FHWA/TPF Research Project
Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials

HMA IC Demonstration
I-66, Fauquier County, Virginia
Final Report
Intelligent compaction (IC) is an emerging technology, and for some applications it is mature enough for implementation in field compaction of pavement materials. The intent of this project is to realize the blueprint in the FHWA IC strategic plan. This study was initiated under the Transportation Pooled Fund (TPF) Solicitation No. 954, which includes 12 participating state department of transportation (DOTs): Georgia, Wisconsin, Kansas, Maryland, Wisconsin, Mississippi, North Dakota, Mississippi, Pennsylvania, Texas, Virginia, and Wisconsin.

This document is the final report for the VADOT HMA IC field demonstration.
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*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)
TABLE OF CONTENTS

Executive Summary ...................................................................................................................................... 1
  Major Findings ........................................................................................................................................ 1
    New Findings: ....................................................................................................................................... 1
    Confirming Past Findings: .................................................................................................................... 4
  Recommendations ..................................................................................................................................... 4
Acknowledgement ........................................................................................................................................ 6

Introduction  7

Description of the Test Site ........................................................................................................................... 8

Description of IC Rollers .............................................................................................................................. 9
  Sakai Tandem IC Roller ............................................................................................................................ 9
    Overall System Description .................................................................................................................. 9
    Measurement Value ............................................................................................................................ 12
    Feedback Control ............................................................................................................................. 12
    Documentation System ....................................................................................................................... 12

GPS System  15

Description of In-situ Testing Methods ...................................................................................................... 15
  Nuclear Density Gauge (NG) .................................................................................................................. 15
  LWD Tests .............................................................................................................................................. 16

HMA IC Demonstration ............................................................................................................................. 18

Demonstration Activities ........................................................................................................................... 18

Analysis Approaches ............................................................................................................................... 20
  Viewing of IC Data and Maps .............................................................................................................. 20
  Statistics Evaluation of Compaction Quality and Uniformity .............................................................. 20
  Correlation of IC Data and In-Situ Measurements ............................................................................ 22

Results Analysis and Discussion ............................................................................................................. 23
  IC Results ............................................................................................................................................. 23
  In-Situ Test Results and Correlation of IC Data .................................................................................. 34
  Summary Tables .................................................................................................................................... 39

Conclusions and Recommendation .......................................................................................................... 41
  Conclusions and Findings ................................................................................................................... 41
  Recommendations ............................................................................................................................. 41

Open House  43

References  47
LIST OF TABLES

Table 1. Features of the Sakai SW880 Tandem IC Rollers. ................................................................. 10
Table 2. Test bed description for HMA IC. ............................................................................................ 18
Table 3. Test Settings for HMA IC....................................................................................................... 18
Table 4: Roller measurement value, Sakai CCV .................................................................................. 39
Table 5: Optimum roller passes ............................................................................................................ 39
Table 6: Summary of Semi-variogram parameters for Sakai CCV ..................................................... 40

LIST OF FIGURES

Figure 1. Location of the test site (the red bulb area). ........................................................................ 8
Figure 2. Sakai SW880 Tandem IC Roller. ........................................................................................ 9
Figure 3. RTK GPS receiver and antenna on a Sakai roller................................................................. 10
Figure 4. Sakai Compaction Information System (CIS) display at the operator station. ................... 11
Figure 5. The Sakai IC system. ........................................................................................................... 11
Figure 6. Sakai CCV - Changes in amplitude spectrum with increasing ground stiffness. .............. 12
Figure 7. Sakai Aithon MT-R software output for number of rollers passes ....................................... 13
Figure 8. Sakai Aithon MT-R software output for CCV. ................................................................... 14
Figure 9. Sakai Aithon MT-R software output for surface temperatures ........................................... 14
Figure 10. Nuclear density gauge. .................................................................................................... 16
Figure 11. Nuclear density gauge mechanism. .................................................................................... 16
Figure 12. LWD Prototype similar to ZFG 2000A LWD. .................................................................. 17
Figure 13. A Trimble GPS base station. ............................................................................................ 19
Figure 14. Interface of the IC Viewer. ................................................................................................ 20
Figure 15. Description of a typical experimental and exponential semi-variogram and its parameters ... 21
Figure 16. Semi-variogram models.................................................................................................... 22
Figure 17. Mapping existing HMA course (TB01). .......................................................................... 23
Figure 18. TB 01B Sakai SW880 CCV and frequency for the mapping of the existing milled HMA surface (TB 01M) ............................................................................................. 24
Figure 19. Sakai SW880 CCV, surface temperatures, and frequency histograms for the breakdown/intermediate compaction of the HMA base course (TB01B - Section 1). ................. 25
LIST OF MAIN ACRONYMS OR TERMS

LIST OF SYMBOLS

\[ A_{0.5\Omega}, A_{0.5\Omega}, A_{0.5\Omega} \]  Acceleration at sub-harmonic frequency

\[ A_{\Omega} \]  Acceleration at fundamental frequency
$A_{2\Omega}$  Acceleration at second order harmonic frequency

$A_{3\Omega}$  Acceleration at higher order harmonic frequency

RMV  Roller Measurement Value

CCV  Compaction Control Value for Sakai roller

W  Machine weight

A  Vibration amplitude

v  Roller speed

f  Vibration frequency

d  Diameter of the FWD plate

E  Elastic modulus of LWD measurement

$\gamma(h)$  Semivariogram

R  Semivariogram range

C  Semivariogram sill

$C_0$  Semivariogram nugget
Executive Summary

This report describes the FHWA/TPF intelligent compaction (IC) demonstration for hot mix asphalt. It is an HMA overlay project on I-66 west of Washington D.C. on MP 23, conducted on September 27 to September 30 2010.

The goals of this demonstration project that were successfully achieved include:

1. Demonstration of HMA IC technologies to VADOT personnel, contractors, etc.;
2. Develop an experienced and knowledgeable IC expertise base within VADOT,
3. Assisting VADOT in the development of IC quality control (QC) specifications for the HMA pavement materials, and
4. Identification and prioritization of improvements and further research for IC equipment and data analysis.

Goal number 1 was accomplished by demonstrating the abilities of the IC system such as: tracking roller passes, HMA surface temperatures, and roller measurement values (RMV).

Goal number 2 was achieved by building the IC knowledge base including field data and lessons learned from this demonstration and past demonstrations. Valuable information was collected from this demonstration and served as solid proof for the IC technologies.

Goal number 3 was achieved, albeit still a work in progress, by training VADOT staff, paving contractors, and etc. on the IC technologies via this field demonstration and an Open House activity. The research team will continue provide support to VADOT on the development of IC QC specifications during this project period.

Goal number 4 was achieved by compiling a “wish list” or recommendation for the IC roller vendors to further improve their systems for widespread use of the IC technologies. Data of IC system was also reviewed and potential problems are identified for future research and engineering practices.

Major Findings

One of the repeated evidence of immediate benefits is improvement of rolling patterns.

New Findings:

- Measurements of IC roller GPS can be verified by placing a GPS rover receiver on the top of roller GPS receiver unit to eliminate the potential error resulted from offset and movement angles (see figure below);
• Mapping of exiting HMA surfaces can be used to evaluate pavement conditions in order to identify relatively weaker areas (see figure below that shoulder area –right hand side- has lower CCV than pavement lane –left hand side-);

• Compaction uniformity for different construction sections can be compared using semi-variogram analysis (see figure below). Lower sill values in combination with higher range values indicate better uniformity;
Mapping of existing HMA pavement shows a relatively higher uniformity than that from compaction of hot mixture asphalt overlay. This observation may be due to the uniform (colder) temperatures of existing HMA. However, more research is needed to quantify the effects of temperature distribution on compaction uniformity;

Compaction curves can be established using IC technology to determine optimum roller pass number (see figure below for compaction curves of three different sections of HMA overlay);

Nuclear density gauge measurements of fresh HMA overlay behind the Volvo IACA roller forms a compaction curve within a narrow range of densities (see figure below);
Confirming Past Findings:

- The IC roller can track roller pass numbers, roller speeds, HMA surface temperatures, and the RMVs, which provides important metrics for compaction quality;
- With real-time information of IC roller passes, HMA surface temperatures and RMVs displayed on the onboard screen, roller operators can adjust rolling patterns to improve the compaction quality.

Recommendations

- Validation of the IC GPS setup prior to the compaction operation using a survey grade GPS handheld unit on the same position of the IC roller GPS receiver is crucial to providing precise and correct measurements.
- To correlate in-situ tests with IC data properly, in-situ test locations must be established using a hand-held GPS “rover” unit that is tied into the project base station and offers survey grade accuracy.
- It is highly recommended to perform IC measurements (mapping) of the underlying layers prior to the paving of upper layers in order to identify possible weak spots and facilitate the interpretation of the measurements on the asphalt surface layers.
- Long term pavement performance monitoring is recommended in order to identify performance trends that may relate to RMV values.
- Temperature correction for the RMV of HMA material is recommended for future development.
- Indicators of undesirable IC measurement conditions (such as bouncing, sudden start/stop, loss of real-time kinematic GPS measurements, etc.) are strongly recommended to be stored in order to filter out invalid IC data.
- Standardization is strongly recommended to accelerate the implementation IC for State agencies. The recommended items include: a standard IC data storage format, an independent viewing/analysis software tool, and detailed data collection plan (include any in-situ/lab test results). The research team is currently developing guidelines for IC data collection, storage requirements, data processing, and a prototype of an independent software tool.
- Further investigation on a global scale (e.g., segment-by-segment analysis of entire paved sections) is recommended to provide guidance of usage of IC mapping data on existing pavement layer with subsequent IC measurements during HMA paving. This would include: setting a target RMV value.
from test trip data based on the onsite support condition and asphalt job mix formula.

- To overcome GPS signal shadows at difficult terrains, there are three alternatives: (1) select a proper location for the GPS base station, then use signal repeaters to fill in the GPS “shadow areas”. (2) Use virtual reference station (VRS) as long as there are good cellular reception. (3) Use internet base station and make use of server/client systems to transmit the signals.

Notes: The Volvo IACA results will be included once the IACA data are available to the IC team.
Acknowledgement

This demonstration would not have been possible without the help of all the parties involved in this project. The primary parties that were involved with planning and conducting the demonstration projects were the ICPF project team, VADOT, the Sakai roller vendor, and the paving contractors. The ICPF project team for this demonstration included Dr. George Chang, Qinwu Xu, Bob Horan, Larry Michael, and Victor (Lee) Gallivan. Mr. Gallivan is the contracting officer’s technical representative; Mr. Horan was the facilitator; Dr. Chang was main contact for the ICPF project team, and Mr. Brian Diefenderfer was the main contact for VADOT.

The authors would like to acknowledge the following individuals for their contribution to this demonstration:

- **VADOT**: Brian Diefenderfer, Trenton Clark, Michael Wells;
- **Sakai**: Todd Mansell;
- **Volvo**: Dale Starry and Chad Fluent;
- **Keystone Precision Instrument**: Mike Windsor;
- **University of Oklahoma**: Sesh Commuri and his students;
- **Kessler Soils Engineering**: Larry Aicken;
- **Superior Paving Corp**: Chris Griffith, James Mitchell, Dave Helmick and others.
Introduction

This is the report for the hot mixture asphalt (HMA) intelligent compaction (IC) field demonstration conducted in September 2010 for the Virginia Department of Transportation (VADOT). This was an IC demonstration under the Transportation Pooled Fund (TPF) study “Accelerated Implementation of Intelligent Compaction Technology for Subbase, Base, and Asphalt Pavement Materials.” Key attributes for this field demonstration included on-site training of VADOT and contractor personnel, comparison of IC roller technologies to traditional compaction equipment and practices, correlating IC roller measurements to in-situ spot test measurements, mapping the existing milled HMA surface to understand the influence of underlying layer support, selecting the appropriate machine operation parameters (e.g., speed, amplitude, frequency, etc.), and managing and analyzing the IC and in-situ test data.

The specific goals of this demonstration project were to:

- Demonstration of Hot Mix Asphalt (HMA) IC technologies to VADOT personnel, contractors, etc.;
- Develop an experienced and knowledgeable IC expertise base within VADOT;
- Assisting VADOT in the development of IC quality control (QC) specifications for the HMA pavement materials, and
- Identification and prioritization of needed improvements and further research for IC equipment and data analysis.

The objectives of this demonstration project were short-term goals for introducing HMA IC technology to VADOT and contractors who may not have prior experience with IC technology. The project was intended to demonstrate the benefits of IC for improving the compaction process and quality by achieving more uniform density and modulus of the HMA material and providing roller operators (and superintendents) better feedback tools to make right decisions, and ultimately real-time quality control.

The demonstration site and material of interest were selected by VADOT. The field IC demonstration was performed from September 26 to 30, 2010 on I-66 west of DC.

This report includes:

- Description of the test site;
- Description of IC rollers;
- Description of in-situ test devices;
- Details of field demonstration activities and data analysis;
- Open house activities; and
- Summary and recommendations.
Description of the Test Site

It is an HMA overlay project on I-66 west of DC on MP 23 (Figure 1). The existing pavement is HMA pavement. During the demonstration, the existing HMA surface layer was milled and removed before paving HMA overlay.

Figure 1. Location of the test site (the red bulb area).
Description of IC Rollers

One Sakai tandem drum IC roller and a Volvo IACA roller were used for the HMA IC demonstration.

Both IC rollers are equipped with a global position system (GPS), a roller response measurement system, and a document system. The detailed features of the Sakai IC rollers are described in the following sections. The description for the Volvo IACA roller will be included once it is provided by Volvo.

*Sakai Tandem IC Roller*

Overall System Description

The Sakai SW880 tandem IC roller is shown in Figure 2. The features of this roller are described in Table 1.

![Figure 2. Sakai SW880 Tandem IC Roller.](image-url)
Table 1. Features of the Sakai SW880 Tandem IC Rollers.

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The Sakai Compaction Information System (CIS) is the IC hardware and software that map roller passes, temperature, and stiffness of the compacted surface. CIS can be installed on Sakai single drum vibratory soil rollers or double drum asphalt rollers with or without the continuous compaction value (CCV) sensor. The Real Time Kinematic (RTK) Global Position Systems (GPS) provided by Trimble Navigation Limited was used for Sakai SW880 roller, to obtain the precise roller position for recording the roller pass data as well as data from the CCV sensor, as shown in Figure 3.

Figure 3. RTK GPS receiver and antenna on a Sakai roller

Figure 4 shows a view of the Sakai IC system installed on the roller where the monitor on the left displays the IC color coded maps. The monitor is portable and has good visibility in bright daylight it also has a
reduced brightness “Night” mode. The Exact Compact display and IPF controls are located on the standard roller dash panel with the other instruments and controls for the roller. Exact Compact is a standard feature on Sakai SW880 and SW990 roller models.

Figure 4. Sakai Compaction Information System (CIS) display at the operator station.

The schematic of the Sakai IC system (for both soil and HMA) can be best demonstrated by the diagram shown in Figure 5. The basis of this system is the IC roller (equipped with CCV measurement system, temperature sensors, and GPS radio/receiver) and a GPS with radio base station. All measurements are consolidated to the CIS display. IC data can then be transferred to PCs via USB ports for further reporting/documentation and integration with CAD systems.

Figure 5. The Sakai IC system.
Measurement Value

The Sakai Compaction control value (CCV) is a unitless vibratory-based technology which makes use of an accelerometer mounted to the roller drum to create a record of machine-ground interaction. Its value represents the stiffness of the compacted pavement layers underneath. The concept behind the CCV is that as the ground stiffness increases, the roller drum starts to enter into a “jumping” motion which results in vibration accelerations at various frequency components, as illustrated in Figure 6. The CCV is calculated by using the acceleration data from first sub-harmonic (0.5\(\Omega\)), fundamental (\(\Omega\)), and higher-order harmonics (1.5\(\Omega\), 2\(\Omega\), 2.5\(\Omega\), 3\(\Omega\)) as presented in Eq. 1. The vibration acceleration signal from the accelerometer is transformed through the Fast Fourier Transform (FFT) method and then filtered through band pass filters to detect the acceleration amplitude spectrum (Nohse and Kitano, 2002; Scherocman et al., 2007).

\[ CCV = \left( \frac{A_{0.5\Omega} + A_{1\Omega} + A_{1.5\Omega} + A_{2\Omega}}{A_{0.5\Omega} + A_{2\Omega}} \right) \times 100 \]

(Modified from the Sakai manual)

**Figure 6. Sakai CCV - Changes in amplitude spectrum with increasing ground stiffness.**

Feedback Control

NA

Documentation System

The Sakai IC documentation system is called Compaction Information System. The system makes use of field software—Aithon MT-R, and an office version—Aithon PD-R software.

Prior to the compaction operation, a plan file that delineates the pavement edges can be loaded to the Sakai CIS system in order to be overlaid with the color-coded map. The plan file can be generated using the Aithon MT-R software provided that the GPS locations of the paved edges are known. The IC measurements by the Sakai system are stored in a proprietary binary file format (with file name extension, GPS). To replay the compaction data, one would need to load both the plan file and the IC data file using the Aithon MT-R software. The Aithon MT-R software can also generate “construction result” files in ASCII format (with a file name extension, PLN) that can be imported to AUTOCAD 2007/8 using a
A 0.3 m by 0.3 m (1 ft by 1 ft) mesh often is used to present the data and display in graphics.

Figure 7, Figure 8, and Figure 9 show screenshots of the Sakai Aithon MT-A software that can be viewed by the roller operator in real time during the compaction process in order to track roller passes, CCV, and surface temperatures, respectively. The purpose of this graphical display is to provide an easy way to understand system for eliminating the common problem of not getting uniform coverage of the desired number of passes.

Figure 7. Sakai Aithon MT-R software output for number of rollers passes.
Figure 8. Sakai Aithon MT-R software output for CCV.

Figure 9. Sakai Aithon MT-R software output for surface temperatures.
GPS System

The Trimble GPS system was used for both the Sakai SW880 and Volvo rollers.

- A Trimble GPS receiver and a radio were mounted on the Sakai SW880 and Volvo machine.
- A Trimble GPS base station was setup to provide RTK correction signals.
- A hand-held Trimble GPS rover was used for in-situ point measurements.

Description of In-situ Testing Methods

Various in-situ testing methods were employed in this study to evaluate the in-situ pavement physical and mechanical properties:

- Nuclear gauge (NG) to determine in-situ HMA densities,
- Laboratory test on HMA core samples to determine the bulk densities;
- LWD test on hot mixture to measure the deflection and CBR.

The above tests were conducted by the research team, and New Enterprise personnel. For each discrete in-situ test location, the GPS location was recorded.

Nuclear Density Gauge (NG)

The nuclear density gauge (NG) was used to measure the densities of HMA materials, as shown in Figure 10. The nuclear density gauge measures the in-place material density based on the gamma radiation. NG usually contain a small gamma source (about 10 mCi) such as Cesium-137 on the end of a retractable rod (University of Washington website, see reference).

The device consists of a hander, a retractable rod, the frame, a shielding, a source, and a Geiger-Mueller detector as shown in Figure 11. The source emits gamma rays that interact with electrons in the HMA pavement through absorption, Compton scattering, and the photoelectric effect. The detector (situated in the gauge opposite from the handle) counts gamma rays that reach it from the source. Then, the received number of gamma rays by the detector is correlated to the density of HMA materials (see Figure 11).
**LWD Tests**

The LWD data were collected using a prototype similar to the Zorn ZFG 2000A device (see Figure 12) to measure the stiffness of hot mix following the Volvo intermediate compaction. This LWD is designed for testing freshly paved HMA layers. The test settings were as follows:

- Drop weight: 10 kg;
- Drop height: 70 cm;
- Pulse time: 17 ms;

The collected data for each drop includes the deflections with time series, the drop speed, etc. By using the deflection data collected from these sensors, the CBR of pavement layers were back-calculated by its program.
Figure 12. LWD Prototype similar to ZFG 2000A LWD.
HMA IC Demonstration

Demonstration Activities

The IC demonstration activities include mapping of the milled HMA surface layer and compaction of HMA overlay afterwards.

The Sakai SW880 double-drum IC roller was used as the break-down roller, the Volvo was used as the intermediate roller, and the Ingersoll Rand was used as the finishing roller. In-situ tests including the NG density, cores, and LWD measurements.

Existing HMA surface was milled, and then HMA overlay was paved on it afterwards. Due to the rain weather, construction and IC demonstration were only performed on September 28 (Tuesday). The demonstration consists two test beds: TB01M for mapping existing milled HMA surface, and TB 01 for paving fresh HMA overlay.

For the in-situ tests, NG density, cores, and LWD tests were performed on the hot mixture asphalt following the Volvo intermediate compaction.

These test beds are described in Table 2. Test schedule and IC machine settings are summarized in Table 3.

<table>
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<tr>
<th>Table 2. Test bed description for HMA IC.</th>
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<th>Table 3. Test Settings for HMA IC.</th>
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<tr>
<td>01M</td>
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The GPS base station (Trimble) was setup on this project (see Figure 13). Communication was established between the GPS base station and the RTK receivers on the IC rollers as well as handheld GPS rover. The UTM 18 North zone was used as the grid reference during GPS calibration.
Figure 13. A Trimble GPS base station.

As an important finding in this demonstration, the GPS base station has to be re-located and reset in this area with many obstacles including hills, tall trees, and road curves.
Analysis Approaches

Viewing of IC Data and Maps

The Sakai AthonMT® software was used to export data from the measured IC data files. The IC Viewer program developed by the Transtec Group (see Figure 14) are used to view, process the exported IC data (roller pass, surface temperature, RMV, etc.) and perform data analysis including the statistical/geostatistical analysis, correlation study, and compaction curves, etc.

![Figure 14. Interface of the IC Viewer.](image)

Statistics Evaluation of Compaction Quality and Uniformity

The basic statistics including the mean value, standard deviation of IC data are analyzed using the IC viewer software.

Geostatistics is used for analysis of the compaction uniformity using the IC viewer software. Spatially referenced IC measurement values provide an opportunity to quantify “uniformity” of compacted fill materials. This topic is slowly gaining popularity among the pavement engineering community. Vennapusa and White (2009b) demonstrated the use of semi-variogram analysis in combination with conventional statistical analysis to effectively address the issue of uniformity in quality assurance during earthwork construction.
A semi-variogram is a plot of the average squared differences between data values as a function of separation distance, and is a common tool used in geostatistical studies to describe spatial variation. A typical semi-variogram plot is presented in Figure 15. The semi-variogram $\gamma(h)$ is defined as one-half of the average squared differences between data values that are separated at a distance $h$ (Isaaks and Srivastava 1989). If this calculation is repeated for many different values of $h$ (as the sample data will support) the result can be graphically presented as experimental semi-variogram shown as circles in Figure 15. More details on experimental semi-variogram calculation procedure are available elsewhere in the literature (e.g., Clark and Harper 2002, Isaaks and Srivastava 1989).

Figure 15. Description of a typical experimental and exponential semi-variogram and its parameters

To obtain an algebraic expression for the relationship between separation distance and experimental semi-variogram, a theoretical model is fit to the data. Some commonly used models include linear, spherical, exponential, and Gaussian models. Previous work by White et al. (2007a), White et al. (2007b), Vennapusa and White (2009b), and results from Texas field investigation conducted as part of this project showed that an exponential model generally fits well for IC measurement data.

An exponential semi-variogram is illustrated in Figure 15 as solid line. Three important features to construct a theoretical semi-variogram include: sill ($C+C_0$), range ($R$), and nugget ($C_0$). These parameters are briefly described in Figure 15. Arithmetic expressions and detailed descriptions of theoretical models can be found elsewhere in the literature (e.g., Clark and Harper 2002, Isaaks and Srivastava 1989). For the results presented in this section, the sill, range, and nugget values during theoretical model fitting were determined by checking the models for “goodness” using the modified Cressie goodness fit method (see Clark and Harper 2002) and cross-validation process (see Isaaks and Srivastava 1989). From a theoretical semi-variogram model, a low “sill” and longer “range of influence” represent best conditions for uniformity, while the opposite represents an increasingly non-uniform condition.

In this project the IC Viewer program is used to produce semi-variograms of IC data. Different models, e.g. the exponential and Gaussian models (see Figure 16), were used to fit the semi-variogram in order to obtain the semi-variogram parameters (e.g. range, sill, scale, and nugget.).
Correlation of IC Data and In-Situ Measurements

The IC data are correlated with the in-situ measurements: including in-situ LWDD measured deflection and CBR, nuclear density gauge measurements, and laboratory bulk densities of cored samples.
Results Analysis and Discussion

IC Results

TB 01M – Mapping Existing Milled HMA Surface EB Travel Lane

This test bed consists of compacting on the existing HMA surface using the Sakai SW880 double-drum IC roller. The Sakai machine settings were as follows: frequency of 2500 vpm; low amplitude; and speed of 3 kmh. Only one roller pass with front drum vibration was performed.

Figure 17 shows the mapping area of TB 1M. Figure 18 present the maps of Sakai CCV and frequency of TB 01M from Sakai roller mapping. Results show that obviously the pavement lane area has higher Sakai CCVs than the shoulder area, indicating its higher stiffness of support.

Figure 19 shows the statistical histograms of the Sakai CCV and frequency resulted from the SW880 mapping on the exiting HMA surface. The mean Sakai CCV is 26.33.

Figure 20 displays the semi-variogram of mapping the existing HMA surface. The exponential model fit was applied with the semi-variogram parameters as follows: a range of 14.42 and a sill of 0.27.

Figure 17. Mapping existing HMA course (TB01).
Figure 18. TB 01B Sakai SW880 CCV and frequency for the mapping of the existing milled HMA surface (TB 01M).
Figure 19. Sakai SW880 CCV, surface temperatures, and frequency histograms for the breakdown/intermediate compaction of the HMA base course (TB01B - Section 1).
Figure 20. Semivariogram for the Sakai SW880 mapping of the existing milled HMA surface (TB 01M).

**TB 01 – HMA Overlay on the EB Travel Lane**

This test bed consists of paving the HMA overlay on the milled HMA surface using the Sakai SW880 and Volvo double-drum IC rollers on September 28. The Sakai SW880 was used as the breakdown roller with 3 passes, and the Volvo was used as the intermediate roller with 4 passes. The Sakai machine settings were as follows: frequency of 4000 vpm; low amplitude; and speed of 3 kmh.

Figure 21 shows the compaction area of the test bed on the highway I-66 EB travel lane.

Figure 22 summarizes the test location, roller machines and compaction parameters (frequency, amplitude, and speed), and the in-situ tests.

Figure 23 presents the maps of Sakai CCV, roller pass number, and HMA surface temperature of TB 01 resulted from the SW880 breakdown compaction.

Figure 24 to Figure 26 show the histograms for Sakai CCV, HMA surface temperature, and frequency resulted from the SW880 breakdown compaction for section 1 to 3, respectively. Results show that section 1 and 2 have higher CCV/stiffness than section 1.

Figure 27 displays the semi-variograms of the HMA overlay under the Sakai SW880 breakdown compaction for section 1 to 3. Results show that section 3 has a larger range value, indicating its better uniformity. Compared to the mapping on the exiting cold HMA surface, it seems that the compaction on the hot mix results in a lower uniformity, which is likely due to its less uniform temperature distribution. However, more research to quantify the effects of temperature and its distribution on the compaction uniformity is needed.

Figure 28 presents the compaction curves of the HMA overlay under the SW880 breakdown compaction. It shows that Sakai CCV increases with increasing roller pass number. For section 1, it seems that a roller pass number of 4 or 5 would be optimum (note that the roller pass number 6 was only performed on very limited zones and thus may not represent the whole compaction area, see Figure 23).
Figure 21. Compaction area.
Test bed 01 (9/28/2010)

Description
This test bed consists of compacting the HMA overlay on the milled existing HMA surface, on the East Bound travel lane. Sakai SW880 double-drum IC roller was used as breakdown and Volvo was used as intermediate rollers. The in-situ NG and LWD measurements were performed.

Sakai Machine Setting:
vibration frequency was 4000 vpm; the low amplitude (0.3mm) was used; the speed was set about 3 kmh.

Figure 22. Compacting HMA overlay on the milled existing HMA surface (TB 01).
Figure 23. Sakai SW880 CCV, pass number, and surface temperatures for the breakdown compaction of the HMA overlay. (TB 01).
Figure 24. Sakai SW880 CCV, surface temperatures, and frequency for the breakdown compaction of the HMA overlay (TB 01 - Section 1).
Figure 25. Sakai SW880 CCV, surface temperatures, and frequency for the breakdown compaction of the HMA overlay (TB 01 - Section 2).
Figure 26. Sakai SW880 CCV, surface temperatures, and frequency for the breakdown compaction of the HMA overlay (TB 01 - Section 3).
Figure 27. Semivariogram for the Sakai SW880 breakdown compaction of the HMA overlay (TB 01).

Figure 28. Compaction curve for the Sakai SW880 breakdown compaction of the HMA overlay (TB 01).
In-Situ Test Results and Correlation of IC Data

When correlating results from various different tests, it is important to recognize that the differences in nature of these test devices and test methods. As seen in Figure 29, the “influence depths” of various devices are quite different. The test results are also affected by the in-situ conditions: such as moistures to soil/aggregate tests and temperatures to asphalt tests.

Furthermore, the roller measurement values (RMV) at various stages (subbase paving, base course paving, and HMA wearing course paving) cover the influence depths incrementally as pavement layers being laid on (see Figure 30). Also, the RMVs represent the measurements at “points” in time and in space when roller drums contact the underlying of pavement structure: i.e., the “states” of the pavement (e.g. HMA layer temperatures and compacted levels) are unique at these locations.

As stated by Scherocman (2007) to comment on the RMV vs. asphalt densities, “the RMV represent a relative value that computed from the acceleration signal (i.e., roller-pavement interaction) but this value does not give the absolute percent compaction, stiffness, or density measured (i.e. the level and state of compaction of the HMA bound layer)”. Therefore, cautions should be taken when interpretation of any correlations of RMVs with any other measurements in the following sections.

(Courtesy of Dr. David White)

Figure 29. Influence depths of various test methods.
Figure 30. Influence depths of RMVs at various paving stages.

**LWD Tests**

Figure 31 shows the measured LWD deflections and CBR values on the HMA overlay of TB 01 HMA overlay following the final pass of Volvo intermediate compaction. Results show that a higher deflection corresponds to a lower CBR value. Figure 32 represents the correlation between Sakai IC measurements and LWD measurements. Results show poor correlation, which may be expected since the LWD tests were performed following the final pass (4th) of the Volvo intermediate roller rather than the Sakai IC breakdown roller. Since no data from Volvo is available to the research team the correlation between Volvo measurements and LWD tests are not presented yet. However, this correlation here is primarily for a demonstration rather than validation purpose.
Figure 31. LWD Measurements.
NG Densities

Figure 33 shows the NG density vs. Volvo roller pass. Results show that NG density increases first and then decreases, and the optimum NG density appear at the 3rd roller pass of Volvo machine. For test point 1 the optimum density is 155.28 kg/m$^3$, and for test point 2 the optimum density is 155 kg/m$^3$. 
Figure 33. NG measurements following Volvo intermediate compaction.
Summary Tables

Roller Measurement Value

Table 4 summarizes the Sakai CCV mean values for each test bed. It is noted that mapping existing HMA surface results in the highest CCV/stiffness, which is due to the cold temperature of existing HMA. For the compaction of hot mix, section 3 has a lower CCV than the other two sections, which could be due to different support condition.

Table 4: Roller measurement value, Sakai CCV

<table>
<thead>
<tr>
<th>Test Bed and Sections</th>
<th>CCV mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB 01M</td>
<td>26.33</td>
</tr>
<tr>
<td>TB 01 Section 1</td>
<td>22.12</td>
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<tr>
<td>TB 01 Section 2</td>
<td>21.88</td>
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<tr>
<td>TB 01 Section 3</td>
<td>17.79</td>
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</table>

Optimum Roller Passes Determined from Compaction Curves

Table 5 summarizes the optimum roller passes for each section of TB 01 for HMA overlay. The compaction curve has provided important information to help prevent under-compaction or over-compaction.

Table 5: Optimum roller passes

<table>
<thead>
<tr>
<th>Test Bed and Sections</th>
<th>Optimum roller pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB 01 Section 1</td>
<td>6</td>
</tr>
<tr>
<td>TB 01 Section 2</td>
<td>6</td>
</tr>
<tr>
<td>TB 01 Section 3</td>
<td>6</td>
</tr>
</tbody>
</table>
Compaction Uniformity

Table 6 summarizes the semi-vario gram parameters for each section of each test bed. Results show that TB 01M for mapping the existing HMA has a relatively better uniformity than TB 01 for paving the hot mixture as indicated by its higher range while lower sill values. This could be due to the more uniform and cold temperature of the existing HMA. However, how to quantify the effects of temperature and its distribution on the compaction uniformity needs to be further investigated.

Table 6: Summary of Semi-vario gram parameters for Sakai CCV

<table>
<thead>
<tr>
<th>Test bed and section</th>
<th>Range</th>
<th>Sill</th>
<th>Nugget</th>
</tr>
</thead>
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<td>TB 01M</td>
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<td>0.00</td>
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<td>11.80</td>
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<td>TB 01 Section 2</td>
<td>10.50</td>
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<tr>
<td>TB 01 Section 3</td>
<td>13.13</td>
<td>1.11</td>
<td>0.00</td>
</tr>
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</table>
Conclusions and Recommendation

Conclusions and Findings

This HMA IC demonstration project has successfully demonstrated the ability of the IC roller to map the existing HMA surface, and tracking the compaction levels for the HMA overlay compaction. Major findings of this project included:

- The IC roller can track the roller pass numbers, roller speeds, HMA surface temperatures, and the RMVs, which provides important metrics for the compaction quality;
- With the real-time information of IC roller passes, HMA surface temperatures and RMVs displayed on the screen, the roller operator can adjust rolling patterns to improve the compaction quality;
- Measurements of IC roller GPS can be verified by placing a GPS rover receiver on the top of roller GPS receiver unit to eliminate the potential error resulted from offset and direction angle (see figure below showing how to verify GPS of IC roller);
- Mapping of exiting HMA surface can be used to evaluate pavement conditions, to identify the relatively stronger or weaker zone (i.e. the shoulder area has lower CCV than the center of pavement lane);
- Compaction uniformity can be evaluated and compared for different sections of compaction area using semi-variogram analysis (e.g. a higher range value indicates a higher compaction uniformity);
- Mapping of existing HMA pavement shows a relatively higher uniformity than paving hot mixture asphalt overly, which could be due to the uniform cold temperature of the existing HMA; however, more research to quantify the effects of temperature amplitude and distribution is needed;
- Optimum roller passes can be determined by the “compaction curves” that help avoiding the over compaction or under compaction;
- In situ NG measurement after Volvo intermediate compaction indicates that NG density increases first and then decreases, and at the 3rd Volvo roller pass it reaches the optimum value.

Recommendations

- Validation of the IC Global Positioning System (GPS) setup prior to the compaction operation using a survey grade GPS hand-held unit on the same position of the IC roller GPS receiver is crucial to providing precise and correct measurements.
- To correlate in-situ tests with IC data properly, in-situ test locations must be established using a hand-held GPS “rover” unit that is tied into the project base station and offers survey grade accuracy.
- It is highly recommended to perform IC measurements (mapping) of the underlying layers prior to the paving of upper layers in order to identify possible weak spots and facilitate the interpretation of the measurements on the asphalt surface layers.
- Long term pavement performance monitoring is recommended in order to identify performance trends that may relate to RMV values.
Temperature correction for the RMV of HMA material is recommended with developing models.

Indicators of undesirable IC measurement conditions (such as bouncing, sudden start/stop, etc.) are strongly recommended to be stored in order to filter out invalid IC data.

Standardization is strongly recommended to accelerate the implementation IC for State agencies. The recommended items include: a standard IC data storage format, an independent viewing/analysis software tool, and detailed data collection plan (include any in-situ/lab test results). The research team is currently developing guidelines for IC data collection, storage requirements, data processing, and a prototype of an independent software tool.

Further investigation on a global scale (e.g., segment-by-segment analysis of entire paved sections) is recommended to provide guidance of usage of IC mapping data on existing pavement layer with subsequent IC measurements during HMA paving. This would include: setting a target RMV value from test trip data based on the onsite support condition and asphalt job mix formula.
**Open House**

An Open House was conducted on September 30, 2010 as part of this field investigation. There were about 40 people attended the Open House including FHWA and VADOT engineers/technicians, academics, paving contractors, roller manufacturers/dealer personnel, GPS manufacturers/technical supports, etc. The Open House included three-hour indoor presentation and question-&-answer sessions.

The in-door presentation included:

- FHWA/TPF Intelligent Compaction Project - by Dr. George Chang (Transtec Group)
- Asphalt Intelligent Compaction - by Bob Horan (Asphalt Institute)
- VADOT HMA IC Demo and Prelim Results - by Dr. George Chang (Transtec Group)
- Volvo compaction – by Chad Fluent (Volvo)
- Trimble GPS System - by Mike Windsor (Keystone Precision Instrument)
- Kessler’s In-Situ Test Device – by Larry and Virginia Aicken (Kessler Engineering)

Issues discussed during the question-&-answer (Q&A) session included:

Q: What are the status the IC technologies and its implementation? A: IC is a proven technology and implemented well in Europe. We are primarily demonstrating the IC technologies, building local experiences and training DOT and paving personnel.

Q: What is the plot of Volvo density profile in the color contour shown in the presentation? A (Volvo): The plot includes the averaged values of IACA measurements during the post-process. Such lots are not implemented in the onboard computer system for real-time display yet.

Q: How can we handle IC measurements from different manufacturers? A: All IC vendors’ measurement systems are patented. A work-around is to correlate different IC measurements to a common in-situ measurement, so we can compare them indirectly. Therefore, there is a need to develop a standard IC model and index.

Q: Can IC be used for concrete materials? A: IC can be theoretically used for concrete materials, such as roller-compacted concrete. This topic may be covered in the on-going FHWA Intelligent Construction project.
Figure 34. Open House – participants.

Figure 35. Open House – Research team’s presentation (Victor Lee Gallivan).
Figure 36. Open House – Research team’s presentation (Bob Horan).

Figure 37. Open House – Volvo’s presentation.
Figure 38. Open House – Keystone Precision Instrument’s s presentation.

Figure 39. Open House – Kessler’s presentation.
References


Sakai Heavy Industries, Ltd. Vibrating Roller Type Soil Compaction Quality Controller RMV (Compaction Control Value), Operating & Maintenance Instructions.


http://training.ce.washington.edu/WSDOT/Modules/07_construction/nuclear_gauge.htm.
## Appendix A: On-Site Participant List

<table>
<thead>
<tr>
<th>Last name</th>
<th>First name</th>
<th>Affiliation</th>
<th>Telephone</th>
<th>Email</th>
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<tbody>
<tr>
<td>Chang</td>
<td>George</td>
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<td>C 512-659-1231</td>
<td><a href="mailto:gkchang@thetranstecgroup.com">gkchang@thetranstecgroup.com</a></td>
</tr>
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<td><a href="mailto:bhoran@AsphaltInstitute.org">bhoran@AsphaltInstitute.org</a></td>
</tr>
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<td>Larry</td>
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<td>C 301331-6150</td>
<td><a href="mailto:larry@larrylmichael.com">larry@larrylmichael.com</a></td>
</tr>
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<td>317-226-7493</td>
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<tr>
<td>Xu</td>
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<td>Starry</td>
<td>Dale</td>
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<td>Keystone Precision</td>
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<td>Aicken</td>
<td>Larry</td>
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<td>703-589-5586</td>
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<td>Helmick</td>
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<td>703-631-0004</td>
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<td>Mitchell</td>
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