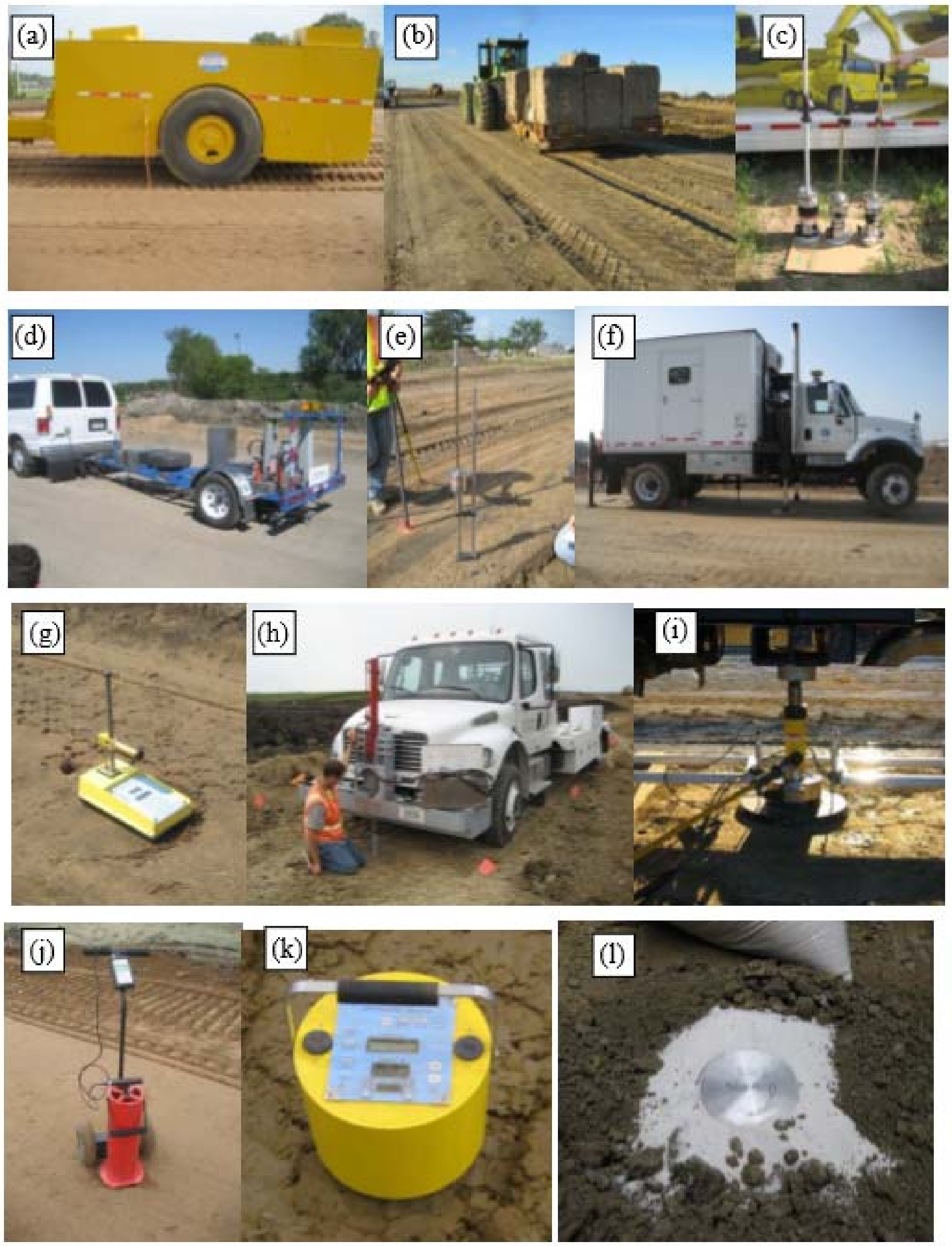


**Figure 10.** Photographs showing different in-situ test measurements used by White et al. (2009): (a), (b) towed pneumatic dual-wheel test rollers, (c) LWD, (d) FWD, (e) DCP, (f) CPT, (g) nuclear moisture-density gauge, (h) shelby tube sampler, (i) static plate load

test, (j) Clegg Hammer, (k), Humboldt SSG, and (l) Piezoelectric EPC (Source: MN/RC 2009-14 report [White et al., 2009]).

It is important to consider the advantages and disadvantages of different in-situ testing methods, when using these testing methods for QC of the compacted area. Table 7 summarizes the advantages and disadvantages of different in-situ testing methods, based on available data in literature.

**Table 7.** Advantages and disadvantages of different in-situ testing methods for QC of IC

| Method | Advantages | Disadvantages |
| --- | --- | --- |
| **LWD** | • Portable/hand-operated<br>• Estimation of modulus/deflection<br>• Immediate and repeatable results<br>• Very light compared to traditional equipment | • More stress dependent compared to FWD (Fleming et al., 2007)<br>• Uniform application of load is more difficult compared to FWD (Fleming et al., 2007)<br>• Not suitable for thicker layers (Fleming et al., 2007) |
| **FWD** | • Less stress dependent compared to LWD (Fleming et al., 2007)<br>• Uniform application of load is possible for variety of soils (Fleming et al., 2007) | • Higher load duration and higher applied force compared to LWD (Fleming et al., 2007)<br>• Higher cost compared to LWD (Fleming et al., 2007) |
| **PLT** | • Most suited for sand and clay | • Does not account for ultimate settlement<br>• Expensive compared to other methods<br>• Reliable mostly for homogenous soils |
| **NG** | • Fast (Soil Compaction Handbook, 2011)<br>• Easy-to-redo (Soil Compaction Handbook) | • Certified workers are necessary (APNGA)<br>• Particular attention is needed to make sure the nuclear gauge is fully enclosed (Nuclear Gauge Testing) |
| **CPT** | • Continuous data collection<br>• Repeatable test results | • Requires special equipment/skilled operator |

| | | |
|---|---|---|
| **Shelby Sampler** | • Fast (Soil Compaction Handbook, 2011)<br>• Deep sample (Soil Compaction Handbook, 2011) | • Inappropriate for granular non-cohesive soils (Brouwer, 2007)<br>• Small samples (Soil Compaction Handbook, 2011) |
| **SPT** | • Simple and quick<br>• Easy to implement | • Not appropriate for fine-grained soils<br>• Less reliable results |
| **Clegg Hammer** | • Easy to use | • Weights used are very light |
| **Soil Stiffness Gauge** | • Time- and cost-effective (Sawangsuriya et al., 2002)<br>• Quick and easy to use (Sawangsuriya et al., 2002) | • Inappropriate for multi-layer structures (Sawangsuriya et al., 2002) |

The MN/RC 2009-14 report (White et al., 2009) implemented IC pilot specifications at four earthwork construction in Minnesota including (a) Metro District TH36, North St. Paul (b) District 3 US10, Staples, (c) District 7 TH60, Bigelow, and (d) CSAH 2, Olmsted County. A brief summary of each project and key findings including how the IC measurement values were correlated to in-situ measurements in each project is provided in the next section (MN/RC 2009-14 report [White et al., 2009]).

### 2.4.1 Metro District TH 36, North St. Paul

The materials used for this project were granular base, granular sub-base and non-granular or granular subgrade. Four test strips were used in this project. Tables 8-10 in the Appendix section present the regression relationship for strips 1, 2 and 4, respectively. The report argues that compaction quality of granular embankment materials can be reliably reported by ICMVs and correlations between CMV and in-situ measurements are reliable, with the exception of one strip (MN/RC 2009-14 report [White et al., 2009]). A comparison between ICMVs and in-situ measurements from CPTU, FWD, and DCP showed good correlation values (MN/RC 2009-14 report [White et al., 2009]).

### 2.4.2 District 2 US 10, Staples

The materials used for this project were "Class 6 aggregate base layer of MN/DOT underlined by sub-cut backfill with select and suitable granular grading layers" (MN/RC 2009-14 report [White et al., 2009)]. The in-situ measurements of DCP, LWD, and PLT were used to find correlations with CMV/RMV measurement values of rollers. Table 11 in the Appendix section presents the correlations between IC-MVs and in-situ point measurements for strips 1, 2 and 3. For cohesionless sand, in-situ measurements and IC-MVs were shown to be highly-correlated by measurements 150 mm below the compaction surface (MN/RC 2009-14 report [White et al., 2009]). They also found that the correlation between modulus values and CMV is linear, while the correlation between LWD deflections and CMV is non-linear (MN/RC 2009-14 report [White et al., 2009]).

### 2.4.3 District 7 TH 60, Bigelow

Non-granular materials derived from glacial deposits and lean clay to sandy lean clay soils were used in this project (MN/RC 2009-14 report [White et al., 2009]). The in-situ point measurements including DCP, LWD, NG, DC were correlated with IC-MVs. The correlation results were reported in Table 12 in the Appendix section of the report. Reliable correlation between LWD modulus and compaction layer DPI measurements with varying degree of uncertainty was reported (MN/RC 2009-14 report [White et al., 2009]).

### 2.4.4 CSAH 2, Olmsted County

According to the roller operator IC-MVs were influenced by the slope of the grade and machine speed in this project (MN/RC 2009-14 report [White et al., 2009]). As stated in the report, travel direction (e.g. slope), speed, and vibration setting influenced MDP values. The correlation values are presented in Table 13 in the Appendix section of this report. Very positive correlations between MDP values and LWD modulus were found (MN/RC 2009-14 report [White et al., 2009]).

### 2.4.5 Granular versus non-granular soils

MN/RC 2009-14 report (White et al., 2009) provides results obtained from projects TH36 and US10, constructed on granular soils as well as results from projects TH60 and Olmstead County constructed on non-granular soils. Key findings for each of soil types are summarized in the following sections.

### 2.4.6 Granular soils

CMV values were linearly correlated with LWD modulus (MN/RC 2009-14 report [White et al., 2009]). The measurement influence depth is the depth in which stresses drop to 10% of the maximum stresses at the surface. Between the two projects with granular soils, measurement depths were different due to variation in soil stiffness and layering conditions as stated in the report. RMV values were found to be robust against roller jumping, however, CMV values were affected significantly (MN/RC 2009-14 report [White et al., 2009]).

### 2.4.7 Non-granular soils

LWD modulus and DPI better predicted MDP when the moisture content of soil was taken into account for analysis (MN/RC 2009-14 report [White et al., 2009]). The report has proposed simultaneous measurement of CMV and RMV to better characterize the condition of the compacted soil (MN/RC 2009-14 report [White et al., 2009]).

### 2.4.8 QA/QC assessment approach

MN/RC 2009-14 report (White et al., 2009) has recommended a statistical framework for the development of the IC specifications for QA/QC in earthwork construction projects. The report provides several QA options, including but not limited to:

(i) Using roller-integrated CCC to identify the weakest areas of the evaluation section (i.e. lowest roller MVs recorded), and acceptance is based on spot-test measurements from the weakest areas (MN/RC 2009-14 report [White et al., 2009]);

(ii) Using the pass-to-pass percentage change in roller MVs to determine acceptance, which is based on achieving a threshold between two consecutive measurement passes (MN/RC 2009-14 report [White et al., 2009]); and

(iii) Requiring that a specified percentage of roller MVs in an evaluation section exceed a roller MV target value.

## 2.5. Investigation of IC for Asphalt Compaction

Most of the state agencies use density as a criterion for the asphalt pavement acceptance (FHWA-HIF-14-017 report [Chang et al., 2014]). Intelligent compaction enables us to continuously monitor the compaction level of the area. FHWA performed an extensive research study to address whether it is possible to implement ICMV in asphalt pavements instead of coring (FHWA-HIF-14-017 report [Chang et al., 2014]). In 2012, two projects involving Hot Mix Asphalt (HMA) were performed in Utah and Florida, followed by three projects in California, Maine, and Ohio in 2013. In 2014, there were other projects in Idaho, Kentucky, Maryland, and Washington.

Double drum IC rollers used in these projects were BOMAG, Caterpillar, Hamm, and Sakai (FHWA-HIF-14-017 report [Chang et al., 2014]). BOMAG provides vibration modulus as its ICMV, Caterpillar provides compaction meter value (CMV), which correlates with layer stiffness, Hamm implements Hamm Measurement Value (HMV), which is very similar to CMV, and Sakai uses compaction control value (CCV) as its ICMV (FHWA-HIF-14-017 report [Chang et al., 2014]).

The report emphasizes that the setting of an IC roller should not be altered during the compaction of a test strip, and it is not appropriate to compare the ICMV for different IC rollers as they have different operating parameters, which can affect the results (FHWA-HIF-14-017 report [Chang et al., 2014]). Correlation with ICMV, core densities, LWD, FWD and NDG measurements are provided in the FHWA-HIF-14-017 report (Chang et al., 2011). The report found that for the breakdown rollers (i.e. rollers which compact the asphalt immediately), ICMVs correlate well with NDG measurements, however, for the intermediate rollers the correlations were not promising. Therefore, in-situ density measurements were found better validated by ICMV when the asphalt temperatures were high (FHWA-HIF-14-017 report [Chang et al., 2014]). The report did not find a promising correlation between LWD and FWD data with asphalt core density, however, it did find well enough correlation between asphalt core density and NDG measurements. FHWA-HIF-14-017 report (Chang et al., 2014) concluded that ICMVs cannot be solely implemented as an acceptance criterion for asphalt pavements and cannot be implemented as QA.

MPC 15-281 report (Savan et al., 2015) provides another comprehensive study on IC implementation for asphalt. The rollers used for the Wyoming project were from Bomag, Caterpillar, Hamm, and Sakai (MPC 15-281 report [Savan et al., 2015]). The report indicates that the measurement and acceptance criterion for the asphalt pavement is based on the ratio of achieved density to its maximum density. The maximum density of the pavement is measured by coring the asphalt pavement, and then performing the test within two days of coring (MPC 15-281 report [Savan et al., 2015]).

In 2008, a project was conducted in Minnesota aimed at monitoring the reliability of the IC rollers' temperature sensors. They also evaluated the relationships of asphalt MVs and the sub-base conditions along with correlations to spot-test measurements (MPC 15-281 report [Savan et al., 2015]). There are other case studies in different states such as Mississippi, Indiana, Utah, New York, Maryland, Texas and California after 2009. All of these projects were FHWA-sponsored aiming at familiarizing contractors and state DOT officials with the IC technology for asphalt pavements, which is less-developed compared to IC for soil compaction. Since 2010, some states started to adopt QA specifications for intelligent compaction in asphalt pavements including Utah, Colorado, Florida, Wyoming, Texas, Iowa, Minnesota, and California. The key findings of these studies can be summarized as follow (MPC 15-281 report [Savan et al., 2015]):

a. The correlations between MVs and spot-test measurements in both soil and asphalt pavements are promising but not consistent.
b. Some of the case studies show poor correlations and others are very strong.
c. Correlations between IC measured values and in-situ test measurements are more consistent for IC in soil than asphalt pavements.
d. Adjustment of MVs based on soil types, climate conditions and soil heterogeneity is of great importance.

Several states (e.g. Wyoming, Texas, Iowa, Colorado, Utah, Florida, Minnesota, and California) have adopted QA options using CCC/IC into their soil compaction specifications, however the criteria is different state-by-state (MPC 15-281 report [Savan et al., 2015]). For instance, Wyoming DOT allows up to 5% less than maximum dry density to be achieved, whereas Texas DOT only accepts the maximum dry density according to the MPC 15-281 report (Savan et al., 2015). In addition, there are other parameters, which vary between different states, such as moisture content (MPC 15-281 report [Savan et al., 2015]).

As part of the study performed by the Wyoming DOT, a national survey was conducted on different aspects of IC technology, in which officials and agencies across the United States participated (MPC 15-281 report [Savan et al., 2015]). The results show that participants received most of their information from FHWA representatives or publications. They were most familiar with the technology used in IC and least familiar with cost and benefits (MPC 15-281 report (Savan et al., 2015)). The survey found that most of the participants' concerns were related to the lack of experienced staff, ability of IC for approved QA, cost, and reliability of the data (MPC 15-281 report [Savan et al., 2015]). The survey also found that among the agencies that have or are drafting QC/QA for intelligent compaction, the criteria for most of them are correlation of spot-test measurements with intelligent compaction values (MPC 15-281 report [Savan et al., 2015]).

## 2.6. Cost-Benefit Analysis

The MPC 15-281 report (Savan et al., 2015) developed a cost-benefit analysis framework in order to evaluate the construction costs versus the benefits achieved over the lifetime of the road. The report provides two hypothetical case studies. One of the case studies involved a thick asphalt layer and the other a new roadway section which included both soil and asphalt construction. The input data and construction cost per line-mile of the thick asphalt layer project is presented in Tables 14 and 15 in the Appendix. The input data for the hypothetical new roadway, and the associated construction cost is included in Tables 16 and 17 in the Appendix as well.

The MPC 15-281 report (Savan et al., 2015) concluded that intelligent compaction is more reliable when it is used for soils compared to asphalt pavements. From the hypothetical cost analysis, it was found that there is a 37% reduction in costs when IC is used for a thick asphalt layer and 54% reduction of costs for a new road (MPC 15-281 report [Savan et al., 2015]). The report suggests that further research and more data from field-work are needed to better quantify the savings from IC for an actual roadway construction (MPC 15-281 report [Savan et al., 2015]).

# CHAPTER 3 – CONCLUSIONS

IC is a promising technology that can be implemented for both asphalt and soil compaction. Although the upfront costs of IC are higher than conventional density-based spot-test measurement methods, the possibility of 100% compaction coverage of the roadway along with more reliable stiffness measurements makes the IC a viable option to be used in earthwork construction. Table 8 summarizes the main advantages and disadvantages of IC implementation for soil/asphalt compaction.

**Table 8.** Advantages and disadvantages of IC implementation for asphalt and soil

| Advantages | Disadvantages |
| --- | --- |
| • Optimal number of passes<br>• 100% compaction of the roadway<br>• Cost-effective<br>• Provides better QA/QC<br>• Longer performance of pavements | • High capital cost<br>• Unfamiliarity of contractors and state officials with the method<br>• Uncertainty in correlation between ICMVs and spot-test measurements<br>• Inappropriate for layered structures with high base-to-subbase stiffness ratio<br>• Not very appropriate for asphalt compaction |

Generally, spot-test measurements correlate better with roller measurements in soil compared to asphalt. Based on the literature review performed in this study it was found that IC measured stiffness correlates weakly with spot-test measurements for layered soil profiles compared to homogeneous soils. For homogeneous soils, moduli and stiffness values have a positive correlation with the amplitude of the roller, however, for layered earthworks as excitation amplitude increases the moduli decreases and stiffness increases.

It is very important to note that both reliability of stiffness measurements and quality assurance options are substantially affected by the stiffness ratio between base and sub-base materials. For implementation of IC as a QA assessment tool, it is necessary to keep the frequency and amplitude of excitation constant since the soil properties might vary over the earthwork. Implementation of IC for asphalt compaction is more effective when the compaction is performed quickly as the temperature of the asphalt mix remains high. The hypothetical cost-benefit analysis for the State of Wyoming shows that the long-term performance and costs of the project implemented with IC outweighs the conventional compaction methods. However, more data from field-work is needed to more reliably assess the savings from IC compared to conventional methods over the life-cycle of the project.

# CHAPTER 4 – RECOMMENDATIONS

Adopting intelligent compaction in Vermont is a multi-fold issue. Given the relatively small size of the State, Vermont has roads with two or three lanes, which is different from relatively larger states such as Texas or California. In addition, the harsh winters in Vermont, is another issue that should be taken into account while addressing implementation of IC for earthwork constructions.

It is also important for Agency of Transportation officials to educate contractors regarding this relatively newly developed technology. Based on the literature review performed in this study, the authors provide the following list of recommendations regarding implementation of IC for embankments, subgrade, and base materials construction in Vermont:

1. There are important factors in evaluating appropriateness of IC for a given project based on soil types, moisture content, base-to-subbase stiffness ratio, the thickness of the layers, and so on. Therefore, it is necessary to first identify the soil types/layers to be used and other parameters in any proposed earthwork construction project prior to determining whether IC is appropriate for the project.
2. The Vermont Agency of Transportation has limited data from field IC implementation with limited success. It may be beneficial to continue building local experience in the technology by incorporating IC in future earthwork/asphalt projects.
3. There are several sets of QA/QC specifications available in the literature that are state specific, which may not be directly transferrable to Vermont. It may be beneficial to first adopt guidelines from states with similar climate and projects of similar size, and modify them based on local experience gained from the test projects (item 2 above).
4. Collaboration between the Agency and other states, specifically in New England could be beneficial both from technical and cost analysis points of view. It appears that experience with IC in New England states is limited.
5. Despite very limited existing cost analysis associated with implementing IC in different earthwork/asphalt construction projects, it is difficult to assess if the existing resources (e.g. contractors) support immediate implementation of IC in Vermont.
6. Given the harsh winters in Vermont, it is very important to take into account both weather and available resources (item 5) for QA/QC assessment of stiffness measurements.
7. It is important to evaluate the correlation between ICMVs with spot-test measurements in different seasons.
8. The theoretical and research work in the field of intelligent compaction for asphalt are not sufficient. Additional research is necessary to prepare the appropriate

specifications and the feasibility assessment of implementing IC for asphalt compaction in Vermont.

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## APPENDIX

**Table 8.** Correlation coefficients for Strip 1 at TH 36 at Minnesota (Source: MN/RC 2009-14 report [White et al., 2009])

| Relationship | n | $R^2$ |
|---|---|---|
| $CMV = -1.1 + 0.71\ E_{LWD\text{-}Z2}$ | 5 | 0.82 |
| $CMV = 16.2 – 1.89\ d_{LWD\text{-}Z2}$ | 5 | 0.82 |
| $CMV = -2.0 + 0.29\ E_{SSG}$ | 7 | 0.96 |
| $CMV = -21.4 + 4.98\ CIV_{20\text{-}kg}$ | 6 | 0.51 |
| $CMV = 13.5 – 0.16\ DPI_{300}$ | 22 | 0.56 |

**Table 9.** Correlation coefficients for Strip 2 at TH 36 at Minnesota (Source: MN/RC 2009-14 report [White et al., 2009])

| Relationship | n | $R^2$ |
|---|---|---|
| $CMV = 0.11 + 0.31\ E_{LWD-Z2}$ | 23 | 0.80 |
| $CMV = 14.12\ d_{LWD-Z2}^{-0.91}$ | 23 | 0.80 |
| $CMV = 1.04 + 0.56\ E_{V1}$ | 12 | 0.60 |
| $CMV = 1.09 + 0.16\ E_{V2}$ | 12 | 0.69 |
| $CMV = 184.61\ (DPI)^{-0.82}$ | 22 | 0.20 |

**Table 10.** Correlation coefficients for Strip 4 at TH 36 at Minnesota (Source: MN/RC 2009-14 report [White et al., 2009])

| Relationship | n | $R^2$ |
|---|---|---|
| FWD Applied Force, F ~ 26.7 kN | | |
| $E_{FWD-D3}$ (MPa) = 76.31 + 1.04 $E_{LWD-Z2}$ (MPa) | 11 | 0.55 |
| $E_{FWD-D3}$ (MPa) = 99.88 + 0.50 $E_{LWD-D2}$ (MPa) | 11 | 0.24 |
| $E_{FWD-D3}$ (MPa) = 43.53 $(q_t)^{0.45}$ (MPa) | 100 | 0.70 |
| $E_{FWD-D3}$ (MPa) = 422.84 $(DPI)^{-0.60}$ (mm/blow) | 157 | 0.65 |
| $E_{FWD-D3}$ (MPa) = 75.42 + 2.65 CMV | 11 | 0.50 |
| FWD Applied Force, F ~ 53.4 kN | | |
| $E_{FWD-D3}$ (MPa) = 68.26 + 1.31 $E_{LWD-Z2}$ (MPa) | 11 | 0.52 |
| $E_{FWD-D3}$ (MPa) = 106.73 + 0.55 $E_{LWD-D2}$ (MPa) | 11 | 0.20 |
| $E_{FWD-D3}$ (MPa) = 37.11 $(q_t)^{0.49}$ (MPa) | 100 | 0.62 |
| $E_{FWD-D3}$ (MPa) = 341.99 $(DPI)^{-0.51}$ (mm/blow) | 157 | 0.52 |
| $E_{FWD-D3}$ (MPa) = 59.87 + 3.56 CMV | 11 | 0.59 |
| DPI (mm/blow) = 22.42 – 0.39 CMV | 10 | 0.69 |
| DPI (mm/blow) = 78.35 $(q_t)^{-0.97}$ (mm/blow) | 371 | 0.69 |

**Table 11.** Correlation coefficients for US 10 at Minnesota (Source: MN/RC 2009-14 report [White et al., 2009])

| Test strip(s) | Point Measurement | Relationship | $a$ (mm) | n | $R^2$ |
|---|---|---|---|---|---|
| 1 | Surface | $CMV = 0.72 + 0.36\ E_{LWD\text{-}Z3}$ | 0.85 | 15 | 0.41 |
| 1 | | $CMV = 11.96\ (d_{LWD\text{-}Z3})^{-0.80}$ | | 15 | 0.34 |
| 1 | 150 mm below surface | $CMV = -0.79 + 0.24\ E_{LWD\text{-}Z3}$ | | 15 | 0.70 |
| 1 | | $CMV = 7.50\ (d_{LWD\text{-}Z3})^{-1.00}$ | | 15 | 0.60 |
| 3 | Surface | $CMV = 4.64 + 0.35\ E_{LWD\text{-}Z2}$ | | 23 | 0.19 |
| 3 | | $CMV = 19.50\ (d_{LWD\text{-}Z2})^{-0.68}$ | | 23 | 0.21 |
| 3 | 150 mm below surface | $CMV = 0.78 + 0.25\ E_{LWD\text{-}Z2}$ | | 23 | 0.82 |
| 3 | | $CMV = 11.79\ (d_{LWD\text{-}Z2})^{-0.96}$ | | 23 | 0.81 |
| 2 | Surface | $CMV = 12.04 + 0.07\ E_{LWD\text{-}D2}$ | | 42 | 0.17 |
| 2 | | $CMV = 14.09\ (d_{LWD\text{-}D2})^{-0.18}$ | | 42 | 0.18 |
| 2 | Surface | $CMV = 44.18\ (DPI_{300})^{-0.31}$ | | 42 | 0.27 |
| 2, 3 | After seating | $CMV = 92.26\ (DPI_{S\text{-}300})^{-0.57}$ | | 65 | 0.72 |
| 1 | 150 mm below surface | $CMV = -3.03 + 0.24\ E_{V1}$ | | 15 | 0.65 |
| 1 | Surface | $CMV = 3.89 + 0.46\ E_{LWD\text{-}Z3}$ | 1.70 | 15 | 0.28 |
| 1 | | $CMV = 18.25\ (d_{LWD\text{-}Z3})^{-0.68}$ | | 15 | 0.21 |
| 1 | 150 mm below surface | $CMV = 0.42 + 0.35\ E_{LWD\text{-}Z3}$ | | 15 | 0.62 |
| 1 | | $CMV = 12.12\ (d_{LWD\text{-}Z3})^{-1.03}$ | | 15 | 0.57 |
| 3 | Surface | $CMV = 5.24 + 0.48\ E_{LWD\text{-}Z2}$ | | 23 | 0.19 |
| 3 | | $CMV = 24.07\ (d_{LWD\text{-}Z2})^{-0.64}$ | | 23 | 0.17 |
| 3 | 150 mm below surface | $CMV = -0.94 + 0.35\ E_{LWD\text{-}Z2}$ | | 23 | 0.90 |
| 3 | | $CMV = 14.87\ (d_{LWD\text{-}Z2})^{-1.03}$ | | 23 | 0.89 |
| 2 | Surface | $CMV = 15.55 + 0.07\ E_{LWD\text{-}D2}$ | | 42 | 0.26 |
| 2 | | $CMV = 17.35\ (d_{LWD\text{-}D2})^{-0.19}$ | | 42 | 0.31 |
| 2, 3 | After seating | $CMV = 91.49\ (DPI_{S\text{-}300})^{-0.50}$ | | 65 | 0.59 |
| 1 | 150 mm below surface | $CMV = -1.89 + 0.33\ E_{V1}$ | | 15 | 0.51 |

**Table 12.** Correlation coefficients at TH 60 at Minnesota (Source: MN/RC 2009-14 report [White et al., 2009])

| Test strip(s) | Relationship | *a* (mm) | n | $R^2$ |
|---|---|---|---|---|
| 1, 2 | $MDP^* = 0.57\ E_{LWD\text{-}Z2} + 135.7$ | 1.87 | 28 | 0.37 |
| 1, 2 | $MDP^* = -3.43\ d_{LWD\text{-}Z2} + 150.2$ | | 28 | 0.36 |
| 3 | $MDP^* = 7.81\ E_{LWD\text{-}Z2} + 48.7$ | | 20 | 0.75 |
| 3 | $MDP^* = -16.81\ d_{LWD\text{-}Z2} + 166.9$ | | 20 | 0.82 |
| 2 | $MDP^* = 0.39\ E_{LWD\text{-}Z2} + 137.3$ | 0.85 | 9 | 0.40 |
| 2 | $MDP^* = -5.37\ d_{LWD\text{-}Z2} + 152.7$ | | 9 | 0.53 |
| 3 | $MDP^* = 7.11\ E_{LWD\text{-}Z2} + 51.6$ | | 25 | 0.57 |
| 3 | $MDP^* = -14.20\ d_{LWD\text{-}Z2} + 154.9$ | | 25 | 0.55 |
| 3 | $MDP^* = 3.78\ E_{LWD\text{-}Z2} + 83.5$ | static | 30 | 0.42 |
| 3 | $MDP^* = -8.57\ d_{LWD\text{-}Z2} + 142.1$ | | 30 | 0.42 |
| 1, 2 | $MDP^* = 0.46\ E_{LWD\text{-}Z2} + 137.0$ | static, 0.85, and 1.87 | 37 | 0.35 |
| 1, 2 | $MDP^* = -3.66\ d_{LWD\text{-}Z2} + 150.4$ | | 37 | 0.38 |
| 3 | $MDP^* = 6.32\ E_{LWD\text{-}Z2} + 59.7$ | | 75 | 0.59 |
| 3 | $MDP^* = -12.75\ d_{LWD\text{-}Z2} + 153.2$ | | 75 | 0.58 |
| 1 | $MDP^* = 0.26\ E_{LWD\text{-}K2} + 136.7$ | 1.87 | 8 | 0.74 |
| 1 | $MDP^* = -4.26\ d_{LWD\text{-}K2} + 148.5$ | | 8 | 0.47 |
| 1 | $MDP^* = 0.19\ E_{LWD\text{-}D2} + 138.2$ | 1.87 | 8 | 0.62 |
| 1 | $MDP^* = -5.82\ E_{LWD\text{-}D2} + 147.6$ | | 8 | 0.38 |
| 1, 2 | $MDP^* = 1.39\ \gamma_d + 121.7$ | 1.87 | 28 | 0.12 |
| 1, 2 | $MDP^* = 1.75\ \gamma_d + 116.8$ | 0.85 | 9 | 0.10 |
| 3 | $MDP^* = 18.62\ \gamma_d - 187.14$ | 0.85 | 5 | 0.74 |
| 3 | —[§] | static | 10 | 0.0 |
| 1, 2 | $MDP^* = 1.37\ \gamma_d + 122.1$ | static, 0.85, and 1.87 | 39 | 0.10 |
| 3 | $MDP^* = 10.13\ \gamma_d + 44.7$ | | 15 | 0.28 |
| 1, 2 | $MDP^* = -0.19 DPI_{300} + 149.8$ | 1.87 | 30 | 0.30 |
| 2 | $MDP^* = -0.27 DPI_{300} + 152.3$ | 0.85 | 7 | 0.33 |
| 1, 2 | $MDP^* = -0.21 DPI_{300} + 150.3$ | 0.85, 1.87 | 39 | 0.30 |
| 1, 2[¥] | $MDP^* = 0.27\ E_{LWD\text{-}Z2} - 0.54\ w + 150.0$ | 0.85, and 1.87 | 39 | 0.48 |
| 1, 2[¥] | $MDP^* = -0.55\ DPI_{300} - 0.11\ w + 157.7$ | | 39 | 0.45 |
| 4[₩] | $CMV = 0.22\ E_{LWD\text{-}Z2} + 7.3$ | 0.85 | 43 | 0.41 |
| 5 | $CMV = 0.22\ E_{LWD\text{-}Z2} + 7.3$ | 0.85 | 10 | 0.84 |
| 4[₩] | $CMV = 12.85\ (d_{LWD\text{-}Z2})^{-0.36}$ | 0.85 | 43 | 0.31 |
| 5 | $CMV = 20.90\ (d_{LWD\text{-}Z2})^{-0.79}$ | 0.85 | 10 | 0.87 |
| 4[₩] | —[§] | 0.85 | 43 | 0.00 |
| 5 | —[§] | 0.85 | 10 | 0.00 |
| 5 | —[§§] | 0.85 | 10 | 0.00 |

**Table 13.** Correlation coefficients at CSAH 2 at Minnesota (Source: MN/RC 2009-14 report [White et al., 2009])

| Test strip | Relationship | *a* (mm) | Direction | *v* (km/h) | n | $R^2$ |
|---|---|---|---|---|---|---|
| 1 | $MDP^* = 114.6 + 1.15\ E_{LWD\text{-}Z2}$ | Static | East to West | 3.2 | 5 | 0.64 |
| | $MDP^* = 137.1 – 3.00\ d_{LWD\text{-}Z2}$ | Static | East to West | 3.2 | 5 | 0.66 |
| | $MDP^* = 118.5 + 1.17\ E_{LWD\text{-}Z2}$ | Static | West to East | 3.2 | 5 | 0.83 |
| | $MDP^* = 141.9 – 3.20\ d_{LWD\text{-}Z2}$ | Static | West to East | 3.2 | 5 | 0.95 |
| | $MDP^* = 72.0 + 1.40\ E_{LWD\text{-}Z2}$ | Static | East to West | 6.4 | 5 | 0.93 |
| | $MDP^* = 97.8 – 3.21\ d_{LWD\text{-}Z2}$ | Static | East to West | 6.4 | 5 | 0.79 |
| | $MDP^* = 82.5 + 1.16\ E_{LWD\text{-}Z2}$ | Static | West to East | 6.4 | 5 | 0.37 |
| | $MDP^* = 108.3 – 3.91\ d_{LWD\text{-}Z2}$ | Static | West to East | 6.4 | 5 | 0.63 |
| 2 | $MDP^* = 105.8 + 1.34\ E_{LWD\text{-}Z2}$ | 0.90 | East to West | 3.2 | 8 | 0.81 |
| | $MDP^* = 137.3 – 6.11\ d_{LWD\text{-}Z2}$ | 0.90 | East to West | 3.2 | 8 | 0.71 |
| | $MDP^* = 110.1 + 1.11\ E_{LWD\text{-}Z2}$ | 0.90 | West to East | 3.2 | 8 | 0.82 |
| | $MDP^* = 135.9 – 4.93\ d_{LWD\text{-}Z2}$ | 0.90 | West to East | 3.2 | 8 | 0.69 |
| | $MDP^* = 55.0 + 2.57\ E_{LWD\text{-}Z2}$ | 0.90 | East to West | 6.4 | 8 | 0.91 |
| | $MDP^* = 116.3 – 12.10\ d_{LWD\text{-}Z2}$ | 0.90 | East to West | 6.4 | 8 | 0.86 |
| | $MDP^* = 62.7 + 2.27\ E_{LWD\text{-}Z2}$ | 0.90 | West to East | 6.4 | 8 | 0.81 |
| | $MDP^* = 117.2 – 10.82\ d_{LWD\text{-}Z2}$ | 0.90 | West to East | 6.4 | 8 | 0.78 |
| | $MDP^* = 106.8 + 0.83\ E_{LWD\text{-}Z2}$ | 1.80 | East to West | 3.2 | 8 | 0.63 |
| | $MDP^* = 127.0 – 4.07\ d_{LWD\text{-}Z2}$ | 1.80 | East to West | 3.2 | 8 | 0.64 |
| | $MDP^* = 101.8 + 1.38\ E_{LWD\text{-}Z2}$ | 1.80 | West to East | 3.2 | 8 | 0.83 |
| | $MDP^* = 133.5 – 5.99\ d_{LWD\text{-}Z2}$ | 1.80 | West to East | 3.2 | 8 | 0.66 |
| | $MDP^* = 62.3 + 1.70\ E_{LWD\text{-}Z2}$ | 1.80 | East to West | 6.4 | 8 | 0.73 |
| | $MDP^* = 103.1 – 8.07\ d_{LWD\text{-}Z2}$ | 1.80 | East to West | 6.4 | 8 | 0.69 |
| | $MDP^* = 64.4 + 1.9\ E_{LWD\text{-}Z2}$ | 1.80 | West to East | 6.4 | 8 | 0.66 |
| | $MDP^* = 107.9 – 8.22\ d_{LWD\text{-}Z2}$ | 1.80 | West to East | 6.4 | 8 | 0.53 |

**Table 14.** Hypothetical input data for the overlay IC project at Wyoming (Source: MPC 15-281 report [Savan et al., 2015])

| Item | Unit Cost ($)/ Quantity | Source |
|---|---|---|
| Construction Costs | | |
| QC/QA per square yard | $ 0.04 | Simon Contractors, WY (Bastian, 2014) |
| IC Reduction in compaction cost | 30% | Briaud & Seo (Briaud & Seo, 2003) |
| Lane width, feet | 12 | Assumption |
| IC to conventional QC/QA cost | 10% | NCHRP 676 (Mooney, et al., 2010) |
| Conventional roller cost per hour | $ 36 | High Country Construction, WY (Newman, 2014) |
| IC pavement roller cost per month | $ 7,500 | Sakai America (Jones, 2014) |
| Roller operator per hour | $ 30 | High Country Construction, WY (Newman, 2014) |
| Conventional compaction hours/lane-mile | 10 | High Country Construction, WY (Newman, 2014) |
| Compaction cost per square yard | $ 0.20 | Simon Contractors, WY (Newman, 2014) |
| GPS System rental per year | $ 1,800 | Trimble (Trimble Navigation Limited, 2014) |
| Test Section Length, feet | 500 | NCHRP 676 (Mooney, et al., 2010), DOT IC Specs (The Transtec Group, Inc, 2014) |
| Work hours per week | 40 | Assumption |
| Lifecycle Costs | | |
| Increased service life with IC, multiplier | 2.6 | (Chang, Gallivan, Horan, & Xu, 2012) |
| Average asphalt life, years | 10 | Average overlay service life |
| Cost per lane-mile | $ 250,000 | WYDOT (Wyoming Department of Transportation, 2011), Caltrans (Caltrans, 2011), Woodland (City of Woodland, 2008) |

**Table 15.** Cost of construction cycle per lane-mile for the overlay IC project (Source: MPC 15-281 report [Savan et al., 2015])

| | Conventional Compaction | | | | Intelligent Compaction | | | |
|---|---|---|---|---|---|---|---|---|
| **Item** | **Cost per Unit** | **Unit** | **Number of Units** | **Total Cost** | **Cost per Unit** | **Unit** | **Number of Units** | **Total Cost** |
| Roller | $ 36.00 | hour | 10 | $ 360.00 | $ 42.61 | hour | 7.7 | $ 328.10 |
| Operator | $ 30.00 | hour | 10 | $ 300.00 | $ 30.00 | hour | 7.7 | $ 231.00 |
| GPS | n/a | n/a | n/a | n/a | $ 0.89 | hour | 7.7 | $ 6.85 |
| QC/QA | $ 0.04 | $yd^2$ | 7040 | $ 281.60 | $ 0.04 | $yd^2$ | 667 | $ 26.68 |
| Total | | | | $ 941.60 | | | | $ 592.63 |

n/a - Data is not applicable

**Table 16.** Hypothetical input data for the new construction IC project at Wyoming (Source: MPC 15-281 report [Savan et al., 2015])

| **Construction Cycle** | | |
|---|---|---|
| **Item** | **Cost / Quantity** | **Source** |
| QC / QA per square yard per layer | $ 0.04 | Simon Contractors, WY |
| IC Reduction in Compaction Cost | 30% | Briaud & Seo, 2003 |
| Lane Width, feet | 12 | Assumption |
| IC to Conventional QC/QA cost | 10% | NCHRP 676 based on test section size |
| Conventional Soil Roller Cost per hour | $ 34.03 | Wagner Rents, Fort Collins, CO |
| Conventional Pavement Roller Cost per hour | $ 36.00 | High Country Construction, WY |
| IC Soil Roller Cost per month | $ 7,000 | Sakai America |
| IC Pavement Roller Cost per month | $ 7,500 | Sakai America |
| Operator Cost per hour | $ 30.00 | High Country Construction, WY |
| Number of passes per layer | 6 | Assumption |
| Average Roller Speed (mph) | 3 and 8 | Assumption |
| Layer Thickness, inches (Subgrade/ subbase/ base/ binder/ surface) | 8 / 8 / 8 / 4 / 2 | Assumption |
| GPS System, per year | $ 1,800.00 | Trimble |

**Table 17.** Cost of construction cycle per lane-mile for the new construction (Source: MPC 15-281 report [Savan et al., 2015])

| | Conventional Compaction | | | | Intelligent Compaction | | | |
|---|---|---|---|---|---|---|---|---|
| **Item** | **Cost per Unit** | **Unit** | **Number of Units** | **Total Cost** | **Cost per Unit** | **Unit** | **Number of Units** | **Total Cost** |
| Soil Roller | $ 34.03 | hour | 12.0 | $ 408.41 | $ 39.77 | hour | 9.2 | $ 365.83 |
| Pav. Roller | $ 36.00 | hour | 8.0 | $ 288.00 | $ 42.61 | hour | 6.1 | $ 261.31 |
| Operator | $ 30.00 | hour | 20.0 | $ 600.00 | $ 30.00 | hour | 15.3 | $ 459.90 |
| GPS | - | - | - | $ - | $ 0.89 | hour | 15.3 | $ 13.64 |
| QC/QA | $ 0.20 | sq yd | 7040 | $ 1,408.00 | $ 0.20 | sq yd | 667 | $ 133.40 |
| Total | | | | $ 2,704.41 | | | | $ 1,234.08 |