Date: 2024 FHWA-HIF-24-097

Tech Brief

Utilizing Intelligent Compaction to Ensure Quality and Uniformity of Pavement Foundation

Introduction

Figure 1. Single-drum roller used in this study.
(Source: The Transtec Group, 2023)

Intelligent Compaction (IC) is a vibratory roller-based technology equipped with a global navigation satellite system (GNSS), an accelerometer, and an onboard computer display. The accelerometer is mounted on the axle of the vibrating drum and records the drum rebound signals, which are used to produce Intelligent Compaction Measurement Values (ICMVs). ICMVs reflect the levels of compaction of compacted materials. IC can provide measurements for up to 100% coverage of the compacted area. The onboard computer display provides operators with real-time measurements and feedback. Therefore, IC can be used to overcome the limitations of conventional spot testing by providing near-full coverage and real-time compaction measurement (which relates to the stiffness of the foundation layers) to evaluate the pavement foundations' uniformity and adequacy.
This project aimed to assess the feasibility of utilizing IC to ensure the uniformity and adequacy of the pavement foundation so that potential foundation problems can be corrected before paving. The project objectives were to develop a field procedure for the IC application and to demonstrate the feasibility of implementation in the field projects.

This document presents a summary of the state of technology review, field demonstration methodology, three field demonstration results and key findings, proposed field procedures, and recommendations for using IC to evaluate pavement foundations.

Contents

This TechBrief includes the following contents:

U.S. Department of Transportation
Federal Highway Administration

State of Technology Review

IC Systems

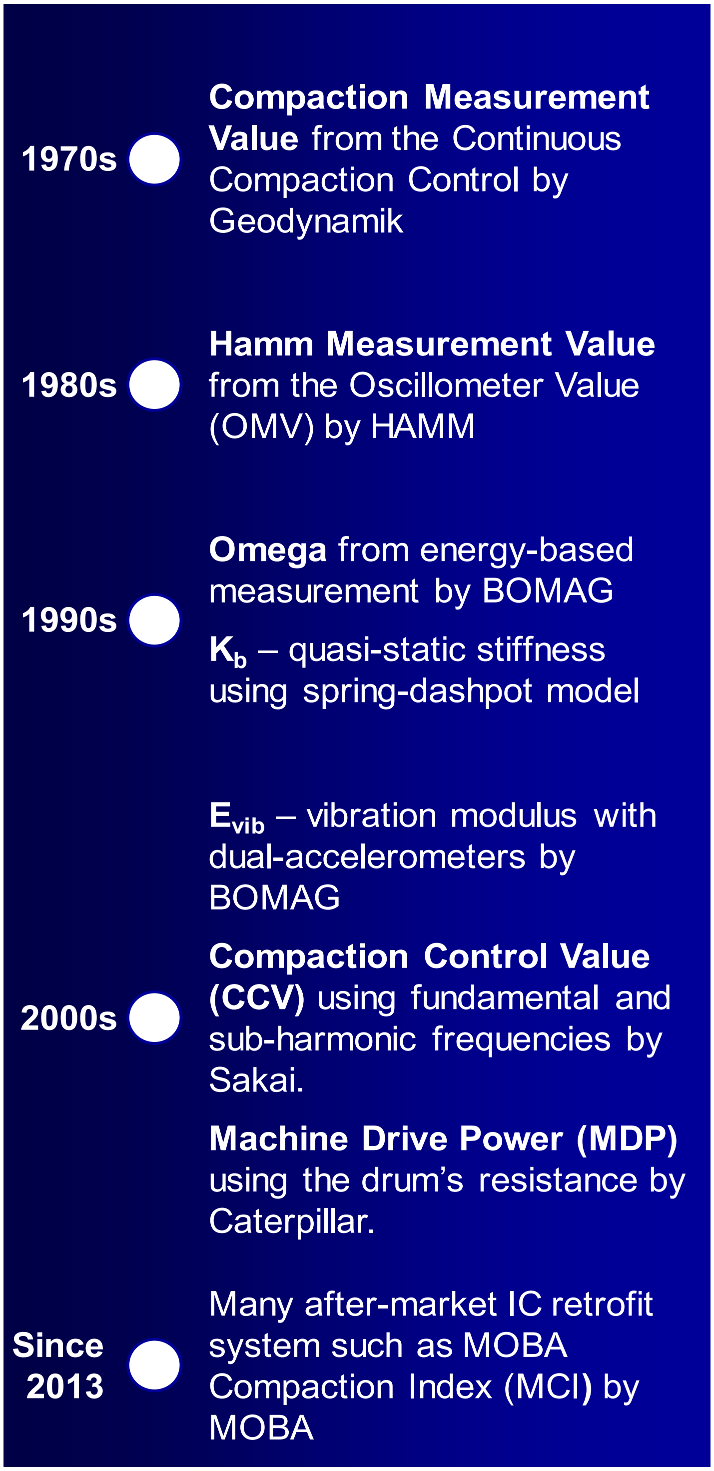
Geodynamik invented Continuous Compaction Control (CCC) in the 1970s (Thurner and Sandström, 1980). This concept was adopted as Intelligent Compaction (IC) in a US FHWA Roadmap in 2004 (Horan and Ferregut, 2005). In 2007, the Transportation Pooled Fund (TPF) study for IC significantly accelerated IC's adoption in the US. IC systems are available as factory-installed original equipment manufacturer (OEM) systems or after-market retrofit systems. The most up-to-date IC systems are listed on the Intelligent Construction Technologies website (Transtec Group, 2024).

Intelligent Compaction Measurement Value (ICMV)

ICMV is the generic term by FHWA to represent a measure of compaction reported by various IC systems. ICMVs vary based on the different models to process the raw acceleration data into a compaction measure. The timeline of the ICMV development is illustrated in Figure 1.

The FHWA ICMV Road Map TechBrief provides the ICMV classifications and guidance for further development (FHWA, 2017). ICMVs are classified into five levels, from Level 1 to Level 5, with increasing capabilities based on four criteria in this document. Most commercially available ICMVs are Levels 1 and 2, with some available at Level 3. The more sophisticated Levels 4 and 5 are currently used for research purposes. A complete ICMV theoretical background and applications are in Chang et al. (2023).

The major differences between ICMV and spot tests, such as lightweight deflectometer (LWD), soil stiffness gauge, nuclear density gauge (NDG), and dynamic cone penetrometer (DCP), are in their measurement footprint sizes and influence depths (Figure 3). The ICMV footprint is approximately 6.6 ft (2 m) wide, which is much larger than those of spot tests. ICMV's influence depths are approximately 20 inches to 5 feet (0.5 m to 1.6 m), which is much deeper than most spot tests. The range of ICMV influence depth depends on the roller footprint, operating weight, vibration frequency, vibration amplitude, and the stiffness of compacted materials (FHWA, 2017).



1970s

Compaction Measurement Value from the Continuous Compaction Control by Geodynamik

1980s

Hamm Measurement Value from the Oscillometer Value (OMV) by HAMM

1990s

Omega from energy-based measurement by BOMAG

K_b – quasi-static stiffness using spring-dashpot model

E_{vib} – vibration modulus with dual-accelerometers by BOMAG

2000s

Compaction Control Value (CCV) using fundamental and sub-harmonic frequencies by Sakai.

Machine Drive Power (MDP) using the drum's resistance by Caterpillar.

Since 2013

Many after-market IC retrofit system such as MOBA Compaction Index (MCI) by MOBA

Figure 2. ICMV development timeline.
(Source: The Transtec Group, 2023)

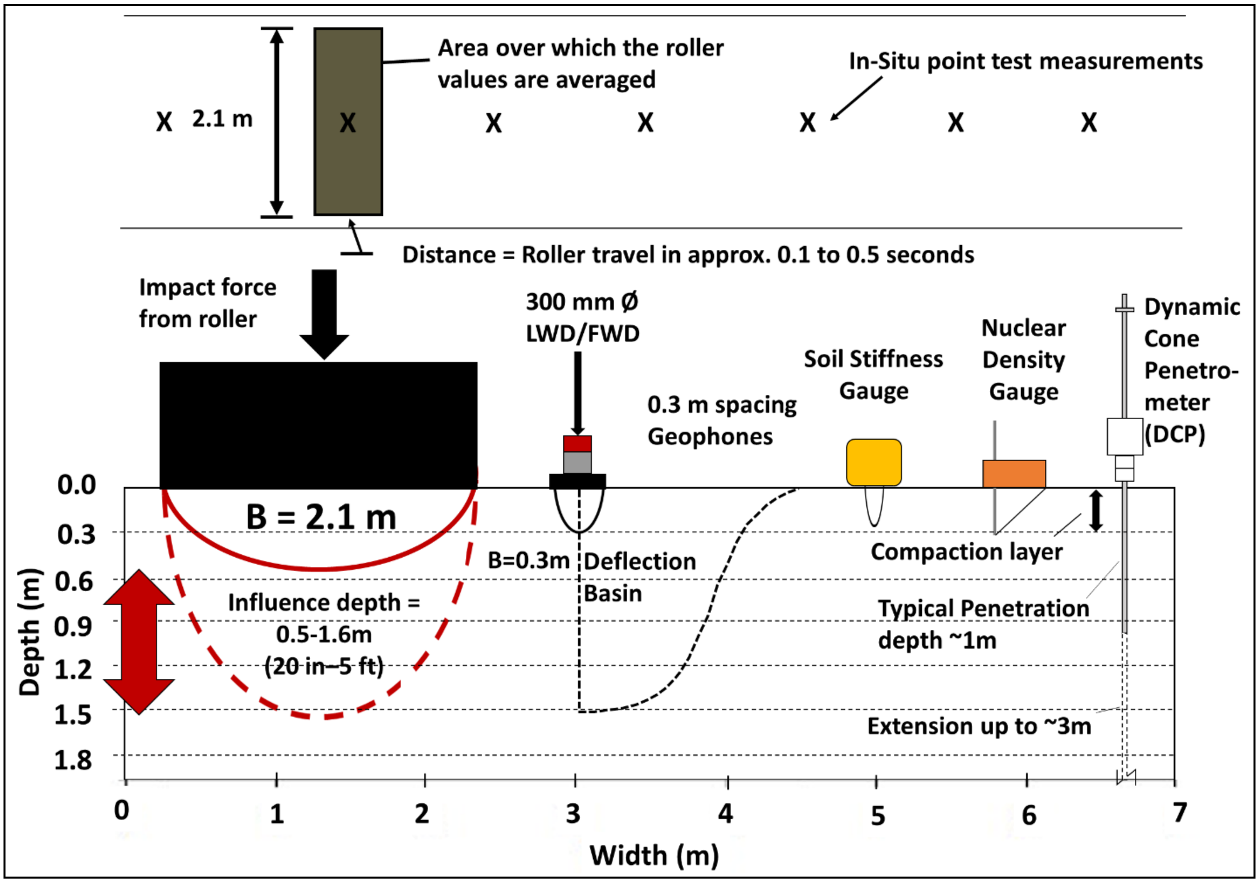


Figure 3. Influence depths and footprints of ICMV and spot tests.
(Source: Adapted from FHWA Tech Brief IC for Pre-mapping)

IC Specifications

US IC Specifications

The US FHWA IC specifications were developed between 2012 and 2015 to guide State Departments of Transportation (DOTs) in creating their specifications. AASHTO published the IC standard R 111, data file format MP 39, and the provisional standard for data lot names PP 114 in 2022 (AASHTO, 2022a, 2022b, and 2022c). All US state DOT specifications require the standard Veta software recommended in the above AASHTO standards for IC data analysis and management. Veta facilitates consistent data analysis and reporting for practical IC implementation. The US DOT IC specifications can be found on the Intelligent Construction Technologies website.

International IC Specifications

Various European Union (EU) countries, including Austria, Germany, Finland, and Sweden, developed IC standards in the 1990s. The EU emphasized harmonization and standardization of IC specifications to benefit from sharing national practices, updating best practices, and bridging gaps in existing design codes. The EU specification's development began in 2005, led by the Technical Committee TC3 'Geotechnics of Pavements' of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) in collaboration with other European agencies. The ISSMGE IC specification became the EU IC standard (CEN, 2016).

Several Asian countries have developed their IC specifications, too. China Railway and Road Administration published the Chinese IC Specification from 2011 to 2016 (China Railway and Road, 2016). While its correlation analysis is like EU specifications, the Chinese specifications require the data transfer method to be wireless and managed by cloud servers. Wireless data transfer can mitigate issues related to data security and data tampering.

The first Australian IC specification was published by the Department of Transport and Main Roads (TMR) in 2020. TMR's IC specification content resembles that of the US FHWA and AASHTO R 111 IC specifications.

Foundation Evaluation Using IC

IC mapping of the pavement foundation can provide a continuous record of material stiffness, which can help identify areas with low ICMV values (or soft spots). The problem areas can be further characterized with conventional spot tests and can be addressed, if needed, thus improving the quality of the pavement foundation.

An adequate pavement foundation stiffness and uniformity based on ICMV (i.e., target ICMV) can be established by correlating ICMV with spot tests in a calibration strip. According to Chang and Xu (2019), areas with low, medium, and high ICMVs should be identified from the IC map, and three to six spot tests should be conducted in each area. This ensures an adequate spread or range of data. The ICMV and spot tests can then be correlated to determine the optimum roller passes and target ICMV. This method is considered valid if the correlation coefficient, R, is greater or equal to 0.7 (or $R^2 \geq 0.5$). During production compaction, foundation quality can be assessed based on the percentage of compacted areas meeting the target ICMV and satisfying the minimum acceptable value criteria (e.g., no less than 20% below the maximum value measured anywhere). For example, the EU IC specification (CEN, 2016) recommends that 80% of the compacted area meet the target ICMV.

Because of the differences in footprint and influence depth (Fig 3), the correlation between ICMV and spot tests may not meet the common correlation threshold of R=0.7 (R^2=0.5). However, IC can still be used to identify weak areas based on the relative ICMVs. For instance, the EU IC specification defines the threshold for weak areas as the 10th percentile ICMV value (i.e., mean ICMV – 1.28 X standard deviation ICMV). The identified weak areas can be further inspected with conventional spot tests for validation.

Statistical methods can be used to evaluate the uniformity of the foundation stiffness based on ICMV. For example, the coefficient of variance (CoV) thresholds may be established to determine foundations with low uniformity, such as CoV ≤ 20% recommended by the EU IC specification or CoV ≤ 25% recommended by Nazarian et al. (2020). Another method is the semi-variogram for evaluating geospatial uniformity. The parameters can be identified based on the fitted semi-variogram model: range, sill, and nugget. The sill is approximately equal to the variance of the data. The larger the sill, the lower the uniformity.

Field Demonstration Methodology

This project included three field IC demonstrations of full-scale construction sites, including new asphalt construction, asphalt rehabilitation, and concrete pavement construction projects. The testing comprised IC mapping and spot tests with an LWD and NDG. A hand-held GNSS rover was used to determine the GNSS coordinates of the spot test locations.

IC Roller Setup

The IC setup consisted of a MOBA IC retrofit system mounted on an XCMG roller. The XCMG roller was a 16-ton, smooth, single-drum vibratory roller typically used for compacting base, sub-base, and rock fill for roads. The MCA-3000, from MOBA, was used as the IC retrofit with two ICMV sensors: MAS-180 and SineCore (Figure 4). The MAS-180 sensor uses the roller parameters and the measured acceleration to determine the MOBA Compaction Index (MCI) (unitless). The SineCore sensor uses the compacted material type, the roller parameters, and the measured acceleration to determine the Resistance Modulus (E_R) (MPa/m^2), working frequencies, and working amplitudes. E_R is considered a Level 3 ICMV based on the compaction force and derived deformation from the acceleration signals with some level of simplification. Further, all levels' ICMV theoretical background and practical examples are described in Appendix A of the Level 3-4 ICMV evaluation report (Chang, G.K. et al., 2023).

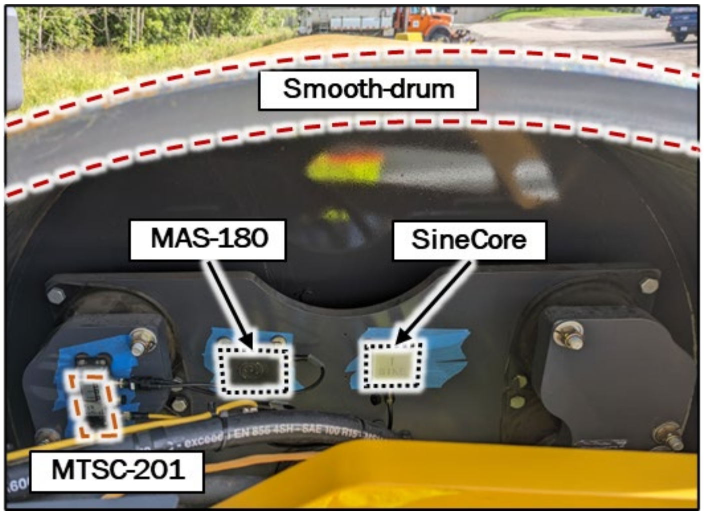


Figure 4. Two ICMV sensors mounted to the roller drum’s frame. (Source: The Transtec Group, 2023)

Data Collection

Two types of test sections, the grid-based section and the ICMV-based section, were designated for each demonstration. The IC mapping was conducted in both grid-based and ICMV-based sections. Additionally, spot testing with LWD and NDG was conducted in all subsections of the grid-based section. In the ICMV-based section, the spot testing was conducted only on a few spots showing low, medium, and high ICMV values.

The grid-based section consisted of a 250-foot section of the roadway divided into three or four test lanes that were each 6 feet wide and ran the length of the section. Each test lane was subdivided into 25 feet sublots resulting in a rectangular grid-like layout with a total of 30 to 40 sublots. Figure 5 shows the center of the test lanes along lines A, B, and C in Demonstration No. 1. The spot tests were conducted at the center of each grid. If the site adjacent to the grid-based section was available, a 2000-foot length of the site was marked as an ICMV-based section. IC mapping was conducted in the entire 2,000-ft section to determine areas of low, medium, and high ICMVs for the subsequent spot tests.

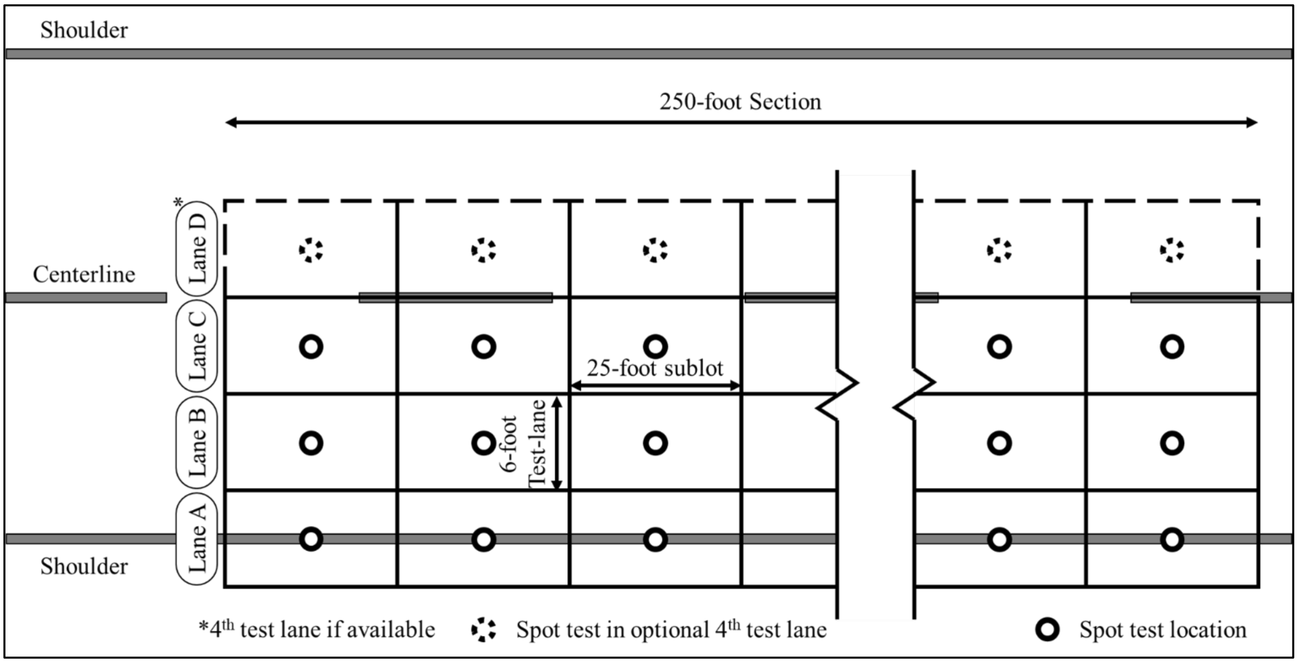


Figure 5. Layout of a grid-based test section.
(Source: The Transtec Group, 2023)

The data collection sequence was:

(1) Pre-mapped with IC and performed spot tests on existing subgrade (on grid-based section only, if accessible).
(2) Proof-mapped with IC (on grid-based section & ICMV-based section) and performed spot tests (in grid-based section only) on constructed sub-base/base.
(3) Performed spot tests in the low, medium, and high ICMV areas identified from the ICMV-based section data.

Data Analysis

The data analysis was performed in Veta as follows:

- The analysis was conducted separately for the grid-based section and ICMV-based section.
- For each section, IC maps were generated based on MCI and E_R.
- For each section, the results of the LWD and NDG tests were overlaid on the corresponding maps.
- For each section, correlation analysis was performed between ICMVs, and spot test results as follows:
  - mean MCI vs. LWD modulus (E_{LWD}).
  - mean MCI vs. NDG dry density (ρ_d).
  - mean E_R vs. E_{LWD}.
  - mean E_R vs. ρ_d.

Field Demonstration No. 1

Field Demonstration No. 1 took place on a 2500-foot test section along the TH 34, east of Detroit Lakes, MN, on a new asphalt construction project. The testing was performed on top of the 8-inch-thick reclaimed lift only; the subgrade was not available for IC pre-mapping. The grid-based section was over a newly replaced culvert, backfilled with engineered material with a geogrid 6 inches below the surface of the pavement foundation. The ICMV-based section, constructed over the existing natural subgrade, was adjacent to the grid-based section.

Key Findings

- Foundation IC maps can be used to identify problem areas with low ICMV which can be further evaluated using traditional spot tests.
- IC system has a deeper influence depth than LWD and NDG. In cases with engineered subgrade (such as in the grid-based section), it may be possible to get good correlation of ICMV with spot tests.
- Areas with natural subgrade (such as in the ICMV-based section) have too much underlying variability to correlate with spot tests (as further supported in subsequent tests).
- ICMV, being a measure of the foundation stiffness, is likely to show stronger correlation with LWD than NDG.

Table 1. Timeline in Demonstration No. 1

Day	Activity
Day 0	Reclamation/construction
Day 1	Grid-based section layout and testing
Day 2	ICMV-based section layout and testing

Grid-Based Section

The grid-based section was 250 feet in length and divided into three test lines (A, B, and C) spaced six feet apart transversely. The MCI map (Figure 6) and E_R map of the grid-based section showed the range of ICMVs observed using color-coded heatmaps. Red, orange, and yellow indicated areas with lower ICMVs, while shades of blue represented areas with moderate ICMVs, whereas purple and white showed areas with the highest ICMVs. It was observed that the ICMVs along test line A (corresponding to the shoulder) showed lower ICMVs. ICMVs increased from test line A to C (corresponding to the middle of the pavement), with some portions of test line C measuring the highest ICMVs (MCI > 80). Spot tests were conducted at the centers of the 25-foot sublots along each test line for a total of 30 spot test locations. The LWD modulus and NDG dry density were correlated with the ICMVs. The strongest correlation is found between the MCI values and E_{LWD} (Figure 7), with a correlation coefficient $R = 0.87$ (≥ 0.70). Other correlations in the grid-based section are as follows. MCI vs. ρ_d, $R = 0.78$; E_R vs. E_{LWD}, $R = 0.66$; E_R vs. ρ_d, $R = 0.67$.

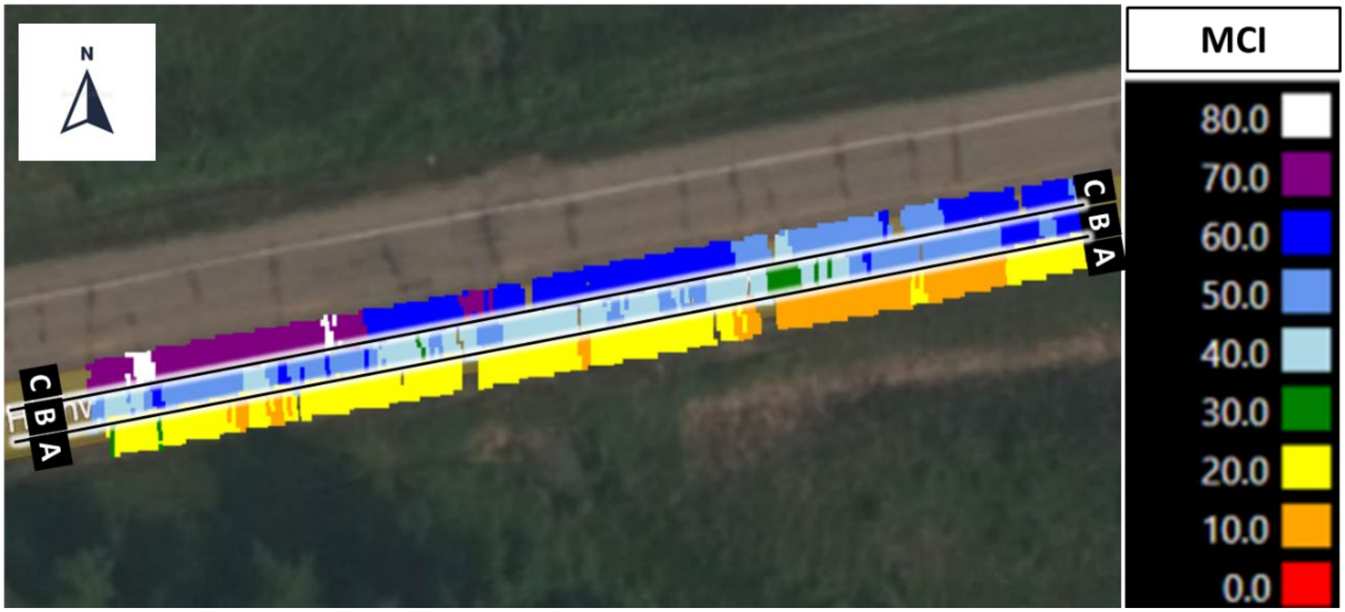


Figure 6. MCI map of the subbase in Demonstration No. 1.

ICMV-Based Section

The ICMV-based section was 2000 feet in length and to the west of the grid-based section. The western end was identified as the area with high ICMV with seven (7) spot test locations, while the areas with medium and low ICMV were identified closer to the eastern end with six (6) spot test locations each. The correlations of the ICMVs with the spot tests were low (Figure 8). The LWD and NDG test results showed low correlations with both MCI and E_R. This was likely due to the less uniform natural subgrade conditions in the test areas and the deeper influence depth of the IC system compared to LWD and NDG.

The spot test results measure a shallower depth and are influenced by the properties of the subbase only. In contrast, the deeper influence depth indicates that the ICMV is also sensitive to variations in the stiffness of the subgrade beneath the subbase. Since the spot test locations in the ICMV-based section are separated by over 1500 feet, the variation in natural subgrade stiffness results in a weak correlation between ICMV and spot test.

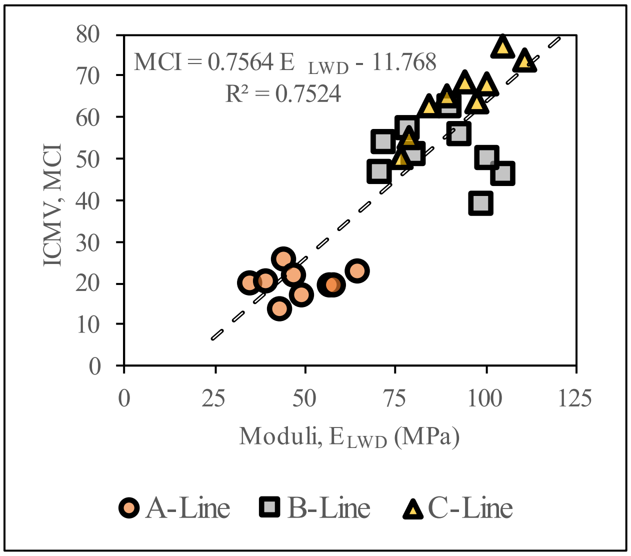


Figure 7. Correlation between MCI and E_{LWD} in the grid-based section of Demonstration No. 1.

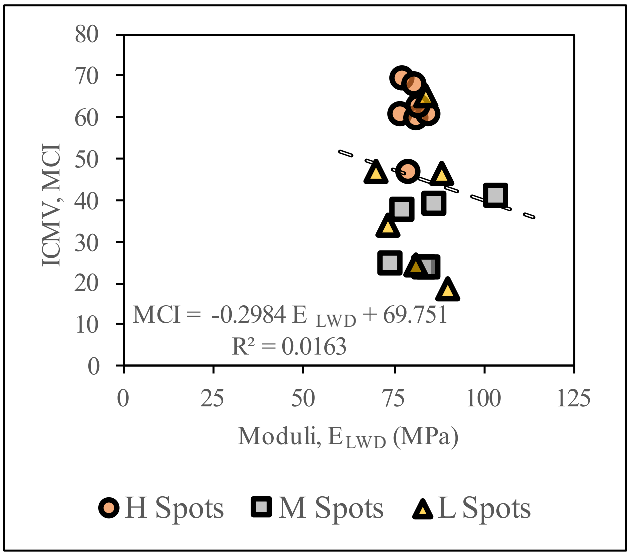


Figure 8. Correlation between MCI and E_{LWD} in the ICMV-based section of Demonstration No. 1.

Field Demonstration No. 2

Field Demonstration No. 2 took place on a 1900-ft test section along TH 34, North of Dassel, MN, on an asphalt rehabilitation project. This field demonstration involved IC mapping of a stabilized base section. The subgrade was not available for IC pre-mapping; the testing was performed on top of the 6-inch thick, cement-treated, reclaimed lift only. The entire section was constructed over the existing natural subgrade. The stabilized sub-base was tested on three consecutive days to evaluate the effects of curing on the ICMV.

Key Findings

- The variability of the underlying subgrade significantly impacted the overall uniformity of the pavement foundation. This effect was less pronounced with increase in stiffness of the top layer from curing.
- The MAS-180 system (MCI) could measure the stiffness gain in cement-treated sub-base during/after curing. Thus, it can be an excellent tool to assess the degree of curing in treated bases prior to adding subsequent layers. This can potentially replace the FWD tests to determine base readiness with improved coverage.
- The MAS-180 sensor (MCI) showed better performance on stabilized sub-base than the SineCore sensor (E_R).
- Various factors including moisture content, cement content, and curing time affect the stabilized pavement layer stiffness in addition to density. Therefore, dry density measurements showed very weak correlations. with both ICMVs (MCI and E_R).

Grid-Based Section

The grid-based section was 250 feet in length and divided into four test lines (A to D) spaced six feet apart transversely. The MCI maps showed that the shoulder (line A) had a lower stiffness, and the pavement got progressively stiffer from test lines A to D. The MCI values in the grid-based section increased on subsequent days of testing, reflecting the gain in strength and stiffness of the stabilized sub-base with curing time. The E_R values were higher for the shoulder than the center, and the E_R values did not increase with curing time.

LWD and NDG tests were conducted at the centers of the 25-foot sublots along each test line. Overall, correlations between MCI and LWD modulus (Figure 10 to Figure 12) on all three days of testing showed expected trends with weak correlation ($0.21 \leq R \leq 0.47$). The LWD modulus is a measure of the stiffness of the top 8 to 12 inches of the foundation, while the MCI is a measure of the stiffness of the top 20 inches to 5 feet of the foundation. Thus, the variation in stiffness of the deeper natural subgrade contributes to variation in MCI but not the LWD modulus. Further, due to the chemical stabilization of the foundation, at some of the spot test locations, the stiffness exceeded the limits of the LWD device. These effects contributed to the overall weak correlation. However, the correlation coefficient improved on subsequent days of testing (from 0.21, 0.36 to 0.47). This may be due to the increase in stiffness of the top layer from curing (Figure 9) and the consequent reduced influence depth of the IC system.

Correlations between ICMVs (MCI and E_R) and NDG dry densities were very weak, with correlations on Day 1 and Day 2 being predominantly negative. This highlighted the significance of other factors affecting pavement layer stiffness, such as moisture content, cement content, and curing time, in addition to density.

Table 2. Timeline in Demonstration No. 2

Day	Activity
Day 0	Reclamation/construction
Day 1	Test location layout. Testing after one day of curing
Day 2	Testing after two days of curing
Day 3	Testing after three days of curing

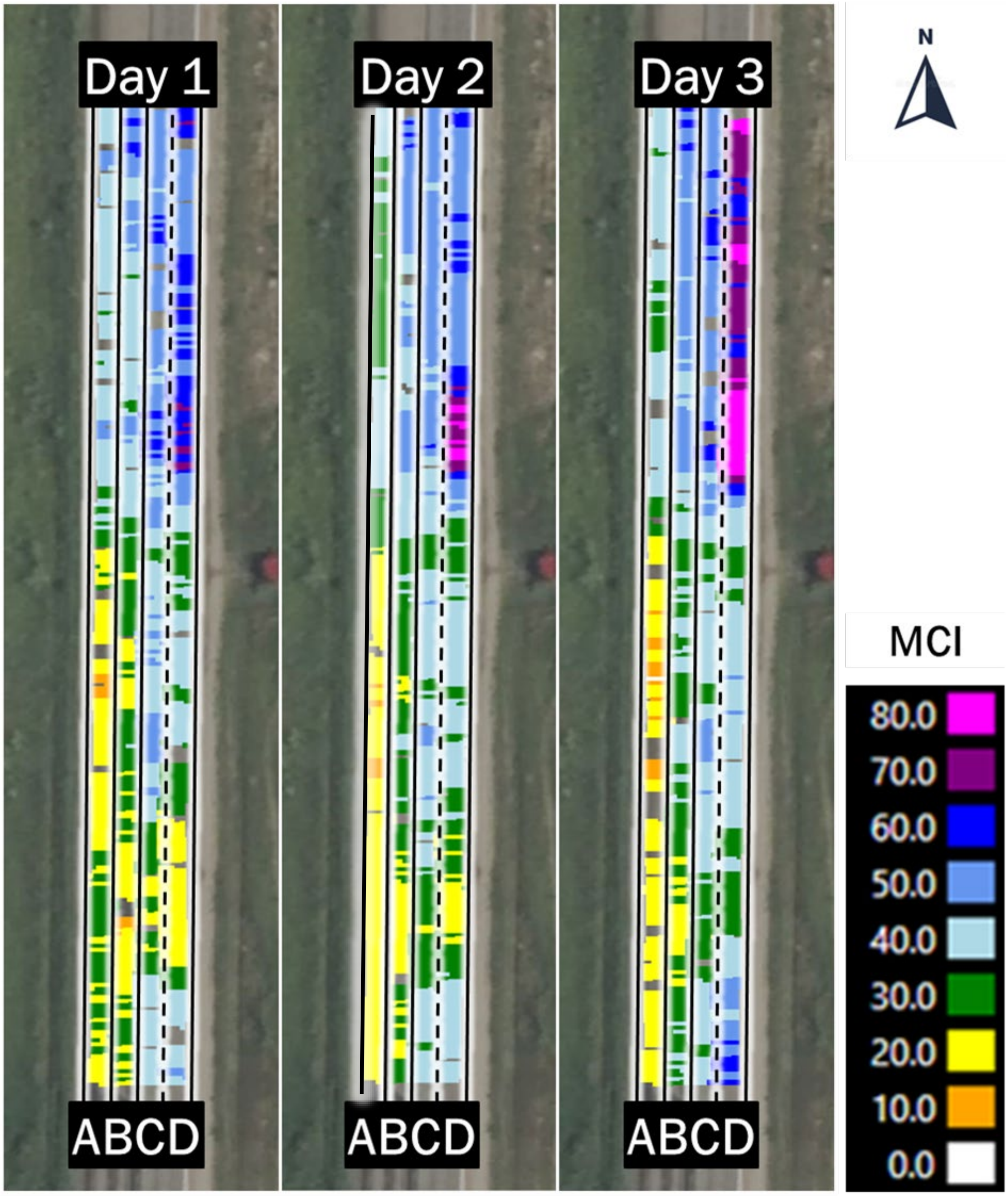


Figure 9. MCI map of grid-based section in Demonstration No. 2.

ICMV-Based Section

The ICMV-based section was 1650 feet in length and to the south of the grid-based section. The northern end of the ICMV-based section was identified as the area with medium ICMV, and the area with low and high ICMV was identified towards the middle of the ICMV-based section. Six LWD tests were performed in each zone on day 2 and day 3.

Correlation analysis was performed between the LWD modulus and the ICMVs (MCI and E_R), resulting in a similar trend as the grid-based section (Figure 13 and Figure 14), where subsequent testing days show increased correlation as follows:

- The correlation with MCI improved from a correlation coefficient of R = 0.64 on day 2 to R = 0.71 on day 3.
- The correlation with ER improved from R = 0.51 on day 2 to R = 0.66 on day 3.

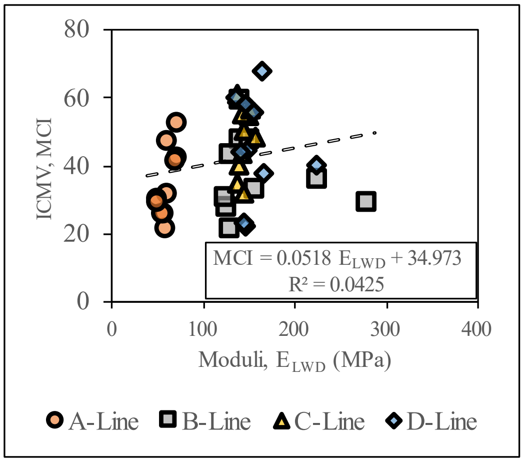


Figure 10. Correlation between MCI and E_{LWD} in grid-based section of Demonstration No. 2 on Day 1.

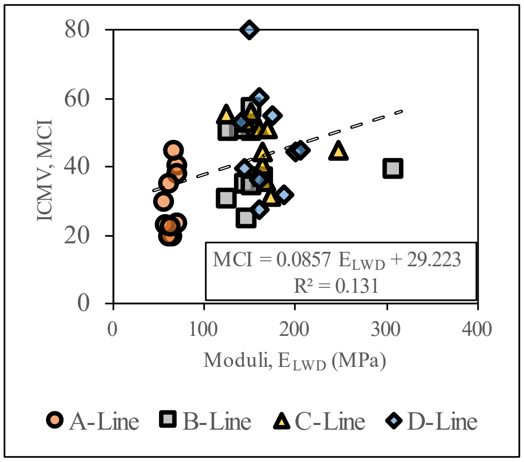


Figure 11. Correlation between MCI and E_{LWD} in grid-based section of Demonstration No. 2 on Day 2.

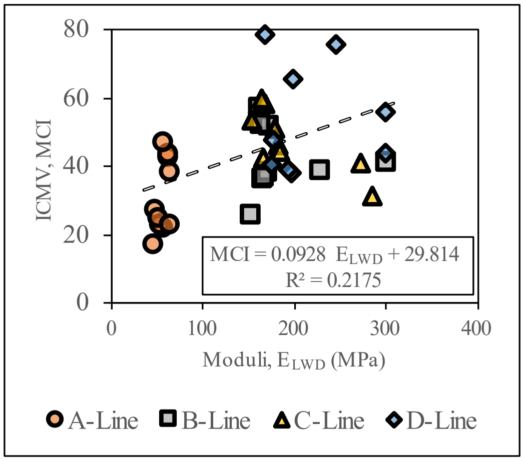


Figure 12. Correlation between MCI and E_{LWD} in grid-based section of Demonstration No. 2 on Day 3.

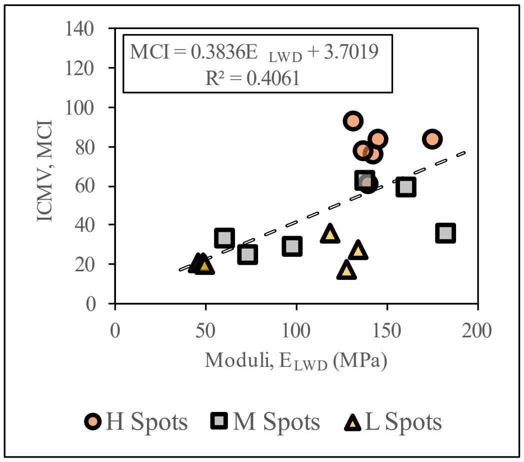


Figure 13. Correlation between MCI and ELWD in ICMV-based section of Demonstration No. 2 on Day 2.

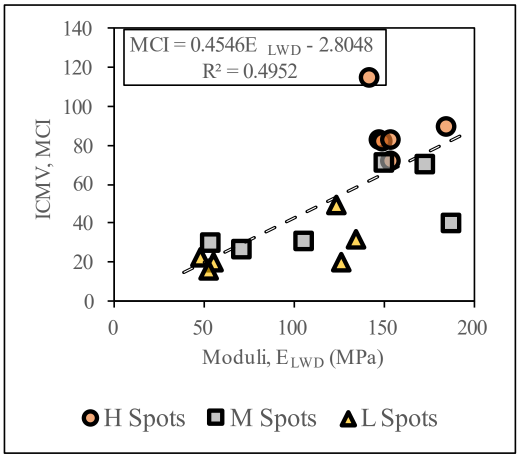


Figure 14. Correlation between MCI and ELWD in ICMV-based section of Demonstration No. 2 on Day 3.

Field Demonstration No. 3

Field Demonstration No. 3 took place on a 225-ft grid-based section along the IH 44, east of Rolla, MO, of a concrete pavement reconstruction project. The pavement foundation preparation involved full-depth reconstruction with

1. Excavation of the existing road to the subgrade.
2. Installation of geogrid on top of the subgrade.
3. Construction of 18-inch rockbase with 2-inch of capping material.

Thus, the subgrade was available for pre-mapping. This allowed testing to be performed on the subgrade and the 18-inch base course (rock base).

Key Findings

- IC systems have a deeper influence depth than conventional stiffness measurement devices such as LWD.
- ICMVs measured on top of the foundation layer are influenced by the variations in the stiffness of the subgrade, while the LWD moduli measurements are not due to their shallower influence depths.
- A successful characterization of foundation layer stiffness would involve pre-mapping the underlying soil beneath the foundation layer.

Table 3. Timeline in Demonstration No. 3

Day	Activity
Day 0	Rubblization of old pavement/Grading
Day 1	Test location layout and testing of subgrade. Construction: Geogrid + 18” Rockbase
Day 2	Construction: 18” Rockbase + 2” Cap Material Testing of subbase/foundation layer

Testing on Subgrade

The test section was divided into three test lines (A, B, and C) spaced six feet apart transversely. A portion of the subgrade has very low stiffness, as evidenced by the large rut caused by the construction traffic. The MCI values appeared invalid, as the material was so soft that the measurements registered as 0. The SineCore sensor did produce valid E_R data under the low stiffness conditions, and the areas with large rut had the lowest E_R values (Figure 15). LWD tests were conducted at 25-foot intervals along each test line, and correlations with E_R were positive with R = 0.69 (Figure 16).

Testing on Rockbase

The E_R map on the rockbase showed that the equivalent stiffness of the rockbase and subgrade was higher than that of subgrade pre-mapping. Due to the deeper influence depth of the IC system, areas with low stiffness in the subgrade were reflected closely in the rockbase E_R map (Figure 15). This resulted in a weak correlation between the LWD modulus (influenced by rockbase stiffness only) and the E_R values (influenced by both rockbase and subgrade stiffness) with R = 0.38 (Figure 17).

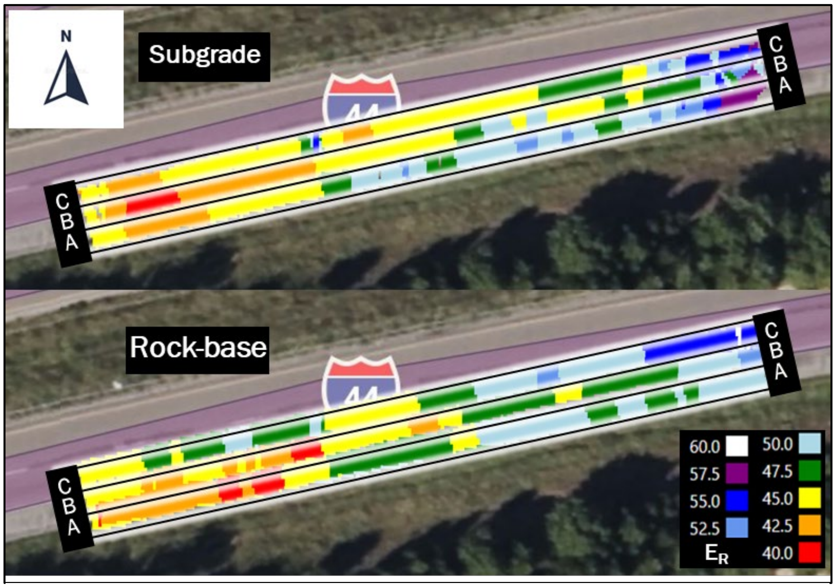


Figure 15. E_R map of Subgrade and Rockbase in Demonstration No. 3.

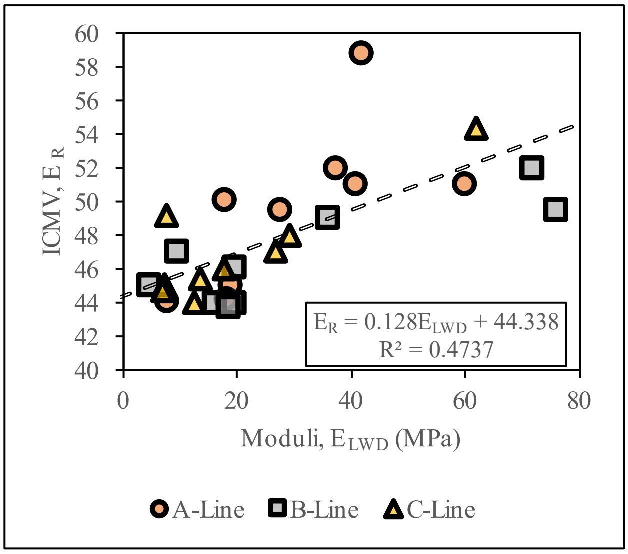


Figure 16. Correlation between E_R and E_{LWD} in subgrade of Demonstration No. 3.

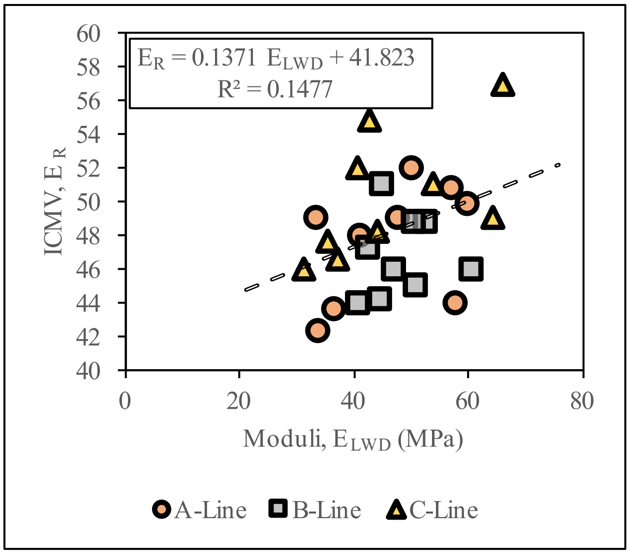


Figure 17. Correlation between E_R and E_{LWD} in rockbase of Demonstration No. 3.

Influence Depth of IC

The LWD modulus on top of the subgrade is plotted against that on top of the 18" thick base (rockbase) in Figure 17. Due to the shallow influence depth of the LWD (8" to 12"), the rockbase E_{LWD} does not reflect the variation in the subgrade E_{LWD}, as illustrated by the weak correlation shown in Fig 17. The analysis was repeated for E_R of the subgrade and base in Figure 18. The higher correlation shows that the subgrade E_R influenced the E_R on top of the rockbase, confirming the deeper influence depth of the IC system. Because of the difference in influence depth, poor correlation between spot testing results and ICMV does not necessarily indicate any errors in ICMV results. Rather, because of the greater influence depth, ICMV may be a better indicator of the support conditions provided by the pavement foundation layers. A device with similar influence (e.g., FWD) could be used for further validation.

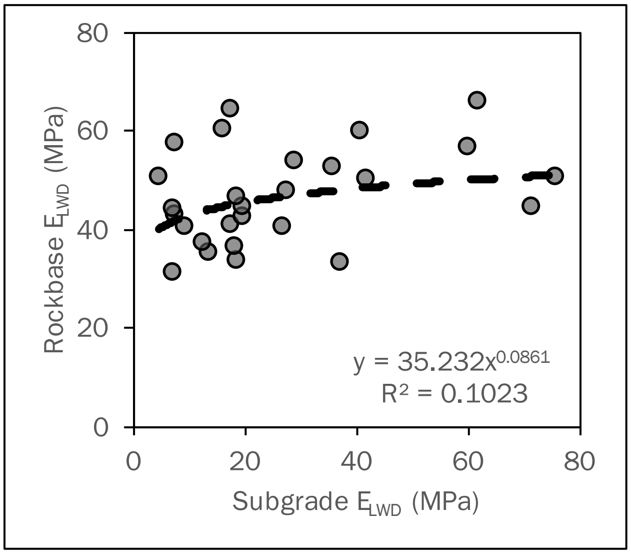


Figure 18. Correlation between E_{LWD} of subgrade and rockbase.

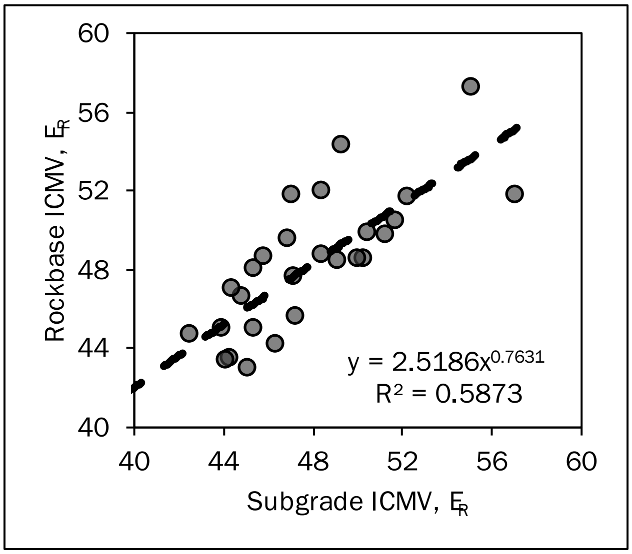


Figure 19. Correlation between E_R of subgrade and rockbase.

Proposed Field Procedure

The proposed IC field procedures for future large-scale projects are as follows. Specific criteria can be modified based on further studies from full-scale tests of various foundation materials.

If subgrade pre-mapping is not available, the IC field procedure is proposed as follows:

1. Trial Section (e.g., 250 ft X 20 ft):
   - Construct a lift of subbase materials.
   - Perform IC proof-mapping on the subbase.
   - Evaluate subbase ICMV to obtain mean ICMV and its STD for the trial section.
   - Identify potential weak locations based on subbase ICMV values (e.g., areas with less than the 10th percentile ICMV value) and verify the potential weak areas with the conventional acceptance tests. See an example in Figure 19.

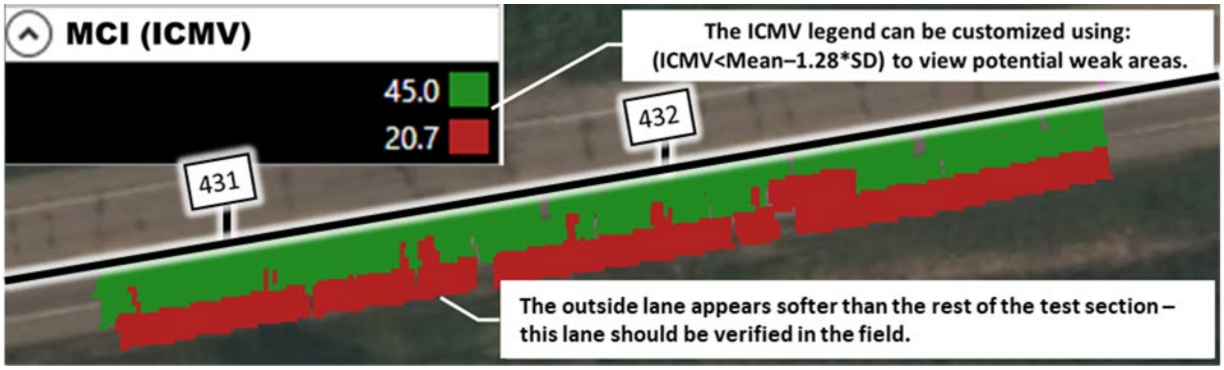


Figure 20. An example of identifying potential weak areas on an ICMV map.

2. Production Areas (e.g., lot by lot):
   - Perform IC proof-mapping on the subbase.
   - Evaluate subbase ICMV to obtain mean ICMV and its STD for each lot.
   - Select potential weak locations based on subbase ICMV values (e.g., areas with less than 10th percentile ICMV value) and verify the potential weak area with the conventional acceptance tests.

If subgrade pre-mapping is available, the IC field procedure is proposed as follows:

1. Trial Section (e.g., 250 ft X 20 ft):
   - Perform pre-mapping on the existing subgrade.
   - Evaluate subgrade ICMV to obtain mean ICMV and its STD for the trial section.
   - Identify potential weak locations based on subgrade ICMV value (e.g., areas with less than 10th percentile ICMV value) and verify them with visual observation or similar.
   - Construct a lift of subbase materials.
   - Perform proof-mapping on the subbase.
   - Identify the weak locations based on subbase ICMV value (e.g., areas with less than the 10th percentile ICMV value) and verify the weak areas with the conventional acceptance tests. Conventional acceptance tests may be more applicable to subbase lifts if the constructed and tested layers are approximately 12 inches. Choices of conventional tests need to be considered regarding their influence depth when the evaluated layer thickness is greater than 12 inches. Compare the subgrade ICMV and subbase ICMV map to see whether the weak areas are overlapped. Problem areas should be corrected before placing the next layer per agency's decisions.
2. Production Areas (e.g., lot by lot):
   - Perform pre-mapping of the existing subgrade.
   - Identify the potential weak locations based on subgrade ICMV value (e.g., areas with less than 10th percentile ICMV value) and take corrective actions as necessary.
   - Perform proof-mapping the subbase of large production areas, e.g., lot by lot.
   - Evaluate subbase ICMV to obtain mean ICMV and its STD.
   - Select potential weak locations based on subbase ICMV values (e.g., areas with less than the 10th percentile ICMV value) and verify them with the conventional acceptance tests.

Summary

Uniformity and adequate stiffness of pavement foundation are critical to pavement performance. Using IC technology to evaluate the stiffness and uniformity of the foundation layer is highly efficient compared to conventional spot tests and allows 100% coverage of the constructed areas. This project aimed to determine the feasibility of using IC technology to evaluate the adequacy and uniformity of the pavement foundation. A field demonstration methodology was developed to accomplish the objectives, including IC system setup, data collection, and data analysis protocols. Three field demonstrations were conducted to evaluate the IC procedures: No. 1 for the foundation of a new asphalt construction project, No. 2 for the foundation of an asphalt rehabilitation project, and No. 3 for the foundation of a new concrete construction project.

Some of the key findings from the various demonstrations are listed below.

- The 100% coverage provided by the IC system can help identify problem areas with low stiffness.
- ICMV represents the equivalent stiffness of a larger thickness of the pavement foundation compared to conventional spot tests (e.g., LWD or NDG) because of the deeper influence depth.
- Due to the deeper influence depth, a good correlation of ICMV with spot tests is possible only in cases with a uniform subgrade. Areas with non-uniform subgrades may have underlying variability that results in weak correlation. Thus, subgrade pre-mapping to evaluate the subgrade uniformity is crucial.
- The MAS-180 sensor (MCI) showed more expected trends on the stabilized sub-base, while the SineCore sensor (E_R) was better at registering valid data on subgrade with low stiffness. This highlights the need for a certification program to identify the appropriate systems under appropriate conditions.
- The MAS-180 system (MCI) measured the stiffness gain (degree of curing) in the cement-treated sub-base. This can be an excellent tool for such assessment.

Based on the extensive state-of-technology review and three field demonstration projects, a simplified IC field procedure was proposed to use IC mapping as a quality control tool to evaluate the stiffness and uniformity of the foundation. The proposed step-by-step procedure includes two scenarios depending on whether the subgrade pre-mapping is available. Correlation between ICMV and spot tests is not recommended due to the differences in test footprint and influence depths. Setting target ICMVs based on their correlation with spot tests from a test strip is also not recommended due to the uncertainty of the support conditions of the production areas. The uniformity evaluation still requires further studies.

Subgrade pre-mapping is useful to assess the baseline support condition and identify potential weak areas for corrective actions before sub-base construction. Without subgrade pre-mapping, the subbase ICMV can be considered to evaluate the combined subbase and subgrade layers. Conventional acceptance spot test devices can be used to test the potential weak areas identified by subbase mapping. However, the verification is reliable only when the spot test's influence depth can include the subbase and subgrade layers. Therefore, the simplified procedures, by avoiding the above pitfalls, would allow the IC technologies to be practically implemented in the fields.

Recommendations

The following recommendations are for future work to accelerate widespread IC implementation to evaluate foundations' stiffness and uniformity:

- Further full-scale pilot projects are recommended to implement the proposed, simplified IC procedures on various foundation materials.
- A special provision is recommended to be a part of the construction contacts of pilot projects to include the proposed IC procedures so that the IC procedure can be implemented.
- Further studies are recommended to draw from the results of the above-recommended full-scale studies to establish the criteria for identifying weak areas and uniformity for various foundation materials.
- The AASHTO standard for IC for foundation is recommended to be developed based on the above full-scale study by following a simplified approach.
- The roadmap for IC system certification is recommended to follow the path of inertial profiler certification to qualify the IC systems used in the above AASHTO standard.

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Acronyms and Symbols

CCC	Continuous Compaction Control
CMV	Compaction Measurement Value
CoV	Coefficient of Variance
DCP	Dynamic Cone Penetrometer
E_{LWD}	Modulus from LWD
E_R	Resistance Modulus
EU	European Union
GNSS	Global Navigation Satellite System
IC	Intelligent Compaction
ICMV	Intelligent Compaction Measurement Values
ISSMGE	International Society for Soil Mechanics and Geotechnical Engineering
LWD	Lightweight Deflectometer
MCI	MOBA Compaction Index
NDG	Nuclear Density Gauge
QC	Conventional Quality Control
R	Correlation Coefficient
R^2	Coefficient of Determination (R X R)
STD	Standard Deviation
TMR	Department of Transport and Main Roads
TPF	Transportation Pooled Fund
ρ_d	Dry Density

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