Report of the 3rd Workshop for Technology Transfer for Intelligent Compaction Consortium

March 2015



Sponsored through Transportation Pooled Fund TPF-5(233)





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16. Abstract

This document summarizes the discussion and findings of the 3rd workshop held on September 3–4, 2014 in Harrisburg, PA, as part of the Technology Transfer Intelligent Compaction Consortium (TTICC) Transportation Pooled Fund (TPF-5(233)) study. The TTICC project is led by the Iowa Department of Transportation (DOT) and partnered by the following state DOTs: California DOT, Georgia DOT, Iowa DOT, Kentucky DOT, Missouri DOT, Ohio DOT, Pennsylvania DOT, Virginia DOT, and Wisconsin DOT.

The workshop was hosted by the Pennsylvania DOT and was organized by the Center for Earthworks Engineering Research (CEER) at Iowa State University of Science and Technology. The objective of the workshop was to generate a focused discussion to identify the research, education, and implementation goals necessary for advancing intelligent compaction for earthworks and asphalt. The workshop consisted of a review of the TTICC goals, state DOT briefings on intelligent compaction implementation activities in their state, voting and brainstorming sessions on intelligent compaction road map research and implementation needs, and identification of action items for TTICC, industry, and Federal Highway Administration (FHWA) on each of the road map elements to help accelerate implementation of the technology. Twenty-two attendees representing the state DOTs participating in this pooled fund study, Vermont DOT, FHWA, researchers from Iowa State University, and industry participated in this workshop.

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March, 2015

David J. White, Ph.D., P.E.

Associate Professor and holder of Wegner Professorship

Dept. of Civil Construction and Environmental Engineering

Director, Center for Earthworks Engineering Research

2711 South Loop Drive, Suite 4700

Ames, Iowa 50010-8664

515-294-1463

djwhite@iastate.edu

Pavana K. R. Vennapusa, Ph.D., P.E.

Research Assistant Professor

Dept. of Civil Construction and Environmental Engineering

Associate Director, Center for Earthworks Engineering Research

2711 South Loop Drive, Suite 4700

Ames, Iowa 50010-8664

515-294-2395

pavanv@iastate.edu

Participating States: California, Georgia, Iowa, Kentucky, Missouri, Ohio, Pennsylvania, Virginia, and Wisconsin

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Preface

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Acknowledgments

The Center for Earthworks Engineering Research (CEER) at Iowa State University of Science and Technology gratefully acknowledges the Pennsylvania Department of Transportation (DOT) for hosting the workshop and the support of the following participating state agencies: California DOT, Georgia DOT, Iowa DOT, Kentucky DOT, Missouri DOT, Ohio DOT, Pennsylvania DOT, Virginia DOT, and Wisconsin DOT. Sharon Prochnow and Denise Wagner of the CEER provided administrative support in organizing and executing the workshop. The CEER also sincerely thanks the following individuals for their support of this workshop:

Planning Committee

Pennsylvania DOT • Daniel Clark, Sheri Little

CEER, Iowa State University • David White, Pavana Vennapusa

Intrans, Iowa State University • Denise Wagner

State/Federal Agency Participants

CalTrans • James Lee

Georgia DOT • Ian Rish, Alfred Casteel

Iowa DOT • Melissa Serio

Kentucky DOT • Adam Ross, David Hunsucker

Missouri DOT • William Stone, Kevin McLain

Ohio DOT • Stephen Slomski

Pennsylvania DOT • Daniel Clark, Sheri Little

Virginia DOT • Edward Hoppe

Wisconsin DOT • Judith Ryan

Vermont DOT ■ Mark Woolaver, Bill Ahearn

FHWA • Antonio Nieves

Other Workshop Participants

AB Consultants • Kirk McClelland

Groff Tractor and Equipment • Matt Wilson

Hamm/Writgen America, Inc. ■ Tim Kowalski

SITECH Allegheny • Todd Pollock

Executive Summary

On September 3–4, 2014, the Pennsylvania DOT hosted the 3rd workshop for the Technology Transfer for Intelligent Compaction Consortium (TTICC), a Transportation Pooled Fund (TPF-5(233)) initiative designed to identify, support, facilitate, and fund intelligent compaction (IC) research and technology transfer initiatives. The following were the key objectives of the workshop:

- Review and exchange experiences of state DOTs in implementing IC for earthwork and HMA
- Review TTICC IC case history summaries
- Facilitate a collaborative exchange of information between state DOTs, FHWA, and industry to accelerate effective implementation of IC technologies
- Update the IC roadmap for identifying key research/implementation/education needs, and action items for TTICC group, FHWA, and industry

The workshop's attendees—representing 10 state DOTs, the Federal Highway Administration (FHWA), Hamm/Writgen America, Groff Tractor and Equipment, SITECH Allegheny, AB Consultants, and Iowa State University—reviewed IC case history summaries, discussed recent IC pilot specifications implemented by state DOTs or demonstration projects conducted by state DOTs, and voted and brainstormed IC research, implementation, and educational needs.

A key outcome of the workshop was the evaluation and update of the IC Road Map, a prioritized list of IC technology research/implementation needs initially created in a 2008 IC workshop meeting and updated in 2009, 2010, 2011, and 2012 workshops. The top three IC research/implementation needs are now (1) data management and analysis, (2) education/certification programs for IC, and (3) correlations between IC and in situ test measurements. The revised IC road map is presented in Table 1. After updating the IC roadmap, the group identified action items for the TTICC group, FHWA, and industry for advancing the top five road map elements.

This workshop served as a forum to facilitate information exchange and collaboration and developing a list of action items to advance and accelerate implementation of IC technology into earthwork and asphalt construction practice and developing a short list of items that the TTICC team can use to help advance the IC road map research/implementation priorities.

Table 1. Prioritized IC technology research/implementation needs – 2014 TTICC workshop

Prioritized IC/CCCT	echnology Resear	ch/Implemer	ntation Needs
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- 1. Data Management and Analysis (31*)
- 2. Education Program/Certification Program (18*)
- 3. Intelligent Compaction and In Situ Correlations (17*)
- 4. Sustainability/ROI (15*)
- 5. Intelligent Compaction Specifications/Guidance (14*)
- Understanding Impact of Non-Uniformity of Performance (13*)
- 7. In Situ Testing Advancements and New Mechanistic Based QC/QA (12*)

- 8. Standardization of Roller Sensor Calibration Protocols (8*)
- 9. Understanding Roller Measurement Influence Depth (8*)
- 10. Intelligent Compaction Technology Advancements and Innovations (6*)
- 11. Intelligent Compaction Research Database (6*)
- 12. Project Scale Demonstration and Case Histories (4*)
- 13. Standardization of Roller Outputs and Format Files (0*)

*total votes are provided in parenthesis

Introduction

Technology Transfer Intelligent Compaction Consortium (TTICC)

Increasingly, state departments of transportation (DOTs) are challenged to design and build longer life pavements that result in a higher level of user satisfaction for the public. One of the strategies for achieving longer life pavements is to use innovative technologies and practices. In order to foster new technologies and practices, experts from state DOTs, Federal Highway Administration (FHWA), academia and industry must collaborate to identify and examine new and emerging technologies and systems. As a part of this effort, the Iowa DOT and the Center for Earthworks Engineering Research (CEER) hosted three workshops on Intelligent Compaction for Soils and HMA since 2008 and developed a roadmap to address the research, implementation, and educational needs to integrate IC into practice. Realizing that a national forum is needed to provide broad leadership that can rapidly address the needs and challenges facing DOTs with the adoption of IC technologies, the Iowa DOT initiated the TTICC project under the Transportation Pooled Fund Program (TPF Study Number 5(233)). The purpose of this pooled fund project is to identify, support, facilitate and fund intelligent compaction (IC) research and technology transfer initiatives. At this time, the following state highway agencies are part of this pooled fund study: California DOT, Georgia DOT, Iowa DOT, Kentucky DOT, Missouri DOT, Ohio DOT, Pennsylvania DOT, Virginia DOT, and Wisconsin DOT (Figure 1).

The goals of the TTICC are as follows:

- Identify needed research projects
- Develop pooled fund initiatives
- Plan and conduct an annual workshop on intelligent compaction for soils and asphalt
- Provide a forum for technology exchange between participants
- Develop and fund technology transfer materials
- Provide ongoing communication of research needs faced by state agencies to the FHWA, states, industry, and the CEER

This report presents the details and summary of findings from the 3rd TTICC Workshop held on September 3–4 in Harrisburg, Pennsylvania. The workshop was attended by fifteen representatives from state DOTs, one representative from the FHWA, two representatives from Iowa State University, and four representatives from industry (Hamm/Writgen America, Groff Tractor and Equipment, SITECH Allegheny, and AB Consultants). A picture of the participants on day two is provided in Figure 2.

¹White D.J., (2008). *Report of the Workshop on Intelligent Compaction for Soils and HMA*. ER08-01, Workshop Organized by the Earthworks Engineering Research Center at Iowa State University and the Iowa Department of Transportation, April 2–4, West Des Moines, Iowa.

²White D.J., and Vennapusa, P. (2009). *Report of the Workshop on Intelligent Construction for Earthworks*. ER09-02, Workshop Organized by the Earthworks Engineering Research Center at Iowa State University and the Iowa Department of Transportation, April 14–16, West Des

³White, D.J., and Vennapusa, P. (2010). *Report of the Webinar Workshop on Intelligent Compaction for Earthworks and HMA*. ER10-02, Workshop Organized by the Earthworks Engineering Research Center at Iowa State University and the Iowa Department of Transportation, March 1–2.



Figure 1. TTICC pooled fund study participating states (highlighted in red) as of 2014



Figure 2. Picture showing TTICC participants on Day 2

Workshop Objectives and Agenda

The following were the key objectives of this workshop:

- Review and exchange experiences of state DOTs in implementing IC for earthwork and HMA
- Review TTICC IC case history summaries
- Facilitate a collaborative exchange of information between state DOTs, FHWA, and industry to accelerate effective implementation of IC technologies
- Update the IC roadmap for identifying key research/implementation/education needs, and action items for TTICC group, FHWA, and industry

The workshop was held over two days. The workshop events involved introductions with a brief review of each participant's technical focus and job responsibilities; overview of TTICC project goals, objectives, and deliverables; state DOT briefings for IC projects and implementation; review of previous TTICC workshops; overview of recent IC specifications; breakout sessions to review overall grading and HMA compaction and quality control and quality assurance problems, challenges, and opportunities; reprioritizing IC research, implementation, and educational needs; defining training needs for contractors and agency personnel; and defining TTICC goals for 2015.

Based on feedback from workshop participants, information obtained from FHWA, and this report authors review of information available online and personal communication with various agency personnel, a map showing IC projects in the U.S. on earthwork, hot-mix asphalt (HMA), and cold in-place recycling are identified in Figure 3. A picture showing the IC 101 video developed by the TTICC group and posted on YouTube is shown in Figure 4. This video is about fifteen minutes long and a shorter version of this video (< 5 minutes) has been discussed by the TTICC group and is currently under development.

In the following sections of this report, state DOT briefings for IC projects and implementation, results of breakout sessions, prioritized IC implementation road map, and proposed action items for TTICC, FHWA, and industry to advance IC research and implementation are presented.

The complete workshop agenda is included in Appendix A, and a list of attendees is provided in Appendix B. A copy of all workshop presentations and products provided to the participants is provided in Appendix C. Photos of the workshop and comments evaluating the workshop are included in Appendices C and D, respectively.

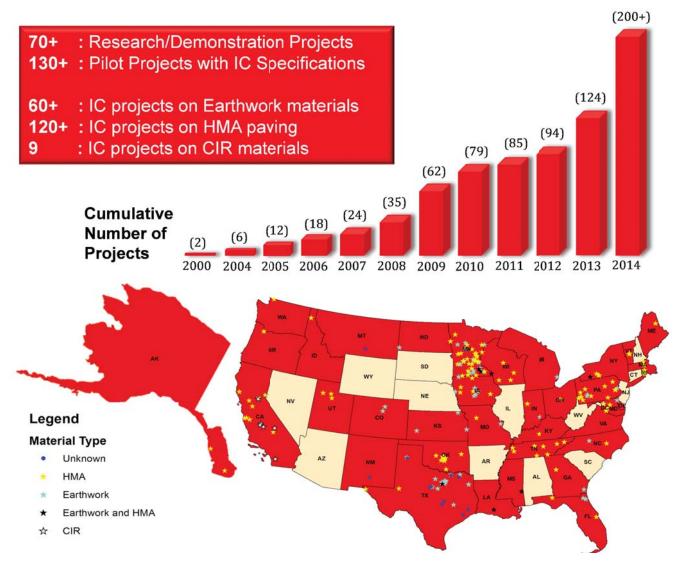


Figure 3. IC project in U.S. from 2012 to 2014 (includes earthwork, hot mix asphalt (HMA), and continuous in place recycling (CIR) projects)





Date Published: 1/31/2014

Statistics as of 10/17/2014:

No. of views: 1801 No. of Countries: 70

Figure 4. IC 101 video developed by TTICC on YouTube (https://www.youtube.com/watch?v=6ZlcBx21Txs)

State DOT Briefings for IC Projects and Implementation

The following is a log of state DOT briefings for IC projects and implementation during the day one sessions.

Kentucky DOT: Used IC roller on two projects—one project did not generate much data because of utilities issue and one project was on wet soils. HMA 4-day demo was recently done by Transtech. A new project is being led by March 2015—it will consist of 3D model development, use of AMG, and subgrade/base/HMA compacted using IC. Project will consist of 4 miles of grading with cohesive soils and crushed limestone base. Working on specifications for HMA and base. There is ongoing discussion on pay factors in the specifications internally. Calibrations strips are being considered in the specifications. Nuclear gauge will be used for QA on subgrade and base, and both nuclear and nonnuclear gauges will be used for QA on HMA. Minimum percentage coverage requirements will be considered in the specifications.

Georgia DOT: Three projects are ongoing on subgrade and subbase. Not ready for HMA yet in GA. On the subgrade/base projects, Caterpillar's MDP on CS74 machine was used because of its benefit to use in static mode. CMV was used on subbase. Contractor had positive feedback using the equipment but the projects were relatively small to be able to buy the equipment. Larger projects would be better to evaluate the benefits. Learned Veda software and working through some issues related to importing data. Visionlink to Veda data formats is a problem. Need a more user friendly software. GDOT performed calibration strips on the project to relate with densities. Selected QA based on bad areas identified by the roller.

Comment by FHWA: Veda software is being updated. Version 3.0 is being released soon. FHWA is working with manufacturers to make data more compatible to Veda.

Discussion by other participants: Need a color scale that would work for people with color blindness. Could use a numerical scale instead of colors as an option.

CalTrans: Twenty pilot projects have been let so far with ten on CIR and ten on HMA. Until now, nine on CIR and seven on HMA have started with nearly 100 miles of work. A FHWA workshop was held in Sacramento. Major IC work is on CIR and HMA for California. Nothing on soils yet. Aim is to get a uniform mat on HMA. CalTrans is evaluating GPR, LWD, and nuclear gauge devices for testing. The goal is to use IC on all paving projects in the next five years. Preliminary evaluations showed poor correlations between IC measurements and density measurements on HMA.

Iowa DOT: How did the districts respond to the use of IC on their projects and new specifications? **CalTrans**: There is one key person in each district (three in North and two in South) who are leading the effort. Only half of the districts are aware of the technology. Once we have good results, we can take it to other districts.

Iowa DOT: What type of staff/resources did you allocate to handle the data?

CalTrans: Not many resources available. It took 2–3 years to properly implement smoothness specification. We anticipate a bit of learning curve here as well.

Group discussion and general comments:

Hamm/Writgen: Suggest considering just one roller on project for HMA, gain experience, evaluate, and then go with multiple rollers.

Georgia DOT: Currently using IC for QC only. QA is being performed by nuclear gauge. Currently, GDOT is concerned of final map only.

FHWA: Oregon has organized a conference themed at using 3D modeling data and IC data. http://designtopaver.org

Ohio DOT: ODOT conducted three demonstration projects last year. One on HMA with FHWA pooled fund study and two on soils with CAT roller on loan. There was a learning curve for people on ground to get used to the technology. Correlations were poor with nuclear gauge testing. One soil project was done on level ground and one was on 2% slope—there were problems interpreting data on slope. We see that IC can be used for QC by the contractor now. Contractor indicated that they liked the technology but not ready in investing yet. There are no plans for next year in ODOT.

Vermont DOT: One project done so far in open topography. We used IC as a testing tool during QC rather than for QA. Used on HMA with multiple mix designs. There is another one ongoing with complicated topography with both in place recycling and manufactured material. Results showed that there is a lot of process induced variability. Using IC during QC can be a great QC measure during processing to achieve uniformity in stiffness values. We could not find good correlations with density to use for acceptance. We want to use performance specs with uniformity as a criteria. Major problem in reclaimed projects is rutting because of consolidation of base and there is a lot of spatial variability which can be captured by IC and verify using point testing. Planning on three phases. Phase I to use IC as just QC and move to QA level in Phase II within 3–5 years. Phase III is long-term performance monitoring. Using nuclear gauge for QA is not correct—small change in density causes a lot of changes in modulus. Need performance specs for reclaimed base materials. Currently using NRCS data for modulus profiles of subgrades. Looking at a research project to evaluate stiffness of fresh and cured reclaimed and cement stabilized material.

Question by David White: Do you think your current data collection plan is statistically valid or you need to have a new statistically valid QA plan?

Vermont DOT: The current plan is not and IC has a significant advantage over traditional testing that it can cover the uniformity aspect as well as the stiffness aspect of testing.

Missouri DOT: In early 2014, MoDOT did a proof of concept with pass count and coverage only on HMA. Hosted a workshop in 2014 for FHWA and used FHWA's technical services center. Twenty MoDOT people and city, contractor, and other attended the meetings. Used Hamm and CAT rollers. Goal was to expose contractor to IC. Mo141 pilot project (on soils) successfully completed as described during the last workshop meeting. That project required ten QC tests by contractor and one QA test by MoDOT. The demo project improved confidence in obtaining good coverage maps. IC demo on a superpave project was recently done with multiple IC rollers (US63, just north of Jefferson City). The project involved 4-lane divided highway and shoulder repave with superpave. Contractor rented the rollers. Data imported to Veda. Data filtering and processing became challenging with data from multiple rollers. We did blind study for two days and then used IC on the remaining days. Visionlink was used to get data from rollers. NOBA IR scanner was used for one week. This project was done as "proof-of-concept" with temperature and roller passes only, no stiffness measurements were used. One more project was planned in a rural area, but had poor GPS coverage.

Iowa DOT: Iowa DOT sponsored constructing and testing Central Iowa Expo research test sections in 2012. IC was used on foundation layers and also on HMA layers with Hamm roller. ISU is analyzing the data. Caterpillar CS74 loaned for TTICC was used on Hwy 65 grading project. IC was not part of the specifications, but contractor used it for evaluating its use for QC. Feedback from contractor was that it was useful in a sense that they had comfort that they would pass the QA. Another project planned with CS74 in 2015. We received some funding FHWA Technology and Innovation Program. As part of that, we did technology transfer with Minnesota DOT. Learned a lot from their specifications and experience with Veda. Learned that Minnesota DOT has done 35 projects so far and 10 more projects this year. They have a lot of management support and use of IC is expected to increase financial effectiveness. Their district personnel showed interest in using for HMA—they experienced challenges in setting target values with earthwork. Currently using IC for QC only and contractor gets paid based on coverage. Minnesota DOT is initiating pooled fund study for Veda. Iowa DOT is not currently setup to handle data, would like to move towards contractor administering the data. We have a strategic asphalt committee setup to keep moving towards using IC on HMA in Iowa.

Wisconsin DOT: There has been transition of expertise in house. No IC projects this year. We are looking at premapping with IC before overlays with HMA using IC. We will look at information related to long-term performance. It is all about mitigating cracks. We have scheduled new cold-in-place recycling projects for 2015. Wisconsin will push for using IC on HMA. Contractors are not currently interested with soils and base. This will be the focus later on.

Virginia DOT: There are no IC projects this year. VDOT wants to assess cost-benefit ratio with using IC. Willing to use IC as a QC tool, but not ready to accept as a QA tool. Contract language and specifications are the stumbling blocks. Working on a specification for unbound + RAP materials. There are reported problems with using nuclear gauge on those materials, IC can be good substitute. Will explore using on granular materials first.

Pennsylvania DOT: See presentation slides in Appendix C.

FHWA: Technical support service center will be active until 2016. They can help with specifications. Twenty-two specifications are available on website. There is ongoing research with UT at El Paso on a retrofit kit for IC. Results will be compared with a traditional unit. Report to be done by early 2015. There are two upcoming roadeos with one in Texas on soils (October 2015) and one in California in Sacramento area for HMA (September 2015). Veda software is being updated. Version 3.0 is being released soon. FHWA is working with manufacturers to make data more compatible to Veda. Oregon recently conducted a full scale demo with IC and AMG systems.

Breakout Sessions and Updated IC Implementation Road Map and Action Items for TTICC, Industry, and FHWA

On day two, one hour long breakout sessions were conducted by separating the workshop participants into three groups. Each group had a facilitator. A brief agenda used to facilitate discussion in the breakout sessions is provided below.

- 1. Discuss the challenges associated with the current state of the QC/QA practice on earthwork (grading) projects and HMA paving projects, and how IC can help overcome those challenges.
- 2. Review the road map with the thirteen research, implementation, and educational topic areas identified in the 1st TTICC workshop report. The participants were asked to provide comments regarding topics that should be removed, revised, or added.
- 3. Develop an updated road map by ranking the topic areas using participant voting. Each participant was allowed seven votes and could apply the votes to any of the topic areas.
- 4. Identify action plans for the TTICC group, FHWA, and industry to move forward on all of the topic areas.

Following is a compiled list of challenges described in the breakout sessions for Topic A on earthwork/grading projects:

- Inspector oversight is currently very limited. DOTs are reducing personnel for field inspections. IC can be helpful because of the 100% coverage with information.
- Materials are generally more variable than assumed in the design. This creates challenge in implementing the right QA target values using the moisture-density method. Stiffness based target values are better, but currently there is no clear guidance on how to implement them.
- Proctor test results are often unrepresentative because of material variability.
- Moisture control is a huge challenge. Need an efficient way to measure moisture and integrate information into IC. How can IC be used for QA?
- Need to assess the return-of-investment (ROI) with using IC in terms of both cost savings during construction and long-term with potentially improved performance.

Following is a compiled list of challenges described in the breakout sessions for Topic A on HMA paving projects:

- Rolling pattern is often non-uniform. Using IC can help solve this problem with real-time display.
- IC results showed reflection of base layer stiffness values, so it creates challenge for QA? Need to premap the foundation layer.
- Specifications are very generic and do not address specific project related issues. Need to rely on the engineer. Each district (in Pennsylvania) does things very differently. It is therefore very hard to write specifications that can apply to all districts.
- IC stiffness based values are not critical on HMA projects.

The prioritized list of IC technology research/implementation needs, by combining the results obtained from the breakout sessions, is presented in Table 1. Table 2 presents the change in the ratings of different roadmap elements since 2008, highlighting the transitions of top rated elements. The *intelligent compaction specifications* and *in situ correlations* road map elements have remained in the top two between 2009 and 2011. The *data management* road map element was rated as the top one in 2012 and this year.

Progress with pilot IC specifications recently implemented by the DOTs and first-hand experience on challenges associated with real-time data transfer and analysis has shaped the prioritized rankings. Also, participants felt there is adequate training required for both contractors and DOT engineers on how to handle data. The *sustainability/return of investment* element was moved from rank thirteen (in 2012) to four this year, as a result of many participants feeling the importance of characterizing the economic advantage associated with using IC both during construction and in long-term because of potentially improved performance.

The revised roadmap elements are presented in Table 3. After reviewing the revised road map, discussion focused on defining action items needed to advance for each element. The outcome was to identify not only needed action items, but linking the action items to TTICC, FHWA, and industry. Table 4 presents the action items identified for the TTTIC group, industry, and FHWA, on each of the roadmap elements.

Table 1. Prioritized IC technology research/implementation needs – 2014 TTICC workshop

Prioritized IC/CCC Technology Research/Implementation Needs

- 1. Data Management and Analysis (31*)
- 2. Education Program/Certification Program (18*)
- 3. Intelligent Compaction and In Situ Correlations (17*)
- 4. Sustainability/ROI (15*)
- 5. Intelligent Compaction Specifications/Guidance (14*)
- Understanding Impact of Non-Uniformity of Performance (13*)
- In Situ Testing Advancements and New Mechanistic Based QC/QA (12*)

- 8. Standardization of Roller Sensor Calibration Protocols (8*)
- 9. Understanding Roller Measurement Influence Depth (8*)
- Intelligent Compaction Technology Advancements and Innovations (6*)
- 11. Intelligent Compaction Research Database (6*)
- 12. Project Scale Demonstration and Case Histories (4*)
- 13. Standardization of Roller Outputs and Format Files (0*)

*total votes are provided in parenthesis

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Table 2. IC/CCC research, implementation, and educational elements, ratings from 2008 to 2014

Rating	2008¹	2009²	2010³	20114	2012	2014
1	Correlations	Specifications	Correlations	Correlations	Data Management	Data Management
2	Education	Correlations	Specifications	Specifications	Specifications	Education
3	Moisture Content Influence	Mechanistic QC/QA	Mechanistic QC/QA	Data Management	Correlations	Correlations
4	Data Management	Non-Uniformity	IC Advancements	Demo Projects	Non-Uniformity	Sustainability/ ROI
5	Demo Projects	Data Management	Demo Projects	Education	Output Standardization	Specifications
6	Mechanistic QC/QA	Demo Projects	Non-Uniformity	Non-Uniformity	Sensor Calibration	Non-Uniformity
7	Non-Uniformity	Influence Depth	Data Management	Output Standardization	Education	Mechanistic QC/QA
8	Specifications	IC Advancements	Output Standardization	Database	Influence Depth	Influence Depth
9	Influence Depth	Education	Influence Depth	Mechanistic QC/QA	Demo Projects	Sensor Calibration
10	Promoting Best Practices	Database	Education	Influence Depth	Mechanistic QC/QA	IC Advancements
11	_	_	Database	IC Advancements	IC Advancements	Database
12	_	_	Sensor Calibration	Sustainability	Database	Demo Projects
13	_	_	_	Sensor Calibration	Sustainability	Output Standardization

IC Road Map Research, Implementation, and Educational Elements

- 1. **Data Management and Analysis [1*].** The data generated from IC compaction operations is 100+ times more than traditional compaction QC/QA operations and presents new challenges. The research element should focus on data analysis, visualization, management, and be based on a statistically reliable framework that provides useful information to assist with the construction process control. This research element is cross cutting with elements 2, 3, 5, 7, 8, 11, and 12.
- 2. Education Program/Certification Programs [7*]. This educational element will be the driver behind IC technology and specification implementation. Materials generated for this element should include a broadly accepted and integrated certification program that can be delivered through short courses and via the web for rapid training needs. Operator/inspector guidebook and troubleshooting manuals should be developed. The educational programs need to provide clear and concise information to contractors and state DOT field personnel and engineers. A potential outcome of this element would be materials for NHI training courses.
- 3. Intelligent Compaction and In Situ Correlations [3*]. This research element will develop field investigation protocols for conducting detailed correlation studies between IC measurement values and various in situ testing techniques for earth materials and HMA. Standard protocols will ensure complete and reliable data collection and analysis. Machine operations (speed, frequency, vibration amplitude) and detailed measurements of ground conditions will be required for a wide range of conditions. Relationships between HMA and WMA mix temperature, roller measurement values, and performance should be developed. A comprehensive research database and methods for establishing IC target values will be the outcome of this study. Information generated from this research element will contribute to elements 2, 7, 8, 10, and 12. There is a need to define "gold" standard QC/QA in situ test measurement for correlations depending on the material type (i.e., soils, base, or asphalt).
- 4. **Sustainability/Return of Investment (ROI) [12*].** This research element involves evaluating benefits of IC in terms of sustainability aspects such as the potential for use of less fuel during construction, reduced life-cycle and infrastructure maintenance costs, etc.
- 5. Intelligent Compaction Specifications/Guidance [2*]. This research element will result in several specifications encompassing method, end-result, performance-related, and performance-based options. This work should build on the work conducted by various state DOTs, NCHRP 21-09, and the ongoing FHWA IC Pooled Fund Study 954. The new specifications should be technology independent and should allow use of different QC/QA testing devices and IC measurement values. This research element is cross cutting with elements 3, 5, 6, 7, and 8.
- 6. Understanding Impact of Non-Uniformity on Performance [4*]. This track will investigate relationships between compaction non-uniformity and performance/service life of infrastructure systems—specifically pavement systems. Design of pavements is primarily based on average values, whereas failure conditions are affected by extreme values and spatial variations. The results of the research element should be linked to MEPDG input parameters. Much needs to be learned about spatial variability for earth materials and HMA and the impact on system performance. This element is cross cutting with elements 1, 2, and 7.
- 7. In Situ Testing Advancements and New Mechanistic Based QC/QA [10*]. This research element will result in new in situ testing equipment and testing plans that target measurement of performance related parameter values including strength and modulus. This approach lays the groundwork for better understanding the relationships between the characteristics of the geo-materials used in construction and the long-term performance of the system.

*1st TTICC workshop rating

Table 3. Revised IC road map research, implementation, and educational elements, 4th TTICC workshop

- 8. Standardization of Roller Sensor Calibration Protocols [6*]. IC rollers are equipped with measurement sensors (e.g., accelerometers in the case of vibratory-based technologies), GPS, data logging systems, and many on-board electronics. These sensors and electronics need periodic maintenance and calibration to ensure good repeatability in the measurement systems. This research element will involve developing a highly mobile mechanical system that could simulate a range of soil conditions and be deployed to a project site to periodically verify the roller output values. Further, establishment of a localized calibration center (similar to a falling weight deflectometer calibration center) by a state agency can help state agencies periodically verify the repeatability and reproducibility of the measurements from their sensors and other electronics.
- 9. Understanding Roller Measurement Influence Depth [8*]. Potential products of this research element include improved understanding of roller operations, roller selection, interpretation of roller measurement values, better field compaction problem diagnostics, selection of in situ QA testing methods, and development of analytical models that relate to mechanistic performance parameter values. This element represents a major hurdle for linking IC measurement values to traditional in situ test measurements.
- 10. Intelligent Compaction Technology Advancements and Innovations [11*]. Potential outcomes of this research element include development of improved IC measurement systems, addition of new sensor systems such as moisture content and mat core temperature, new onboard data analysis and visualization tools, and integrated wireless data transfer and archival analysis. Further, this research element will also explore retrofitting capabilities of IC measurement systems on existing rollers. It is envisioned that much of this research will be incremental and several subelements will need to be developed.
- 11. Intelligent Compaction Research Database [12*]. This research element would define IC project database input parameters and generate web-based input protocols with common format and data mining capabilities. This element creates the vehicle for state DOTs to input and share data and an archival element. In addition to data management/ sharing, results should provide an option for assessment of effectiveness of project results. Over the long term the database should be supplemented with pavement performance information. It is important for the contractor and state agencies to have standard guidelines and a single source for the most recent information. Information generated from this element will contribute to elements 2, 3, 7, 9, and 10.
- 12. Project Scale Demonstration and Case Histories [9*]. The product from this research element will be documented experiences and results from selected project level case histories for a range of materials, site conditions, and locations across the United States. Input from contractor and state agencies should further address implementation strategies and needed educational/technology transfer needs. Conclusive results with respect to benefits of IC technology should be reported and analyzed. Information from this research element will be integrated into elements 1, 2, 4, and 7.
- **13. Standardization of Roller Outputs and Format Files [5*].** This research element involves developing a standardized format for roller output and format files. This element crosscuts with specification element 2.

^{*2}nd TTICC workshop (2012) rating.

Table 4. Updated action items for the TTICC project team, industry, and FHWA

List of Action Items	TTICC	Industry	FHWA	
1. Data Management and Analysis				
a. Define requirements (how to deal with legal issues in data sharing, and	x ¹			
how to archive data)	X.			
b. Discuss with other state DOTs	х			
c. Enhance Capabilities of Software's		х		
d. Need Real Time Data Processing/Delivery Capabilities		х		
e. Identify Future Use Needs for Data	х		х	
2. Education and Certification Programs				
a. Develop Videos (IC101, 201, 202)	X ²			
b. Operator Training Programs		х		
c. Certifications for IC Data	х			
3. IC and In Situ Correlations				
a. Develop a Standard Calibration Procedure (Nonnuclear Gauge)	X ³			
b. Problem Statement to Better Assess Influence of Moisture Content	х			
d. Support Research Efforts			х	
4. Sustainability/Return of Investment (ROI)				
a. Develop a Green Value Proposition	х			
b. Cost Information (Capital and Life-Cycle)	х			
c. Improvement in Safety	х		х	
6. IC Specifications/Guidance				
a. Post Examples and Current Specifications Online (Use CEER Website)	х			
b. Establish a Review Committee	х			
c. Create Online Mechanism to Track Document Updates (versions)	х			
d. Be Informed of TTICC Activities (CEER Website)		х	х	
e. Review Specifications		х	х	
f. Share TTICC Vision		х		

¹Identify GIS data archival protocal (1 page)

²Develop IC101 3 minute version video

³NCHRP synthesis on existing correlations

Report of the 3rd Workshop for Technology Transfer for Intelligent Compaction Consortium (TTICC) Transportation Pooled Fund Study Number TPF-5(233)

Summary of Key Outcomes

Some of the key outcomes from this workshop were as follows:

- 1. Served as a forum for discussion between state DOT, FHWA, and industry representatives in addressing the challenges in implementing the IC technology.
- 2. Updated and prioritized the IC technology research, implementation, and educational needs road map.
- 3. Developed list of action items for the TTICC group, industry, and FHWA to advance and accelerate implementation of IC technology into earthwork and asphalt construction practice.

Appendices

Appendix A: Workshop Agenda

Wednesday, September 3, 2014

8:00 am	Shuttle picks u	p participants at	Crowne Plaza entrance	and transports to PennDOT
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8:15 am Coffee and continental breakfast available

8:30 am Introductions

9:00 am TTICC update by CEER (tech transfer, video, upcoming IC opportunities)

9:30 am State DOT IC implementation updates (CA, GA, IA, KY, MO, OH, PA, VA, WI, VT, FHWA)

10:00 am Morning break

10:15 am State DOT IC implementation updates (continued)

11:00 am PennDOT IC experience and showcase project

12:00 pm Lunch

1:00 pm Working breakout sessions to identify and discuss:

- Overall grading and HMA compaction and QC/QA problems, challenges, opportunities
- Reprioritize/add/delete IC/CCC technology research/implementation needs
- Training needs for contractors and agency personnel
- Review for HMA, aggregate bases, and soils specifications (Mn/DOT, FHWA, SHRP2 R02)
- TTICC goals for 2015
- 3:00 pm Afternoon break
- 3:15 pm Working breakout discussions (continued)
- 4:30 pm Wrap up and transport participants back to Crowne Plaza
- 6:00 pm **Working dinner** TTICC business meeting at the Crowne Plaza, Pennsylvania DE Room
 - TTICC budget review
 - Identify demonstration projects
 - Availability for Geotechnical Mobile Lab for projects/training

8:00 pm Adjourn for the day

Thursday, September 4, 2014

7:45 am Shuttle picks up participants at Crowne Plaza Hotel and transports to PennDOT

8:00 am Coffee and continental breakfast available

8:15 am Working session to discuss IC spec development for HMA, aggregate bases, and soils

10:00 am Morning break

10:15 am Working session (continued)

11:00 am Summary and direction forward

11:30 am Wrap up

Report of the 3rd Workshop for Technology Transfer for Intelligent Compaction Consortium (TTICC) Transportation Pooled Fund Study Number TPF-5(233)

Appendix B: Workshop Attendees

Bill Ahearn

Vermont DOT Materials and Research Section 2178 Airport Road Unit B Berlin, VT 05641 802 828 2561 bill.ahearn@state.vt.us

Alfred Casteel

Georgia DOT 15 Kennedy Drive Forest Park, GA 30297 404 694 6657 acasteel@dot.ga.gov

Daniel Clark

Pennsylvania DOT 81 Lab Lane Harrisburg, PA 17110 717 787 3137 danielclar@pa.gov

Edward Hoppe

Virginia DOT 530 Edgemont Road Charlottesville, VA 22903 434 293 1960 edward.hoppe@vdot.virginia.gov

David Hunsucker

Kentucky Transportation Center 176 Raymond Building Lexington, KY 40506 859 257 8313 david.hunsucker@uky.edu

Tim Kowalski

Hamm/Wirtgen America 615 501 0600 tkowalski@wirtgenamerica.com

James Lee

CalTrans 1801 30th Street Sacramento, CA 95816 916 274 6095 james_n_lee@dot.ca.gov

Sheri Little

Pennsylvania DOT 81 Lab Lane Harrisburg, PA 17110 717 787 3584 slittle@pa.gov

Kirk McClelland

AB Consultants
7020 Tudsbury Road
Baltimore, MD 21244
443 729 2650
kirk.mcclelland@abconsultantsinc.com

Kevin McLain

Missouri DOT Construction and Materials 1617 Missouri Blvd, PO Box 270 Jefferson City, MO 65102 573 680 0737 kevin.mclain@modot.mo.gov

Antonio Nieves

Federal Highway Administration Office of Infrastructure 1200 New Jersey Ave. SE E73-446 Washington, DC 20590 202 366 4597 antonio.nieves@dot.gov

Todd Pollock

SITECH Allegheny 200 Bursca Drive, Suite 205 Bridgeville, PA 15017 855 417 0290 tpollock@sitechallegheny.com

Ian Rish

Georgia DOT Office of Materials and Research 15 Kennedy Drive Forest Park, GA 30297 404 608 4726 irish@dot.ga.gov

Adam Ross

Kentucky Transportation Cabinet 360 Crossfield Drive Versailles, KY 40383 502 782 5155 adam.ross@ky.gov

Judith Ryan

Wisconsin DOT Bureau of Technical Services 4802 Sheboygan Ave Madison WI 53705 608 246 5456 judith.ryan@dot.wi.gov

Melissa Serio

Iowa DOT Office of Construction & Materials 800 Lincoln Way Ames, IA 50010 515 239 1280 melissa.serio@dot.iowa.gov

Stephen Slomski

Ohio DOT Construction Administration 1980 West Broad Street Columbus Ohio 43223 614 466 4318 stephen.slomski@dot.state.oh.us

William Stone

Missouri DOT Construction and Materials 1617 Missouri Blvd, PO Box 270 Jefferson City, MO 65102 573 526 4328 william.stone@modot.mo.gov

Pavana Vennapusa

CEER, ISU 2711 S Loop Drive, Suite 4700 Ames, IA 50010 515 294 2395 pavanv@iastate.edu

David White

CEER, ISU 2711 S Loop Drive, Suite 4700 Ames, IA 50010 515 294 1463 djwhite@iastate.edu

Matt Wilson

Groff Tractor and Equipment Paving & Recycling Products 100 Smith Drive Cranberry Township, PA 16066 724 242 3567 mattwilson@grofftractor.com

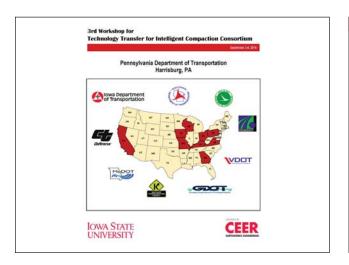
Mark Woolaver

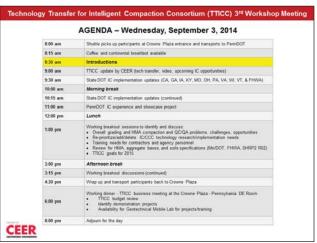
Vermont DOT 802 828 2593 mark.woolaver@state.vt.us

Appendix C: Workshop Presentations

The following presentations were made at the workshop event and are provided herein in that order:

- 1. TTICC General Meeting Slides
- 2. "Rules of Thumb for Using Stiffness-Based Testing in Earthworks" by David J. White
- 3. "Intelligent Compaction: The Initial PennDOT Experience" by Daniel E. Clark
 - a. Presentation Outline
 - b. Presentation Slides



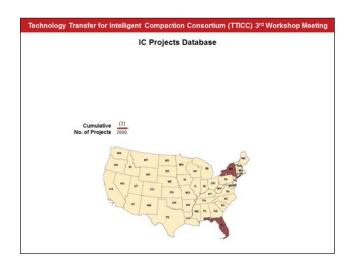








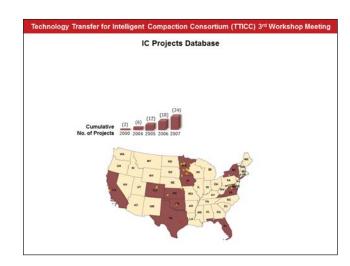


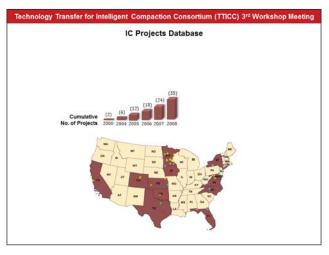


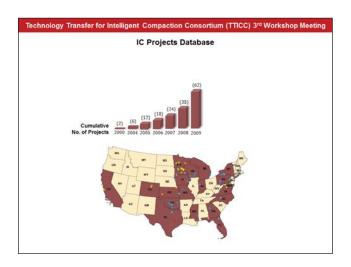




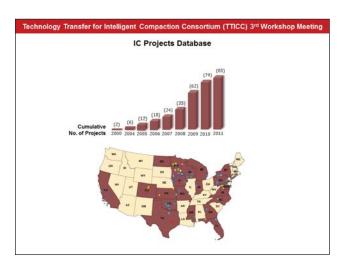


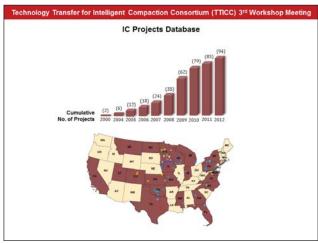


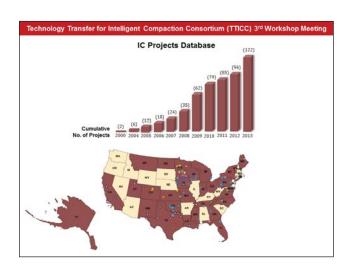




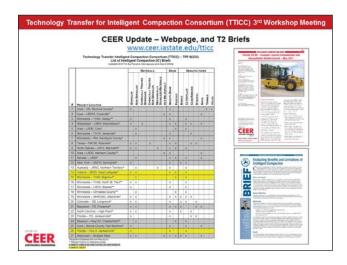




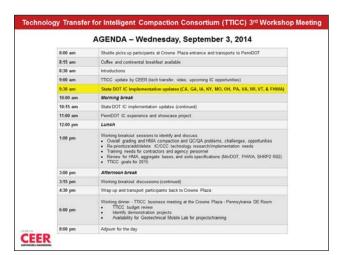


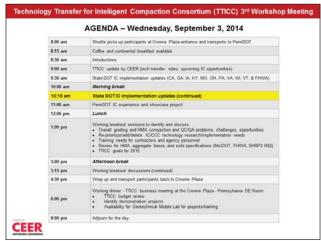












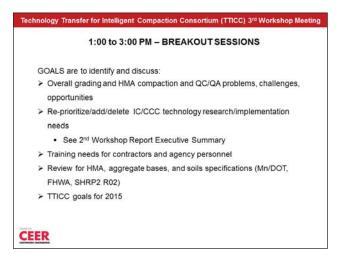
Technology Transfer for Intelligent Compaction Consortium (TTICC) 3rd Workshop Meeting AGENDA - Wednesday, September 3, 2014 8:15 am Coffee and continental breakfast available 8:30 am 9:00 am TTICC update by CEER (tech transfer, video, upcoming IC opportunities) 9:30 am State DOT IC implementation updates (CA, GA, IA, KY, MO, OH, PA, VA, WI, VT, & FHWA) 10:15 am State DOT IC implementation updates (continued) 12:00 pm Working breatout sessions to identify and discuss:

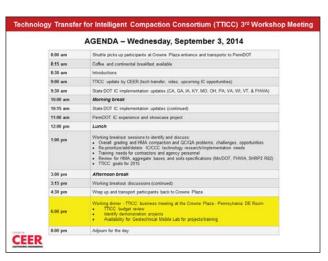
Overall grading and HMA compaction and CICIA problems, challenges, opportunities.
Re-prioritize/addioletes. ICICC technology research/implementation needs
Repropriate and the property of the property personnel.
Review for HMA, aggregate is bases, and soils specifications (Mn/DOT, FHNA, SHRP2 R22).
TICIC goals for 2015. 1:00 pm 3:00 pm 3:15 pm Working breakout discussions (continu Wrap up and transport participants back to Crowne Plaza 4:30 pm Working dinner -TTCC business meeting at the Crowne Plaza - Pennsylvania DE Room
TTCC budget review
- TTCC budget review
- Identify demonstration projects
- Availability for Geotechnical Mobile Lab for projects/training 6:00 pm CEER



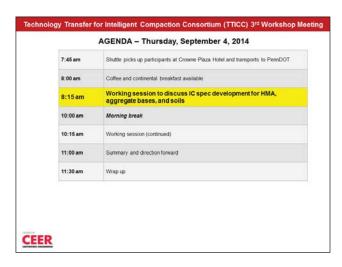
CEER

TTICC General Meeting Slides





Technology Transfer for Intelligent Compaction Consortium (TTICC) 3rd Workshop Meeting 6:00 to 8:00 PM - WORKING DINNER > TTICC budget review > Identify demonstration projects > Availability for Geotechnical Mobile Lab for projects/ training



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Rules of Thumb for Using Stiffness-Based

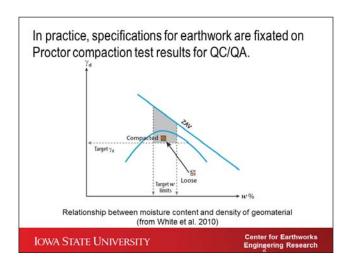
David J. White, Ph.D., P.E.

Associate Professor and holder of Richard L. Handy Professorship Director, Center for Earthworks Engineering Research (CEER) Department of Civil Construction and Environmental Engineering Iowa State University, 515.294.1463 djwhite@iastate.edu

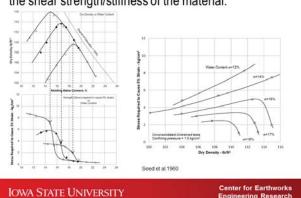
Testing in Earthworks

http://www.ceer.iastate.edu

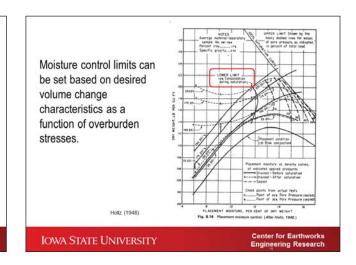




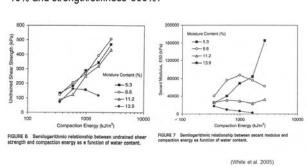
An important consideration for compacted materials is the shear strength/stiffness of the material.



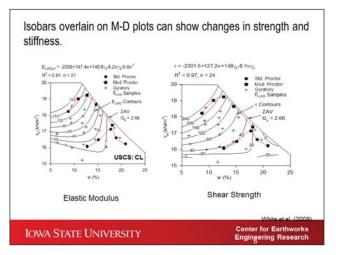
Center for Earthworks Engineering Research

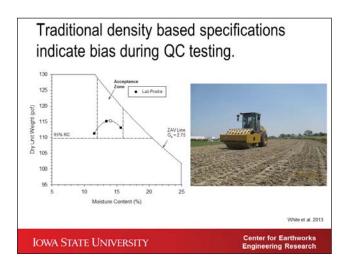


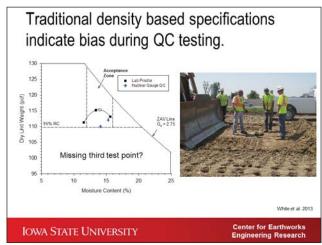
Compaction energy and moisture content change density about 10% and strength/stiffness 500%.

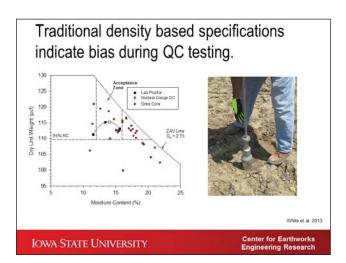


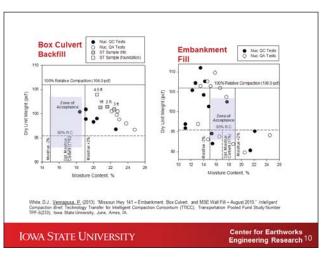
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— A long habit of not thinking a thing wrong, gives it a superficial appearance of being right, and raises at first a formidable outcry in defense of custom .-



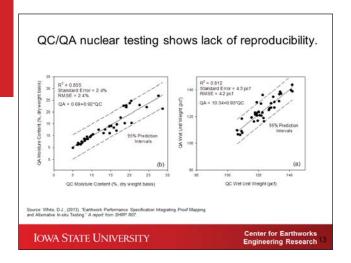
(Paine, 1776).

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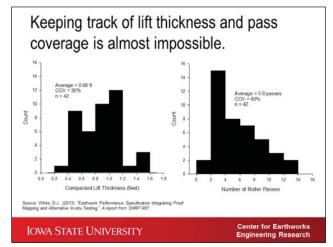


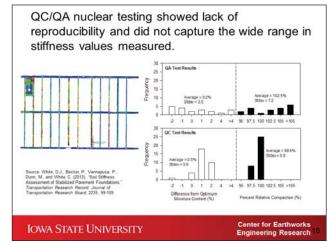
— MoDOT is looking for a technology that both MoDOT and the construction industry can utilize during QC/QA that can provide information with more uniform coverage of compaction data than traditional methods with an outcome being the elimination of nuclear density testing.

(Stone, 2011)

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Center for Earthworks Engineering Research





Acknowledgment of problems and mistakes is difficult.

— they are an essential part of experimentation and a prerequisite for innovation. So don't worry. —

(Harvard Business Review, 2014)

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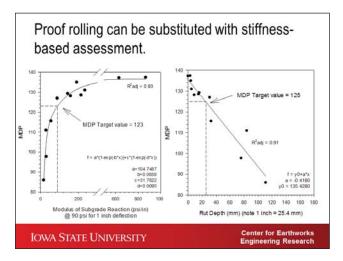
Center for Earthworks Engineering Research

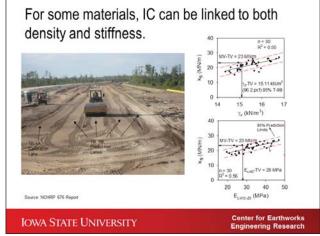
Proof rolling can be substituted with stiffness-based assessment.

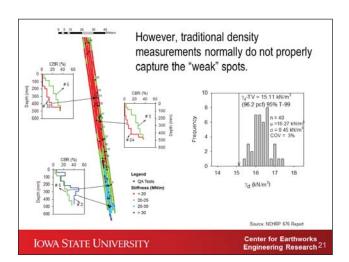


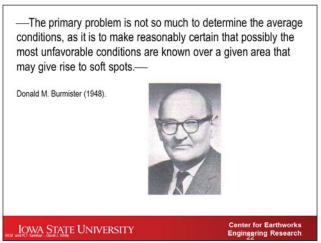
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Center for Earthworks









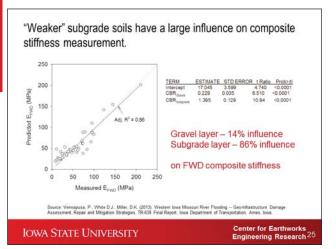
- The AASHTO design methodology requires the mean k-value, not the lowest value measured or some other conservative value —
- Exclude from the calculation of the mean k-value...values that appear to be significantly out of line with the rest of the values —

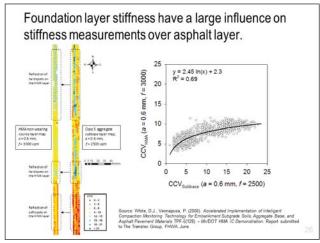
(MEPDG Design Guide from NCHRP 1-37A Part III, March 2004)

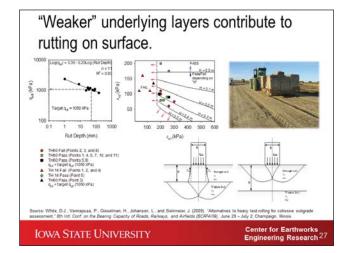
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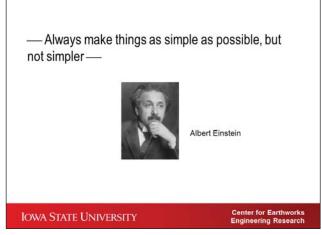
Center for Earthworks

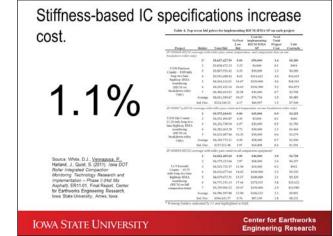
Cement stabilization process does not necessarily provide uniform support conditions Cement-dealized Subgrate Cement-dea













Daniel E. Clark, P.E. PA Department of Transportation

A Department of Transportation
Harrisburg, PA 17110
Phone: 717.787.3137

PennDOT IC Presentation Outline

Technology Transfer Intelligent Compaction Consortium September 3-4, 2014

Intelligent Compaction of Asphalt (Bituminous) Pavements

- Cove
- "Road Work" sign
- Authorization

The PennDOT IC Process

- District proposes a project
- NPI reviews the proposal
- NPI drafts a spec and a cost estimate
- NPI attends the preconstruction meeting
- NPI attends the pre-pave meeting
- NPI attends the training
- NPI attends the construction start up
- NPI collects the data and reviews it
- Based on the review, NPI recommends payment

The PennDOT IC Process - Deviations

The Districts do not always coordinate with NPI in accordance with the IC process.

IC Technical Challenges

- Multiple projects, limited staffing
- · Overwhelming amount of data generated
- Difficulty of using VEDA software

IC Policy Challenges

- · Changes needed by the contractors
 - Personnel training
 - Change operations as a result of the IC data
- Construction changes needed by PennDOT
 - Existing mat acceptance criteria 408 Sec 409.3(j)
 - Non-movement scratch/leveling, small patches
 - Optimum Rolling Pattern small quantities (< one lot), unstable base, thick leveling courses, non-critical areas, thin lifts
 - Pavement Cores random locations, 6" cores ASAP, not later than the day following placement, 2500-ton lots, 500-ton sublots
 - Proposed mat acceptance criteria
 - Include strategic sampling based on IC data
 - How many samples? As many as needed to explore all anomalies?
 - When take the samples? Need more time to review the data.
 - What actions are required if the IC samples fail?
 - Should we add the IC samples to regular acceptance samples to determining averages?
 - Or remove and replace (R/R) based on per sample basis? If R/R is required for 50%+, then R/R the entire lot?

Daniel E. Clark, P.E.

PA Department of Transportation Harrisburg, PA 17110 Phone: 717.787.3137

PennDOT IC Presentation Outline

Technology Transfer Intelligent Compaction Consortium September 3-4, 2014

- Non-construction changes which could benefit PennDOT
 - o Pavement Design Unit
 - Pavement Asset Management Section
 - Do we want to keep the IC data for posterity?
- If yes, then who is going to keep / review / archive the data?
- Where is the data going to be kept?
- Who will have access to the data?
 - Whoever accesses the data should be properly trained
 - Should this task be added to existing responsibilities or should there be a new position for this work?

IC Project Details

- SR 18, 3.2 miles, rural, small towns, 2-lane, mill & fill, many pavement sections
- 1-79, 4.8 miles of 6-lane interstate, shallow mill & fill, thin lift overlay, static compaction
- D-11 group project, mill & fill SR 30, 4.3 miles, rural, 2-lane SR 51, 2.5 miles, urban, 2-lane 3.9 miles of bituminous pavement over old RCCP, layer thicknesses unknown 0.4 miles of bituminous pavement over native stone subbase, layer thicknesses unknown.
- SR 422, 3.7 miles, rural, 3-lane, high volume principal arterial NHS route, mill & fill
- I-180, 6.5 miles, 4-lane interstate, mill & fill, SMA

IC Implementation / Construction

- Non-IC issues
- IC Issues
 - Specifications
 - o Contractor IC QC plan
 - > Test section data not available therefore, no ICMV target value
 - > Presumes you can analyze the data in the field on-the-fly
 - Contractor IC Workplan
 - Photos of IC Equipment
 - ✓ Rollers
 - ✓ Accelerometer
 - ✓ Temperature Sensors
 - ✓ On-Board Computer
 - ✓ Display
 - ✓ GPS
 - ✓ Rover
 - ✓ Base Station
 - Manufacturers classroom and field training
 - > Content
 - Execution
 - ✓ Roller operator training (photos)
 - ✓ Roller operators ignoring IC display (photos)
- Construction Issues
 - Tree shadowing

Daniel E. Clark, P.E.

PA Department of Transportation Harrisburg, PA 17110 Phone: 717.787.3137

PennDOT IC Presentation Outline

Technology Transfer Intelligent Compaction Consortium September 3-4, 2014

- Roller networking
- Processing the data in the field
- Having a rover is absolutely essential

IC Data Analysis

- Existing pavement sections
 - Mark in field
 - Correlate with IC data obtained
- Look for incompleteness & inconsistencies
- Future uses of IC data

IC Software Commentary

- HAMM Software
 - Unique advantages
 - Still working with the IC Technical Support to get all the required features running properly.
 - Default datafile locations
- HAMM & VEDA Software
 - o Common hard-to-use features resolution and zoom features
- VEDA software
 - Default datafile locations VEDA software saves data where it found it this is a good feature.
 - Nonetheless, the VEDA software is generally hard to use and not at all user friendly.
 - o It takes a long time to load, and shuts down without notice if you click a button too fast, etc.
 - The VEDA software locates data points only by coordinates.
 - Suggested improvements
 - Distance measuring tool
 - Higher resolution
 - > Faster processing
 - Continuous zoom in/out
 - Mapping activity indicator hourglass
 - Input list of coordinates
 - Make sections by distances, boxes, computer generate its own coordinates. Make sections endto-end.

Conclusions

- The contractual obligations went fairly smoothly.
- The IC equipment performed as expected. A minor amount of GPS data was lost due to overhanging trees. Some data was lost due to operator error.
- The manufacturers training had mixed results depending on the location and the trainer.
 - Contractor attitude
 - Operator attitude
- The HAMM data collection system worked well on most projects the I-79 project has been a
 problem from the start
- The Sitech data collection system worked well on all projects however, it has large data files, and requires access to Sitech server.

Daniel E. Clark, P.E.

PA Department of Transportation Harrisburg, PA 17110 Phone: 717.787.3137

PennDOT IC Presentation Outline

Technology Transfer Intelligent Compaction Consortium September 3-4, 2014

• At this time, data analysis in the field is difficult at best.

IC Lessons Learned

- More cooperation required between Districts and NPI
- More cooperation required between contractor QC person and PennDOT Inspector
- PennDOT should supply thumbdrives
- Roller operators really need an attitude adjustment work with Local Operating Engineers?
- Districts need to understand / embrace the purpose of the Research Cores
- "Real time" data analysis may be possible with a high level of proficiency, but it is not hardly remotely
 possible at this time.
- A high level of proficiency is required to minimize confusion, frustration and misleading results.
- Always safeguard the original data files.
- Good files names and storage locations are <u>absolutely</u> essential to good data management.

IC Issues to be Resolved

- AAR with the contractors are planned. We hope they will be mutually beneficial.
- PennDOT and contractor observations should be used to help shape the next draft of the IC specification.
- Handling / processing / storage of data files who, how, where, when, why, etc.

INTELLIGENT COMPACTION: The Initial PennDOT Experience

Technology Transfer Intelligent Compaction Consortium September 3-4, 2014

Daniel E. Clark, P.E. Chief, Evaluations & Research Unit PennDOT Bureau of Project Delivery Innovation & Support Services Division 717.787.3137 danielelar pages





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Intelligent Compaction of Asphalt Pavements

- The FHWA, the Administration, and the Bureau of Planning and Research are driving the implementation of STIC Initiative F-2012-001, Intelligent Compaction (IC).
- Dan Clark, from the Central Office (NPI), and Bill Kovach, ADE Construction from District 12-0, have been charged to implement IC.

The PennDOT IC Process

- The Districts contact NPI with a proposed project. NPI collects information about the location and size of the project, the nature of the proposed improvements, the existing pavement sections, and assesses the likelihood of this project generating beneficial information. If the project is considered to be a viable candidate, the project is accepted for IC and moves forward.
- NPI prepares a project specific special provision for use on the project, and, based on contracts awarded to date, a cost estimate for the District's information. The District fills in the Item Numbers in the special provision and lets NPI review it before it goes to contracting.

A

The PennDOT IC Process

- After the contract is awarded, NPI attends the preconstruction conference to meet the various parties and responds to questions that may arise regarding the IC specification.
- The PennDOT Project Manager keeps NPI informed of the construction schedule so NPI may participate in key activities.
- NPI attends the pre-pave conference to again confer with the parties and to respond to questions that may arise regarding the IC specification.

The PennDOT IC Process

- NPI attends the manufacturer's training program to become more familiar with it, to ask questions, to respond to questions that may arise regarding the IC specification, and to discuss lessons learned.
- NPI attends the start up of the intelligent compaction paving work in the field to observe the implementation, to meet with various parties, to note any items in the specification which may need adjustment to improve the work flow in the field, and to respond to questions that may arise regarding the IC specification.
- · NPI collects the IC data and reviews it for completeness.

The PennDOT IC Process

- Payment for IC is presently based on completeness.
 The quality of the work as disclosed by the data is expected to be worked into the payment formula at some point in the future after the Department and a sufficient number of contractors have developed some experience with IC.
- If the data is complete as required by the contract, NPI recommends that the contractor be paid in full for this item.
- · This concludes the construction portion of this IC project.

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The PennDOT IC Process - Deviations

- The Districts do not always contact NPI before an IC project is awarded.
- The Districts have been known to swap special provisions without checking with NPI for the latest version
- The Districts sometimes inform NPI about a project the day before paving starts. Consequently, NPI has to scramble to get to the site to observe the project start up, which is when most of the things that can go wrong, do go wrong.

8

IC Technical Challenges

- Sometimes, NPI works the day shift at one site and the night shift at another because there are simply not enough NPI staff to go around.
- NPI collects the IC data and attempts to review it for completeness.
- Using the VEDA software is a formidable challenge.
 NPI has been struggling to learn this on-the-fly. The data is coming in much faster than possible for one person to review in addition to their other duties. Small accomplishments, i.e., being able to get anything useful out of the program, are recognized as milestones.

IC Technical Challenges

 NPI is grateful for our new friends at the IC Technical Support Services in Texas!

However, this is just the beginning ...

0

IC Policy Challenges

- NPI is collecting massive amounts of data. This data has some immediate uses and some other on-going uses.
- Immediate uses to the contractor are to optimize the paving operations – however, this requires the paving foreman / superintendent to pay attention to the roller operator and / or the IC data being generated by the roller

\$ PROFIT \$

- Current mat acceptance criteria is per 408 Section 409.3(j).
 - Non-movement scratch, leveling, small patches
 - Optimum rolling pattern small quantities (< one lot), unstable base, thick leveling courses, non-critical area, thin lifts.

IC Policy Challenges

 Pavement cores – random locations, 6" cores ASAP, not later than the day following placement, 2500-ton lots, 500-ton sublots.

IC Policy Challenges

 Immediate uses to the Department include monitoring the number of passes and the temperature during compaction. With this information, the Department can consider revising Pub 408 Sec 409.3(j)3 "Optimum Rolling Pattern" to allow more liberal use of this mat acceptance method or to increase the lot size for mat acceptance under Pub 408 Sec 409.3(j)4 "Pavement Cores."

!! QUALITY !!

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IC Policy Challenges

- The bituminous mat acceptance procedure should be changed from entirely random sampling to allow for strategic sampling of suspect areas based on the IC data.
 - The IC data must be analyzed quickly so that cores can be obtained at strategic locations prior to opening to traffic – OR – cores can be taken later, with traffic control if necessary.



For example: the above map indicates the right side of the road was compacted at 200°F while a good portion of the left side of the road was only 100°F. Was the required density achieved in the cold spots?

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IC Policy Challenges

- · Proposed mat acceptance criteria:
- . . Include strategic sampling based on IC data.
 - How many samples are required? As many as needed to explore all anomalies? Need to define the size of an anomaly that warrants investigation.
- . When take the samples? Need time to review the data
- . What actions are required if the IC samples fail?
- Should we add the IC samples to the regular acceptance cores to determine averages?

IC Policy Challenges

Sidebar: Should we consider two modes of IC sampling

 one for when cores are taken within minutes of
 completion, and another for when cores are taken later?
 The IC sampling criteria will need to be indicated in the
 contract documents in advance of construction.

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IC Policy Challenges

- Other on-going uses may include the pavement design section and pavement maintenance forces.
 - For instance, the Pavement Design Unit might be interested to know if 17 pavement sections all provided the same stiffness value. Perhaps some of these sections are more economical to construct than others. PennDOT might be able to save money by using the more cost effective pavement section that provides the desired stiffness value.
 - The Pavement Asset Management Section might like to flag areas that the IC reveals to be "soft". Those areas could be put on a watch list and repairs / mitigation could be scheduled sooner than just waiting until failure occurs.

Low stiffness (0-20) is indicated when underlain by brick pavement.

Zones of higher stiffness (40-100) are indicated when underlain by PCC pavem't.

IC Policy Challenges

- Referring to the massive amounts of data NPI is collecting:
 - . Does PennDOT want to keep the data?
 - . Who is going to be the gatekeeper of the data?
 - Who is going to be notified when data is available for downloading and / or analysis?
 - . How will that notification be done? By auto-generated email?
 - . How will that data be identified / labelled?
 - Who is going to review all the data generated?

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IC Policy Challenges

- What are we looking for in the data? Each unit may have its own, and different, purposes. Should each unit review the data for themselves or should there be one person reviewing the data and disseminating it to the various interested parties as warranted?
- Who is going to reformat the data when the Department moves on to a newer computer system?
- . Should the data be kept in the Central Office or in the Districts?
- . Who needs to have access to the data?
- Which servers should be used to store the data and what permissions need to be granted for the appropriate people to access the data?

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IC Policy Challenges

- Everyone involved with handling and/or reviewing the IC data needs to understand the origin (theoretical basis) of the data, the idiosyncrasies (limitations) of the data, and the use of the proprietary software. This could get to be a long list of people who will need training. We will not likely know who all these people are initially we will need a way to train people on an as-needed basis.
- Adding these responsibilities on top of existing workloads will likely result in less than optimum benefit.
 Where would we insert a person dedicated to IC? Who would they answer to? What would that job description look like? If they ever ran out of IC work, what would be their back up assignment(s)?

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IC Policy Challenges

 From the above discussion, it seems that there needs to be some guidance from the Administration with possible modifications to a number of current PennDOT policies / standards / protocols. Funding also needs to accompany these changes.

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IC Project Details

5 Current Projects

INCELT LOCATIONS

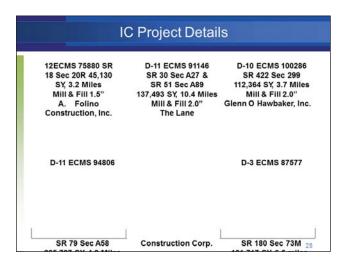
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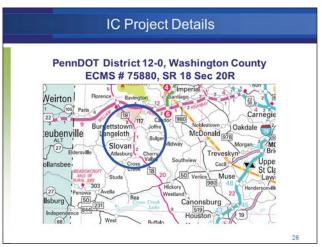
INCOME Project A Intelligent Companion Projects

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IC Project Details

- PennDOT District 12-0, Washington County, ECMS # 75880, SR 18 Sec 20R, Burgettstown to Atlasburg
- SR 18 is 3.2 miles of a 2-lane road connecting one small community with two villages to the south.
- The project plans indicated 8 different pavement sections along the length of the roadway.
 - 4 sections consisted of 5.0 to 8.5 inches of HMA over concrete payement
 - 2 sections were ID-2 over brick.
 - 1 section was 6 inches of HMA over recycled BCBC.
 - 1 section was 13.5 inches of HMA over 18 inches of subbase.
- · The proposed improvement was to mill & fill 1.5 inches.

IC Project Details From To (ft) 798+30 876+18 7,788 (In.) 14.5 8.5" ID-2 HMA on top of a $(6^nx 8^nx 6^n)$ concrete pavement with a 3" HMA widening Lt & Rt consisting of 9" of ID-2 HMA on top of 3" Bituminous Concrete on top of 12" of Natural Stone Base 5° of ID-2 on top of a (5"x 8"x 6") concrete pavement with an 11' HMA widening Lt & Rt consisting of 8" of ID-2 on a 6" Slag Base 876+18 882+12 594 11.0 8.5" ID-2 HMA on top of a (6"x 8"x 6") concrete pave Rt consisting of 9" ID-2 HMA on top of a concrete pav Stone Base 8° of ID-2 HMA on top of a (6°x 8°x 6°) concrete pavement with a 3' HMA widening Lt & Rt consisting of 9° of ID-2 HMA on top of a 12° Natural Stone Base 924+79 928+00 928+00 936+00 6" of ID-2 HMA on top of 3.5" of Brick 3" of ID-2 HMA on top of 3.5" of Brick 936+00 952+91 1.691 6.5 952+91 954+22 4" of HMA SuperPave on top of 2" of ID-2 HMA on top of 10"x 24" Recycled Bitum 131 16.0 4" of HMA SuperPave on top of 2.5" of ID-2 HMA on top of 7" Bituminous Concrete Base on top of 18" of Subbase 16.048 LF

PennDOT District 11-0, Allegheny County ECMS # 94806, SR 79 Sec A58 Corappolis Avalor Etna Corappolis Avalor Etna Corappolis Blaw McKees Blaw McKees Blaw Millinall Turtle Corappolis Mindall Turtle Mindall Turtle Corappolis Southview Corappolis Findervise Finder

IC Project Details

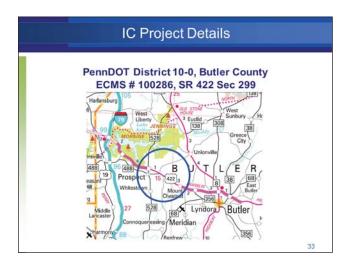
- PennDOT District 11-0, Allegheny County, ECMS # 94806, SR 79 Sec A58, Bridgeville to Carnegie
- · SR 79 is 4.8 miles of a 6-lane interstate highway.
- The project plans indicated 2 different pavement sections along the length of the roadway.
 - The ramps on SR 8005, SR 8007 and SR 8009 consist of 1.5"
 SP WC over 2.5" Binder over 13" SP BC over 8" subbase.
 - The mainline sections consist of 1.5" SP WC over 2.5" Binder over 17" SP BC over 8" subbase.
- The proposed improvement was to mill 0.5" and backfill with 0.75" thin warm mix overlay. Static compaction only.

PennDOT District 11-0, Allegheny County ECMS # 91146, SR 30 & SR 51 Less Edgeworth ALLE EG H Allisor Bellevue German Moon 12 Landor 12 Landor 12 Landor 12 Landor 13 Landor 14 Landor 15 Lan

IC Project Details

- PennDOT District 11-0, Allegheny County, ECMS # 91146, SR 0030 Sec A27 & SR 0051 Sec A89
- This project consists of 6.8 miles of 2-lane roadway:
 2.5 miles in an urban setting and 4.3 miles in a country setting.
- The project plans indicated 2 different pavement sections along the length of the roadways.
 - 3.9 miles of SR 0030 and all of SR 0051 consists of existing bituminous surface over parabolic RCCP. Layer thicknesses unknown
 - 0.4 miles of SR 0030 consists of existing bituminous surface over existing native stone subbase. Layer thicknesses unknown.
- · The proposed improvement was to mill & fill 2.0 inches.

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IC Project Details

- PennDOT District 10-0, Butler County, ECMS # 100286, SR 422 Sec 299
- SR 422 is 3.7 miles of a 3-lane fairly high volume road connecting Butler to Interstate 79 to the west.
- The project plans indicated the pavement section along the length of the roadway consisted of 1.0" ID-2 WC over 0.5" ID-2 scratch over 1.5" ID-2 WC over 2.0" ID-2 Binder over 4.0" BCBC over 9.0" RCP.
- · The proposed improvement was to mill & fill 2.0 inches.

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IC Project Details

- PennDOT District 3-0, Northumberland County, ECMS # 87577, SR 180 Sec 73M
- SR 180 is 6.5 miles of a 4-lane interstate highway extending from Interstate 80 northwest to Williamsport.
- The project plans indicated the pavement section along the mainline roadway consisted primarily of 1.5" of SMA over 4" Binder over a 90# WC scratch.
- The proposed improvement was to mill & fill 2.25 inches.

IC Implementation / Construction

- Non-IC Issues: cold temperatures, long haul distances, coordination of trucks, tack not breaking, rain delays, traffic, inspector parking, working double shifts, etc.
- · IC Issues include specifications, contractor IC QC plan, contractor IC workplan, and manufacturers classroom and field training.

IC Implementation / Construction

- Specifications
 - These projects used three variations of the spec: a draft CT Step 1 dated 08-02-2013, a draft CT Step 1 dated 8-28-2013, and a draft CT Step 2 dated 02-18-2014. As each project came up, we issued the latest version of the specification complete with any modifications resulting from recent experiences
- · The contractor IC QC Plan
 - Theoretically, the data from the test section is used to develop a density-ICMV correlation curve.
 - 1. Data from the test section was generally not made available to us (if at all) until well after the job was completed.
 - 2. This presumes that you have the capability to process the data on-the-fly in

IC Implementation / Construction

- . The IC plan generally requires the contractor to pay attention to the IC data coming off the roller. There has been no indication that the roller data has been used by the contractor to guide the rolling operations.
- The IC plan requires the roller GPS to be verified. We have backed off this requirement because we are told that the HAMM and Sitech systems are more or less "self-calibrating". However, one contractor had an independent rover that he could have used to verify the roller GPS but no data was submitted to confirm that this was done.
- The Districts do not always ask us to review the contractors' IC QC Plan and IC Workplan. Consequently, opportunities to catch misconceptions, errors, or omissions are sometimes missed.

IC Implementation / Construction

- · The contractor IC Workplan
 - The equipment to be supplied is supposed to be listed on the contractor's IC workplan.
 - However, the equipment supplied does not always match that listed in the workplan - therefore, take pictures of the equipment on-site to document what was used.

Intelligent Compaction Equipment





Ingersoll Rand Roller



Sakai Rolle



Intelligent Compaction Equipment



Caterpillar Roller





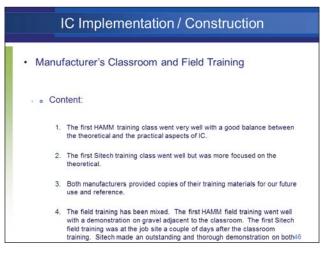
Temperature Sensor











IC Implementation / Construction

- Execution:
 - The classroom training went relatively smoothly except that many of the
 people attending had worked the night before and were tired.
 Consideration needs to be given to scheduling the training at a time when
 the contractor's personnel report for work i.e., morning for day-shift
 people and evening for night-shift people.
 - The field demonstration on gravel was not the same as rolling HMA; but it did demonstrate all the features of the machine. The instructor subsequently showed us how to process the field data to complete the training.
 - The field demonstration at the job site, rolling a small quantity of production material, best illustrated the features of the machine.

IC Implementation / Construction

- 4. It seems that over time, the quality of the instruction is diminishing either the instructor is forgetting that the audience has new faces, or a proxy trainer is used who does not have the same presenting skills as the original trainer. It is noted that everyone is having scheduling problems; and the manufacturer is no exception.
- It is also realized that the trainers are working through the contractor; so
 the contractor has considerable influence over what, when, and where the
 training occurs all of which affect the ability of the trainer to communicate
 information essential to understanding the IC process.
- It is possible but not practical to process the raw (HAMM) data on the roller and export it as VEDA compatible files. Therefore, the manufacturer has provided us their software free of charge so we can independently view and process the raw (HAMM) IC data.

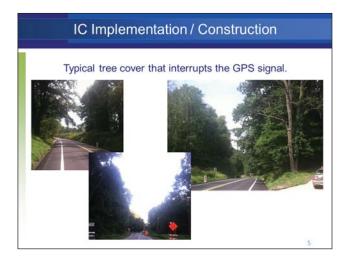
7. While the contractor is contractually obligated to provide us VEDA compatible files, the raw data, together with the HAMM software, provides a field expedient alternative. 8. The manufacturer also provided a user manual for the software and continuing technical support. 9. While you can lead a horse to water, you cannot make him drink ...



IC Roller Operator Training

IC Implementation / Construction

- The IC features generally performed as expected.
- There was some GPS shadowing due to trees with both the HAMM system and the Sitech system.
- There were also some problems with the HAMM roller "networking." On the first night of the first project, the contractor provided 2 HAMM IC rollers and ran them in "linked" or "network" mode where the data from both rollers was accumulated into one file. This made it very confusing to review individual passes because you couldn't tell which roller did what. Moreover, the number of passes grew to be very large. Subsequently, we directed the contractor to "un-link" the rollers. Perhaps with more experience in analyzing the data, roller networking may be a desirable feature but for now it just adds to the confusion.



IC Implementation / Construction

- On the I-79 project, there were some problems with processing the raw HAMM data in the field; but with successes on other projects, this I-79 project is not considered typical of the HAMM capabilities.
- NPI having a laptop at the job site was handy to collect and view the roller data during down times. While waiting on water, or asphalt trucks, the raw data could be downloaded onto a thumbdrive and reviewed on the spot. During the course of the night, the HAMM data was transferred a couple of times and passed on to the Department. The transfer of the data was confirmed at the field office at the end of the shift when the data was imported into the VEDA program.

IC Implementation / Construction

 However, PennDOT inspectors do not necessarily have laptops or other devices with the roller / VEDA software installed with them in the field. Also, the field office is not necessarily near the job site - it can be as much as 40+ miles away. Given the distance and oftentimes multiple projects to monitor, the inspectors may not return to the field office every day. Thus, there may be a time lag between receiving the IC data and the ability to review / confirm it.

IC Implementation / Construction

The importance of having a rover on-site at all times became apparent after the first couple of projects were under contract. The contractor needs to have a person with a rover on-site for the entire shift to obtain the coordinates of the core locations and any other locations of interest to the Department (such as changes in the underlying pavement section if known in advance). This worked well and is absolutely necessary for entering the core (and pavement section) data into the VEDA program. Contractors may not want to spend the money for the surveyor, but it should be considered non-negotiable

IC Data Analysis

- · The project plans generally indicate the various pavement sections along the length of the roadway located by Station and Offset. However, finding those locations in the field requires converting the Station / Offset to Segment / Offset. This requires the assistance of the the District Chief of Surveys.
- The sections tend to be variations on a theme, and the stiffness values are expected to vary with the varying thicknesses and types of materials: we were not disappointed.

IC Data Analysis

- · On the District 12-0 project, the thinnest pavement consisted of 3" to 6" of ID-2 over brick while most of the pavement consisted of 8.5" of ID-2 over PCC. The HMV over the brick pavements ranged from 78 to 93 while HMV for the ID-2 over concrete ranged from 100 to 153.
- Also, even in our early stages of learning how to use the VEDA software, NPI has uncovered instances of incompleteness and inconsistencies in some data files. We consider these to be significant milestones.

IC Data Analysis

· Future uses of the data may include the comparison of various pavement designs based on the IC stiffness values, and flagging soft spots to watching for indications of premature failure. Preventative maintenance may be able to mitigate a soft spot and buy additional time until the entire roadway needs rehabilitation.

IC Software - Commentary

· HAMM Software:

- The HAMM software has a distance measuring tool and a replay tool that are helpful.
- The final coverage data files from HAMM could not be properly imported into VEDA. The IC Technical Support is aware of this and is working with HAMM to develop a solution.
- The HAMM software stores the data on your computer in the "public users" C Drive. This is not where I would look for datafiles I am using; and you cannot share information from this location with other users on a network. This default location can be changed but I have not tried that yet. I do not know if you need to reset the default location every time you boot up the software.

IC Software - Commentary

 It would be good if the program asked you where you want to store the data rather than just assign it to a default location.
 Then you could assign the data to your local laptop or to a server depending on where you are and what you are doing.

· Both HAMM & VEDA software

Both programs (HAMM / VEDA): The color coding is a function
of the image size. From a distance the color looks uniform but
when you zoom in, more details appear, which can change your
conclusions about what you are looking at. Also, the zoom in/out
features are not the most user friendly; so it is not easy to check
this all the time.

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IC Software - Commentary

· VEDA Software:

- The VEDA software stores their results in the same file folder as they get the data from. This is good and helps keep all the data together.
- Nonetheless, the VEDA software is generally hard to use and not at all user friendly. It takes a long time to load, and shuts down without notice if you click a button too fast, etc.
- The VEDA software locates data points by coordinates.
 However, only surveyors use coordinates. The rest of us locate information (pavement changes, etc.) on plans by Station and Offset

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IC Software - Commentary

- To look at the potential correlation of the ICMV with existing pavement changes, you need to:
 - Review the project plans, find the typical sections, and make a list of the beginning and end Stations of each pavement section.
 - Ask the District Chief of Surveys to convert this information to Segments and Offsets.
 - Have someone(?) find these spots in the field and mark them so the contractor can use the rover to get coordinates on them.
 - The contractor needs to give you the coordinates for the pavement section changes along with the coordinates for the acceptance / research cores, and any other points of interest.

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IC Software - Commentary

- Dividing the project into sections for analysis is also very difficult. Again, VEDA uses coordinates while the rest of us use other systems which are NOT readily converted into VEDA coordinates.
- If you have planned far enough ahead and pre-determined the locations of sections for analysis, you can have the contractor use the rover to get coordinates for your sections during construction. However, this requires better than average coordination with construction personnel.

IC Software - Commentary

If you have the coordinates, you can enter them into the VEDA program – the easiest way I have found so far is to start at the east or west end of the section I want to develop and then go due north or south to frame out the box. You will end up with a parallelogram encompassing that piece of the road. You can adjust the extent north / south to capture the entire piece of roadway in the box (especially if there is a curve in the road). The VEDA analysis computes the averages of all the data points it finds within the box.

66

IC Software - Commentary

- o If during your analysis you find that it might be helpful to add a couple of sections, or break a section into pieces, then you are stuck without coordinates and you literally have to eveball the sections or do the best you can working from the last known coordinates. This is time consuming and does not seem to be
- Because there is no distance measuring tool in the VEDA program, you have to eyeball the point you want based on intersecting streets shown in common on the project plans and on the VEDA map.

IC Software - Commentary

- . Entering the core test data is equally clumsy. You can write down the coordinates and manually enter them one at a time, or you can copy and paste them from an excel spreadsheet one cell at a time. However, you cannot copy and paste a list of coordinates. This is frustrating and time consuming.
- VEDA also has another very annoying feature when it is generating a map, there is no indication that it is working - it looks frozen - and you are tempted to click on the button again. BUT the program will shut down without notice if you are impatient and try to click on something else before it is ready. So sorry - start over again!

IC Software - Commentary

There are many features of the VEDA program that I do not understand - and I am looking forward to the ICDM training that is coming to Pennsylvania this fall.

Conclusions

- · The contractual obligations went fairly smoothly.
- · The IC equipment performed as expected. A minor amount of GPS data was lost due to overhanging trees. Some data was lost due to operator error.
- The manufacturers training had mixed results depending on the location and the trainer.
- Some contractors are excited about using IC and want to cooperate. Being our first IC projects, we are letting things play out in the field somewhat even though we are not getting 100% compliance with everything. We are making notes of what to change in future editions of our specification so we can get 100% compliance.

Conclusions

· Most of the roller operators were not very concerned with paying attention to the pretty colored display screens. On-the-job training does not seem to convince the roller operators to change the way they have always done it. We are considering asking the local Operating Engineers for their help in training roller operators in the use of IC.

Conclusions

It appears that some of the HAMM roller operators did not adequately understand how to use the tablet.

- a outages occurred, and getting the data out of the tablet got to be more complicated than it needed to be.
- · The Sitech data transfer is entirely automatic so the roller operators have minimal impact on the data transfer - turn the IC box on and off - that's it.
- · Transferring the data from the Sitech equipped rollers to the "cloud" went well. It took a couple of iterations to figure out how to get the large datafiles to a place where we could access them. But once we got that figured out, it has been seamless ever since.

Conclusions

- It appears that some of the HAMM roller operators did not adequately understand how to use the tablet. Data outages occurred, and getting the data out of the tablet got to be more complicated than it needed to be.
- While transferring the data generally went smoothly, finding "down time" to actually download the data from the HAMM rollers was not so easy. The end of the shift is the only guaranteed "down time", and you need to be paying attention or you will have to chase down the roller. I discovered that the shift may end early for a variety of reasons, and you can be waiting for the paving train to come around the curve and it never shows up!

Conclusions

Analyzing the data in the field is not easy – the field office is not always near the site; the laptop is not always reliable or convenient to set up in your vehicle; you need the reference manuals to adequately review the data. The software training provided by the manufacturer only gives you an introduction – everyone who needs to look at the data needs comprehensive hands-on training to become proficient. Perhaps we need to rethink the type and intensity of the training we want the manufacturers to provide.

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IC Lessons Learned

 The relationship between the contractor QC person and the PennDOT inspector needs to be upgraded to achieve a smooth understanding of the IC features being added into a normal asphalt paving job. For example, test strip data, pass counts, and HMV data need to be coordinated and passed on to appropriate parties immediately during construction, not hours, days, or weeks later.

IC Lessons Learned

 PennDOT should provide 2 thumbdrives for the collection of the data (check with the IT section) – the inspector should be the keeper of the thumbdrives.
 When requested, the contractor should download the data onto both of them and give them back to us. (The second thumbdrive is for backup in case the first one suffers some sort of electrical or mechanical damage.)

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IC Lessons Learned

- The inspector should download the data onto the field office computer at such intervals as may be reasonably convenient. The inspector-in-charge should upload the raw data into a NPI project folder on the P-Drive so both Central Office and District personnel can access / process the data.
- It is important to get the roller operators on-board with this new technology. The superintendent may be onboard, but if the roller operator does not feel comfortable with it, then the potential benefit to the contractor may not be realized.

IC Lessons Learned

• The idea behind taking research cores is to be able to assess the variance in the ICMV data. We have the ICMV at the acceptance core locations but that does not tell us about the densities of places that have low stiffness, or low temperature, or any other anomaly. If the acceptance cores are taken immediately after completion of the mat, there is not likely to be sufficient time to collect and review the roller data for determining where we want to take the research cores. Under such conditions, we are allowing the research cores to be taken at additional pre-determined random locations. Highways that are closed for a relatively long period of time would be better candidates for obtaining research cores at locations of interest.

Report of the 3rd Workshop for Technology Transfer for Intelligent Compaction Consortium (TTICC) Transportation Pooled Fund Study Number TPF-5(233)

Intelligent Compaction: The Initial PennDOT Experience

IC Lessons Learned

- Some Districts want to minimize the number of cores taken in the new pavement and are reluctant to take <u>any</u> research cores. Or, they want to take the acceptance cores and research cores in close proximity to minimize the number of locations that might need to be patched in the future – however, research cores taken in close proximity to the acceptance cores are less likely to give us different information from that obtained from the acceptance cores, and this defeats the purpose.
- While the IC people say that the data can be reviewed in 'real-time", the practical matter is that PennDOT has NOT found this to be the case. Perhaps with a very high level of proficiency, it may be possible; but that is a long way off from where we are right now.

IC Lessons Learned

- Working with a laptop on-site in a vehicle is not an ideal place to conduct sophisticated data analysis. Add night work to that package and lighting / vision issues as well as tiredness to further impede the analysis. Why not include dampness, humidity, fog, and light rain to the mix just to make it more fun?
- Working in a field office typically provides a satisfactory
 work environment with adequate lighting; however, it can
 be somewhat remote from the site 30 to 60 minutes
 away is not unusual for a PennDOT project. The
 inspector can accomplish nothing else if they make 2
 roundtrips to the field office to review the data collected
 during the course of the shift.

B/

IC Lessons Learned

- People who will be working with the software must be trained to a high level of proficiency. Inexperience results in confusion, frustration, and misleading results.
- It is important to safeguard the original data set. Always work with a copy to prevent accidental corruption or loss of the original data.
- Give some thought to naming data files File 1, 2, 3 does not cut it. ECMS #, SR #, Lane #, Roller #, Date, Time, etc. are all valuable components to a good name for a datafile.

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IC Issues To Be Resolved

- We need to continue our analyses of the data and have AAR meetings with the contractors to share what we each have learned regarding the field application of IC, and how to improve the process / specification.
- We need to incorporate the contractor's input and our construction observation notes for the next round of revisions to the draft specification.
- We need to confirm who will be supplying the thumbdrives and mention that fact in the specification.
- Do we need to keep interim data sets once we have the end-of-day or final set?

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IC Issues To Be Resolved

- Who will be collecting the data and posting it to the P-Drive?
- Who is to be notified, and how, when data has been posted?
- · Who is going to review the data for payment purposes?
- · Who is going to review the data for scientific inquiry?

IC Issues To Be Resolved

- How is this data to be archived? Storage needs to be compatible with future use. Corruption of electronic files could result in a lot of lost files. Printing out paper copies takes a lot of paper and shelf space.
- Who is going to keep the archival records compatible with the current computer system? VEDA 1.0 files cannot be read by the VEDA 2.0 software. The VEDA 3.0 software due out later this year is supposed to be able to read VEDA 2.0 files.

Appendix D: Workshop Products

The following is a list of the products provided for the workshop participants. These are included in the following pages.

- 1. TTICC Problem Statement
- 2. Update on CEER-TTICC webpage and IC 101 video viewing statistics on YouTube.
- 3. Report of the 1st Workshop for Technology Transfer for Intelligent Compaction Consortium (available for download from www.ceer.iastate.edu/tticc)
- 4. Report of the 2nd Workshop for Technology Transfer for Intelligent Compaction Consortium (available for download from www.ceer.iastate.edu/tticc)
- 5. List of Potential Intelligent Compaction Briefs, by Pavana Vennapusa and David White
- 6. Intelligent Compaction Briefs:
 - a. Indiana SR 25, Granular and Non-Granular Embankment Subgrade Fill, August 2010 [Draft]
 - b. Minnesota TH 60, Non-Granular Embankment Subgrade Fill, August-October 2007 [Draft]
 - c. Florida SR 9B, Granular Layered Embankment and Geosynthetic Reinforcement, May 2011 [Draft]
 - d. Evaluating Benefits and Limitations of Intelligent Compaction, Wisconsin DOT
- 7. GeoCongress 2014 Article, A Road Map for Implementation of Intelligent Compaction Technology, by David J. White, Pavana K. R. Vennapusa, and Mark Dunn, presented at GeoCongress 2014 held in Atlanta, GA.
- 8. Geostrata 2014 Article, Geotechnical IT Revolution: Intelligent Compaction and Beyond, by David J. White.
- 9. List of IC Specifications Developed for Soils and HMA in the United States
- 10. Specifications:
 - a. FHWA Asphalt IC Specification 2014
 - b. FHWA Soils IC Specification 2014
 - c. MnDOT Soils-Asphalt IC Specification 2014
 - d. SHRP2 R07 Performance Specifications for Earthwork/Pavement Foundation 2014



Technology Transfer Intelligent Compaction Consortium (TTICC) TPF-5(233)

PROJECT OBJECTIVE

Establishment of a Technology Transfer Intelligent Compaction Consortium (TTICC) to identify, support, and facilitate research and technology transfer for intelligent compaction technologies.

PROBLEM STATEMENT

Increasingly, state departments of transportation (DOTs) are challenged to design and build longer life pavements that result in a higher level of user satisfaction for the public. One of the strategies for achieving longer life pavements is to use innovative technologies and practices. In order to foster new technologies and practices, experts from state DOTs, Federal Highway Administration (FHWA), academia and industry must collaborate to identify and examine new and emerging technologies and systems. The purpose of this pooled fund project is to identify, support, facilitate and fund intelligent compaction research and technology transfer initiatives.

PROJECT GOALS

The goal of the TTICC is to:

- · Identify needed research projects
- Develop pooled fund initiatives
- Plan and conduct an annual workshop on intelligent compaction for soils and HMA.
- Provide a forum for technology exchange between participants
- Develop and fund technology transfer materials
- Provide on-going communication of research needs faced by state agencies to the FHWA, states, and industry

This consortium will be the national forum for state involvement in the technical exchange needed for collaboration and new initiatives, and be a forum for advancing the application and benefit of intelligent compaction technologies for soils, bases, and asphalt pavement uses.

State participation in this process will be through the pooled fund. FHWA, industry and others may be invited to participate in the project discussions and activities.

BACKGROUND

In 2008 and 2009, the Iowa DOT and EERC (now CEER) hosted an annual workshop on Intelligent Compaction for Soils and HMA. As part of the workshop, a road map for addressing the research and educational needs for integrating intelligent compaction technologies into practice was developed. An ongoing forum is needed to provide broad national leadership that can rapidly address the needs and challenges facing state transportation agencies (STAs) with the adoption of intelligent compaction technologies. The vision for the road map was to identify and prioritize action items that accelerate and effectively implement IC technologies into earthwork and HMA construction practices. Coupled with the IC technologies are advancements with in situ testing technologies, data analysis and analytical models to better understand performance of geotechnical systems supported by compacted fill, software and

wireless data transfer, GPS and 3D digital plan integration, new specification development, and risk assessment. What follows in Table 1 is the road map with the 2008 and 2009 priority rankings. For information on the first two workshops please refer to the reports on the CEER website: http://www.ceer.iastate.edu/publications.cfm

RESEARCH PLAN AND DELIVERABLES

The proposed project is for the establishment of a pooled fund for state representatives to continue this collaborative effort regarding intelligent compaction. The TTICC will be open to any state desiring to be a part of new developments in intelligent compaction leading to the implementation of new technologies which will lead to longer life pavements through the use of an integrated system of emerging innovative technologies. Two workshop meetings will be conducted each year. One of the meetings will be in person and is anticipated to occur during the fall. The location of the in-person workshop meetings will be determined by the Executive Committee and moved regionally each year to participating states. The second meeting will be a webinar and occur in early spring hosted by CEER.

All efforts by the TTICC will be focused towards these project activities and deliverables:

- Identify and guide the development and funding of technology transfer materials such as tech brief summaries and training materials from research results
- Review the IC Road Map as updated annually and provide feedback to the FHWA, industry, states, and the CEER on those initiatives
- Be a forum for states and researchers to share their experience with IC technologies
- · Provide research ideas to funding agencies
- · Identify and instigate needed research projects
- Include current activities and deliverables of the pooled fund on the TTICC website
- Maintain pooled fund project website with current activities and deliverables
- Develop pooled fund research projects for solutions to intelligent compaction issues
- Act as a technology exchange forum for the participating entities
- Contribute to a technology transfer newsletter on intelligent compaction research activities every six months in cooperation with the CEER
- Post minutes to the website following web meetings
- · Post a report following each in-person workshop to the website

EXECUTIVE COMMITTEE

An Executive Committee will be formed from the TTICC to review and approve the pooled fund activities and budget. The Executive Committee will meet at a schedule to be determined by the Executive Committee via conference calls.

RESEARCH TEAM

The project managers for the TTICC will be the CEER; lead by Dr. David White. Dr. White is the director of the Center for Earthworks Engineering Research (CEER) at Iowa State University. Dr. White's M.S. and Ph.D. research involved large-scale field testing to evaluate embankment construction methods and development of design and construction guidelines for stabilized subgrade. Since Dr. White's start as an assistant professor at ISU in August 2001 he has been successful in directing research from a diverse group of organizations for a total of aggregate dollar total of over \$10 million. Dr. White has ten years of experience with earthwork and pavement foundation layer improvement, ground systems, QC/QA testing, specification development, and six years of experience evaluating intelligent compaction systems. Dr. Pavana Vennapusa and Mr. Heath Gieselman will also contribute to the project and have extensive experience with intelligent compaction technologies.

Report of the 3rd Workshop for Technology Transfer for Intelligent Compaction Consortium (TTICC) Transportation Pooled Fund Study Number TPF-5(233)

This project will be conducted through the CEER. CEER works with partners to bring about rapid advancements in quality, economy, and performance of the geotechnical aspects of civil infrastructure through a fundamental understanding of earth mechanics, and by providing enabling technologies and supportive public policies.

ESTIMATED PROJECT DURATION and COST

The pooled fund project duration is for five years. The annual cost of participation for one person is \$7,000; which includes travel expenses and registration for the annual workshop and web-based meetings. Additional participants can be added for \$2000/year.

SUMMARY OF PROJECT SPONSOR REQUIREMENTS

- Financial support
- Meeting participation twice a year, in person and via a webinar
- Active collaboration with each other and others to identify, support, facilitate and fund intelligent compaction research and technology transfer initiatives.
- Championing within their state the deliverables from the pooled fund, such as technical material
 to key staff, and facilitate implementation of new technologies and practices.

CONTACT FOR FURTHER INFORMATION

Lead State Lead State Technical Contact Administrative Contact Steve Megivern, P.E. Sandra Q. Larson, P.E. Soils Design Section Director, Research & Technology Bureau Iowa DOT Iowa DOT 800 Lincoln Way 800 Lincoln Way Ames, Iowa 50010 Ames, Iowa 50010 515-239-1936 515-239-1205 stephen.megivern@dot.iowa.gov sandra.larson@dot.iowa.gov

CEER/ISU Contact

David J. White, Ph.D.
Assoc Professor and holder of
Richard L. Handy Professorship
Director, CEER
Department of CCEE, ISU
2711 S. Loop Dr, Ste 4700
Ames, Iowa 50010
515-294-1463
djwhite@iastate.edu

Table 1. Intelligent Compaction Road Map for Research and Training

IC Road Map Research and Educational Elements

- Intelligent Compaction Specifications/Guidance (4*). This research element will result in several specifications encompassing method, end-result, performance-related, and performance-based options. This work should build on the work conducted by various state DOTs, NCHRP 21-09, and the ongoing FHWA IC Pooled Fund Study 954.
- Intelligent Compaction and In-Situ Correlations (2*). This research element will develop field investigation protocols for conducting detailed correlation studies between IC measurement values and various in situ testing techniques for earth materials and HMA. Standard protocols will ensure complete and reliable data collection and analysis. Machine operations (speed, frequency, vibration amplitude) and detailed measurements of ground conditions will be required for a wide range of conditions. A database and methods for establishing IC target values will be the outcome of this study. Information generated from this research element will contribute to research elements 1, 9, and 10.
- In-Situ Testing Advancements and New Mechanistic Based QC/QA (8*). This research element will result in new in situ testing equipment and testing plans that target measurement of performance related parameter values including strength and modulus. This approach lays the groundwork for better understanding the relationships between the characteristics of the geo-materials used in construction and the long-term performance of the system.
- Understanding Impact of Non-Uniformity of Performance (10*). This track will investigate relationships between compaction non-uniformity and performance/service life of infrastructure systems—specifically pavement systems. Design of pavements is primarily based on average values, whereas failure conditions are affected by extreme values and spatial variations. The results of the research element should be linked to MEPDG input parameters. Much needs to be learned about spatial variability for earth materials and HMA and the impact on system performance. This element is cross cutting with research elements 1, 5, and 9.
- Data management and Analysis (9*). The data generated from IC compaction operations is 100+ times more than traditional compaction QC/QA operations and presents new challenges. The research element should focus on data analysis, visualization, management, and be based on a statistically reliable framework that provides useful information to assist with the construction process control. This research element is cross cutting with research elements 1, 2, 3, 6,
- 6. Project Scale Demonstration and Case Histories (3*). The product from this research element will be documented experiences and results from selected project level case histories for a range of materials, site conditions, and locations across the United States. Input from contractor and state agencies should further address implementation strategies and needed educational/technology transfer needs. Conclusive results with respect to benefits of IC technology should be reported and analyzed. Information from this research element will be integrated into research element 1, 9, and 10.
- Understanding Roller Measurement Influence Depth (6*). Potential products of this research element include improved understanding of roller operations, roller selection, interpretation of roller measurement values, better field compaction problem diagnostics, selection of in situ QA testing methods, and development of analytical models that relate to mechanistic performance parameter values. This element represents a major hurdle for linking IC measurement values to traditional in situ test measurements
- Intelligent Compaction Technology Advancements and Innovations (7*). Potential outcomes of this research element include development of improved IC measurement systems, addition of new sensor systems such as moisture content and mat core temperature, new onboard data analysis and visualization tools, and integrated wireless data transfer and archival analysis. It is envisioned that much of this research will be incremental and several sub-elements will need to be developed.
- Education Program/Certification Program (5*). This educational element will be the driver behind IC technology and specification implementation. Materials generated for this element should include a broadly accepted and integrated certification program than can be delivered through short courses and via the web for rapid training needs. Operator/inspector guidebook and troubleshooting manuals should be developed. The educational programs need to provide clear and concise information to contractors and state DOT field personnel and engineers. A potential outcome of this element would be materials for NHI training courses.
- 10. Intelligent Compaction Research Database (1*). This research element would define IC project database input parameters and generate web-based input protocols with common format and data mining capabilities. This element creates the vehicle for state DOTs to input and share data and an archival element. In addition to data management/sharing, results should provide an option for assessment of effectiveness of project results. Over the long term the database should be supplemented with payement performance information. It is important for the contractor and state agencies to have standard guidelines and a single source for the most recent information. Information generated from this research element will contribute to research elements 1, 2, 6, 9.

^{*2008} Workshop Ranking

Update on CEER-TTICC Webpage and IC 101 Video Viewing Statistics on Youtube



Technology Transfer Intelligent Compaction Consortium Intelligent Compaction 101 Video Statistics



CEER YouTube Channel Date Published: 1/31/2014

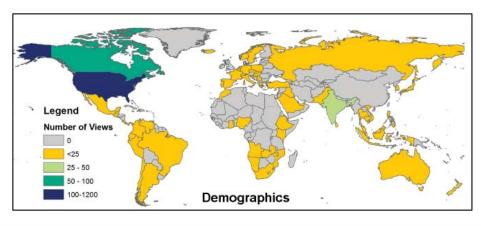
Statistics as of 8/27/14*:

Number of Views: 1,552

Minutes Watched: 8,152

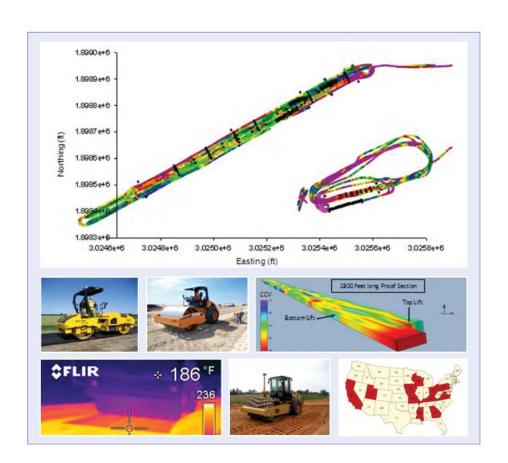
No. of Countries: 70

*Source YouTube



Report of the 1st Workshop for Technology Transfer for Intelligent Compaction Consortium

December 14-15, 2010



IOWA STATE UNIVERSITY





Report of the 1st Workshop for TTICC

Report of the 1st Workshop for Technology Transfer for Intelligent Compaction Consortium (TTICC)

Transportation Pooled Fund Study Number TPF-5(233)

December 14-15, 2010

David J. White, Ph.D.

Associate Professor

Department of Civil, Construction, and Environmental Engineering

2711 South Loop Drive, Suite 4700

Ames, Iowa 50010

515-294-1892

djwhite@iastate.edu

Pavana KR. Vennapusa, Ph.D.
Research Assistant Professor

Department of Civil, Construction, and Environmental Engineering
2711 South Loop Drive, Suite 4700

Ames, Iowa 50010
515-294-2395
pavanv@iastate.edu

Participating States: California, Georgia, Iowa, Kentucky, Mississippi, Missouri, Ohio, Pennsylvania, Utah, Virginia, and Wisconsin

Report of the 1st Workshop for TTICC

Executive Summary

On December 14-15, 2010, the Iowa Department of Transportation (Iowa DOT) and Iowa State University co-hosted a workshop for the Technology Transfer for Intelligent Compaction Consortium (TTICC), a Transportation Pooled Fund (TPF-5(233)) initiative designed to identify, support, facilitate, and fund intelligent compaction (IC) research and technology transfer initiatives. The objective of the 2010 workshop was to generate a focused discussion to identify the research, education, and implementation goals necessary for advancing IC for earthworks and asphalt.

To develop these goals, the workshop's 20 attendees—representing the Federal Highway Administration (FHWA), Iowa State University and the University of Kentucky, and the 11 state DOTs participating in the study—reviewed previous workshops, attended technical presentations, discussed specifications, voted and brain-stormed about IC research, and discussed future meetings.

A key outcome of the workshop was the evaluation and update of the IC Road Map, a prioritized list of IC technology research/implementation needs initially created in a 2008 IC workshop meeting and developed in 2009 and 2010 workshops. Though a new element was added and descriptions of exiting elements were modified, the top two IC research needs remained (1) developing and providing evidence of correlations between IC or continuous compaction control (CCC) measurements and in situ test measurements and (2) developing IC/CCC specifications and guidance. The revised IC road map is presented in Table 1.

Table 1. Prioritized IC road map of technology research/implementation needs

Prioritized IC/CCC Technology Research/Implementation Needs

- Intelligent Compaction and In situ Correlations (24*)
- Intelligent Compaction Specifications/Guidance (19*)
- Data Management and analysis (8*)
- Project Scale Demonstrations and Case Histories (7*)
- Education/Certifications Programs (4*)
- Understanding Impact of Non-Uniformity on Performance (4*)
- Standardization of Roller Outputs and Format Files (4*)
- IC Compaction Research Database (3*)
- In Situ Testing Advancements and New Mechanistic Based QC/QA (2*)
- 10. Understanding Roller Measurement Influence Depth (1*)
- 11. IC Technology Advancements and Innovations (1*)
- 12. Sustainability** (1*)
- 13. Standardization of Roller Sensor Calibration Protocols (0*)

Transfer for Intelligent Compaction Consortium (TTICC) TPF-5(233) Report of the 1st Workshop for Technology fransportation Pooled Fund Study Number

Report of the 3rd Workshop for Technology Transfer for Intelligent Compaction Consortium (TTICC)

Transportation Pooled Fund Study Number TPF-5(233)

^{*}total votes are provided in parenthesis

^{**}newly added roadmap element

Report of the 1st Workshop for TTICC

Executive Summary

Other important outcomes from the 2010 TTICC workshop included providing a forum to facilitate information exchange and collaboration, developing a list of key products that need to be developed as part of the TTICC project, and developing plans for further TTICC meetings and other events.

Table 2 presents a list of products/items to be developed as part of the TTICC study, and Table 3 presents an action plan that the TTICC team can use to help advance IC/CCC technologies into earthworks and hot-mix asphalt (HMA) construction practice.

Table 2. List of products/items to be developed for the TTICC project

List of Products/Items to be developed for TTICC project

- Develop at least 20 IC briefs based on existing field demonstration projects/research reports in the US. Develop one IC brief a month.
- Update EERC's TTICC website regularly and include all IC briefs with videos, and updated information related to TTICC project activities and workshop findings.
- Develop a Technology Overview Presentation for executive level officials in DOT.
- Explore funding opportunities for writing synthesis documents explaining IC technologies, QC/QA correlations, etc.

Table 3. Action plan for advancing IC technologies into earthwork and HMA practices

Action Plan for Advancing IC/CCC Technologies into Earthwork and HMA

- Develop case study information on different QC devices/correlations/ methods and strategies
 of data analysis.
- Compile a data base to evaluate correlations of in situ measurements to IC measurement values and evaluate in situ measurement tools.
- Develop Technology Independent Guide Specifications (FHWA/industry/ manufacturer/contractors/stage agencies review)
- · Develop data analysis software by involving computer programmers.
- Conduct demonstration projects and open houses. Work with interested contractors in the state to get their buy-in and implement IC on pilot projects.
- Conduct a survey among different states in the US and European countries to learn from their experiences.
- Work toward development of NHI course and certification for operators, inspectors and engineers.
- · Submit problem statements to TRB/NCHRP to create funding opportunities.

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Report of the 1st Annual Workshop for Technology Transfer for Intelligent Compaction Consortium Transportation Pooled Fund Study Number TPF-5(233)

Report of the 2nd Workshop for Technology Transfer for Intelligent Compaction Consortium

une 2012







Report of the 2nd Workshop for TTICC

Report of the 2nd Workshop for Technology Transfer for Intelligent Compaction Consortium (TTICC)

Transportation Pooled Fund Study Number TPF-5(233)

March 6-7, 2012

David J. White, Ph.D.

Associate Professor and holder of Wegner Professorship
Dept. of Civil Construction and Environmental Engineering
Director, Center for Earthworks Engineering Research
2711 South Loop Drive, Suite 4700
Ames, Iowa 50010
515-294-1892
djwhite@iastate.edu

Pavana KR. Vennapusa, Ph.D.
Research Assistant Professor
Dept. of Civil Construction and Environmental Engineering
Associate Director, Center for Earthworks Engineering Research
2711 South Loop Drive, Suite 4700
Ames, Iowa 50010
515-294-2395
pavany@iastate.edu

Participating States: California, Georgia, Iowa, Kentucky, Mississippi, Missouri, Ohio, Pennsylvania, Utah, Virginia, and Wisconsin

Executive Summary

On March 6-7, 2012, the Iowa Department of Transportation (Iowa DOT) and Iowa State University's Center for Earthworks Engineering Research (CEER) co-hosted a workshop for the *Technology Transfer for Intelligent Compaction Consortium* (TTICC), a Transportation Pooled Fund (TPF–5(233)) initiative designed to identify, support, facilitate, and fund intelligent compaction (IC) research and technology transfer initiatives. The following were the key objectives of the workshop:

- · Review current state DOT and current IC specifications for earthwork and HMA
- Review TTICC IC case history summaries
- Facilitate a collaborative exchange of information between state DOTs, FHWA, and Industry to
 accelerate effective implementation of IC technologies
- Update the IC roadmap for identifying key research/implementation/education needs, and action items for TTICC group, FHWA, and industry

The workshop's attendees—representing 9 state DOTs, the Federal Highway Administration (FHWA), Advanced Drainage Systems, Bomag Americas, Caterpillar, Trimble Navigation Ltd., and Iowa State University—reviewed IC case history summaries, discussed recent IC pilot specifications implemented by state DOTs or demonstration projects conducted by state DOTs, and voted and brain-stormed IC research, implementation, and educational needs.

A key outcome of the workshop was the evaluation and update of the IC Road Map, a prioritized list of IC technology research/implementation needs initially created in a 2008 IC workshop meeting and updated in 2009, 2010, and 2011 workshops. The top two IC research needs are now (1) data management and analysis, and (2) developing IC/CCC specifications and guidance. The revised IC road map is presented in Table 1. After updating the IC roadmap, the group identified action items for the TTICC group, FHWA, and industry for advancing each of the road map elements.

Table 1. Prioritized IC technology research/implementation needs - 2012 TTICC workshop

Prioritized	IC/CCC Technology	ogy Research/Im	plementation Needs

- Data management and Analysis (18*)
- 2. Intelligent Compaction Specifications/Guidance (14*)
- 3. Intelligent Compaction and In-Situ Correlations (13*)
- Understanding Impact of Non-Uniformity of Performance (11*)
- 5. Standardization of Roller Outputs and Format Files (11*)
- 6. Standardization of Roller Sensor Calibration Protocols (10*)
- 7. Education Program/Certification Program (8*)

- Understanding Roller Measurement Influence Depth (7*)
- 9. Project Scale Demonstration and Case Histories (6*)
- 10. In-Situ Testing Advancements and New Mechanistic Based QC/QA (3*)
- Intelligent Compaction Technology Advancements and Innovations (2*)
- 12. Intelligent Compaction Research Database (2*)
- 13. Sustainability (1*)

*total votos are newirled in nasenthesi

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Report of the 3rd Workshop for Technology Transfer for Intelligent Compaction Consortium (TTICC) Transportation Pooled Fund Study Number TPF-5(233)

Report of the 2nd Workshop for TTICC

Other important outcomes from the 2012 TTICC workshop included: (a) providing a forum to facilitate information exchange and collaboration and developing a list of action items to advance and accelerate implementation of IC technology into earthwork and asphalt construction practice, (b) developing an outline of content for an IC 101 video, and (c) developing a short list of items that the TTICC team can use to help advance the IC road map research/implementation priorities as shown in Table 5.

Table 5 . Prioritized IC technology research/implementation needs – 2012 TTICC workshop

High Priority Focus Areas

- 1. Develop new data management, analysis, and visualization tools
- Define and establish new standards for quality in road building (performance based specifications)
- Explore alternative contract delivery modes for construction projects that support innovation

| Report of the 2nd Workshop for Technology Transfer for Intelligent Compaction Consortium (TTICC) Transportation Pooled Fund Study Number TPF-5(233)

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List of Potential Intelligent Compaction Briefs by Pavana Vennapusa and David White

Technology Transfer Intelligent Compaction Consortium (TTICC) – TPF-5(233) List of Intelligent Compaction (IC) Briefs

Updated 8/27/14 By Pavana Vennapusa and David White

		MATERIALS			DR	UM	MANUFACTURER									
#	PROJECT LOCATION	GRANULAR	Non GRANULAR	CHEMICALLY TREATED GRANULAR	/ TREATED	ERIALS	Нот Міх Аѕрнагт	SMOOTH DRUM	PADFOOT	BOMAG	LLAR	z			щ	Λοινο
1	Iowa – I29, Monona County*	Х						Х							Х	Х
2	lowa – US218, Coralville*						х	Х						х		
3	Minnesota – TH64, Akeley**	х						Х			Х					
4	Mississippi – US84, Waynesboro*	Х		Х				Х	Х		Х	Х		Х		
5	lowa – US30, Colo*		х						Х		х					
6	Minnesota – TH14, Janesville*		х					Х				х				
7	Minnesota – Rt4, Kandiyohi County*						Х	Х						Х		
8	Texas – FM156, Roanoke*	х	х		Х			Х	Х			х	Х			
9	North Dakota – US12, Marmarth*	х	х			Х		Х	Х		х					
10	Iowa – US30, Harrison County**						Х	Х						Х		
11	Kansas – US69*		х					Х	Х		Х			Х		
12	New York - US219, Springville*	х						Х		х	х					
13	Australia – JRAC, Northern Territory*		х			Х		Х			Х					
14	Indiana – SR25, West Lafayette*	Х	Х					Х	Х		Х					
15	Minnesota – TH60, Bigelow**		х						Х		х					
16	Minnesota - TH36, North St. Paul**	х	Х					Х			Х					
17	Minnesota – US10, Staples**	Х						Х			Х					
18	Minnesota – Olmstead County**		х						Х		Х					
19	Minnesota – MnROAD, Albertville*	Х	Х					Х	Х	х	Х	Х				
20	Colorado - I29, Longmont*	Х	х					Х		х	Х		Х			
21	Maryland – I70, Frederick*	х	х					Х	Х	х			Х	х		
22	North Carolina – High Point*	х	х					Х		Х		Х				
23	Florida – I10, Jacksonville*	х						Х				Х	Х			
24	Missouri - Hwy141, Chesterfield**		х						Х		Х					
25	Iowa – Boone County Test Sections*	х						Х			Х			Х		
26	Florida – Hwy 9, Jacksonville*	Х						Х			Х					
27	Wisconsin – Multiple Sites	х	х				х	Х	х	х	Х			х		

IC BRIEFS - DRAFT

^{*}RESEARCH/DEMONSTRATION PROJECTS

** PROJECTS WITH IC SPECIFICATIONS
IC BRIEFS COMPLETED AND POSTED ON CEER WEBSITE

List of Potential Intelligent Compaction Briefs by Pavana Vennapusa and David White

Technology Transfer Intelligent Compaction Consortium (TTICC) – TPF-5(233) List of Intelligent Compaction (IC) Briefs

Updated 8/27/14 By Pavana Vennapusa and David White

Dear TTICC Participant,

If you are aware of a project that you would like to include in the list for potential intelligent compaction briefs, please provide the following information and return this sheet to Denise Wagner (dfwagner@iastate.edu).

Thank You,

CEER Research Team

Project Location:
Source of Information/Report:
Lead Researcher/Project Engineer Contact:

Indiana SR 25 – Granular and Non-Granular Embankment Subgrade Fill – August 2010

INTELLIGENT COMPACTION BRIEF

PROJECT DATE

August 16 to 18, 2010

RESEARCH PROJECT TITLE

Accelerated Implementation of Intelligent Compection Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials (FHWA DTFH61-07-C-R0032)

SPONSOR

Federal Highway Administration

PRINCIPAL INVESTIGATOR

George Chang, PhD, PE, Project Manager, The Transtec Group, Inc., 512-451-6233

RESEARCHTEAM

David J. White, PhD, PE; Pavana K. R. Vennapusa, PhD, PE; Barry Christopher, PhD, PE; Heath Gieselman, MS

AUTHORS

David J. White, PhD, PE; Pavana K. R. Vennapusa, PhD, PE; Center for Earthworks Engineering Research, Institute for Transportation, 2711 South Loop Drive, Suite 4700, Ames, IA 50010-8664

MORE INFORMATION

http://www.ceer.iastate.edu/research/ project/project.cfm?projectID=-373342403

This document was developed as part of the Federal Highway Administration (FHWA) transportation pooled fund study (PF-5423) – Technology Transfer for Intelligent Compaction Consortium (TTICC).

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Figure 1. Caterpillar CS56 smooth drum with padfoot shell kit (left) and Caterpillar CS563E smooth drum roller (right) (from White et al. 2011)

Project Description

This demonstration was conducted on State Route (SR) 25 in West Lafayette, Indiana. The machine configurations and roller-integrated compaction measurement (RICM) systems used on this project included a Caterpillar CS56 smooth drum roller with a padfoot shell kit (here after referred to as padfoot roller) and a Caterpillar CS563E smooth drum vibratory roller (Figure 1). Both were equipped with machine drive power (MDP) technology (reported as MDP* and see White et al. 2011 for description of MDP*). Both machines were also equipped with a real-time kinematic (RTK) global positioning system (GPS) and on-board display and documentation systems.

The project involved construction and testing of six test beds consisting of cohesive and granular embankment fill materials. The MDP* values were evaluated by conducting field testing in conjunction with in situ dry density (yd) and moisture content (w) determined from nuclear gauge (NG), California bearing ratio (CBR) determined from dynamic cone penetrometer (DCP), and dynamic modulus determined from light weight deflectometer (LWD).

Field Study Goals

- Document machine vibration amplitude influence on compaction efficiency
- Develop correlations between MDP* measurement values to in situ point measurements (point-MVs)

- Compare roller-integrated compaction monitoring (RICM) results to traditional compaction operations
- Study RICM measurement values in production compaction operations
- Evaluate RICM measurement values in terms of alternative specification options

An open house was conducted near the end of the field investigation to disseminate results from current and previous IC projects.

Materials

The cohesive embankment fill material on the project was classified as sandy lean clay (CL) or A-7-6 (13) soil and the granular embankment fill material was classified as poorly graded sand with silt (SP-SM) or A-3 soil

Field Test Results and Observations

Six test beds (TBs) were evaluated as part of this study. TBs 1 and 2 consisted of granular embankment fill calibration test areas, TBs 3 and 6 consisted of granular embankment fill production areas, and TBs 4 and 5 consisted of cohesive embankment fill calibration areas. Results from selected test beds (TB5 cohesive embankment fill and TBs 3 and 6 granular fill) are presented in this Tech Brief.

In addition, a contractor representative was trained on-site to perform compaction operations on TB6 and his interview

Report of the 3rd Workshop for Technology Transfer for Intelligent Compaction Consortium (TTICC) Transportation Pooled Fund Study Number TPF-5(233)

INTELLIGENT COMPACTION BRIEF August 2014

responses from after the roller operations are also summarized in this Tech Brief.

TB5 Cohesive Embankment Fill Test Strip

This test bed consisted of a 48 m long test strip with compacted cohesive fill and visually showed rutting or sinkage under construction traffic loading (Figure 2). The test bed area was mapped using one roller pass in the low amplitude setting. The MDP* values varied from about 65 to 145 along the test strip. LWD modulus (E_{LWD-23}) measurements were obtained at 72 locations along the test strip at relative dense point-point spacing (-0.65 m). MDP* values in comparison with $E_{\text{\tiny LWD-Z3}}$ values are presented in Figure 3. Both MDP* and $E_{\text{DWD-23}}$ measurements tracked well on this test strip.





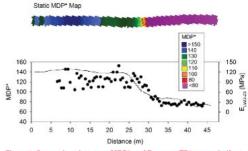
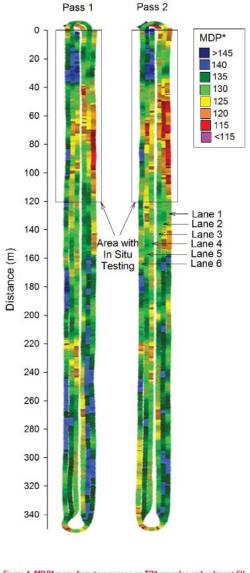


Figure 3. Comparison between MDP* and Epon 23 on TB5 test strip (from White et al. 2011)



Low Amplitude (a = 0.90 mm) MDP* Maps

Figure 4. MDP* maps from two passes on TB3 granular embankment fill production area (from White et al. 2011)

TBs 3 and 6 Granular Embankment Fill Production Areas

TBs 3 and 6 consisted of two lifts in a production area with granular embankment fill (Lift 1 for TB3 and Lift 2 for TB6). Lift 1 was mapped using two roller passes and LWD tests were performed in a selected area with high, medium, and low MDP* values using the on-board display. Tests were performed at 20 locations with relatively high MDP* values; 16 locations with medium range MDP* values, and 28 test locations with relatively low MDP* values. DCP tests were also performed at 7 selected locations. After compaction and testing on Lift 1 (TB3), Lift 2 (TB6) was placed and compacted using four roller passes in low amplitude mode by the contractor.

The roller operator was trained on-site to make use of the on-board display unit and was instructed to perform four roller passes over the production area. After the final pass, LWD tests were performed at 42 test locations across the production area. Test locations were selected based on the IC display to capture high, medium, and low values. In addition, DCP and NG tests were performed at 7 selected locations.

Spatial MDP* maps from TB3 (Lift 1) for the two passes are presented in Figure 4. MDP* plots with distance along each roller lane in comparison with LWD modulus measurements are presented in Figure 5. Spatial MDP* and roller pass coverage maps from TB6 (Lift 2) for the four passes are presented in Figure 6. The LWD values generally tracked well with variations in the MDP* values on both Lift 1 and Lift 2, except at some locations on lanes 2 and 6 on TB3 (Lift 1).

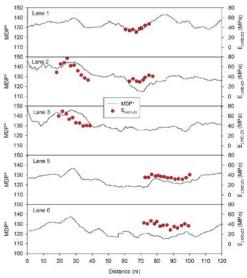


Figure 5. Comparison between MDP* and LWD modulus measurements from multiple lanes on TB3 (from White et al. 2011)

The moisture content of the fill material varied from about 3.5% to 5.1%, which was about -9 to -11% of standard Proctor optimum moisture content, and the relative compaction of the fill material varied from about 95% to 110% with an average of about 97% of standard Proctor maximum density.

Regression Analysis

Relationships between MDP* obtained from the smooth drum roller in low amplitude settings and in situ point-MVs from TBs 1, 3, and 6 are presented in Figure 7. All relationships showed significant scatter with R^2 values < 0.4. Comparatively, correlation between MDP* and $E_{\rm LWD-23}$ showed a better relationship with R^2 = 0.38 compared to dry density (γ_d) and CBR.

Relationships between MDP* obtained from the padfoot roller in static mode and in situ point-MVs from TBs 4 and 5 are presented in Figure 8. Correlation between MDP* and $E_{\rm LWD-25}$ showed a power relationship with $R^2=0.75$, while correlations with γ_d and CBR point measurements did not show a statistically significant relationship. Note that measurements were obtained over a wide range of MDP* measurements (75 to 140) in correlation with $E_{\rm LWD-25}$, while the MDP* measurements ranged only within a narrow range in correlation with γ_d and CBR (80 to 110).

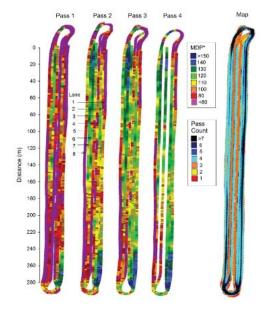


Figure 6. MDP* maps from four passes and pass count map on TB6 granular embankment fill production area (from White et al. 2011)

3

Intelligent Compaction Briefs

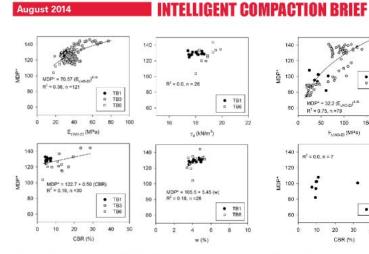


Figure 7. Correlations between MDP* and in situ test measurements from TBs 1, 3, and 6 granular embankment fill compacted in low amplitude settings (from White et al. 2011)

120 120 100 100 150 18 120 120 PP-100 100 80 TB4 20 30 40 **CBR (%)**

Figure 8. Correlations between MDP* and in situ test measurements from TBs 4 and 5 cohesive embankment fill compacted in static mode (from White et al. 2011)

Contractor Interview

A contractor representative was trained on-site to make use of the on-board computer display during compaction operations on TB6 using the CS563 roller. After the roller operations, the research team interviewed him with the following questions and his responses are summarized below.

Question: What to do you think about how the process worked and what information from the display was valuable and not valuable?

Response: The on-board display monitor was helpful to keep track of the number of roller passes. Also, by experience, I know that there would be areas that are relatively softer than other areas just because there was no construction traffic on it.

Question: Did the IC values you see on the monitor confirm what you would expect from experience?

Response: Yes. If you hit a thick lift spot, the IC values went down and if you hit a relatively thin lift spot, the IC values went up.

Question: What did you think about the display? Did you use the display much during compaction operations?

Response: The display worked well. But when you do your first pass, it's all red, so you cannot see the roller icon very well. It's a bit distracting as the screen moves when the station passes.

Question: Would you give a thumbs up or a thumps down for the technology?

Response: I would give thumbs up and it would be good for us to use it more.

Reference

White, D. J., and Vennapusa, P., Gieselman, H. 2011. Accelerated Implementation of Intelligent Compaction Monitoring Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials. TPF-5(128) – SR-25. West Lafayette, Indiana, Report submitted to The Transtec Group, FHWA, April. I INTELLIGENT COMPACTION BRIEF I

PROJECT DATE

August to October 2007

RESEARCH PROJECT TITLE

Implementation of Intelligent Compaction Performance Based Specifications in Minnesota

Federal Highway Administration Minnesota Department of Transportation

PRINCIPAL INVESTIGATOR
David J. White, PhD, PE, Iowa State University, djwhite@iastate.edu, 515-294-1463

RESEARCHTEAM

David J. White, PhD, PE; Pavana K. R. Vennapusa, PhD, PE; Jiake Zhang, Heath Gieselman, MS; Max Morris, PhD

AUTHORS

David J. White, PhD, PE; Pavana K. R. Vennapusa, PhD, PE; Center for Earthworks Engineering Research, Institute for Transportation, 2711 South Loop Drive, Suite 4700, Ames, IA 50010-8664

MORE INFORMATION

http://www.ceer.iastate.edu/research/ project/project.cfm?projectID=-1995638463

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Figure 1. Caterpillar CP563 padfoot roller with MDP* measurement system on TH 60 project (from

Project Overview

This project involved construction of the new four-lane Trunk Highway (TH) 60 bypass around Bigelow, Minnesota. The highway construction extended from just north of 120th Street in Iowa to about 1.6 km north of Nobles County Road (CR) 4 in Minnesota for a total length of about 8 km. Construction involved embankment fill sections varying from 1 m to 10 m in height. The embankment fill material on the project mostly consisted of non-granular materials derived from glacial deposits (lean clay to sandy lean clays).

The project implemented the MnDOT intelligent compaction (IC) pilot specification titled 2106 - Excavation and Embankment - (QA/QC) IC Quality Compaction (Pilot Specification) for Granular and Non-Granular embankment grading materials. Some key elements of the specification are discussed below.

CP563 (Figure 1) and CP663 padfoot

rollers equipped with machine drive power (MDP) measurement technology (measurements reported as MDP* and see White et al. 2009 for description), real-time kinematic global positioning system (GPS), and AccuGrade compaction mapping system were used on this project.

Three test areas were constructed and tested as part of a field study on this project by Iowa State University (ISU) researchers. One test area consisted of a production area and two test areas consisted of calibration test strips. Results from these test areas are presented in this Tech Brief along with MnDOT quality assurance (QA) test results.

Materials

The embankment fill material in the test areas was classified as lean clay (CL or A-6(6), A-7-6(14), and A-6(11)) soil. The liquid limit of the material varied from about 30 to 43 and the plasticity index varied from about 14 to 19.

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Overview of Project Specifications

The key attributes of the MnDOT 2106 pilot specification included the following: Equipment Specifications, Compaction Process and Acceptance Specifications, Location Specifications (including size, depth, and track overlap) for Production and Calibration Areas for Testing, and Documentation and Reporting Requirements.

As part of the compaction process and acceptance guidelines, the contractor was required to construct a control strip to develop a quality control (QC) procedure including proper IC equipment and procedures, collecting and reporting IC compaction results, ensuring uniformity, confirming acceptable moisture limits and compaction pattern and speed of roller passes, etc. The contractor was required to construct one control strip for each different type/source of grading material used on the construction site to determine the Intelligent Compaction – Target Value (IC-TV) and Light Weight Deflectometer Target Value (IWD-TV). IC-TV was defined as the optimum compaction value determined by the Engineer when optimum compaction was reached (i.e., when additional compaction passes do not result in a significant increase in stiffness).

Three LWD tests were performed by the Engineer on each layer of control strip to determine the average and use as LWD-TV. Moisture was controlled to be within 65% to 95% of standard Proctor optimum moisture content. To determine the moisture sensitivity correction for IC-TV and LWD-TV, the control strip was constructed at or near each extreme of 65% and 95% of optimum moisture content and the data were utilized to produce a correction trend line using a linear relationship. As part of QC, the contractor was required to perform moisture content tests at a minimum of 1 per 3,000 cubic meter for compliance.

QA was accomplished by constructing proof layers in production areas. All segments of proof layers were required to be compacted so that at least 90% of the IC measurements were at least 90% of the IC-TV prior to placing the next lift. In areas < 80% of IC-TV, the contractor was required to bring the areas to at least 90% of IC-TV prior to placing the next lift. If a significant portion of the grade was more than 20% in excess of the IC-TV, the Engineer re-evaluated the IC-TV. QA tests were required with one LWD and moisture test per proof layer per 300 m in length for the entire width of the embankment. The LWD value must be at least 90% but not more than 120% of the corrected LWD-TV. Areas that did not meet these requirements were required to be re-compacted (and dried or added moisture as needed).

MnDOT performed moisture tests using "speedy" moisture tester and LWD tests using a Zorn LWD setup with a 200 mm diameter plate.

Selection of Target Values and QA Test Results

Field observations indicated that the embankment material from the borrow areas was generally wet due to prolonged rain events at the time of ISU field testing. Compaction of fill materials was achieved using the padfoot roller and also by scraper traffic. The research team interviewed both MnDOT and contractor personnel to gain insights on challenges with respect to understanding the technology and implementing IC-TVs and LWD-TVs. Some of the findings are summarized below. Further, LWD, moisture content, and average IC values obtained from QA testing are provided.

Selection of IC-TVs

Prior to the beginning of the project, MnDOT field personnel and the contractor/roller operator had limited experience with the MDP* technology. For this project, minimum threshold values as opposed to target values were agreed to by the inspectors and the contractor. In general, the inspectors and contractors displayed a sense of goodwill toward developing the IC threshold values. This provided the flexibility required to develop acceptance values for the IC rollers on the fly to supplement information gathered from control strips. At the time of ISU field testing, a minimum threshold value of MDP* = 138 was being used at the project site.

Selection of LWD-TVs

MnDOT personnel indicated that similar to IC-TVs, there was limited information on what are reasonable target values for LWD measurements. Therefore, for this project, some common sense and practicality contributed to developing LWD-TVs. Observing pad foot indentations and roller walkout was one of the elements used in developing LWD-TVs. Materials difficult to trim with a motor grader produced LWD moduli ($E_{\rm 1WC}$) values = 60 to 70

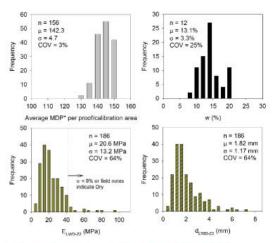


Figure 2. Histogram plots of moisture content, LWD, and MDP* measurements (from White et al. 2009)

QA Test Results by MnDOT

The QA test results of moisture content (w), $E_{\rm LWD}$, LWD deflection values ($d_{\rm LWD}$), and MDP* values are summarized as histograms in Figure 2. Simple linear regression analysis was performed between these measurements to assess the influence of moisture content on $E_{\rm LWD}$ and MDP*, and the relationship between MDP* and $E_{\rm LWD}$. The results are summarized in White et al. 2009, which indicated that the LWD and MDP* values were influenced by changes in moisture content (increasing moisture decreases $E_{\rm LWD}$ and MDP*), MDP* values are empirically correlated with $E_{\rm LWD}$ measurements, and $E_{\rm LWD}$ values are affected by wet/soft layers below the testing surface. Significant scatter was observed in those relationships with R^2 values ranging from 0.1 to 0.2. Regression relationships between these parameter values are further explored through controlled test trip construction and testing and the results are summarized below.

Results from Research Test Strips

Test strips 2 and 3 involved calibration test areas. Test strip 2 consisted of a 36 m long one-dimensional test strip. Motor scrapers were used to place the fill material and a bulldozer was used to level the material in the test strip area (Figure 3). The uncompacted lift thickness of the fill was in the range of 0.3 to 0.5 m. The test strip was compacted with 15 roller passes with two nominal vibration amplitude (a) settings: Pass 1 through 8 at a = 1.87 mm and Pass 9 through 15 at a = 0.85 mm. In situ point measurements were obtained using nuclear gauge (NG), dynamic cone penetrometer (DCP), and Zorn LWD test devices at 0, 4, 8, and 15 roller passes. DCP test results are reported as dynamic penetration index values for top 300 mm (DPI $_{\rm ano}$).

Figure 4 presents MDP* data plots along test strip 2 and corresponding point measurement values after 1, 4, 8, and 15 roller passes. Point measurements showed variations that generally coincided well with variations in MDP* along the test strip. The target minimum E_{190D} and MDP* values used for QA are also shown in Figure 4, for reference.

To assess influence of vibration amplitude on MDP* values, tests strip 3 was evaluated with three 45 m long lanes compacted using different amplitude settings as follows: (3a) static, (3b) a = 0.85 $\,$

mm, and (3c) a = 1.87 mm. LWD tests were conducted after 1, 2, 4, 8, and 12 roller passes, and NG tests were conducted after 12 passes at five test locations across each lane. MDP* compaction growth curves for each lane are presented in Figure 5.

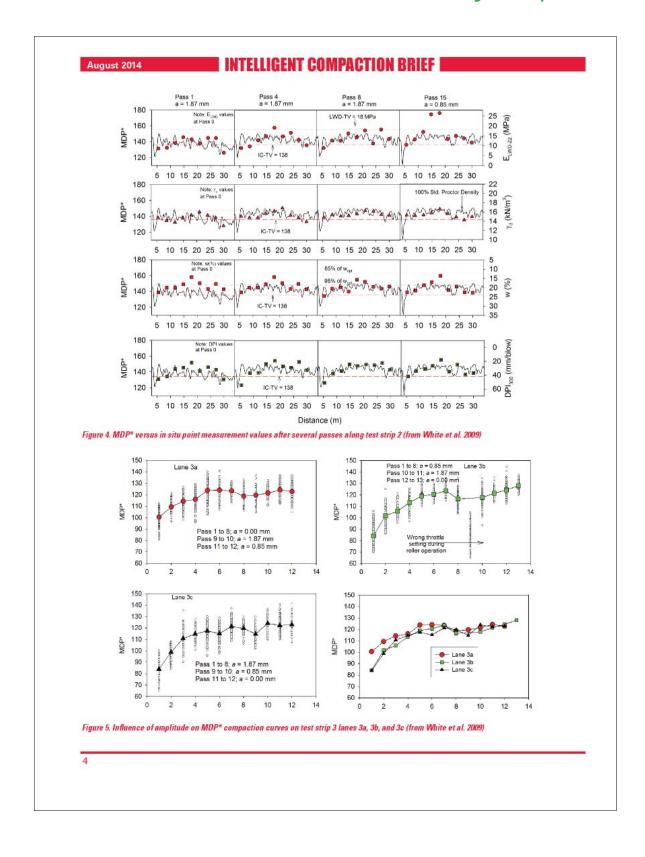
The compaction curves for all lanes followed the same path of increasing average MDP* from pass 1 through 7, some decrease in MDP* after passes 8 and 9, and then a slight increase in MDP* and/or relatively constant MDP* after pass 10. Low MDP* values were recorded for pass 9 on lane 3b, which is a result of a low throttle setting during roller operation. The results did not show any evidence of the influence of vibration amplitude on MDP* on this test strip. However, the material was generally wet of optimum moisture content and variable on this test strip.







Figure 3. Test strip 2 construction and testing (from White et al. 2009)



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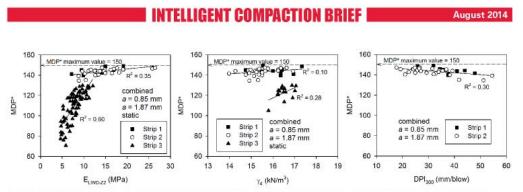


Figure 6. Linear regression relationships between MDP* and LWD, nuclear gauge, and DCP test measurements from test strips 1, 2, and 3 (from White et al. 2009)

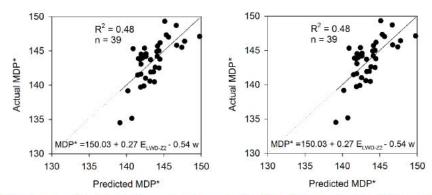


Figure 7. Multiple linear regression relationships incorporating moisture content in predicting MDP* values from DCP and LWD test results (from White et al. 2009)

Regression relationships based on data obtained from research test areas are summarized in Figure 6. MDP* data obtained from test strips 1 and 2 and test strip 3 showed different trends in the relationships with LWD measurement values. MDP* values tended to reach an asymptotic value of 150. The MDP* versus $E_{\rm LWD}$ relationships showed improved correlations for the trends observed with MDP* values less than 138 ($R^2 > 0.4$) and greater than 138 ($R^2 < 0.3$).

MDP*and dry density (γ_d) relationships showed poor correlations with R² values between 0.0 and 0.3.

Similar to correlations between MDP* and E_{LWD} measurements, at MDP* values greater than 138, MDP* and DPI $_{500}$ relationships showed relatively poor correlations with R^2 of about 0.3.

Multiple regression analysis was performed on the data to assess the influence of moisture content and amplitude on relationships between MDP* and E_{LWD} , MDP and γ_0 , and MDP-DPI $_{200}$. The analysis indicated that vibration amplitude was not statistically significant. Moisture content was statistically significant in

predicting MDP* from E_{LWD} and DPl $_{300}$ measurements and improved the R^2 values from 0.37 to 0.48 and 0.30 to 0.45, respectively (Figure 7). Moisture content was not statistically significant in predicting MDP* from γ_d measurements for this dataset.

Summary of Key Findings

- MDP* measurements showed positive correlations with surface $E_{\rm LWD}$ and compaction layer DPI measurements. The regression relationships, however, showed varying degrees of uncertainty with R^2 values varying from about 0.3 to 0.8. Relationships between MDP* and γ_d generally showed poor correlations ($R^2 < 0.3$). Soft or uncompacted zones at depths below about 0.25 m on tests strips 1 and 2 did not affect the MDP*
- Regression relationships improve in predicting MDP* from E_{LWD}
 and DPI when moisture content is included in the regression
 analysis. This illustrates the sensitivity of soil moisture content in
 interpreting MDP* values.

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- Separate trends were observed in MDP* correlations with E_{LWD}, which present a challenge in implementing the QA requirement of a production area meeting 90% to 120% of IC-TV as the limits are applicable only with one linear trend in the data with increasing compaction.
- The wrong throttle and gear settings used during roller operations invalidated IC measurement values for some sections.
 The roller manufacturer recommendation is that the roller should be operated at a high throttle and low gear setting during compaction operations.
- No evidence of influence in vibration amplitude on MDP* was
 found for the material tested on tests strips 2 and 3. On test strip
 3, the average MDP* achieved on all lanes was almost the same
 as on pass 8. The material in the test strips was either close to or
 wet and of optimum moisture content.

Reference

White, D. J., Vennapusa, P., Zhang, J., Gieselman, H., and Morris, M. 2009. Implementation of Intelligent Compaction Performance Based Specifications in Minnesota, Final Report, MN/RC 2009-14, Minnesota Department of Transportation, St. Paul, MN.

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Florida SR 9B – Granular Layered Embankment and Geosynthetic Reinforcement – May 2011

INTELLIGENT COMPACTION BRIEF

PROJECT DATE May 2011

RESEARCH PROJECTTITLE

Geotechnical Solutions for Soil Improvement, Rapid embankment Construction, and Stabilization of the Pavement Working Platform (SHRP 2 Project R02) - Compaction "Roadeo" Field Demonstration

SPONSOR

Second Strategic Highway research Program (SHRP 2)

PRINCIPAL INVESTIGATOR

Vernon R. Schaefer, PhD, PE, Professor of Civil Engineering, Iowa State University

RESEARCHTEAM

David J. White, PhD, PE; Pavana K. R. Vennapusa, PhD, PE; Barry Christopher, PhD, PE; Heath Gieselman, MS; Shiyun Wang, MS; Wayne Rilko, PE; Peter Becker, PE, David Horhota, PE; Sanat Pokharel, PhD; Jitendra Thakur

AUTHORS

Pavana K. R. Vennapusa, PhD, PE; David J. White, PhD, PE; Conter for Earthworks Engineering Research, Institute for Transportation, 2711 South Loop Drive, Suite 4700, Ames, IA 50010-8664

MORE INFORMATION

http://www.ceer.iastate.edu/research/ project/project.cfm?projectID=-159867489

This document was developed as part of the Federal Highway Administration @HWA) transportation pooled fund study TPF-5(233) – Technology Transfer for Intelligent Compaction Consortium (TTICC).

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Project Description

This field demonstration project was conducted on the Florida State Road (SR) 9B construction project in Jacksonville, Florida from May 16 through May 19, 2011. A Caterpillar CS74 vibratory smooth drum self-propelled roller was used on the project. The machine was set up with a roller-integrated compaction monitoring (RICM) system.

Four test beds (TBs) were evaluated using the on-site granular embankment fill material. TBs 1 and 2 involved constructing and testing sections with different types of geosynthetic reinforcement materials. TBs 3 and 4 involved mapping project production areas and selecting test locations based on the color-coded on-board computer display in the roller for in situ testing.

Field testing involved obtaining RICM measurements during the compaction and mapping process and point tests including the following: dynamic cone penetrometer (DCP), static cone penetrometer test (CPT), static plate load test (PLT), falling

weight deflectometer (FWD), light weight deflectometer (LWD), nuclear gauge (NG), and sand cone density. In addition, all test sections of TB1 were instrumented with piezoelectric earth pressure cells (EPCs) to monitor in-ground total vertical and horizontal stresses before, during, and after compaction.

Project Objectives

- Evaluate the use of RICM technology with on-board computer display for compacted fill quality control (QC) and quality assurance (QA) testing
- Evaluate compaction influence depth under the RICM roller
- Evaluate differences in engineering properties between different types of geosynthetic and geocell reinforced fill test sections along with unreinforced fill test section using different QC/QA testing methods
- Evaluate differences in the in-ground dynamic stresses under the roller between different test sections

August 2014

INTELLIGENT COMPACTION BRIEF

· Provide researchers and practitioners with hands-on experience using RICM technology and various QC/QA testing technologies and geosynthetic/geocell reinforcement products

This tech brief presents results of some key findings from the TB1 test area and TBs 3 and 4 production areas. (Detailed results are available in White et al. 2012 and Vennapusa and White 2014).

RICM System Overview

The Caterpillar CS74 roller was equipped with compaction meter value (CMV) and machine drive power (MDP) measurement

CMV is an index parameter (measure of non-linearity) computed as the ratio of drum acceleration amplitude of the first harmonic divided by the acceleration amplitude at the fundamental (eccentric excitation) frequency. This value requires only the measurement of vertical drum acceleration.

MDP relates to the soil properties controlling drum sinkage and uses the concepts of rolling resistance and sinkage to determine the

stresses acting on the drum and the energy necessary to overcome the resistance to motion. MDP is a relative value referencing the





material properties of a calibration surface. Positive MDP values indicate material that is softer than the calibration surface, while negative MDP values indicate material that is stiffer than the calibration surface.

The MDP values obtained from the CS74 machine used in this study were scaled by the manufacturer to range between 1 (high machine resistance) and 150 (low machine resistance) and these re-scaled values are noted as MDP* in this brief.

More information about CMV and MDP* measurements is provided in White et al. 2012.

Test Beds and Material Properties

TB1 involved constructing a test area about 6.2 m wide by 75 m long with six test sections incorporating one control section and several different geosynthetic reinforcement materials into one or two layers of poorly graded sand (A-3 or SP) embankment fill material as follows (Figure 1): biaxial geogrid (BX), nonwoven geotextile geocomposite (C30), polypropylene woven fabric (PPWF), 100 mm geocell (GC100), and 150 mm geocell (GC150)





Figure 1. Geosynthetic reinforcement used on TB1: (a) BX geogrid, (b) GC100/150, (c) C30, and (d) PPWF



Figure 2. TB3 with RAP surfacing (top) and TB4 with embankment

TB3 involved testing a production area with 30 to 120 mm thick recycled asphalt pavement (RAP) surfacing over natural (uncompacted) sand subgrade, which was constructed to serve as a haul road for construction traffic at the site (Figure 2). Plan dimensions of the test area were about 10 m wide by 95 m long. The area was mapped in four roller lanes in low amplitude (a = 0.90 mm), high amplitude (a = 1.80 mm), and static modes. The vibration frequency was set at 30 Hz and the machine was operated at a nominal speed of 4.5 km/h. LWD and DCP tests were conducted at 11 to 12 test locations in the area that were selected using CMV and MDP* color-coded maps on the screen. Test locations were then selected at three to four locations in the low, medium, and high CMV or MDP* values. The RAP material was visually classified as well-graded sand with gravel.

TB4 consisted of a production embankment fill area with A-3 or SP material (Figure 2). Pull-behind scrapers were used for hauling fill material in this area. Compaction occurring under scraper tires and other construction traffic was considered acceptable on this project (i.e., no compactors were used). Plan dimensions of the TB4 area was about 12.5 m wide by 65 m long. The area was mapped in four roller lanes in low amplitude, high amplitude, and static modes. LWD and DCP tests were conducted at 10 test locations in the area.

Field Test Results

Test Bed 1 - Geosynthetic Reinforced Test

On TB1, MDP* and CMV measurements were obtained for multiple passes by operating the machine in opposite travel directions. Results from two passes are shown in Figure 3 for MDP* and Figure 4 for CMV.

These results indicated that both MDP* and CMV RICM measurements are influenced by the roller direction of travel. The MDP* data are reported at the center of the drum. However, the measurements represent the mechanical performance of the whole roller, which are affected by the roller-soil interaction at the front drum and the rear tires.

To assess the amount of influence that the front drum versus the rear tire has on the MDP* measurements, the data obtained from the two passes were repositioned to match the sharp transitions or peaks observed along the TB (Figure 3).

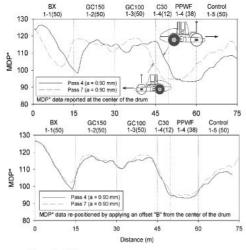
The offset distance for repositioning was observed to be about 2.60 m behind the drum center. Note that this offset calculation inherently assumes that the subsurface conditions under the full length of the roller are the same in both directions of travel when the drum is positioned at a point, which is not true given that each section along this TB has distinctly different reinforcement systems. For example, if the roller is traveling from left to right (0 m to 75 m) and the drum center is positioned at 30 m (BX/GC150 transition), the rear tire is in the BX section. In contrary, if the roller is traveling from right to left (75 m to 0 m), the rear tire is in

Further research is warranted to clearly identify and characterize the relative influence of the front drum versus the rear tires on MDP* measurements and this is an important aspect to further evaluate, because it directly affects how QC/QA test measurements should be obtained to conduct calibration tests and establish target values for acceptance.

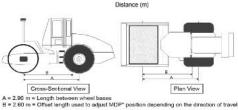
Using a similar procedure explained above for MDP* measurements, the offset distance for CMV measurements was obtained as 0.9 m. Unlike MDP* measurements, the CMV measurements are based purely on drum/soil interaction with minimal influence of rear tires. However, the offsetting occurs because the CMV at a given point indicates an average value over a roller travel length of about 0.5 sec (Geodynamik ALFA-030 undated). The roller travel speed for passes 4 and 7 was about 5.0 km/h. Therefore, the travel distance in 0.5 sec was about 0.7 m, which is very close to the calculated 0.9 m offset distance.

Comparison of RICM measurements between different test sections revealed that the average MDP* was about 1.07 times higher in the geocell sections compared to the control section. The BX section average MDP* was about the same, while the C30 and PPWF section average MDP*s were about 0.90 to 0.95 times the control section average MDP*.

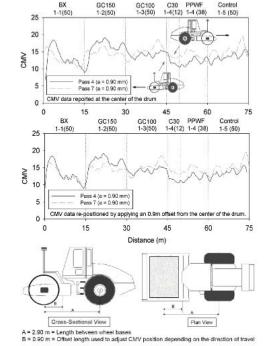
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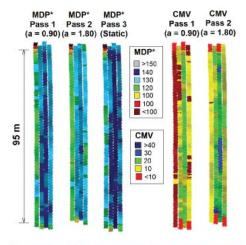






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Figure 4. CMV measurements for two passes in opposite directions before and after offsetting measurement positions and roller schematic showing the measurement offset



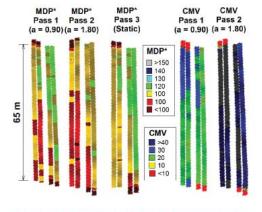


Figure 5. MDP* and CMV maps at different amplitude settings on TB3

Figure 6. MDP* and CMV maps at different amplitude settings on TB4

Test Beds 3 and 4 - Production Areas

CMV and MDP color-coded maps from TBs $\it 3$ and $\it 4$ are presented in Figures 5 and 6, respectively.

On average, MDP* values were higher in TB3 than in TB4. CMV measurements were higher in TB4. These differences between CMV and MDP* measurements on the two test sections are attributed to the differences between their measurement influence depths (MIDs). MID is further explained through correlation analysis below.

Representative DCP-CBR and cumulative blows profiles from each test section are shown in Figure 7. The DCP profile from TB3 shows a thin stiff crust at the surface (CBR > 40) with the RAP material and a relatively uniform CBR with depth (CBR-10) in the underlying natural sand subgrade. The DCP profile from TB4 shows increasing CBR with depth. This trend is due to increasing confinement with depth.

Weighted average CBR up to a depth of 300 mm (CBR $_{200}$) and 800 mm (CBR $_{200}$) below the surface were calculated from each test location for correlation analysis. On TB4, these measurements were calculated by excluding data from the first drop (considering the drop as the seating drop over loose surface material), as well as including data from the first drop.

Correlations between LWD modulus (E_{LWD}) and CBR measurements and roller CMV and MDP* measurements are presented in Figure 8.

Regression relationships and the corresponding statistics (i.e., coefficient of determination (R^2) value, standard error, and number of measurements (n)) are also presented in the figure. The statistical relationship between CMV and E_{LWD} yielded a linear regression model with R^2 = 0.66 for TB3 (Figure 8a).

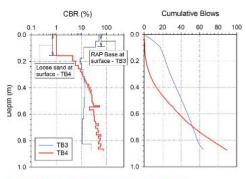


Figure 7. Sample DCP-CBR profiles from TB3 and TB4

The TB4 data did not follow the same trend as the TB3 data. Similarly, the relationship between CMV and CBR $_{300}$ showed that the TB4 data did not follow the same trend as the TB3 data. CMV versus CBR $_{300}$ for TB3 data yielded a non-linear relationship with $R^2=0.77$ (Figure 8c). There was no statistically significant relationship for the TB4 $E_{\tiny LWD}$ and CBR $_{300}$ data with CMV.

The relationship between CMV and CBR $_{800}$ yielded a non-linear exponential model with R 2 = 0.77, including data from both test beds (Figure 8e). The CBR $_{800}$ data calculated excluding first-blow DCP data, correlated better with CMVs than data calculated including first-blow DCP data. This suggests that CMV measurements are not particularly sensitive to loose sand at the surface.

MDP* versus $E_{\rm LWD}$ and MDP* versus CBR $_{\rm 300}$ relationships (Figures 8b and 8d) yielded a non-linear hyperbolic model with $R^2=0.65$ and 0.86, respectively, including data from both test beds. The CBR $_{\rm 300}$ data calculated, including first-blow DCP data, correlated better with MDP* than data calculated excluding first-blow DCP data. This suggests that MDP* values are sensitive to loose material at the surface.

The hyperbolic relationship between CBR $_{300}$ and MDP* suggests that the MDP* values are more sensitive to changes in CBR $_{300}$ up to about 7 than at values less than 7. The relationship between MDP* and CBR $_{800}$ yielded a linear regression model with R^2 = 0.83 for TB4 (Figure 8f). TB3 data did not follow the same trend as TB4 data.

Summary of Key Findings

- Color-coded display with 100% coverage of compaction area was effective in selecting "soft" and "stiff" areas for spot testing.
- RICM measurements generally were better correlated with LWD and DCP-CBR spot test measurements than with NG density measurements (see White et al. 2012 for results).
- MDP* measurements were influenced by the direction of travel. This is because the MDP* measurements represent the mechanical performance of the whole roller, which are affected by the roller-soil interaction at the front drum and the rear tires, and the results are only reported at the center of the drum. The offset distance for MDP* measurements is observed to be about 2.60 m behind the drum center. This is an important aspect to further evaluate because it directly affects how QC/QA test measurements should be obtained to conduct calibration tests and establish target values for acceptance.
- CMV measurements were also influenced by the direction
 of travel. The offsetting occurs because the CMV at a given
 point indicates an average value over a roller travel length
 corresponding to a measurement interval of about 0.5 sec.
- CMV has a deeper measurement influence depth (up to 1 m) than MDP* (< 0.5 m). The stiff surface layer of RAP material on TB3 influenced MDP* measurements more than CMV measurements.

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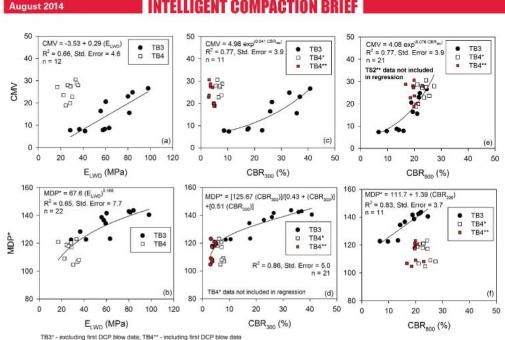


Figure 8. Regression relationships between (a) CMV and E_{two} (b) MDP* and E_{two} (c) CMV and CBR_{so} (d) MDP* and CBR_{so} (e) CMV and CBR_{so} and (f) MDP* and CBR_{seo}

- · When data from TBs 3 and 4 are combined, MDP* correlated well with E_{DWD} and CBR_{300} (which represents the material properties in the top 300 mm). The data did not follow the same trend when MDP* data was correlated with CBR₈₀₀ (which represents the material properties in the top 800 mm).
- · When data from TBs 3 and 4 are combined, CMV correlated well with CBR₅₀₀. The data did not follow the same trend when CMV was correlated with E_{LWD} and CBR₃₀₀.
- CBR_{son} correlated better with CMV measurements when the first DCP drop was excluded (considering it as a seating drop) for TB4 data, where the material was loose at the surface due to no confinement, than when the first DCP drop was included. On the other hand, CBR₃₀₀ data correlated better with MDP measurements when the first DCP drop was included for TB4 data. This suggests that the MDP* measurements are influenced by the loose sand at the surface, while CMV is not.

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Evaluating Benefits and Limitations of Intelligent Compaction

onstruction of high-quality pavements is dependent on achieving adequate density or compaction throughout the supporting soil, base and pavement layers. The objective of achieving a specified density is to ensure a minimum layer stiffness and strength of the upper layers and to reduce the likelihood of detrimental, long-term changes in the properties of the supporting materials. Currently, density is evaluated by either visual inspection (typical for embankments in Wisconsin) or in-place density measurements with nuclear density gauges or other devices.

What's the Problem?

Because of soil variability and other factors, it can be difficult to achieve and measure the desired density during compaction. A technology called intelligent compaction shows promise for improving this process on unbound soil and aggregate materials as well as on in-place asphalt mixtures. IC is called "intelligent" because the compaction rollers are equipped with sensors that measure density on a continuous basis; and an on-board computer collects and displays density measurements for each small section of the site as determined by a Global Positioning System unit. The operator is then able to monitor layer stiffness and adjust compactive effort in real time to achieve uniform and acceptable density across the entire site.

Research Objectives

The goals of this project were to help WisDOT evaluate the advantages and limitations of IC for achieving density, and to determine the material types and conditions that might cause inaccuracies in IC roller output concerning layer stiffness and other properties.

Methodology

Researchers evaluated IC technologies on three projects in Wisconsin, including two for unbound materials and one for HMA. IC rollers were used to evaluate the densification of unbound subgrade, subbase and base materials on WIS 18 west of Jefferson, WIS 80 north of Highland and US 45 near Eden. Specifically, material types included:

- · Subgrade: Low (WIS 18) and high (WIS 80) plasticity clays
- · Subbase: One lift of silty sand (WIS 18)
- Base layers: Crushed aggregate base course (WIS 18/WIS 80) and recycled asphalt (WIS 80)
- · HMA overlay (US 45)

To evaluate the accuracy of IC measurements, researchers compared IC output to the results of various field tests. For the WIS 18 and WIS 80 unbound materials projects, researchers used a dynamic cone penetrometer to measure stiffness and strength, a nuclear gauge to measure density and water content, and a geogauge to measure elasticity. On the US 45 HMA project, researchers evaluated in-place density using a non-nuclear density gauge and portable seismic pavement analyzer. As a measure of uniformity, an infrared camera was used to monitor surface temperatures, variations in which can indicate potential differences in air void content and gradation. Samples were collected from each project for laboratory characterization of physical and mechanical properties to compare to the data output from the IC rollers.

Results

For unbound materials, demonstration projects indicate that IC is an effective technology for contractors to map the stiffness of layers and identify weak areas prior to the placement of subsequent layers. IC rollers can also be used to determine the best rolling patterns and number of passes to achieve a





technology for compaction of by contractors to more efficiently meet WisDOT's compaction requirements.

-Harold L. Von

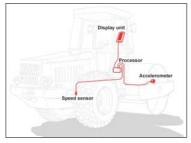
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technology has the potential to provide feedback on the uniformity and degree of compactive effort on both subgrades would be valuable information for hoth contractors

Len Makowski





Intelligent compaction rollers are equipped with a speed sensor, an accelerometer to measure drum vibration, and a processor that analyzes this data and sends it to a unit that displays a color-coded map of stiffness in the area being compacted.

specific stiffness level in unbound layers, identify when aggregates are being damaged by over-rolling, compact deeper lifts by optimizing compactive effort, and identify locations for point measurements with field devices during construction quality assurance.

However, interpretation of IC data is not a simple process, and IC rollers produce a composite stiffness value that is influenced by both the layer being compacted and its supporting layers. The research recommends that these challenges be addressed through use of control strips and field-test devices in conjunction with IC to develop adjustment factors and to define rolling patterns and roller settings.

Researchers cautioned against the immediate use of IC for HMA because at this point, IC rollers are only used as the breakdown roller; thus further densification of the HMA layer due to compaction by intermediate and finish rollers cannot be captured through use of IC technology. Furthermore, roller response for HMA layers is heavily influenced by supporting layers; as a result, stiffness measurements by IC rollers differ significantly from laboratory tests.

Benefits and Implementation

With further research, IC has the potential to lower construction costs, improve the uniformity of compaction, and increase pavement performance and service life. However, researchers cautioned against requiring contractors to use IC until this technology is more established and uniform equipment output values are established. Rather, IC provides an additional tool that some contractors may utilize to meet WisDOT's compaction requirements in a cost-effective manner. Researchers presented the details of their findings in a Webinar, available at http://www.whrp.org/research-areas/flex/flex_0092-08-07_closeout_webinar.html.

Further Research

More research is needed on the reliability and accuracy of the IC measures, confirmation of improvement in the uniformity of compaction, and quantification of IC's economic benefits. Research is also needed to investigate the effect of lift thickness on IC output and to correlate the IC output from different manufacturers' reporting systems to standard measures of acceptance. WisDOT has no plans in the near future for additional IC pilot projects, but will follow national research on IC as the technology is developed.

This brief summarizes Project 0092-08-07, "Evaluation of Intelligent Compaction Technology for Densification of Roadway Subgrades and Structural Layers," produced through the Wisconsin Highway Research Program for the Wisconsin Department of Transportation Research Program, P.O. Box 7915, Madison, WI 53707.

Daniel Yeh, WisDOT Research and Communication Services

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2010

A Road Map for Implementation of Intelligent Compaction Technology

David J. White¹, M. ASCE, P.E., Pavana Vennapusa², A.M. ASCE, and Mark Dunn³, P.E.

¹ Associate Professor, Dept. of Civil Construction and Environmental Engineering, Director, Center for Earthworks Engineering Research (CEER), Iowa State University, Ames, Iowa, <u>djwhite@iastate.edu</u>

ABSTRACT: Over the past few years, intelligent compaction (IC) has been a focus of research, demonstration projects, and specification development in the U.S. Federal Highway Administration (FHWA) has recently moved IC to national level implementation. Equipment manufacturers, individual state DOTs and the Technology Transfer for Intelligent Compaction Consortium (TTICC), a Transportation Pooled Fund, TPF–5(233) initiative, are also focusing on implementation efforts. What this paper does is describe the results of a series of workshops attended by more than 400 attendees—representing several state DOTs, FHWA, equipment manufacturers and researchers—that contributed to a detailed roadmap identifying implementation needs and action items. A key outcome of these workshops was the development of a prioritized list initially created in a 2008 and updated annually through 2012. This paper describes in greater details how this list was developed and prioritized and how it has changed since being initiated in 2008. Accompanying this list is a set of action items to overcome the various barriers identified. (Words = 162)

INTRODUCTION

Increasingly, state departments of transportation (DOTs) are challenged to design and build longer life pavements that result in a higher level of user satisfaction for the public. One of the strategies for achieving longer life pavements is to use innovative technologies and practices. In order to foster new technologies and practices, experts from state DOTs, Federal Highway Administration (FHWA), academia and industry must collaborate to identify and examine new and emerging technologies and systems. As a part of this effort, the Iowa DOT and the Center for Earthworks Engineering Research (CEER) have been hosting workshops on Intelligent

² Research Assistant Professor, Dept. of Civil Construction and Environmental Engineering, Assistant Director, Center for Earthworks Engineering Research (CEER), Iowa State University, Ames, Iowa, pavanv@iastate.edu
³ Iowa Department of Transportation, Operations Research Engineer, Office of Research & Analytics, Ames, Iowa, mark.dunn@dot.iowa.gov

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2011

Compaction since 2008, and developed a roadmap to address the research, implementation, and educational needs to integrate IC into practice. Realizing that a national forum is needed to provide broad leadership that can rapidly address the needs and challenges facing DOTs with the adoption of IC technologies, the Iowa DOT initiated the TTICC project under the Transportation Pooled Fund Program (TPF Study Number 5(233)). The purpose of this pooled fund project is to identify, support, facilitate and fund intelligent compaction (IC) research and technology transfer initiatives. The following state highway agencies participated in this study: California, Georgia, Iowa, Kentucky, Missouri, Mississippi, Ohio, Pennsylvania, Utah, Virginia, and Wisconsin. In addition to the partner states, the of workshops have had input from more than 400 attendees—representing several additional state DOTs, FHWA, equipment manufacturers and researchers—that contributed to a detailed roadmap identifying implementation needs and possible action items.

The goals of the TTICC are as follows:

- Identify needed research projects
- Develop pooled fund initiatives
- Plan and conduct an annual workshop on intelligent compaction for soils and asphalt
- Provide a forum for technology exchange between participants
- Develop and fund technology transfer materials
- Provide on-going communication of research needs faced by state agencies to the FHWA, states, industry, and the CEER

This paper presents the details and summary of findings from the various workshops. Additional details of the workshops and outcomes are reported in White et al. 2008, White et al., 2009, White et al., 2010, White et al., 2011 and White et al., 2012.

RESEARCH/IMPLEMENTATION NEEDS

A key outcome of the workshops was the development of a prioritized list initially created in a 2008 and updated in 2009, 2010, 2011, and 2012. The top IC research needs currently include:

- 1. Data management and analysis
- 2. Specifications/Guidance
- 3. In-Situ Correlations
- 4. Understanding impact of non-uniformity of performance
- 5. Standardization of roller outputs and format files
- 6. Standardization of roller sensor calibration protocols
- 7. Education program/certification Program
- 8. Understanding roller measurement influence depth
- Project scale demonstration and case histories
- 10. In-situ testing advancements and new mechanistic based QC/QA
- 11. Intelligent compaction technology advancements and innovations

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2012

- Intelligent compaction research database
- 13. Impact on sustainability

Table 1 provides a detailed description of each of the roadmap elements. Table 2 presents the change in the ratings of different roadmap elements since 2008, highlighting the transition of the top three elements. The intelligent compaction specifications and in situ correlations road map elements have remained in the top two between 2009 and 2011. The data management road map element was rated as the top one this year. Progress with pilot IC specifications recently implemented by the DOTs and first-hand experience on challenges associated with real-time data transfer and analysis has shaped the prioritized rankings. Table 3 presents the action items identified for the TTTIC group, industry, and FHWA, on each of the roadmap elements.

Table 1. IC road map research, implementation, and educational elements

IC Road Map Research, Implementation, and Educational Elements

- 1. Data Management and Analysis. The data generated from IC compaction operations is 100+ times more than traditional compaction QC/QA operations and presents new challenges. The research element should focus on data analysis, visualization, management, and be based on a statistically reliable framework that provides useful information to assist with the construction process control. This research element is cross cutting with elements 2, 3, 5, 7, 8, 11, and 12.
- 2. Intelligent Compaction Specifications/Guidance. This research element will result in several specifications encompassing method, end-result, performance-related, and performance-based options. This work should build on the work conducted by various state DOTs, NCHRP 21-09, and the ongoing FHWA IC Pooled Fund Study 954. The new specifications should be technology independent and should allow use of different QC/QA testing devices and IC measurement values. This research element is cross cutting with elements 3, 5, 6, 7, and 8.
- 3. Intelligent Compaction and In Situ Correlations. This research element will develop field investigation protocols for conducting detailed correlation studies between IC measurement values and various in situ testing techniques for earth materials and HMA. Standard protocols will ensure complete and reliable data collection and analysis. Machine operations (speed, frequency, vibration amplitude) and detailed measurements of ground conditions will be required for a wide range of conditions. Relationships between HMA and WMA mix temperature, roller measurement values, and performance should be developed. A comprehensive research database and methods for establishing IC target values will be the outcome of this study. Information generated from this research element will contribute to elements 2, 7, 8, 10, and 12. There is a need to define "gold" standard QC/QA in-situ test measurement for correlations depending on the material type (i.e., soils, base, or asphalt).
- 4. Understanding Impact of Non-Uniformity on Performance. This track will investigate relationships between compaction non-uniformity and performance/service life of infrastructure systems—specifically pavement systems. Design of pavements is primarily based on average values, whereas failure conditions are affected by extreme values and spatial variations. The results of the research element should be linked to MEPDG input parameters. Much needs to be learned about spatial variability for earth materials and HMA and the impact on system performance. This element is cross cutting with elements 1, 2, and 7.
- Standardization of Roller Outputs and Format Files. This research element involves developing a standardized format for roller output and format files. This element crosscuts with specification element 2.
- 6. Standardization of Roller Sensor Calibration Protocols. IC rollers are equipped with measurement

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sensors (e.g., accelerometers in the case of vibratory-based technologies), GPS, data logging systems, and many on-board electronics. These sensors and electronics need periodic maintenance and calibration to ensure good repeatability in the measurement systems. This research element will involve developing a highly mobile mechanical system that could simulate a range of soil conditions and be deployed to a project site to periodically verify the roller output values. Further, establishment of a localized calibration center (similar to a falling weight deflectometer calibration center) by a state agency can help state agencies periodically verify the repeatability and reproducibility of the measurements from their sensors and other electronics.

- 7. Education Program/Certification Programs. This educational element will be the driver behind IC technology and specification implementation. Materials generated for this element should include a broadly accepted and integrated certification program that can be delivered through short courses and via the web for rapid training needs. Operator/inspector guidebook and troubleshooting manuals should be developed. The educational programs need to provide clear and concise information to contractors and state DOT field personnel and engineers. A potential outcome of this element would be materials for NHI training courses.
- 8. Understanding Roller Measurement Influence Depth. Potential products of this research element include improved understanding of roller operations, roller selection, interpretation of roller measurement values, better field compaction problem diagnostics, selection of in situ QA testing methods, and development of analytical models that relate to mechanistic performance parameter values. This element represents a major hurdle for linking IC measurement values to traditional in situ test measurements.
- 9. Project Scale Demonstration and Case Histories. The product from this research element will be documented experiences and results from selected project level case histories for a range of materials, site conditions, and locations across the United States. Input from contractor and state agencies should further address implementation strategies and needed educational/technology transfer needs. Conclusive results with respect to benefits of IC technology should be reported and analyzed. Information from this research element will be integrated into elements 1, 2, 4, and 7.
- 10. In Situ Testing Advancements and New Mechanistic Based QC/QA. This research element will result in new in situ testing equipment and testing plans that target measurement of performance related parameter values including strength and modulus. This approach lays the groundwork for better understanding the relationships between the characteristics of the geo-materials used in construction and the long-term performance of the system.
- 11. Intelligent Compaction Technology Advancements and Innovations. Potential outcomes of this research element include development of improved IC measurement systems, addition of new sensor systems such as moisture content and mat core temperature, new onboard data analysis and visualization tools, and integrated wireless data transfer and archival analysis. Further, this research element will also explore retrofitting capabilities of IC measurement systems on existing rollers. It is envisioned that much of this research will be incremental and several sub-elements will need to be developed.
- 12. Intelligent Compaction Research Database. This research element would define IC project database input parameters and generate web-based input protocols with common format and data mining capabilities. This element creates the vehicle for state DOTs to input and share data and an archival element. In addition to data management/sharing, results should provide an option for assessment of effectiveness of project results. Over the long term the database should be supplemented with pavement performance information. It is important for the contractor and state agencies to have standard guidelines and a single source for the most recent information. Information generated from this element will contribute to elements 2, 3, 7, 9, and 10.
- 13. Sustainability. This research element involves evaluating benefits of IC in terms of sustainability aspects such as the potential for use of less fuel during construction, reduced life-cycle and infrastructure maintenance costs, etc.

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Table 2. IC Research, Implementation, and Educational Elements – Ratings from 2008 to 2012

Rating	2008 ¹	2009 ²	2010 ³	2011 ⁴	2012
1	Correlations	Specifications	Correlations	Correlations	Data Management
2	Education	Correlations	Specifications	Specifications	Specifications
3	Moisture Content Influence	Mechanistic QC/QA	Mechanistic QC/QA	Data Management	Correlations
4	Data Management	Non-Uniformity	IC Advancements	Demo Projects	Non-Uniformity
5	Demo Projects	Data Management	Demo Projects	Education	Output Standardization
6	Mechanistic QC/QA	Demo Projects	Non-Uniformity	Non-Uniformity	Sensor Calibration
7	Non-Uniformity	Influence Depth	Data Management	Output Standardization	Education
8	Specifications	IC Advancements	Output Standardization	Database	Influence Depth
9	Influence Depth	Education	Influence Depth	Mechanistic QC/QA	Demo Projects
10	Promoting Best Practices	Database	Education	Influence Depth	Mechanistic QC/QA
11	-	-	Database	IC Advancements	IC Advancements
12	-	_	Sensor Calibration	Sustainability	Database
13	-	-	-	Sensor Calibration	Sustainability

DATA VISUALIZATION AND MANAGEMENT

On the topic of data visualization and management, IC technology provides the opportunity to collect and evaluate information for 100 percent of the project area, but it can also produce large data files that create analysis, visualization, transfer, and archival challenges. Thus, approaches for managing the data need to be developed. IC measurement values referenced to GPS coordinates are spatially referenced, which can be useful for targeting QA testing and signaling to the contractor where additional rolling or rework is needed. Figure 1 shows an example data set for visualization and analysis for CMV data overlaid with in situ measurement values. This approach has the advantage of linking IC and in situ test measurements with electronic plans. IC data output files have various formats that include *.xls, *.txt, *.csv, and *.dbf file types. Memory required for data storage will vary with the file type. For a section with plan dimensions of approximately 250 meters by 10 meters with compaction performed in five roller lanes, the memory required for single point data (assigned to one location across the drum) is approximately one to two megabytes for *.xls, *.txt, .csv, and *.dbf file formats.

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2015

Table 3. Possible Action Items for the TTICC Project Team, Industry, and $\ensuremath{\mathrm{FHWA}}$

List of Action Items	TTICC	Industry	FHWA
1. Data Management and Analysis			
a. Define requirements	×		
b. Discuss with other state DOTs	x		
c. Enhance Capabilities of Software's		х	
d. Need Real Time Data Processing/Delivery Capabilities		x	
e. Need Improvements in Position Accuracy (vertical)		x	
f. Data Analysis Software		^	x
2. IC Specifications/Guidance			A
Post Examples and Current Specifications Online (Use CEER Website)	Х		
b. Establish a Review Committee	Х		
c. Develop a Standard Outline	Х		
d. Create On-Line Mechanism to Track Document Updates (versions)	Х		
e. Be Informed of TTICC Activities (CEER Website)		X	X
f. Review Specifications		X	X
g. Share TTICC Vision		x	
3. IC and In Situ Correlations			
 a. Develop a Standard Calibration Procedure (Non-Nuclear Gauge) 	X		
 Problem Statement to Better Assess Influence of Moisture Content 	x		
 Problem Statement for Roller Measurement Value Relationships with Resilient 			
Modulus for Pavement Layers and Shear Strength Measurements for	x		
Embankments			
d. Support Research Efforts			X
4. Understanding Impact of Non-Uniformity on Performance			<u>^</u>
a. Develop problem statement for ACC/PCC pavements – Accelerated Testing	x		
b. Support Research – In-Kind Contributions	^	x	
c. Support Research Efforts		^	x
			X
5. Standardize Roller Outputs and Format			
Define and Establish Criteria	X		
Refine Software Based on TTICC Recommendations		Х	
c. Data Viewing Software Tool			Х
6. Standardize Roller Sensor Calibration Protocols			
 Research to Develop a Standard Calibration Device 	X		
 Discuss at TRB Rock/Instrumentation Committee 	X		
c. "Golden" Accelerometer for Sensor Calibration		x	
d. Calibration Protocols (How Often?)		x	
e. Support Research Efforts			X
7. Education and Certification Programs			
a. Develop Videos (IC101, 201, 202)	x		
b. Operator Training Programs	^	x	
8. Understanding Measurement Influence Depth		^	
	Х		
b. Use 2-Layer Elastic Theory to Describe Behavior (new research)	X		
9. Demonstration Projects and Case Histories			
Continue Developing IC Briefs	X	x	X
 Share IC Briefs to Wider Audience through TRB E-News Letter 	X		
 Address Equipment Availability/Serviceability Issues 		х	
d. Demonstrate Repeatability of Measurement Values		x	
10. In Situ QC/QA Testing Advancements			
a. Link to #3 Correlations and #2 Specifications	x		
11. IC Technology Advancements/Innovations			
a. Describe Need	x		
b. Moisture Content Measurements on Roller for Soils	^	х	
		x	
		X.	
c. Enhancements of Temperature Measurements for HMA [Mat Temperature]			
12. IC Research Database			
12. IC Research Database 1. Continue Developing IC Briefs	х	x	х
12. IC Research Database	x x	х	X

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2016

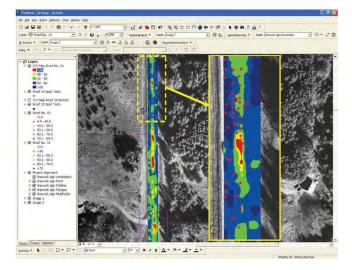


FIG. 1. Example of IC data visualization and management using GIS platform.

Figure 2 shows and example of showing the IC data in a multi-dimensional simulation. The data represents the field measured values while the background is based on the #-D geometry of the projects. Materials are represented by colors. Additional data can be posted to these simulated environments and is an area of ongoing research.

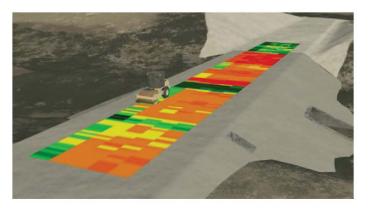


FIG. 2. Example of IC data visualization and multi-dimensional simulation

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CONCLUSIONS

Some of the key outcomes from this workshop were as follows:

- Served as a forum for discussion between state DOT, FHWA, and industry representatives in addressing the challenges in implementing the IC technology.
- 2. Updated and prioritized the IC technology research, implementation, and educational needs road map.
- 3. Developed an outline of content for an IC 101 video
- Developed list of action items for the TTICC group, industry, and FHWA to advance and accelerate implementation of IC technology into earthwork and asphalt construction practice.

The discussion between the TTIC group, FHWA and industry representatives identified three major focus areas that need immediate attention to advance and effectively implement IC technology into US construction practice.

- Develop new data management, analysis, and visualization tools
- Define and establish new standards for quality in road building (performance based specifications)
- Explore alternative contract delivery modes for construction projects that support innovation

ACKNOWLEDGMENTS

The Center for Earthworks Engineering Research (CEER) at Iowa State University of Science and Technology gratefully acknowledges the Iowa Department of Transportation (DOT) for hosting the workshop and the support of the following participating state agencies: California DOT, Georgia DOT, Iowa DOT, Kentucky DOT, Missouri DOT, Mississippi DOT, Ohio DOT, Pennsylvania DOT, Utah DOT, Virginia DOT, and Wisconsin DOT. Sharon Prochnow and Denise Wagner of the CEER provided administrative support in organizing and executing the workshop. The CEER also sincerely thanks the following individuals for their support of this workshop:

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Report of the 3rd Workshop for Technology Transfer for Intelligent Compaction Consortium (TTICC) Transportation Pooled Fund Study Number TPF-5(233)

- GeoCongress 2014 Article — A Road Map for Implementation of Intelligent Compaction Technology by White, Vennapusa, and Dunn

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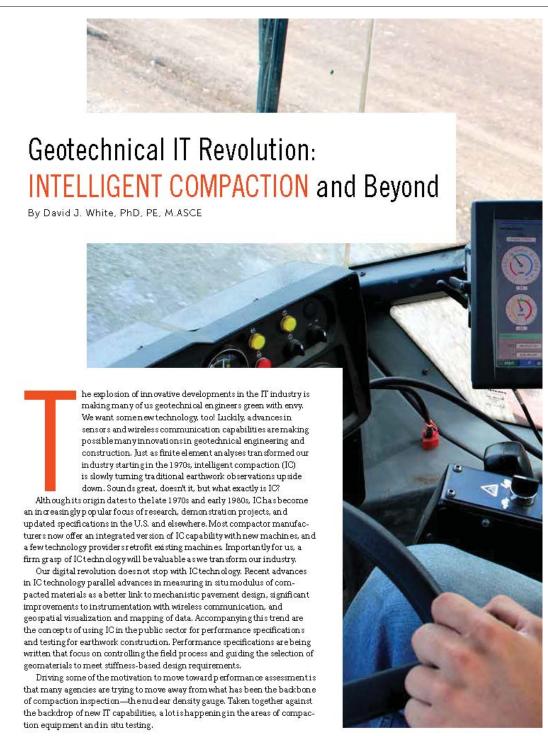
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- White, D.J., and Vennapusa, P. (2012). Report of the 2nd Workshop for Technology Transfer for Intelligent Compaction Consortium (TTICC). Workshop Organized by the Center for Earthworks Engineering Research (CEER) at Iowa State University and the Iowa Department of Transportation, March 6-7, Ames, Iowa

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Technology Transfer for Intelligent Compaction Consortium (TTICC) TPF-5(233) 3rd Workshop Meeting, September 3-4, 2014, Harrisburg, PA

LIST OF IC SPECIFICATIONS FOR SOILS AND HMA IN UNITED STATES UPDATED_8/21/2014

Developed By	HMA (Year)	Soils (Year)		
Alaska DOT	Yes (2013)	No		
California DOT	Yes (2014)	No		
Georgia DOT	Yes (2012)	Yes (2012)		
Iowa DOT	Yes (2013)	Yes (2010)		
Indiana DOT	Yes (2014)	No		
Massachusetts DOT	Yes (2013)	No		
Minnesota DOT	Yes (2014)	Yes (2014)		
Missouri DOT	No	Yes (2009)		
North Carolina DOT	Yes (2013)	Yes (2012)		
Nevada DOT	Yes (2012)	No		
Oklahoma DOT	Yes (2014)	No		
Pennsylvania DOT	Yes (2014)	No		
Rhode Island DOT	Yes (2013)	No		
Tennessee DOT	Yes (2013)	No		
Texas DOT	No	Yes (2013)		
Utah DOT	Yes (2013)	No		
Vermont DOT	Yes (?)	Yes (?)		
SHRP2 R07	No	Yes (2014)		
FHWA (Generic Specs)	Yes (2014)	Yes (2014)		



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Figure 2. Geospatially referenced IC color map

What Is Intelligent Compaction?

The words "intelligent compaction" mean different things to some industries or agencies. IC was originally called "continuous compaction control" (CCC) as defined in Europe, where IC was reserved for CCC compactors with integrated control algorithms that automatically adjust vibration amplitude and/or vibration frequency. The automatic feedback was the "intelligent" aspect and was primarily used to prevent chaotic motion while vibrating on hard ground. However, CCC was limited because the "control" aspect did not exactly reflect control of the actual compaction. Further, CCC and IC definitions were limited only to compactors that vibrated, whereas new technologies provide measurements in the non-vibratory mode. Consequently, the word "intelligent" became trendy as shorthand used at meetings and conferences, which contributed to the confusion.

Now ICr epresents a catch-all category of compactors with integrated sensors that measure machine-ground interaction properties and various machine operation al (e.g., p ass count) and position measurements. Figure 1 provides the operator per spective of the real-time IC monitoring screen. Currently, three approaches relate machine-integrated measurements to ground properties: 1) vibration frequency domain analysis; 2) vibration analysis coupled with dynamic modeling; and 3) non-vibratory machine drive power measurement. There will probably be new approaches developed in the future as well. Without going into the equations, the goal of the different approaches is the same: to output IC values that can be linked

to engineering measurements that contractors can use to monitor compaction productivity and inspection personnel can use to maintain an effective QC/QA process. That said, IC values are machine-specific and require site calibration with independent testing.

Figure 2 shows how IC measurement data can be presented as a color-coded, GPS-referenced spatial map. The color scale can be calibrated using stiffness-based in situ testing, such as plate load tests. In general, density is not used to calibrate IC values for earthworks, but has been reportedly used with some success on asphalt. Many reports and papers describe the limits of IC correlations for earthwork operations (e.g., NCHRP Report 676, Intelligent Soil Compaction Systems).

The data generated from IC measurements include a measurement value, machine position, speed, direction, vibration settings and time of measurement. Figure 3 shows an example of IC data from a project involving compaction of coal combustion waste. The color scale was set so that the green and blue areas met the minimum compaction criteria based on calibration with a dynamic cone penetrometer. In general, areas colored yellow or red have low strength due to high moisture content or inadequate compaction. Presenting the results in this fashion allows operators to spatially identify areas of non-compliance.

Plots of the compactor coverage and pass count can also be produced. This approach can be useful to contractors that have a method specification (e.g., one pass per inch of

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Figure 3.1C data from study on compaction of CCPs showing weak areas.

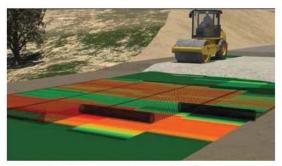


Figure 4. Using I C as precision construction tool to identify and treat localized unstable areas.

loose lift thickness) and to document compaction effort and lift thickness. This real-time information brings value to the contractor during the construction process, but should also have value longer term when things go bad and the attorneys start calling. Using the IC records as part of a defense has yet to be tested. In general, however, the method process of pass counting is losing favor to end-result acceptance criteria. What has been discovered is that the number of roller passes does not guarantee quality of compaction and can be inefficient and expensive for the contractor due to wasted rolling effort and fuel consumption.

Where is intelligent Compaction Being Used?

Recent data compiled by the Center for Earthworks Engineering Research at Iowa State University (CEER) shows that IC has been used on more than 120 public-sector projects in the U.S. and that the annual number of projects is trending upward. These projects include construction of embankments, pavement subgrades and granular bases, chemically stabilized soils, hot-mix asphalt, earth-retaining structures, mechanically reinforced soils, and backfill compaction around box culverts. IC compactors used for asphalt compaction are additionally outfitted with sensors to report surface temperature. Additional details with case histories for many of these projects can be viewed at www.ceer.tastate. edu. Additional details about uses for IC can be found at www.geotechtool.org and www.intelligentcompaction.com. The Federal Highway Administration is currently helping to implement IC technology nationwide, with a primary focus on a sphalt (www.fkwa.dot.gov/everydaycounts).

The U.S. Army Corps of Engineers used IC in 2007 to build a runway in a remote location in Australia. Military projects are partly motivated by rapid construction requirements and limiting "boots on the ground." In short, it appears that IC-equipped compactors can be used anywhere that compactors are used.

Driving some of the motivation to move toward performance assessment is that many agencies are trying to move away from what has been the backbone of compaction inspection—the nuclear density gauge.

What Are Some of the Challenges in implementing IC?

Not unlike adoption of other innovative technologies, IChas suffered from slow implementation over the past 10 years. Barriers to implementation were compiled from workshops with more than 400 participants (primarily public agency engineers) through 2013. The barriers in dude:

- Need for improved data management and analytical software tools
- Lack of proper specifications
- No understanding of calibration and in situ correlation testing
- No guidance on dealing with non-uniformity of compacted materials
- Limited training and no certification
- Need for additional project scale demonstrations and case histories

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Geostrata 2014 Article, Geotechnical IT Revolution: Intelligent Compaction and Beyond, by David J. White

Today, intelligent compaction represents a catch-all category of compactors with integrated sensors that measure machine-ground interaction properties and various machine operational (e.g., pass count) and position measurements.

- Need for better in situ testing capabilities linked to mechanistic design
- Desire for additional IC features and innovations

To address some of these implementation challenges, a group of state departments of transportation developed the Technology Transfer for Intelligent Compaction Consortium (TTICC), a Transportation Pooled Fund, TPF–5(233) to study implementation efforts. The Consortium created a video, "Intelligent Compaction 101," which can be viewed at www. youtube.com/watch?v=6ZIcBx21Txs. The video describes current challenges in earthwork operations and applications of IC to overcome limitations in testing. A downtrend in field inspection staff was identified in the video as a motivation for implementing IC technology. The video highlights features of IC and uses animations to explain the technology.

Figure 4 illustrates the concept of an IC map with colors that show an area with low stiffness. A geogrid is used to fix a "bad spot" before the next layer is placed. This simple illustration represents the powerful idea that local areas of non-compliance can be identified and fixed before they become more costly performance problems. When using traditional sampling techniques, which do not provide continuous coverage, these kinds of localized problem areas often go undetected.

In terms of data management and analytical software tools, IC technology provides the opportunity to collect and evaluate information for 100 percent of a project area, but it also produces very large data sets that create analysis, visualization, transfer, and archival challenges. Also, contractors and field inspection personnel generally are not interested in, nor do they have the time to be involved with, intensive data management and plotting. This major challenge to widely spread IC implementation calls for new approaches for managing IC data. As a result, technology providers have ramped up the development and production of new data analysis tools and processes, such as sending data to the cloud, using local mesh networking for data sharing, and viewing data via hand-held technology. This is a very exciting time to be involved with IC compaction work!

As a reference for data management, IC data can be output in several formats (e.g., *.xls, *.xx, *.csv, and *.dbf). The memory required for data storage will vary with the file type and information collected. For example, IC data for a section with plan dimensions of approximately 1000 ft by 50 ft is normally less than one megabyte.

What Does IC Hold In the Future for Geotechs?

Given the significant investment on the part of equipment manufacturers and U.S. government agencies, the future is bright for continued adoption of IC technologies. There are a few early adaptor agencies such as the Minnesota Department of Transportation, and many other state agencies are in the process of adoption. Given the rapid advancement of technology over the past 10 years, it's exciting to think about what the next decade will hold. It's worth noting that the technology used in today's mature precision agriculture industry and supporting agribusinesses represents a parallel revolution for the future of geo-construction, where instrumented construction machines providing geotechnical information can be supported by new geo-businesses.

Is it possible that IC compactors will be providing real-time analysis to your smart phone for projects anywhere in the world? Yes. Is it possible that the compaction process will become more automated/robotic? Yes. Is it possible that IC technology will contribute to longer lasting infrastructure? Yes. Will new business opportunities be created for contractors and engineers? Yes, definitely!

But some important questions remain. What roles will geotechnical engineers play in the process of IC adoption? What might happen if a new technology with less safety oversight requirements were to replace nuclear density gauge testing as the standard? Like all new things in life, acceptance will diverge. Some folks will hang on to long-established methods, while others will assert a new role for geotechnical engineers. One immediate opportunity will be the linkage between IC measurements and geotechnical engineering properties. This process should involve geotechnical professionals and will likely lead to new business opportunities for field calibration and inspection.

Overall, adoption of new technologies may seem slow now, but technology advancements are arriving at an accelerated rate. Forward-thinking geotechnical professionals should be increasingly ready to take the lead in integrating new technologies. IC is one such technology that is ready now. Geotechnical IT innovation is upon us—what role will you play?

DAVID J. WHITE, PhD, PE, M.ASCE, is the R. L. Handy Professor in the Department of Civil, Construction, and Environmental Engineering and director of the Center for Earthworks Engineering Research (CEER) at Iowa State University of Science and Technology in Ames, IA. Contact him at djwhite@iastate.edu

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Intelligent Compaction Technology for Asphalt Applications

DESCRIPTION

This work shall consist of the compaction of the asphalt mixtures utilizing Intelligent Compaction (IC) rollers within the limits of the work as described in the plans. IC is defined as a process that uses vibratory rollers equipped with a measurement/documentation system that automatically records various critical compaction parameters correlated to agency standard testing protocols in real time during the compaction process. IC uses roller vibration measurements to assess the mechanistic properties of the underlying compacted materials to ensure optimum compaction is achieved through continuous monitoring of the operations.

The Contractor shall supply sufficient numbers of rollers and other associated equipment necessary to complete the compaction requirements for the specific materials. The Contractor will determine the number of IC rollers to use depending on the scope of the project. The primary position for the IC roller is in the initial phase (breakdown) in the paving sequence. IC rollers can also be used in the intermediate phase as long as the mat temperatures are sufficient for compaction. The use of IC rollers in the finish phase is not recommended.

EQUIPMENT

IC Roller - The IC roller(s) shall meet the following specific requirements:

- IC rollers shall be self-propelled double-drum vibratory rollers equipped with
 accelerometers mounted in or about the drum to measure the interactions between the
 rollers and compacted materials in order to evaluate the applied compaction effort. IC
 rollers shall also be equipped with non-contact temperature sensors for measuring
 pavement surface temperatures.
- 2. The output from the roller is designated as the Intelligent Compaction Measurement Value (IC-MV) which represents the stiffness of the materials based on the vibration of the roller drums and the resulting response from the underlying materials.
- 3. GPS radio and receiver units shall be mounted on each IC roller to monitor the drum locations and track the number of passes of the rollers.
- 4. The IC rollers shall include an integrated on-board documentation system that is capable of displaying real-time color-coded maps of IC measurement values including the stiffness response values, location of the roller, number of roller passes, pavement surface temperatures, roller speeds, vibration frequencies and amplitudes of roller drums.
- 5. The display unit shall be capable of transferring the data by means of a USB port.
- An on-board printer capable of printing the identity of the roller, the date of measurements, construction area being mapped, percentage of the construction area

2014

mapped, target IC-MV, and areas not meeting the IC-MV target values. ($Printer\ option\ to\ be\ selected\ by\ the\ xxDOT$)

Vendor	Bomag	Caterpillar
Model	Asphalt Manager	AccuGrade
Model No.	BW190AD-4AM	CD54B, CB54 XW
IC-MV	Evib	CMV
IC-MV Units	MN/m ²	Unitless
Documentation	BCM 05 Office	VisionLink
Company Address	Bomag Americas, Inc.	Caterpillar Corporate HQ
	200 Kentville Road	100 North East Adams Street
	Kewanee, Il. 61443	Peoria, Illinois USA 61629
Contact Information	Dave Dennison	Bryan Downing
	(309) 853-7862	(763) 493-7533
	dave.dennison@bomag.com	Downing_Bryan_J@cat.com

Vendor	Sakai	Wirtgen/Hamm
Model	CIS	HCQ
Model No.	SW880/SW890	HD+ 90 / HD+ 110
		HD+ 120 / HD+ 140
IC-MV	CCV	HMV
IC-MV Units	Unitless	Unitless
Documentation	AithonMT-A	HMV
Company Address	Sakai America, Inc.	Wirtgen America, Inc.
	90 International Parkway	6030 Dana Way
	Adairsville, Ga. 30103	Antioch, TN 37013
Contact Information	Ed Conlin	Tim Kowalski
	(800)-323-0535	(615) 501-0600
	E-conlin@sakaiamerica.com	tkowalski@Wirtgenamerica.com

Notes:

- CCV: Compaction Control Value
- CIS: Sakai Compaction Information System
- CMV: Compaction Meter Value
- Evib: Vibration modulus
- HCQ: HAMM Compaction Quality
- HMV: HAMM Measurement Value

Global Positioning System (GPS). The Contractor shall provide a GPS system that meets the following requirements. The goal of GPS requirements is to achieve accurate and consistent GPS measurements among all GPS devices on the same project. Conversions of GPS data need to be minimized to avoid errors introduced during the process.

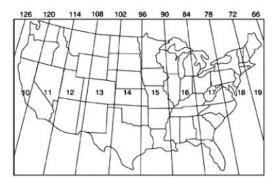
GPS-Related Definitions -

2014

- GPS: A space-based satellite navigation system that provides location and time
 information in all weather, anywhere on or near the Earth to determine the location in
 geodetic coordinates. In this specification, GPS is referred to all GPS-related signals
 including US GPS, and other Global Navigation Satellite Systems (GNSS).
- Hand-Held GPS rover: A portable GPS radio/receiver for in-situ point measurements.
- GPS Base Station: A single ground-based system that consists of a GPS receiver, GPS
 antenna, radio and radio antenna to provide L1/L2 differential GPS correction signals to
 other GPS receivers within a range limited by radio, typically 3 miles (4.8 Km) in radius
 without repeaters.
- Network RTK: Network RTK is a system that use multiple bases in real-time to provide high-accuracy GPS positioning within the coverage area that is generally larger than that covered by a ground-based GPS base station; e.g., VRS.
- GPS Correction Service Subscription: A service that can be subscribed to receive VRS signals in order to achieve higher accuracy GPS positioning normally via cellular wireless data services; i.e., without the need for a ground-based base station. Examples of GPS Correction Service subscriptions are: Trimble VRSTM, Trimble VRS NOWTM, OmniSTAR, etc.
- RTK-GPS: Real Time Kinematic Global Positioning Systems based on the use of carrier phase measurements of the available GPS signals where a single reference station or a reference station network provides the real-time corrections in order to achieve centimeter-level accuracy.
- UTM Coordinates: Universal Transverse Mercator (UTM) is a 2-dimentional Cartesian coordinates system that divides the surface of Earth between 80°S and 84°N latitude into 60 zones, each 6° of longitude in width and centered over a meridian of longitude. Zone 1 is bounded by longitude 180° to 174° W and is centered on the 177th West meridian. The UTM system uses projection techniques to transform an ellipsoidal surface to a flat map the can be printed on paper or displayed on a computer screen. Note that UTM is metric-based.
- Geodetic Coordinates: A non-earth-centric coordinate system to describe a position in longitude, latitude, and altitude above the imaginary ellipsoid surface based on a specific geodetic datum. WGS-84 and NAD83 datum are required for use with UTM and State Plans, respectively.
- ECEF XYZ: Earth-Centered, Earth-Fixed Cartesian X, Y, Z coordinates.
- Grid: Referred to ECEF XYZ in this specification.
- GUI Display: Graphical User Interface Display

- State Plane Coordinate: A set of 124 geographic zones or coordinate systems designed
 for specific regions of the United States. Each state contains one or more state plane
 zones, the boundaries of which usually follow county lines. The current State Plane
 coordinate is based on NAD83. Issues may arise when a project crosses state plane
 boundaries.
- UTC: Coordinated Universal Time (UTC) is commonly referred to as Greenwich Mean Time (GMT) and is based on a 24 hours' time scale from the mean solar time at the Earth's prime meridian (zero degrees longitude) located near Greenwich, England.

All GPS devices for this project shall be set to the same consistent coordinate datum/system no matter whether GPS or Grid data are originally recorded. UTM is the preference and shall be set to zone no. (xx) N for this project. (xxDOT to fill in the appropriate zone number) Zones outside of the continental United States can be acquired on the web at www.dmap.co.uk/utmworld.htm. The records shall be in meters. Use of UTM will facilitate GPS data checks onsite.



If UTM coordinates are not available, the State Plane Coordinate system can be used and set as (xx) for this project. (xxDOT to fill in the appropriate State Plane designation) Ad-hoc local coordinate systems should not be allowed.

Construction Requirements. Contractor shall provide the GPS system (including GPS receivers on IC rollers and hand-held GPS receivers (Rovers)) that makes use of the same reference system that can be a ground-based base station or network-RTK, to achieve RTK-GPS accuracy. Examples of combinations are:

- GPS receivers on IC rollers and hand-held GPS rovers referenced to the same on-ground base station.
- GPS receiver on IC rollers and hand-held GPS receivers referenced to the same network RTK.

Generic - IC Specifications for Asphalt Materials

GPS Data Records and Formats. The recorded GPS data, whether from the IC rollers or hand-held GPS rovers, shall be in the following formats:

- Time: The time stamp shall be in military format, hhmmss.ss in either UTC or local time zone. 0.01 second is required to differentiate sequence of IC data points during post process.
- GPS: Latitudes and longitude shall in ddmm.mmmmmmm or decimal degrees, dd.dddddddd. . Longitudes are negative values when measuring westward from the Prime Meridian
- Grid: Coordinates shall be in meters with at least 3 digits of significance (0.001 m or 1 mm).

When importing IC-MV data into the data analysis management program, the GPS data and associated IC measurements shall be stored with minimum data conversions and minimum loss of precisions. Users can then select unit of preference to allow real time unit conversion for the GUI display.

Post-Process GPS Check. Follow the vendor-specific instructions to export IC-MV data to Veda-compatible formats. The Contractor shall import the IC roller data in to Veda and enter GPS point measurements from the rover and visually inspect the IC map and point measurements on the Veda display screen for consistency.

Data Analysis Software. Standardized data analysis software (Veda) is available on the website www.intelligentcompaction.com or will be provided by xxDOT. The software program will utilize the IC-MV data from the IC roller for analysis of coverage, uniformity, and stiffness values during construction operations. As a minimum, the following Essential IC Data Information and IC Data Elements shall be available for post processing.

• Essential IC Data Header Information for Each Data File or Section:

Item	Description
No.	
1	Section Title
2	Machine Manufacture
3	Machine Type
4	Machine Model
5	Drum Width (m)
6	Drum Diameter (m)
7	Machine Weight (metric ton)
8	Name index of intelligent compaction measurement values (IC-
	MV)
9	Unit index for IC-MV

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10	Reporting resolution for independent IC-MVs – 90 degrees to
	the roller moving direction (mm)
11	Reporting resolution for independent IC-MVs – in the roller
	moving direction (mm)
12	UTM Zone
13	Offset to UTC (hrs)
14	Number of IC data points

• Essential IC Data Elements for Each Data Point:

Item	Date Field Name	Example of Data
No.		
1	Date Stamp (YYYYMMDD)	e.g. 20080701
2	Time Stamp (HHMMSS.SS -military	e.g. 090504.00 (9 hr 5
	format)	min. 4.00 s.)
3	Longitude (decimal degrees)	e.g. 94.85920403
4	Latitude (decimal degrees)	e.g. 45.22777335
5	Easting (m)	e.g. 354048.300
6	Northing (m)	e.g. 5009934.900
7	Height (m)	e.g. 339.9450
8	Roller pass number	e.g. 2
9	Direction index	e.g., 1 forward, 2 reverse
10	Roller speed (kph)	e.g. 4.0
11	Vibration on	e.g., 1 for yes, 2 for no
12	Frequency (vpm)	e.g. 3500.0
13	Amplitude (mm)	e.g. 0.6
14	Surface temperature (°C) -	e.g. 120
15	Intelligent compaction measurement	e.g. 20.0
	values	

Items 3 and 4 can be exclusive with items 5 and 6, and vice versa. Item 14 is only required for asphalt application. The size of data mesh after post-processing shall be less than 18 inches (450 mm) by 18 inches (450 mm) in the X and Y directions.

QUALITY CONTROL PLAN

The Contractor shall prepare and submit a written Quality Control Plan (QCP) for the project. As a minimum, the QCP shall contain the following information:

General Requirements.

QCP shall be contract-specific, stating how the contractor proposes to control the
materials, equipment, and construction operations including subcontractors and suppliers
as well as production facilities and transportation modes to the project for the asphalt
mixture operations.

2014

- The QCP shall include an organizational chart showing all quality control personnel and how these personnel integrate with other management/production and construction functions and personnel.
- 3. The QCP shall be signed and dated by the Contractor's representative at the time the QCP is submitted to the Engineer. The QCP shall be submitted no later than 15 days prior to commencing the paving operations.
- 4. The xxDOT will review, sign, and date the QCP if the contents of the QCP are in compliance with the requirements as stated herein.
- The QCP shall be maintained to reflect the current status of the operations, and revisions shall be provided in writing prior to initiating the change. The QCP revision shall not be implemented until the revision has been accepted.
- 6. The QCP shall contain the name, telephone number, duties, and employer of all quality control personnel necessary to implement the QCP. The minimum qualifications of quality control personnel shall be as follows:
 - a. QCP Field Manager or Plan Administrator. The person responsible for the execution of the QCP and liaison with the Engineer. Additionally the QCP Field Manager requirements include:
 - 1. Full-time employee of the Contractor or an independent consultant not involved with the Quality Assurance (acceptance) activities on the project.
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 - Full authority to institute actions necessary for successful implementation of the OCP.
 - b. Quality Control Technician (QCT). The person(s) responsible for conducting quality control and inspection activities to implement the QCP. There may be more than one QCT on a project.
 - 1. Full-time employee of the Contractor or an independent consultant with a minimum (x) years experience (as determined by the xxDOT) in quality control activities in construction operations.
 - 2. Completed the xxDOT requirements for the applicable testing.
 - Full authority to institute actions necessary for successful implementation of the QCP.

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- c. IC Roller Operator(s). The person responsible for operating the IC roller(s) and attached IC equipment. Sufficient training for the roller operator(s) shall be supplied by a representative of the manufacturer of the equipment.
- 7. IC Equipment. The roller supplier, make, roller model, number of IC rollers to be provided, and the GPS system supplier to be utilized.
- 8. Temperature Controls: The Contractor shall provide details on their plans to achieve minimum mat temperatures during compaction. IC roller compaction process needs to be completed (final IC roller pass) before the mat temperature fall below a minimum of 240° F (115° C) for the initial phase (breakdown) and 200° F (93° C) for the intermediate phase.
- 9. Asphalt pavement operations shall not begin before the QCP has been accepted.
- 10. The Engineer may require the replacement of ineffective or unqualified equipment or Quality Control personnel. Construction operations may be required to stop until Quality Control corrective actions are taken.

References. (xxDOT to modified/expanded as applicable)

1. AASHTO Standards.

AASHTO R 42 Standard Practice for Developing a Quality Assurance Plan for Hot Mix Asphalt (HMA)

2. ASTM Standards.

XXX XXX

3. xxDOT Standards.

XXX XXX

Quality Control Technician. The QCT shall be responsible for the following minimum functions:

- 1. Daily GPS check testing for the IC roller(s) and rover(s).
- Test section construction to establish target compaction pass counts and target values for the strength of the materials using the standard testing devices; i.e., Nondestructive density gauges, pavement cores, and IC roller(s).
- 3. Monitoring of the construction operations and the IC roller(s) during production and final evaluation operations.

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- Quality control testing to monitor the pavement temperature and the required level of compaction.
- 5. Daily download and analysis of the IC data from the roller(s).
- 6. Daily set-up, take down and secure storage of GPS and IC roller components

Testing Facility. The location of the testing facility and a list of test equipment shall be included. The testing facility shall be located so the Quality Control tests results are provided to the Engineer in a timely manner, and be sufficient size to conduct the Quality Control tests. A statement of accessibility of the testing facility shall be included that allows xxDOT personnel to witness Quality Control activities and to review Quality Control tests.

A list of the testing equipment proposed for Quality Control testing and the test methods and frequency of calibration or verification of the equipment shall be included. The Contractor shall maintain a record of all equipment calibration or verification results at the testing facility. The minimum frequency and procedures shall be as follows:

Equipment	Requirement	Minimum Frequency	Procedure
*	*	*	*

*to be filled in by the xxDOT

Materials Sampling and Testing. The procedures for sampling and testing of the pavement shall be identified and include as a minimum the following: (xxDOT to modify/expanded as applicable)

- Temperature. The procedure for monitoring the temperature of the materials during production, transportation, laydown and compaction operations. A minimum frequency shall be one test for two hours of placement and shall include all steps in the process.
- Density/Compaction. Identification of the standard testing device(s) and frequency for measuring the in-place density of the asphalt mixture. The minimum frequency of tests shall be one test for each 250 tons of asphalt mixture placed.
- 3. IC Roller Data. The procedure for obtaining the IC roller data. The minimum frequency of obtaining the data from the roller shall be two (2) times per day of asphalt compaction operations. The data is date/time stamped which permits for external evaluation at a later time. Data from the on-board printer if required shall be given to the Engineer when requested.

The IC roller raw data and results from the analysis software shall be made available to the Engineer within 24 hours of obtaining the roller data and test results.

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GPS Check Testing. Prior to the start of production, the Contractor and representatives of the GPS and IC roller manufacturer shall conduct the following to check the proper setup of the GPS, IC roller(s) and the rover(s) using the same datum:

- 1. On a location nearby or within the project limits, the GPS base station (if required by the GPS) shall be established and the IC roller and the GPS rover tied into the same base station
- 2. Verification that the roller and rover are working properly and that there is a connection with the base station.
- 3. Production shall not begin until proper GPS verification has been obtained. IC vendors' recommended verification process can be used to augment the following procedure.

Move the IC roller around until the GPS header computation is initialized. Move the IC roller and park at a selected location. Record the GPS measurements from the IC roller ensuring the distance offsets are applied so that the GPS coordinate is at the center or at left/right edges of the front drum. Mark two locations on the ground adjacent to the right and left edges of the front drum contact patch. Move the IC roller from the marked locations. Use a hand-held rover to measure at the marked locations. Average the rover GPS measurements if the roller GPS measurement is at the center of the front drum. The differences between the roller GPS and rover measurements shall be within 12 inches (300 mm) for northing and easting.

- 4. The project plan file provided by xxDOT shall be uploaded into the IC Data analysis software and depending on the roller manufacture, the on-board IC computer.
- GPS check testing shall be conducted daily during production operations to ensure consistency and accuracy of GPS measurements for all GPS devices prior to the paving and compaction operations.

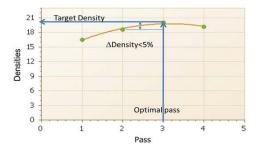
Test Sections. Test section evaluations are intended to verify the mixture volumetric of mixtures and determine a compaction curve of the asphalt mixtures in relationship to number of roller passes and to the stiffness of mixture while meeting the *xxDOT* in-place compaction requirements. (Test section details to be modified/expanded as applicable by the *xxDOT*)

The evaluations shall be conducted every lift and be approximately 300 tons of mainline mixtures. The IC roller in the initial phase shall use low vibration amplitude and the same settings (speed, frequency) throughout the section. After each roller pass, a nondestructive density device shall be used to estimate the density of the asphalt mixture at five (5) locations uniformly spaced throughout the test section. The density readings and the number of roller passes that takes to achieve the desired compaction will be recorded.

The estimated target density will be the peak of the nondestructive readings within the desired compaction temperature range for the mixture. The IC roller data using the IC data analysis software will create an IC compaction curve for the mixture. The target IC-MV is the

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point when the increase in the IC-MV of the material between passes is less than 5 percent on the compaction curve. The IC compaction curve is defined as the relationship between the IC-MV and the roller passes. A compaction curve example is as follows:



Linear regression relationships between the point test results and the IC-MV results will be used to establish the production target IC-MV as the target density (% G_{mm}) meets the xxDOT in-place compaction requirements. A linear regression curve example is as follows.



Pre-Mapping. Pre-paving mapping (pre-mapping) with an IC roller of the existing support materials is recommended prior to tacking operations, if applicable, in order to identify weak areas. The pre-mapping may be part of the test section evaluation of the project. Pre-mapping is recommended on underlying materials such as soils subgrade, aggregate bases, or similar. Mapping is not recommended on stabilized base, milled/non-milled existing asphalt pavements, concrete pavements, or similar underlying hard surfaces.

Response to Test Results. The response to quality control tests for the test sections and during production compaction shall include as a minimum the following:

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- Temperature. The procedure for corrective action when the QC or IC temperature readings are not within the recommended laydown values for the mixtures.
- Density/Compaction. The procedure for corrective action when the maximum specific density (G_{mm}) results fall below the xxDOT specification limits or 92.0% whichever is greater.
- 3. IC Coverage Area and Uniformity Criteria. The procedures to be taken when the IC criteria for coverage or the minimum IC-MV targets criteria are not being met.

Documentation. A statement that the test results for quality control and documentation of equipment and IC roller data shall be given to the Department at the completion of the contract. The documentation shall include the following.

- Quality Control Tests. The results from the temperature and density testing. All quality control test results shall be signed by the QCT and submitted to the Engineer within 24 hours of testing.
- 2. Equipment. Documentation of the manufacture, model, type of paver, and rollers used each day of asphalt materials operations. The positioning of the IC roller(s) in the paving operations shall be noted.
- IC Roller Data. At a minimum, the electronic data from IC roller(s) and the data analysis
 software shall be provided to the Engineer upon the completion of the Test Section,
 Mapping and individual IC Construction Area operations.
- 4. IC Roller Analysis. The Contractor will analyze the IC roller data for conformance to the requirements for coverage area and uniformity and will submit the results to the Engineer at the completion of the individual IC Construction Area operations.
 - IC data shall be exported from the vendor's software in both all passes data and proofing data files. All passes data includes the data from all of the passes and proofing data is the data from just the last pass within a given area.
- Construction Area. The limits of and total tons of the asphalt mixtures within each construction area.

IC CONSTRUCTION

Technical Assistance. The Contractor shall coordinate for on-site technical assistance from the IC roller representatives during the initial seven (7) days of production and then as needed during the remaining operations. As a minimum, the roller representative shall be present during the initial setup and verification testing of the IC roller(s). The roller representative shall also assist the Contractor with data management using the data analysis software including IC data input and processing.

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On-Site Training. The Contractor shall coordinate and provide for on-site training for Contractors and Agency project personnel related to operation of the IC technology. Contractor's personnel shall include the paving superintendent, QC technician(s), and roller operator(s). Agency's personnel shall include the project engineer and field inspector(s). (Appropriate personnel to attend the training to be modified/expanded as applicable by the xxDOT) Arrangements shall be provided that includes an enclosed facility with electrical availability and a projector for presentations and should be 4-8 hours in duration.

Minimum training topics shall include:

- 1. Background information for the specific IC system(s) to be used
- 2. Setup and checks for IC system(s), GPS receiver, base-station and hand held rovers
- 3. Operation of the IC system(s) on the roller; i.e., setup data collection, start/stop of data recording, and on-board display options
- 4. Transferring raw IC data from the rollers(s); i.e., via USB connections
- Operation of vendor's software to open and view raw IC data files and exporting allpasses and proofing data files in Veda-compatible format
- Operation of Veda software to import the above exported all-passes and proofing data files, inspection of IC maps, input point test data, perform statistics analysis, and produce reports for project requirements
- 7. Coverage and uniformity requirements

IC Construction Area. IC Construction areas are defined as subsections of the project being worked continuously by the Contractor. The procedure for determining and documenting the limits of the construction area shall be provided to the Engineer. The magnitude of the evaluation areas may vary with production but they need to be at least 1000 tons per mixture for evaluation. Partial construction areas of 500 tons or less will be included in the previous area evaluation. Partial construction areas of greater than 500 tons will constitute a full area to close out the construction area. Construction areas may extend over multiple days depending on the operations.

IC Construction Operations Criteria. A minimum coverage of 90% of the individual construction area shall meet or exceed the optimal number of roller passes and 70% of the individual construction area shall meet or exceed target IC-MV values determined from the test section. Construction areas not meeting the IC criteria (coverage and/or uniformity) shall be investigated by the *xxDOT* prior to continuing with the paving operations. The IC Construction Operations Criteria does not affect the standard *xxDOT* acceptance processes for the materials or construction operations.

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METHOD OF MEASUREMENT

This item will not be measured as it will be paid as a lump sum for providing for the Intelligent Compaction for Asphalt Mixtures on the project.

BASIS OF PAYMENT

The incorporating of the Intelligent Compaction process will be paid at the contract lump sum price for Intelligent Compaction for Asphalt Mixtures.

Payment will be made under:

 Pay Item
 Unit

 Intelligent Compaction for Asphalt Mixtures
 LS

This item includes all costs related to providing the IC roller(s) including the fuel, roller operator, GPS system, or any other equipment required for the IC process. All quality control procedures including IC rollers and GPS systems representatives support, on-site training and testing facility shall be included in the contract lump sum price.

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Intelligent Compaction Technology for Soils Applications

DESCRIPTION

This work shall consist of the construction of the roadway fill embankment utilizing Intelligent Compaction (IC) rollers within the limits of the work as described in the plans. IC is defined as a process that uses vibratory rollers equipped with a measurement/documentation system that automatically records various critical compaction parameters correlated to agency standard testing protocols in real time during the compaction process. IC uses roller vibration measurements to assess the mechanistic soils properties and to ensure optimum compaction is achieved through continuous monitoring of the operations.

The Contractor shall supply sufficient numbers of rollers and other associated equipment necessary to complete the compaction requirements for the specific materials. The Contractor will determine the number of IC rollers to use depending on the scope of the project. The IC roller(s) may be utilized during production with other standard compaction equipment and shall be used for the evaluation of the compaction operations.

EQUIPMENT

The IC rollers shall meet the following specific requirements:

- IC rollers shall be self-propelled single-drum vibratory rollers equipped with accelerometers mounted in or about the drum to measure the interactions between the rollers and compacted materials in order to evaluate the applied compaction effort. IC rollers may be smooth or pad footed drums.
- The output from the roller is designated as the Intelligent Compaction Measurement Value (IC-MV) which represents the stiffness of the materials based on the vibration of the roller drums and the resulting response from the underlying materials.
- 3. GPS radio and receiver units shall be mounted on each IC roller to monitor the drum locations and track the number of passes of the rollers.
- 4. The IC rollers shall include an integrated on-board documentation system that is capable of displaying real-time color-coded maps of IC measurement values including the stiffness response values, location of the roller, number of roller passes, roller speeds, together with the vibration frequency and amplitude of roller drums.
- 5. The display unit shall be capable of transferring the data by means of a USB port.
- 6. An on-board printer capable of printing the identity of the roller, the date of measurements, construction area being mapped, percentage of the construction area

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mapped, target IC-MV, and areas not meeting the IC-MV target values. (Printer option to be selected by the xxDOT)

Vendor	Bomag	Caterpillar
Model	VarioControl	AccuGrade
Model No.	BW213-4BVC	CS-44-CS78, Cp54-CP74
IC-MV	Evib	CMV
IC-MV Units	MN/m ²	Unitless
Documentation	BCM 05 Office	VisionLink
Company Address	Bomag Americas, Inc.	Caterpillar Corporate HQ
	200 Kentville Road	100 North East Adams Street
	Kewanee, Il. 61443	Peoria, Illinois USA 61629
Contact Information	Dave Dennison	Todd Mansell
	(309) 853-7862	763-315-5518
	dave.dennison@bomag.com	Mansell_Todd_W@cat.com

Vendor	Sakai	Wirtgen/Hamm
Model	CIS	HCQ
Model No.	SV610	All 3000 series rollers
		All new H series rollers
IC-MV	CCV	HMV
IC-MV Units	Unitless	Unitless
Documentation	AithonMT-A	HMV
Company Address	Sakai America, Inc.	Wirtgen America, Inc.
	90 International Parkway	6030 Dana Way
	Adairsville, Ga. 30103	Antioch, TN 37013
Contact Information	Ed Conlin	Tim Kowalski
	(800)-323-0535	(615) 501-0600
	E-conlin@sakaiamerica.com	tkowalski@Wirtgenamerica.com

Notes:

- CCV: Compaction Control Value
- CIS: Sakai Compaction Information SystemCMV: Compaction Meter Value
- Evib: Vibration modulus
- · HCQ: HAMM Compaction Quality
- HMV: HAMM Measurement Value

Global Positioning System (GPS). The Contractor shall provide a GPS system that meets the following requirements. The goal of GPS requirements is to achieve accurate and consistent GPS measurements among all GPS devices on the same project. Conversions of GPS data need to be minimized to avoid errors introduced during the process.

GPS-Related Definitions -

• GPS: A space-based satellite navigation system that provides location and time information in all weather, anywhere on or near the Earth to determine the location in

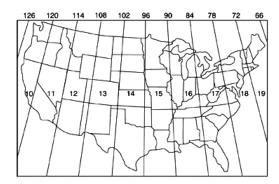
2014

geodetic coordinates. In this specification, GPS is referred to all GPS-related signals including US GPS, and other Global Navigation Satellite Systems (GNSS).

- Hand-Held GPS rover: A portable GPS radio/receiver for in-situ point measurements.
- GPS Base Station: A single ground-based system that consists of a GPS receiver, GPS
 antenna, radio and radio antenna to provide L1/L2 differential GPS correction signals to
 other GPS receivers within a range limited by radio, typically 3 miles (4.8 Km) in radius
 without repeaters.
- Network RTK: Network RTK is a system that use multiple bases in real-time to provide high-accuracy GPS positioning within the coverage area that is generally larger than that covered by a ground-based GPS base station; e.g., VRS.
- GPS Correction Service Subscription: A service that can be subscribed to receive VRS signals in order to achieve higher accuracy GPS positioning normally via cellular wireless data services; i.e., without the need for a ground-based base station. Examples of GPS Correction Service subscriptions are: Trimble VRSTM, Trimble VRS NOWTM, OmniSTAR, etc.
- RTK-GPS: Real Time Kinematic Global Positioning Systems based on the use of carrier
 phase measurements of the available GPS signals where a single reference station or a
 reference station network provides the real-time corrections in order to achieve
 centimeter-level accuracy.
- UTM Coordinates: Universal Transverse Mercator (UTM) is a 2-dimentional Cartesian coordinates system that divides the surface of Earth between 80°S and 84°N latitude into 60 zones, each 6° of longitude in width and centered over a meridian of longitude. Zone 1 is bounded by longitude 180° to 174° W and is centered on the 177th West meridian. The UTM system uses projection techniques to transform an ellipsoidal surface to a flat map the can be printed on paper or displayed on a computer screen. Note that UTM is metric-based
- Geodetic Coordinates: A non-earth-centric coordinate system to describe a position in longitude, latitude, and altitude above the imaginary ellipsoid surface based on a specific geodetic datum. WGS-84 and NAD83 datum are required for use with UTM and State Plans, respectively.
- ECEF XYZ: Earth-Centered, Earth-Fixed Cartesian X, Y, Z coordinates.
- Grid: Referred to ECEF XYZ in this specification.
- GUI Display: Graphical User Interface Display

- State Plane Coordinate: A set of 124 geographic zones or coordinate systems designed
 for specific regions of the United States. Each state contains one or more state plane
 zones, the boundaries of which usually follow county lines. The current State Plane
 coordinate is based on NAD83. Issues may arise when a project crosses state plane
 boundaries.
- UTC: Coordinated Universal Time (UTC) is commonly referred to as Greenwich Mean Time (GMT) and is based on a 24 hours' time scale from the mean solar time at the Earth's prime meridian (zero degrees longitude) located near Greenwich, England.

All GPS devices for this project shall be set to the same consistent coordinate datum/system no matter whether GPS or Grid data are originally recorded. UTM is the preference and shall be set to zone no. (xx) N for this project. (xxDOT to fill in the appropriate zone number) Zones outside of the continental United States can be acquired on the web at www.dmap.co.uk/utmworld.htm. The records shall be in meters. Use of UTM will facilitate GPS data checks onsite.



If UTM coordinates are not available, the State Plane Coordinate system can be used and set as (xx) for this project. (xxDOT to fill in the appropriate State Plane designation) Ad-hoc local coordinate systems should not be allowed.

Construction Requirements. Contractor shall provide the GPS system (including GPS receivers on IC rollers and hand-held GPS receivers (Rovers)) that makes use of the same reference system that can be a ground-based base station or network-RTK, to achieve RTK-GPS accuracy. Examples of combinations are:

- 1. GPS receivers on IC rollers and hand-held GPS rovers referenced to the same on-ground
- GPS receiver on IC rollers and hand-held GPS receivers referenced to the same network RTK.

Report of the 3rd Workshop for Technology Transfer for Intelligent Compaction Consortium (TTICC) Transportation Pooled Fund Study Number TPF-5(233)

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GPS Data Records and Formats. The recorded GPS data, whether from the IC rollers or hand-held GPS rovers, shall be in the following formats:

- Time: The time stamp shall be in military format, hhmmss.ss in either UTC or local time zone. 0.01 second is required to differentiate sequence of IC data points during post process.
- GPS: Latitudes and longitude shall in ddmm.mmmmmmm or decimal degrees, dd.dddddddd. . Longitudes are negative values when measuring westward from the Prime Meridian
- Grid: Coordinates shall be in meters with at least 3 digits of significance (0.001 m or 1 mm).

When importing IC-MV data into the data analysis management program, the GPS data and associated IC measurements shall be stored with minimum data conversions and minimum loss of precisions. Users can then select unit of preference to allow real time unit conversion for the GUI display.

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Generic - IC Specifications for Soils DOT to modify as applicable to meet State Specifications 2014

- 2. The QCP shall include an organizational chart showing all quality control personnel and how these personnel integrate with other management/production and construction functions and personnel.
- 3. The QCP shall be signed and dated by the Contractor's representative at the time the QCP is submitted to the Engineer. The QCP shall be submitted no later than 15 days prior to commencing the embankment operations.
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 - 2. Minimum (x) years' experience (as determined by the DOT) in quality control activities in construction operations
 - 3. Full authority to institute actions necessary for successful implementation of the QCP.
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 - 2. Completed the xxDOT requirements for the applicable testing.
 - 3. Full authority to institute actions necessary for successful implementation of the QCP.

- c. IC Roller Operator. The person responsible for operating the IC roller and attached IC equipment. Sufficient training for the roller operator shall be supplied by a representative of the manufacturer of the equipment.
- 7. IC Equipment. The Roller supplier, make, roller model, number of IC rollers to be provided, and the GPS system supplier to be utilized.
- 8. Embankment operations shall not begin before the QCP has been accepted.
- 9. The Engineer may require the replacement of ineffective or unqualified equipment or Quality Control personnel. Construction operations may be required to stop until Quality Control corrective actions are taken.

References. (to be modified/expanded as applicable by the DOT)

1. AASHTO Standards.

AASHTO T 99	Moisture-Density Relations of Soils Using a 2.5-kg
	(5.5-lb) Rammer and a 305-mm (12-in.) Drop

AASHTO T 272 Family of Curves - One-Point Method

2. ASTM Standards.

ACTM DAGO

AS IM D 2585	Deflectometer (LWD)	
ASTM D 6951	Dynamic Cone Penetrometer in Shallow Pavemer	

Dynamic Cone Penetrometer in Shallow Pavement

Applications (17.6-lb (8-kg) hammer)

3. xxDOT Standards.

XXX	Field Determination of Moisture Content of Soils
XXX	Field Determination of Deflection Using Light Weight Deflectometer

Quality Control Technician. The QCT shall be responsible for the following minimum functions:

- 1. GPS check testing for the IC roller(s) and rover(s).
- 2. Test section construction and establishing target values for the maximum dry density, optimum moisture content, production moisture content, strength of the materials using the dynamic cone penetrometer (DCP), light weight deflectometer (LWD), nuclear gauge, and the IC-roller(s).

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- Monitoring of the construction operations and the IC roller(s) during production and final proofing operations.
- 4. Quality control testing for the maximum dry density and moisture content.
- 5. Downloading and analysis of the IC-data from the roller(s).
- 6. Daily set-up, take down and secure storage of GPS and IC roller components

Testing Facility. The location of the testing facility and a list of test equipment shall be included. The testing facility shall be sufficient size to conduct the Quality Control tests, and a satisfactory base on which compaction of the soil can be achieved in accordance with AASHTO T 99 Method A (*or as otherwise defined by the DOT*) shall be provided. A statement of accessibility of the testing facility shall be included that allows *xxDOT* personnel to witness Quality Control activities and to review Quality Control tests.

A list of the testing equipment proposed for Quality Control testing and the test methods and frequency of calibration or verification of the equipment shall be included. The Contractor shall maintain a record of all equipment calibration or verification results at the testing facility. The minimum frequency and procedures shall be as follows:

Equipment	Requirement	Minimum Frequency	Procedure*
Balances	Verification	12 months	XXX
Sieves	Check Physical Condition	12 months	XXX
Etc.*	*	*	

*to be filled in by the DOT

Materials Sampling and Testing. The procedures for sampling and testing of the soil embankment and the frequency of tests shall be identified and include as a minimum the following: (details to be modified/expanded as applicable by the DOT)

- Moisture. The procedure for measuring the moisture content of the soil during production compaction. The minimum frequency of tests per lift of material shall be one test for each construction area.
- Strength. The procedure for measuring the in-place strength of the soil. The minimum frequency of tests shall be a minimum of one test for each construction area.
- Maximum Dry Density and Optimum Moisture Content. The procedure for measuring the maximum dry density and optimum moisture content of the soil for the test sections and when there is a change in the soil type.
- IC Roller Data. The procedure for obtaining the IC roller data. The frequency of obtaining the data shall be a minimum of two times each day of soil compaction.

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The data is date/time stamped which permits for external evaluation at a later time

GPS Check Testing. Prior to the start of production, the Contractor, GPS representative and IC roller manufacturer shall conduct the following to check the proper setup of the GPS, IC roller(s) and the rover(s) using the same datum:

- On a location nearby or within the project limits, the GPS base station (if required by the GPS) shall be established and the IC roller and the GPS rover tied into the same base station.
- 2. Verification that the roller and rover are working properly and that there is a connection with the base station.
- Production shall not begin until proper GPS verification has been obtained. IC vendors' recommended verification process can be used to augment the following procedure.

Move the IC roller around until the GPS header computation is initialized. Move the IC roller and park at a selected location. Record the GPS measurements from the IC roller ensuring the distance offsets are applied so that the GPS coordinate is at the center or at left/right edges of the front drum. Mark two locations on the ground adjacent to the right and left edges of the front drum contact patch. Move the IC roller from the marked locations. Use a hand-held rover to measure at the marked locations. Average the rover GPS measurements if the roller GPS measurement is at the center of the front drum. The differences between the roller GPS and rover measurements shall be within 12 inches (300 mm) for northing and easting.

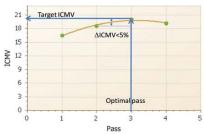
- 4. The project plan file provided by xxDOT shall be uploaded into the IC Data analysis software and depending on the roller manufacture, the on-board IC computer.
- GPS check testing shall be conducted daily during production operations to
 ensure consistency and accuracy of GPS measurements for all GPS devices prior
 to the paying and compaction operations.

Test Sections. Test section evaluations are intended to determine the number of passes it takes to achieve compaction at the optimum moisture content for the materials. Test sections shall be approximately 225 ft (75 m) long and 24 ft (8 m) wide and may be part of the initial production operations. (Test section details to be modified/expanded as applicable by the xxDOT)

The evaluations shall be conducted for the various material types, on every lift where there is a change of materials. The IC rollers shall use the same settings (speed, frequency) throughout the section. After each roller pass, a nondestructive density device shall be used to

estimate the density or stiffness of the material and a hand-held GPS rover to measure the positions at least 10 locations uniformly spaced throughout the test section.

The estimated target density will be the peak of the nondestructive readings within the desired moisture range. The IC roller data using software will create an IC compaction curve for the mixture. The target IC-MV is the point when the increase in the IC-MV of the material between passes is less than 5 percent on the compaction curve. The IC compaction curve is defined as the relationship between the IC-MV and the roller passes. A compaction curve example is as follows:



Linear regression relationships between the point test results and the IC-MV results will be used to establish the production target IC-MV as the target density meets the xxDOT in-place compaction requirements. A linear regression curve example is as follows.



Mapping. Pre-construction mapping/proofing of the initial layer of the fill is recommended to identify weak areas that may need to be addressed in advance of the production fill operations. Subsequent mapping may be conducted at any time to recognize the changes in the fill that affects the target IC-MV or the density verification testing. Mapping operations are intended to provide the Contractor and understanding of the stiffness of the existing roadway being compacted. At a minimum, production mapping is recommended at the final surface of the fill and the elevation levels at 1.0 ft., 2.0 ft., 4.0 ft., and 8.0 ft. below the final surface as applicable. The stiffness of the underlying materials should increase with subsequent lifts of material. The Contractors procedures for mapping shall be included.

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Soil Management. The procedures for management of the borrow pit and soil cut sections to assure uniform soil material shall be included in the QCP. The procedures for the necessary adjustments in compaction because of a change in soil type shall be stated.

Response to Test Results. The response to quality control tests for the test sections and during production compaction shall include as a minimum the following:

- 1. Moisture. The procedure for corrective action when the QC moisture tests are not within -3 and +2 percentage points of the optimum moisture content.
- 2. Strength. The procedure for corrective action when tests do not meet the xxDOT requirements for each soil type.
- 3. Maximum Dry Density and Optimum Moisture Content. The procedure for corrective action when the maximum dry density and optimum moisture content test results indicate that there is a change in the soil type.
- IC Coverage Area and Uniformity Criteria. The procedures for re-working the construction area when IC criteria for coverage area or the minimum IC-MV are not met.

Documentation. The documentation shall include the following:

- Quality Control Tests. The results from the moisture, strength, and maximum dry density and optimum moisture content tests. All quality control test results shall be signed by the QCT and submitted to the Engineer within 24 hours of testing.
- 2. Equipment. Documentation of the manufacture, model, and type of rollers used each day of soil compaction and the IC roller used for mapping the compaction of the soil. The positioning of the IC roller(s) in the paving operations shall be noted.
- IC Roller Data. At a minimum, the electronic data from IC roller(s) and the data
 analysis software shall be provided to the Engineer upon the completion of the
 Test Section, Mapping and individual IC Construction Area operations.
- 4. IC-MV Analysis. The Contractors will analyze the IC-MV data for conformance to the requirements for coverage area and uniformity and will submit the results to the Engineer at the completion of the individual IC Construction Area operations.
 - IC data shall be exported from the vendor's software in both all passes and proofing data files. All passes data includes the data from all of the passes and proofing data is the data from just the last pass within a given area.
- Construction Area. The limits of the construction areas of each lift of embankment.

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IC CONSTRUCTION

Technical Assistance. The Contractor shall coordinate for on-site technical assistance from the IC roller representative during the initial seven (7) days of production and then as needed during the remaining operations. As a minimum, the roller representative shall be present during the initial setup and verification testing of the IC roller(s). The roller representative shall also assist the Contractor with data management using the data analysis software including IC data input and processing.

On-Site Training. The Contractor shall coordinate and provide for on-site training for Contractors and Agency project personnel related to operation of the IC technology. Contractor's personnel shall include the contractor's superintendent, QC technician(s), and roller operator(s). Agency's personnel shall include the project engineer and field inspector(s). (Appropriate personnel to attend the training to be modified/expanded as applicable by the xxDOT) Arrangements shall be provided that includes an enclosed facility with electrical availability and a projector for presentations and should be 4-8 hours in duration.

Minimum training topics shall include:

- 1. Background information for the specific IC system(s) to be used
- 2. Setup and checks for IC system(s), GPS receiver, base-station and hand held rovers
- Operation of the IC system(s) on the roller; i.e., setup data collection, start/stop of data recording, and on-board display options
- 4. Transferring raw IC data from the rollers(s); i.e., via USB connections
- Operation of vendor's software to open and view raw IC data files and exporting allpasses and proofing data files in Veda-compatible format
- Operation of Veda software to import the above exported all-passes and proofing data files, inspection of IC maps, input point test data, perform statistics analysis, and produce reports for project requirements
- 7. Coverage and uniformity requirements

Construction Areas. IC Construction areas are defined as subsections of the project being worked continuously by the Contractor. The magnitude of the evaluation areas may vary with production but they need to be at least $25,000~\rm{ft}^2$ for evaluation and not greater than $100,000~\rm{ft}^2$. Partial construction areas of $5000~\rm{ft}^2$ or less will be included in the previous area evaluation. Partial construction areas of greater than $5000~\rm{ft}^2$ will constitute a full area to close out the mixture. Construction areas may extend over multiple days depending on the operations.

IC Construction Operations Criteria. A minimum coverage of 90% of the individual construction area shall meet the optimal number of roller passes and 70% of the target IC-MV

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Generic - IC Specifications for Soils DOT to modify as applicable to meet State Specifications

determined from the test sections. Construction areas not meeting the IC criteria shall be reworked and re-evaluated prior to continuing with the operations in that area. The IC Construction Operations Criteria does not affect the standard *xxDOT* acceptance processes for the materials or construction operations.

METHOD OF MEASUREMENT

This item will not be measured as it will be paid as a lump sum for providing for the Intelligent Compaction for Soils on the project.

BASIS OF PAYMENT

The incorporating of the Intelligent Compaction process will be paid at the contract lump sum price for Intelligent Compaction for Soils.

Payment will be made under:

Pay Item	
Intelligent Compaction for Soils	LS

This item includes all costs related to providing the IC roller including the fuel, roller operator, GPS system, or any other equipment required for the IC process. All quality control procedures including IC rollers and GPS systems representatives support, on-site training and testing facility shall be included in the contract lump sum price.

S-1 (2016) QUALITY MANAGEMENT SPECIAL – INTELLIGENT COMPACTION (IC) METHOD

REVISED 04/11/14 ◀DO NOT REMOVE THIS. IT NEEDS TO STAY IN FOR THE CONTRACTORS. SP2014-54.2

MnDOT 2105, 2106, 2211, 2215, 2331, 2353, 2360 and 2365 are modified with the following:

All IC forms are available on the MnDOT Advanced Materials and Technology (AMT) Website: http://www.dot.state.mn.us/materials/advancedmaterialsandtechnology.html.

S-1.1 <u>DEFINITIONS</u>

- (A) (1) Cloud—is a web-based user interface.
 - Cloud Storage—is network storage (typically the internet) where the IC data are stored in virtualized pools of storage.
 - (3) Cloud Computing—is the use of computing resources (hardware and software) that are delivered as a service over a network to enable near, real-time visualization (maps) and manipulation of IC data.
- (B) (1) Coordinate System—is a system that uses one or more numbers, or coordinates, to uniquely determine the position of a point or other geometric element on a manifold such as Euclidean space.
 - (2) Geodetic Coordinates—is a non-earth-centric coordinate system used to describe a position in longitude, latitude, and altitude above the imaginary ellipsoid surface based on a specific geodetic datum. WGS-84 and NAD83 datum are required for use with UTM and State Plane, respectively.
 - (3) State Plane Coordinates—is a set of 124 geographic zones or coordinate systems designed for a specific region of the United States. Each state contains one or more state plane zones, the boundaries of which usually follow county lines. There are 110 zones in the continental US, with 10 more in Alaska, 5 in Hawaii, and one for Puerto Rico and US Virgin Islands. The system is widely used for geographic data by state and local governments since it uses a Cartesian Coordinate System to specify locations rather than a spherical coordinate system. By ignoring the curvature of the earth, "plane surveying" methods can be used, speeding up and simplifying calculations. Additionally, the system is highly accurate within each zone (error less than 1:10,000). Outside a specific state plane zone accuracy rapidly declines, thus the system is not useful for regional or national mapping. The current State Plane Coordinate is based on NAD83. Issues may arise when a project crosses State Plane Boundaries.
 - (4) Universal Transverse Mercator (UTM)—is a metric-based, geographic coordinate system that uses a 2-dimensional Cartesian coordinate system to give locations on the surface of the earth. This system divides the earth between 80°S and 84°N latitude into sixty zones, each a six-degree band of longitude width, and uses a secant Transverse Mercator projection in each zone (the scale is reduced so that the cylinder slices through the model globe). Zone 1 covers longitude 180° to 174°W; zone numbering increases eastward to zone 60° that covers longitude 174° to 180° East.



Figure S-xx.1. Image of UTM zones in the United States.

- (C) Coordinated Universal Time (UTC)—is the primary time standard by which the world regulates time. It is one of several closely related successors to Greenwich Mean Time (GMT). For most purposes, UTC is synonymous with GMT. It is based on a 24-hour time scale from the mean solar time at the earth's prime meridian (zero degrees longitude) located near Greenwich, England.
- (D) (1) Data—are measurements recorded by the Instrumented Roller, or information generated/processed from these measurements (e.g., GPS coordinates, stiffness, temperature, pass count, speed, frequency, amplitude).
 - (2) Gridded All Passes Data—includes all Measurement Passes recorded for a given grid (see Figure S-xx 2). This data is generally used to build compaction curves for establishment of rolling patterns.

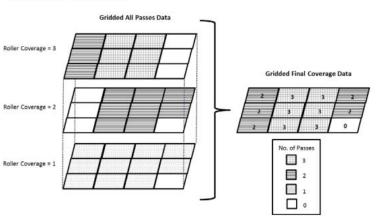


Figure S-xx.2. Schematic of coverage, Gridded All Passes Data and Gridded Final Coverage Data

(3) Gridded Data—is processed from the raw data using meshes. The raw data is duplicated over the meshes for the entire roller drum width, resulting in multiple data points covering the drum width (see Figure S-xx.3). This process is used to track partial drum overlaps among passes.

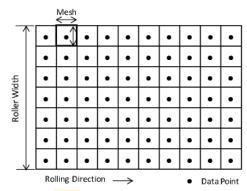


Figure S-xx.3. Schematic of gridded IC data

- (4) Gridded Final Coverage Data—summarizes the final (last) Measurement Passes recorded for a given grid (e.g., total pass count, last stiffness, last temperature [see Figure S-xx.2]).
- (5) Mesh—is a collection of vertices connected to other vertices that defines the shape of the roller drum in two (2) Dimensional (2D) polygons (typically multiple squares). The defined data mesh size is generally 0.3 m by 0.3 m (1 ft by 1 ft) in horizontal directions (see Figure S-xx3).
- (6) Raw Data—is data recorded during compaction operations prior to the gridding process. It consists of one data point for a roller drum width, recorded at approximately 10 Hz or 0.3 m (1 ft) intervals. Therefore, the data mesh (data footprint) is about one drum width by 0.3 m (1 ft) (see Figure S-xx.4).

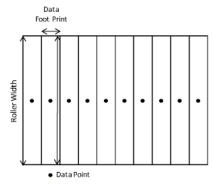


Figure S-xx.4. Schematic of raw data

- (7) Veda—is a standardized intelligent construction data management (ICDM) software that stores, maps and analyzes IC and associated geospatial data (e.g., thermal profiler data, spot test data). This software can perform standardized data processing, analysis and reporting to provide Project summary results quickly in the field from various IC manufacturers. In particular, the software can provide statistics, histograms, correlations for the IC measurements (e.g., speed, temperature, pass count, ICMV), document coverage area and evaluate the uniformity of compaction as part of the Project quality control operations.
- (E) (1) Design Files—are databases containing the vector image data of the roadway alignment. Design files can be exported from software programs in various formats (e.g., DWG, KMZ, LandXML).
 - (2) DGN Files—are MicroStation Design Files. These files contain a database of 2D or 3D drawings containing vector image data of the alignment created with MicroStation.
 - (3) DWG Files—are AutoCAD Drawing Database files. These files contain a database of 2D or 3D drawings containing vector image data of the alignment created with AutoCAD.
 - (4) KML Files—are Keyhole Markup Language Files that store geographic modeling information in LandXML format. These files contain points, lines, polygons, and images, used to identify and label locations, overlay textures and add HTML content.
 - (5) KMZ Files—store the alignment in a format viewable in Google Earth (a global mapping program that provides a bird's eye view of locations throughout the United States and other areas of the world). KMZ files are zipped KML files which make them easier to distribute and share with multiple users.
 - (6) LandXML Files—is an extensible markup language data file that uses tags to define objects and object attributes; formatted much like an HTML document, but uses custom tags to define objects and the data within each object. These files are formatted as a textbased database, and therefore, can be edited by a basic text editor.
- (F) (1) Global Navigation Satellite System (GNSS)—is a satellite system that is used to pinpoint the geographic location of a user's receiver anywhere in the world. Three GNSS systems are currently in operation: the United States' Global Positioning System (GPS), the Russian Federation's Global Orbiting Navigation Satellite System (GLONASS), and

- Europe's Galileo. Each of the GNSS systems employs a constellation of orbiting satellites working in conjunction with a network of ground stations.
- (2) Global Positioning System (GPS)—is a navigation system that uses satellite signals to fix the location of a radio receiver on or above the earth's surface, anywhere on or near the earth, where there is an unobstructed line of sight to four or more GPS satellites. This system also provides the time stamp needed for IC.
- (3) GPS Base Station—is a GPS receiver at an accurately-known fixed location that is used to derive correction information for nearby portable GPS receivers. This correction data allow propagation and other effects to be corrected out of the position data obtained by the portable GPS receivers, which provides increased location precision and accuracy over the results obtained by uncorrected GPS receivers. This system consists of an antenna, radio, radio antenna and power source. The radio and environment/physical conditions control the distance that the correction signal travels. The typical range of the correction signal is about 2 miles in radius without repeaters. A repeater may extend the distance an additional 2 miles.
- (4) Real Time Kinematic (RTK)—satellite navigation is a technique used to enhance the precision of the ground-based data derived from satellite-based positioning systems (e.g., GPS, GLONASS, Galileo). It uses measurements of the signal's carrier wave and relies on a single reference station to provide real-time corrections that are up to centimeter accuracy.
- (5) RTK Network—is a system that uses multiple Base Stations to provide high-accuracy GPS positioning within a coverage area that is generally larger than that covered by a ground-based GPS Base Station.
- (6) Remotely Operated Video Enhanced Receiver (Rover)—is a portable radio/receiver used to determine GPS coordinates for given point locations.
- (7) Virtual Reference Station (VRS)—are networks that use RTK Networks to provide high-accuracy, RTK Global Navigation Satellite Systems typically through the use of cellular wireless services (e.g., OminSTARTM, Trimble VRSTM, Trimble VRS NOWTM). MnDOT has this system available for free to users.
- (G) (1) Instrumented Roller—is a self-propelled roller integrated with a position monitoring system and onboard documentation system that can display real-time color-coded maps of roller location, number of passes, roller speeds, and amplitude and vibration frequencies of the roller drum. Some systems are also equipped with drum vibration instrumentation, infrared temperature sensors, and/or Automatic Feedback Control. The onboard documentation system on these rollers would also display real-time color-coded maps of stiffness response or pavement surface temperatures, or both.
 - (2) Automatic Feedback Control—automatically adjusts roller Operating Settings, such as vibration frequency and amplitude, based upon real-time feedback from the drum vibration measurement system.
 - (3) Finishing Roller—is the final roller used in the compaction process for the given Layer.
 - (4) Instrumented Roller Failure—is when the Instrumented Roller system does not collect and/or store data per the requirements of S-xx 3.D.7 and S-xx 3.D.8, and/or the roller becomes inoperable.
 - (5) Intelligent Compaction (IC) Roller—is used synonymously with Instrumented Roller.

- (6) Operating Settings—are roller settings (e.g., speed, direction, frequency, peak vertical force amplitude).
- (7) Intelligent Compaction Measurement Value (ICMV)—is the stiffness of the materials based on the response of the roller drum vibrations and underlying material responses.
- (H) (1) Layer—is the total thickness of each material type. It may be comprised of single or multiple Lifts.
 - (2) Layer Identification (Layer ID)—is the reference name of the material and lift currently being compacted (e.g., Aggregate Base – Lift 1, Aggregate Base – Lift 2, Asphalt Pavement – Lift 1, Asphalt Pavement – Lift 2).
 - (3) Lift—is a unit of material within a Layer that is placed for compaction.
- (I) Measurement Pass—is a Roller Pass, performed by an Instrumented roller, where all required information (per S-xx.3.D.8) is recorded in a Data File.
 - (2) Coverage—is the total area resulting from Roller Passes on a given Lift/Layer (see Figure S-xx.2).
 - Cumulative Measurement Pass Count—is the Gridded Final Coverage Data for pass count
 - (4) Daily Percent Coverage (DPC)—is the percent of the required daily compaction area where the minimum required Cumulative Measurement Pass Count is achieved.
 - (5) Project Percent Coverage (PPC)—is the percent of required compaction area, for the project, where the minimum required Cumulative Measurement Pass Count is achieved.
 - (6) Roller Pass—is the area covered by one width of the roller in a single direction.
- (J) Quality Control Personnel—are the individuals employed by the Contractor to execute this work.
 - Intelligent Compaction Supervisor—is the Contractor's person responsible for performance and compliance with intelligent compaction requirements.
 - (3) Onsite IC Support—is the Contractor's personnel responsible for the onsite execution of the intelligent compaction requirements. The Onsite IC Support must also understand and perform the responsibilities per form IC-101.
 - (4) Operator(s) of Instrumented Roller(s)—is the Contractor's personnel operating instrumented roller(s). The operator must comply with the requirements of this specification and understand and perform the responsibilities per form IC-102.
- (K) Site—is the Project where the instrumented rollers are required.
 - (2) Site Analysis—is the process where the Contractor determines the number of GPS repeaters needed to cover the entire working length of the Project and to address Project staging of GPS repeaters and base station(s) when used. This process should be completed before or during Site Setup/Calibration.
 - (3) Site Setup/Calibration—is the process of setting up the local, base station and repeaters (or VRS). It also includes determining the coordinate information of each survey marker and storing this information within the IC software.

- (L) Survey Markers—(sometimes referred to as survey marks, monuments, hubs, control points)—are temporary or permanent objects placed to mark key survey points on the earth's surface. These markers are used to indicate elevation and horizontal position.
- S-1.2 <u>ACRONYMS AND ABBREVIATIONS</u>
 - (A) D—dimensional
 - (B) DPC—daily percent coverage
 - (C) GNNS—global navigation satellite system
 - (D) GPS—global positioning system
 - (E) IC—intelligent compaction
 - (F) ICDM—intelligent construction data management
 - (G) ICMV-IC measurement value
 - (H) PPC-Project percent coverage
 - (I) Rover—remotely operated video enhanced receiver
 - (J) RTK—real time kinematic
 - (K) UTC—Coordinated Universal Time
 - (L) UTM-Universal Transverse Mercator
 - (M) Veda-intelligent construction data management software
 - (N) VRS-virtual reference system

S-1.3 EQUIPMENT REQUIREMENTS

The Department does not guarantee the accuracy and compatibility of electronic data provided by the Department. The Plan documents, originally provided with the Contract, remain the basis of the Contract. The Contractor is responsible for any necessary conversions of the provided electronic data.

- (A) Rover
 - The Contractor will provide the Department with One (1) survey grade GNSS Rover Receiver and Receiver Kit (Rover) for use during the Contract.
 - Includes cabling, antenna, charger, accessories, and three (3) sets of rechargeable batteries.
 - (b) Setup to reference the local, ground-based Base Station or the Network RTK used on the Project.
 - (c) Display and store the Date, Time and X, Y, Z Coordinates as required by Table 8-xx.1. The XYZ Coordinates must be collected, unless otherwise specified, in the County Coordinate System used in the background alignment file(s) using NAD83 (1996 adjustment) and NAVD88 vertical datum.

Table S-xx.1	
Required Format of Rover Data	
Description	Data Format Examples
Date Stamp (MDDYY)	3/19/13
Time Stamp	21:46:22.96
(HHMMSS.SS -military format)	(21 hr 46min. 22.96 s.)
Northing (Y)	153328.47
Easting (X)	524195.65
Height (Z)	909.85

- Maintain this equipment for the duration of the Contract (this includes necessary (d) hardware and software upgrades).
- (e) Provide an equivalent replacement, within two (2) working days, should the equipment become lost, stolen, inoperable.
- (2) The Contractor must use Rovers meeting the requirements of S-xx.3.A.1.
- (3) The Department will return the survey equipment no later than ninety (90) days after final acceptance of all work per MnDOT 1516.2
- (B) Survey Markers and Field Stationing
 - The Department will set temporary Survey Markers, meeting the following requirements (see Figure S-xx.5), prior to the Project start date (Permanent Survey Markers meeting the following requirements can also be used):
 - (a) Two (2) Survey Markers, at the start and at the end of the Project (totaling four [4]).
 - One (1) Survey Marker every 1.5 miles on the right-of-way. Alternate the (b) Survey Markers on each side of the alignment.
 - All Survey Markers have a clear line of site to satellites to allow for GPS (c) calibration of the site.
 - (d) Five (5), of the Survey Markers, must meet the following requirements (the remaining survey markers may be two dimensional [2D]):
 - (i) Three Dimensional (3D)
 - (ii) Accuracy ≤ 0.1 ft in the X-, Y- and Z-Direction
 - (iii) Equally spaced throughout the Project.
 - One (1) survey marker at the start and end of the Project. (iv)
 - The remaining Survey Markers must have an accuracy of $\leq 0.1~\mathrm{ft}$ in the X- and (e) Y-Direction.



Figure S-xx.5 Schematic of the required Survey Marker configuration.

- (2) The Department will provide the following coordinate information in a *txt or *csv format, for the permanent and temporary Survey Markers, 7 working-days prior to the start of compaction efforts:
 - (a) Point Name
 - (b) Northing
 - (c) Easting
 - (d) Elevation
 - (e) Location Code / Description

The Department will also include available MnDOT Geodetic Data Sheets that are relevant to the Project limits.

- (3) The Department will ensure that field station markers, when used, match those used in the design file (see S-xx.3.C).
- (C) Design Files
 - Ensure the alignment file is loaded onto the Onboard Documentation System of each instrumented roller and into the Cloud Computing mapping software.
 - (2) The Department will provide background, alignment files(s), in the following formats, within three (3) working days of Contract approval:
 - (a) 2D-DWG (or LandXML) and
 - (b) 2D-KMZ
 - (3) The Department will enclose the following background shapefile features as single, independent polygons (closed 3-sided polylines):
 - (a) Mainline (Driving and Auxiliary Lanes)
 - (b) Exceptions on the Mainline
 - (4) At a minimum, the following text features will be included in the alignment files:
 - (a) Centerline Station Numbering

- (b) Station Limits for Exceptions
- (5) The Department is allowed three (3) working days to update files with Department approved changes requested by the Contractor.
- (D) Instrumented Roller System

Provide the Department with Instrumented Rollers per Table S-xx.2.

	Table <mark>S-xx.2</mark>							
	Required Instrumented Roller Equipment							
Specification	Description	Quantity	Duration	RTK-GPS	Accelerometer	Temperature	Additional Requirements	
	Manufacturer's Intelligent Compaction Computer Software	Optional	14-days prior to certification of the roller(s) until ninety					
2105, 2106, 2211, 2215, 2331,2353, 2360, 2365	Access to Cloud Storage and Cloud Computing	Two (2) User IDs. 1 ID to be provided for use by the Department	(90) days after final acceptance of all work per MnDOT 1516.2.				S-xx: 3.D.1	
2105, 2106, 2211, 2215, 2331	Self-Propelled, Vibratory: Smooth, Single-Drum Steel Smooth, Double-Drum Steel Pad (Sheep's) Foot			√ S-xx.3.D.3	√ S-xx.3.D.4			
2105, 2106, 2211, 2215, 2331	Self-Propelled, Pneumatic Roller	S-xx.3.D.2	Duration of Compaction Efforts.	S-XX.3.D.3			S-xx.3.D.6 S-xx.3.D.7 S-xx.3.D.8	
2353, 2360, 2365	Self-Propelled, Vibratory: Smooth Double-Drum Steel				√ S-xx.3.D.4	V		
2360, 2365	Self-Propelled, Pneumatic Roller					S-xx.3.D.5		

- (1) The Manufacturer's Intelligent Compaction Software, and Cloud Computing, must map and export Gridded All Passes and Gridded Final Coverage Data meeting the requirements of S-xx3D.8. Additionally, the Manufacturer's Intelligent Compaction Software (and Cloud Computing) must support the following features:
 - (a) Filtering by:
 - (i) Instrumented Roller
 - (ii) Date and Time Stamp
 - (iii) Layer ID
 - (b) Creating Boundaries (e.g., Polygon Feature), or the ability to create boundaries using the alignment file.
 - (c) Calculation of Gridded Final Coverage Data using filtered data (e.g., Gridded Final Coverage for a given Roller, for a given day of production and location; Gridded Final Coverage within the entire Project limits).
- (2) All rollers are required to be instrumented with intelligent compaction technology.

Instrumented rollers are required for all compaction efforts under MnDOT 2105, 2106, 2211, 2215, 2331, 2353, 2360 and 2365.

- (3) Instrumented with the capability to connect to a RTK-GPS using either:
 - Local, Ground-Based Base Station(s)-Use either the Trimble GPS system, or (i) TOPCON GPS system. The Engineer may approve other compatible systems.
 - MnDOT's VRS RTK Network. (The Contractor is responsible for verifying (ii) cellular coverage within the Project limits for use of MnDOT's VRS RTK Network.)
- Instrumented with accelerometers mounted in or about the drum to measure the (4) interactions between the rollers and compacted materials.
- Instrumented with one non-contact, temperature sensor, mounted on or near, the front of (5) the roller for measuring pavement surface temperatures. A second temperature sensor may be mounted on, or near, the rear.
- (6) Instrumented with the following:
 - (a) Modem, or Wi-Fi, for transferring data to Cloud Storage.
 - (b) Onboard Documentation System
 - Displays real-time, color-coded maps of:
 - Linework (Alignment File) b. Roller Drum Location
 - Number of Roller Passes
 - C. d. ICMV (for systems with accelerometers)
 - Pavement Surface Temperature (for systems with temperature e. sensors)
 - Displays current value for: (ii)
 - Roller Speed
 - b. Vibration Frequency
 - Vibration Amplitude
 - (iii) Ability to manually export data using a removable media device.
 - Allows operator to define (label) or select each Layer ID.
- Required Instrumented Roller Equipment Accuracy (7)

Table <mark>S-xx.3</mark>					
Required Instrumer	Required Instrumented Roller Equipment Accuracy				
Operating Parameter Accuracy					
Global Positioning System	± 2 in (50 mm) in the X and Y Direction				
Rolling Speed	± 0.3 mph (0.5 kph)				
Frequency	± 2 Hz				
Amplitude	± 0.008 in (0.2 mm)				
Temperature	± 2.7°F (±1.5°C)				

(8) Measurement Pass Data

- (a) Gridded All Passes and Gridded Final Coverage Data are exportable:
 - (a1) as dbase ASCII or Text Format, or
 - (a2) directly into Veda (software can be downloaded from the MnDOT Intelligent Compaction website).
- (b) Gridded All Passes and Gridded Final Coverage Data Files:
 - (b1) The following information is recommended for inclusion within the header of each data file or section, or with each data point:

Data Field Name	Data Format Examples
Project ID	SPXXXX-XX
Machine Trade Name	Manufacturer Name
Roller ID	Serial Number, Machine ID
Drum Configuration	2
(1: single drum; 2: double drum; 3: pad foot;	
4: pneumatic)	
Drum Configuration	2
(1: single drum; 2: double drum; 3: pad foot;	
4: pneumatic)	
Drum Width (m)	2.007
Drum Diameter (m)	1.2
Machine Weight (metric ton)	14.0
Transverse Mesh Size (mm)	300
(direction parallel to roller drum)	
Longitudinal Mesh Size (mm)	300
(direction perpendicular to roller drum)	
EPSG Coordinate System Code	3745
(0 for non-EPSG coordinate system)	
Non-EPSG Coordinate System Zone Name	Dodge County
Name of ICMV Index	3
(1: CCV, 2: CMV; 3: Evib; 4: HMV; 5: Kb;	
6: MDP; 7: Other)	
IC Data Type	3
(1: Raw data; 2: Gridded All Passes Data; 3:	
Gridded Final Coverage Data)	
Number of IC Data Records	100000

Table S-xx.4				
Required Fields in Gridded All Passes and Gridded Final Coverage Data Files				
	for Each Data Point			
Data Field Name	Data Format Examples	Requirements (Section) [S-xx.3.D.8.b2(i), (ii)]		
Date Stamp (YYYYMMDD)	20080701			
Time Stamp (HHMMSS.SS -military format)	214622.962 (21 hr 46min. 22.962 s.)			
Roller Trade Name	Roller Model			
Roller ID	serial number, machine ID			
Northing (Y) (ft)	153328.47	S-xx.3.D.8.b2(iii)		
Easting (X) (ft)	524195.65	S-xx.3.D.8.b2(iii)		
Height (Z) (ft)	909.85	5-XX.3.D.8.02(IV)		
GPS Mode	RTK Fixed			
Roller Pass Number (calculated from Grid)	2			
Roller Direction	Forward, Reverse (or an index)			
Roller Speed	4.0			
Vibration On	Yes, No, On, Off (or an index)			
Frequency	38.4			
Amplitude	0.6			
Surface Temperature	120	S-xx.3.D.8.b2(v) S-xx.3.D.8.b2(vi)		
ICMV	20.0	S-xx.3.D.8.b2(vii)		

- (i) Include measurement units in a header or as part of the field name
- (ii) The data mesh size, after post-processing, must be less than 18 in (450 mm) in the X and Y directions.
- (iii) The XYZ Coordinates must be collected, unless otherwise specified, in the Coordinate System used in the background alignment file(s) using NAD83 (1996 adjustment) and NAVD88 vertical datum.
- (iv) Coordinates indicate the center of the roller drum.
- The surface temperature measurement must reflect the mat surface temperature from leading sensor immediately before rolling.
- (vi) Surface temperature measurements are only required for rollers instrumented with temperature sensors.
- (vii) ICMVs are only required for rollers instrumented with accelerometers.

S-1.4 CONSTRUCTION REQUIREMENT

- (A) Training and Certification of Personnel
 - (1) The Contractor will provide the following personnel, certified per Table S-xx.5:

- (a) Intelligent Compaction Supervisor(s)
- (b) Onsite IC Support
- (c) Operator(s) of the Instrumented Roller(s)

Table <mark>S-xx.5</mark>					
Required (Required Certification Training of Contractor Personnel				
Personnel	Training By	Form			
Intelligent Compaction Supervisors Onsite IC Support	Vendor or Manufacturer	IC-101			
Operator(s) of the Instrumented Rollers	Vendor or Manufacturer, or Intelligent Compaction Supervisor, or Onsite IC Support	IC-102			

- (2) Certification of personnel will be completed, one time per calendar year. Certification must be completed prior to use of equipment for Measurement Passes on this Contract (see S-xx 4 D).
- (3) The Department will provide training to the following Department personnel executing this specification:
 - (a) Project Engineer
 - (b) Inspector(s)
- (B) Site Analysis, Setup and Calibration
 - Complete site setup and calibration at least seven (7) working days prior to the use of the instrumented rollers for roller certifications (see S-xx.4.C) and measurement passes.
 - (2) Provide the Department, prior to instrumented roller certification (8-xx.4.C), with the date that the site was setup and calibrated and the locations of local, ground-base stations when used.
- (C) Department Approval of Instrumented Rollers for Use
 - Provide the proposed demonstration locations and proposed date of roller certification(s) to the Department at least 14-calendar days in advance. The Engineer will approve Project Site demonstration locations at least 7-calendar days prior to roller demonstration.
 - (2) The Department will approve the Instrumented Roller(s) for use using Form IC-103.
 - (3) Complete measurement passes, at the approved demonstration locations, for the cases specified in Table S-xx.6.

	TABLE S-xx.6						
	Department Approval of Instrumented Rollers for Use [see S-xx.4.C.3.a]						
Case		Testing	Paccoc	Measurement Area			
No.	Demonstration	Location		Width	Length		
	Verification of Adequate Sensor Range						
1	Soft Material [see S-xx.4.C.3.b]	Project Site	,	≥ 7 ft (2 m)	≥ 300 ft (100 m)		
2	Stiff Material [see S-xx.4.C.3.b]		1	≥ / II (2 m)	≥ 300 ft (100 m)		
Verification of Data Contained within Measurement pass files							
3	Data Quality [see S-xx.4.C.3.c]	Project Site	2	\geq 7 ft (2 m)	≥ 300 ft (100 m)		

- Department approval of Instrumented Rollers for use must be completed one (a) time per calendar year.
- Verify that the ICMVs can identify differences between weak and strong (b)
- Verify that all measurements are recorded and meet the requirements of (c)

NOTE-The requirements of S-xx.4.C.3 will be modified in the future after establishment of a national standard for calibration of instrumented rollers.

- Provide the Department with the Gridded All Passes Data Files, for cases 1 and 2 in Table S-xx.6, at least 7-calendar days prior to roller certification when the measurements were collected offsite, or were previously approved during the given calendar year.
- Calibration of GPS Accuracy (5)
 - Rover-Verify that the Rover(s) are calibrated to the correct coordinate system, (a) using a Survey Marker, within the Project limits. Complete this verification prior to checking the Intelligent Compaction System's GPS.
 - Intelligent Compaction System (b)
 - Mark a spot on the ground next to the drum location being recorded and displayed by the Onboard Documentation System (e.g., center [or left or right edge] of the roller drum or of the outside edge of a pneumatic roller tire).

NOTE-Ensure that the outside edge of a pneumatic roller tire is used, as not all Pneumatic Rollers have a wide-track width.

- Collect and compare the GPS coordinates from the Rover and the (ii) Instrumented Roller. The coordinates must compare within 0.5 ft (150 mm) of each other in the X and Y direction.
- (6) Calibration of the IC Temperature Accuracy
 - Power on the IC temperature sensors, a minimum of 10 minutes, before (a) verifying measurements.

(b) Collect and compare the temperature measurements from an independent device and the Instrumented Roller for the front sensor (and for the rear mounted sensor when also installed on the roller). The temperatures must compare within 5°F (2.8°C).

(D) Measurement Passes

- The Daily Percent Coverage will be considered zero, for rollers that have not been approved for use by the Department (see S-xx 4.C), or are operated by personnel who have not been certified (see S-xx 4.A).
- (2) Complete Measurement Passes:
 - On 100 percent of the mainline (driving and auxiliary lanes) including Control Strips.
 - (b) Per Table S-xx.7.

Table S-xx.7						
Re	Required Measurement Pass Locations					
Specification	Measurement Pass Location	Requirement				
	All roller passes on the Top of Subgrade.	S-xx.4.D.b1				
2105 / 2106	(When the depth is within 6 ft (2 m) of	S-xx.4.D.b2				
	Grading Grade.)	S-xx.4.D.b3				
	All roller passes on final Grading Grade Lift.	S-xx.4.D.b4				
		S-xx.4.D.b1				
2211, 2215, 2331		S-xx.4.D.b2				
	All roller passes on each Lift.	S-xx.4.D.b4				
2353, 2360, 2365		S-xx.4.D.b1				
(Asphalt Pavement)		S-xx.4.D.b2				

- (b1) Identify the Layer IDs using Project typical sections. The operator must input (or select) the Layer ID, using the on-board display, prior to compacting the given material.
- (b2) Operate the Finishing Roller, on each lift, using consistent Operating Settings for the following:
 - Amplitude and Frequency (when in vibration mode)
 - Speed (between 3 and 5 mph).
- (b3) Avoid performing Measurement Passes, in the vibratory mode, within 4 ft (1.2 m) of the water table.
- (b4) Test roll (MnDOT 2111), when required, immediately after completing the final Measurement Pass. The Department will identify boundaries of failing test rolling per Form IC-104.
- (3) It is recommended that the GPS accuracy on the Instrumented Rollers is verified, prior to use each day, using the procedure outlined in S-xx.4.C.5, or by reviewing the measurement passes, with respect to the alignment, on the onboard documentation system.

It is also recommended that the temperature accuracy on the Instrumented Rollers is periodically verified using the procedure outlined in 8-xx.4.C.6.

- (4) Turn data collection and recording off when not performing Measurement Passes.
- (5) Provide the Department immediate viewing of the Measurement Pass data on the IC Roller.
- (6) Record the number of Instrumented Rollers used, and which rollers are being used in tandem (if any) on form IC-107, on each day of production. This information is needed for the basis of measurement (8-xx.5).
- (E) Instrumented Roller Failure

Contact the Department immediately when Instrumented Roller Failure (see S.xx.1.G.4) occurs and immediately after the issues have been resolved. The day of Instrumented Roller Failure notification, and the following two (2) working days, will be accepted as providing a Daily Percent Coverage of 100% for the given roller, for each day of this grace period. The Daily Percent Coverage (see S-xx.1.I.4) will be reflective of the actual measurements during subsequent days of Instrumented Roller Failure for the given roller.

- (F) GPS Coordinates
 - Ensure GPS point identifications are included on the appropriate sample or testing forms.
 - (2) Use a Rover (meeting S-xx.3.A) to determine the GPS coordinates for all quality control samples and testing locations on the mainline.
 - (3) The Department will use a Rover (meeting S-xx.3.A) to determine the GPS coordinates for:
 - (a) All verification/quality assurance samples and test locations on mainline.

This includes grading and base testing; and/or mix testing and cores for bituminous.

- Boundaries of areas requiring corrective action (record coordinates per form IC-105).
- (c) Boundaries of the daily production area (record coordinates per form IC-106).
- (d) Boundaries of exceptions (see form IC-106). Ensure that the coordinates are collected for each lane (e.g., centerline point is collected for use in per lane evaluations).
- (e) Core location for additional cores (see S-xx.4 H).
- (G) Additional Cores (For Information Purposes Only)
 - Core each lift, at the following locations, for each day of production:
 - (a) One (1) core, randomly selected, between 25 and 100 ft of the start of paving.
 - (b) One (1) core, randomly selected, between 25 and 100 ft of the end of paving.
 - (2) Label Cores as follows:
 - (a) Core from the beginning of paving: "Lot #.5"
 - (b) Core from the end of paving: "Lot #.6"

- (3) The Department will complete density testing on these cores for informational purposes only.
- (H) IC Data Submittal Requirements
 - Data collected during Department Approval of Instrumented Rollers for Use—Transfer IC Raw Data files directly from the roller to the Cloud Storage after completion of the Demonstration Cases at the Project site.

Transfer IC Raw Data Files, collected from an offsite location, directly to the Cloud Storage, or to the Department when storage is not available.

Submit forms IC-101, IC-102 and IC-103 prior to start of Measurement Passes.

- (2) Measurement Pass Data—Transfer IC Raw Data files directly from the roller to the Cloud Storage within 15-minute intervals when adequate cellular coverage is available; and at least one time per day when there is limited cellular coverage.
- (3) Submit Rover GPS Coordinates for QC sample and testing locations, in a *dbase or *csv format, on a weekly basis.
- (4) Submit forms per Table S-xx.9:

Table <mark>S-xx.9</mark>		
Form Submittal Schedule		
Form ID	Schedule	
IC-104 (Boundaries of Failing Test Rolling Areas)	Monthly	
IC-105 (Boundaries of Corrective Action Areas)	Monthly	
IC-106 (Boundaries of Daily Production Areas)	Washin	
IC-107 (Daily Roller Operations)	Weekly	

IC-104 and IC-105 on a monthly basis; and form IC-107 on a weekly basis.

S-1.5 METHOD OF MEASUREMENT

The Department will measure Quality Management Special by determining the Project Percent Coverage of the Cumulative Measurement Pass Count completed by the Instrumented Rollers over the required compaction areas specified in S-xx.4.D.2.

100 Percent Project Percent Coverage is achieved when the Cumulative Measurement Pass Count is greater than or equal to one (1) (Measurement Passes) times the number of Instrumented Rollers used for the given day of production. Instrumented Rollers working in tandem are counted as one (1) Instrumented Roller.

Note—Cumulative Measurement Pass Count is the Gridded Final Coverage Data for pass count (see S-xx.1.D.6). Please note that number of passes reflects the number of roller passes in one area of the mat (e.g., 0.3 m by 0.3 m [1 ft by 1 ft area]), not the total number of passes across the width of the mat for a given roller.

S-1.6 BASIS OF PAYMENT

The Contract lump sum prices for the Instrumented Roller(s) include all costs related to this Special Provision.

Interruptions of satellite reception of signals to operate this system will not result in any adjustment to the "Basis of Payment" for any construction items or to Contract time.

The Department will pay for the Instrumented Roller(s) on the basis of the following schedule:

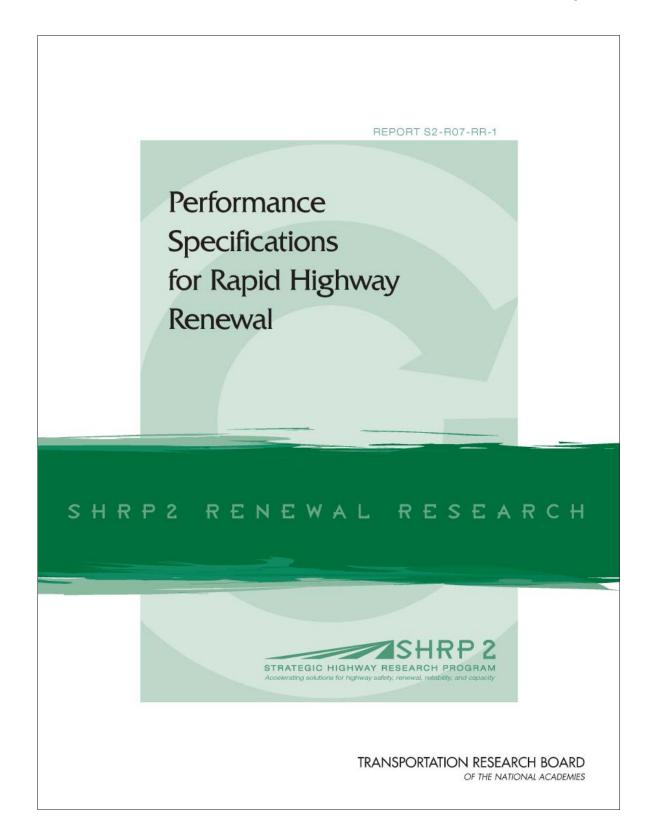
Item No.	Item	Unit
2016.601	Quality Management SpecialLu	mp Sum

(A)

 $\frac{PARTIAL\ PAYMENTS}{PARTIAL\ PAYMENTS}$ The lump sum will be paid in partial payment amounts for completion of the work per Table

S-xx.10:

	Table S-xx.10				
Item	Payment Schedule Criteria	% of Lump Sum Paid			
Α	Certification of the IC Supervisor(s), Onsite IC Support and Operators of the Instrumented Rollers per S-xx. 4 A	10% Payment			
В	Instrumented Roller(s) Approved for Use per S-xx.4.C	10% Payment			
С	Measurement Pass Completion (Form IC-108) Project Percent Coverage (PPC) ≥ 70% Project Percent Coverage (PPC) < 70%	80% Payment % Payment = 0.8×PPC+24			



The Second STRATEGIC HIGHWAY RESEARCH PROGRAM



Performance Specifications for Rapid Highway Renewal

SIDNEY SCOTT III AND LINDA KONRATH Hill International, Inc., Philadelphia, Pennsylvania

> TED FERRAGUT TDC Partners, Ltd., Lewes, Delaware

STUART ANDERSON AND IVAN DAMNJANOVIC Texas A&M, College Station, Texas

GERALD HUBER Heritage Research Group, Indianapolis, Indiana

JIM KATSAFANAS Michael Baker Jr., Inc., Moon Township, Pennsylvania

KEVIN MCGHEE, MICHAEL SPRINKEL, CELIK OZYILDIRIM, AND BRIAN DIEFENDERFER Virginia Center for Transportation Innovation and Research, Charlottesville, Virginia

> David Merritt and Dan Dawood Transtec Group, Austin, Texas

KEITH MOLENAAR University of Colorado at Boulder

MICHAEL C. LOULAKIS Capital Project Strategies, LLC, Reston, Virginia

DAVID WHITE AND VERNON R. SCHAEFFER Iowa State University, Ames, Iowa

TRANSPORTATION RESEARCH BOARD

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APPENDIX C

Performance Specifications for Earthwork/Pavement Foundation

Recent developments and improvements to in situ testing devices and integrated machine sensors (e.g., intelligent compaction rollers with accelerometer-based measurements of ground stiffness) have provided opportunities to develop more performance-oriented specifications in the areas of embankment and pavement subgrade/subbase construction.

Two specifications related to pavement foundation systems were prepared under the SHRP 2 R07 project. The first, and perhaps easiest to implement, entails replacing traditional forms of proof rolling with roller-integrated compaction monitoring (RICM) proof mapping to verify that pavement subgrade support conditions are satisfactory. Compared with traditional proof rolling, proof mapping can provide

- Geospatially referenced documentation of an RICM measurement value (MV);
- Real-time information to the contractor during the construction process; and
- Results that can be correlated to subgrade support values, such as bearing capacity and stiffness.

The second specification represents a more comprehensive attempt to specify the construction of embankment and pavement foundation materials in terms of performance measures and quality statements. Key features of this specification include the following:

- Use of RICM technology to provide 100% sampling coverage to identify areas needing further work;
- Acceptance and verification testing using performance measures and parameters—such as elastic modulus testing, shear strength, and permeability—that relate to design assumptions;
- · Protocols for establishing target values for acceptance;
- Quality statements and assessment methods that require achievement of at least some overall minimal value during

- construction, and achievement of a minimum level of spatial uniformity in a given lot area; and
- Protocols for data analysis and reporting such that the construction process is field controlled in an efficient manner to ensure the final product meets design assumptions.

This second specification may not be ready for immediate implementation on a construction project because of training needs and limitations in technology, data analysis/software, and endorsed test methods/standards. Nevertheless, it presents an approach for establishing target values for acceptance based on engineering parameters that relate to design assumptions.

Roller-Integrated Compaction Monitoring (RICM) Proof Mapping Performance Specification for Subgrade

Commentary: The goal of this guide specification is to describe a new construction quality control (QC) and quality assurance (QA) approach to verify that pavement subgrade support conditions are satisfactory. The specification includes a provision to replace traditional forms of proof rolling with rollerintegrated compaction monitoring (RICM) proof mapping.

Compared with proof rolling, proof mapping has the advantages of (1) providing geospatially referenced documentation of an RICM measurement value (MV), (2) providing realtime information to the contractor during the construction process, and (3) being correlated to subgrade support values such as bearing capacity and stiffness. By incorporating proof mapping capability into rollers, the results can be used as part of the contractor's process control operations.

Through agency verification performance testing, the RICM measurement records are intended to be used in the agency's acceptance decision. For practical reasons, the verification test results in this situation cannot be independent RICM measurements; so it is recommended that verification tests involve in situ testing conducted by the agency and correlated to the RICM MV (e.g., LWD, DCP, PLT').

This specification was drafted as part of the SHRP 2 R07 research effort to develop guide performance specifications for rapid highway renewal. The Missouri Department of Transportation (MoDOT) provided guidance in the development and field testing of this guide specification. An example of the proof mapping output is provided with this document. The MoDOT field results demonstrate an effective application of RICM proof mapping as an alternative to traditional proof rolling via a loaded, tandem-axle dump truck.

Implementation of this specification is not envisioned in the short term because of limitations in technology, data analysis/software, endorsed test/method standards (e.g., AASHTO), and training. A well-planned program will need to be developed to overcome these obstacles. As part of this research, a demonstration project was organized to provide field data to validate parts of this specification. The project report summarizes key findings from the demonstration project.

1 DESCRIPTION

This work shall consist of testing the support conditions of the prepared roadbed subgrade by proof mapping with a roller-integrated compaction monitoring (RICM)—equipped compactor before paving. Perform RICM proof mapping on all prepared subgrade, including main line, outer roadways, ramps, and all side streets. The department will establish target values for proof mapping through on-site RICM verification testing.

Record and document all RICM measurements obtained as part of compaction process control operations. Submit process control results to the department on request. Submit RICM proof mapping passes intended for inclusion in the department's acceptance decision on completion of mapping operations. RICM deliverables shall be current for each payment period.

Commentary: As an alternative to traditional nuclear moisture density testing and moisture content testing, drive core sampling (ASTM 2937), dynamic cone penetration testing (ASTM 6951), plate load testing (ASTM D1196), light weight deflectometer testing (ASTM E2583 or ASTM E2583), and other tests can be considered. A description of target value determination for these alternative methods is beyond the scope of this guide specification. Motivations to use alternatives to nuclear gauges include elimination of the nuclear compliancy and safety training issues and the understanding that current RICM measurements are better correlated to strength and stiffness measurements than to volumetric/gravimetric measurements.

2 TERMS AND DEFINITIONS

For the purpose of this specification, the following definitions shall apply.

- A. Roller-integrated compaction monitoring (RICM):
 RICM for earthwork and pavement foundation materials is defined as the generic gathering of data from roller systems involved with the measurement and recording of roller position, date/time, speed, vibration frequency, vibration amplitude, pass count, travel direction, and a compaction measurement value (MV). The RICM system is supplied by either the roller manufacturer or a third party. The RICM monitoring system shall include calibration records of the sensor systems.
- B. Measurement value (MV): Measurement values are calculated from calibrated sensors integrated into rollers that provide information on machine-ground interaction(s). Machine-ground interaction measurements are typically derived from vibration analysis of accelerometers, sensor systems that monitor machine drive power inputs, or direct measures of sinkage/rutting.
- C. Target value (TV): Target values are the established minimum MVs based on in situ correlation analysis to in situ performance point measurements. Correlation analysis requires statistical analysis of geospatially paired independent point measurement values (PMVs) linked to MVs using global navigation satellite system (GNSS) positioning information.
- D. Subgrade bearing capacity is the plate load test contact pressure required to induce 1 in. of plate deflection (25.4 mm) for a 12-in. (300-mm) diameter plate.
- E. Real-time kinematic (RTK)—based GNSS with base station corrections is used for determining the position of the roller and correlation spot tests. Results from the RICM shall be displayed to the roller operator on a color-coded computer screen in real time during roller operations, and the data shall be saved for transfer and viewing by the engineer.

Commentary: Additional terms and definitions may be needed for modified versions of this specification. The focus on subgrade bearing capacity for this specification is based on MoDOT's current proof rolling specification. Also note that the incorporation of moisture content measurement into the suite of RICM measurements is not commercially available; but it is an ongoing area of research and industry development, and it is expected to be incorporated in the near term.

3 EQUIPMENT/TEST CAPABILITIES

A. Provide RICM-equipped compactor(s) that have the capability to near continuously measure and record a roller-ground interaction measurement value (MV) that correlates to the subgrade bearing capacity as determined from a static plate load test performed in accordance with ASTM 1196.

Commentary: The RICM system requirement of "near continuous measurement" is intended to provide a requirement for reporting the measurement value. Reporting an RICM MV in distance increments ≤12 in. (300 mm) traveled is desirable but is not a set requirement at this point.

An alternative to defining subgrade bearing capacity based on 1 in. of plate deflection is to use a target minimum modulus of subgrade reaction (e.g., k-value used for pavement design purposes) at a defined plate contact stress. In brief, modulus of subgrade reaction is defined as the plate contact stress divided by the average plate deflection (see ASTM D1196 or AASHTO T222). Common plate contact stress values used to define modulus of subgrade reaction are 10 pounds per square inch (psi) (69 kPa) for subgrade and 30 psi (207 kPa) for stabilized subgrade and aggregate base. Although a 12-in. diameter plate is listed above, a plate diameter of 30 in. is normally the reference standard. For plate diameters smaller than 30 in. (762 mm), perimeter to surface area corrections are typically required so that the reported values are equivalent to the standard 30-in. diameter plate.

B. Provide an RTK GNSS to acquire northing, easting, and elevation data for mapping of RICM measurements. Ensure the system has the capability to collect data in an established project coordinate system. Furnish a local base station for broadcasting differential correction data to the rollers with a tolerance less than 0.1 ft in the vertical and horizontal.

Commentary: If a lower accuracy system is substituted for RTK GNSS, the quality of correlation analysis from verification testing is reduced and may require increased in situ testing frequencies and/or high minimum RICM target values to account for position induced measurement error, RTK GNSS position information is recommended.

- C. The RICM system shall have the capability to immediately display and provide a permanent electronic record of the proof mapping results and data as follows:
 - 1. Integrated, color-coded, real-time computer display viewable by roller operator showing RICM measurement value (MV), RICM MV with reference to RICM target value (TV), and roller pass coverage. Provide displayed results to the engineer for review on request.
 - 2. Electronic data file in American Standard Code for Information Interchange (ASCII) format with time stamp, RTK global positioning system (GPS) position in state DOT standard coordinate system, roller operation

parameters (speed, gear, and travel direction), the RICM measurement value (MV), and target value (TV).

4 CONSTRUCTION REQUIREMENTS

4.1 RICM Work Plan

Submit to the engineer an RICM work plan at the time of the preconstruction conference.

- A. Describe in the RICM work plan the following:
 - · Roller vendor,
 - Roller model.
 - Roller dimensions and weights,
 - Description of RICM measurement system(s),
 - Past independent verification of RICM correlations to in situ engineering measurements,
 - Roller data collection methods including sampling rates and intervals,
 - RTK GPS capabilities,
 - Minimum parameters for GPS calibration (required daily),
 - Validation process of RICM equipment and results (required daily),
 - Documentation system and data file types,
 - Software,
 - Roller operations per manufacturer recommendations,
- Proposed rolling patterns for each lift.
- B. Describe the process for RICM operations during the agency's testing to establish RICM target values.
- C. Address quality management of the pavement foundation layers, including testing to be performed and coordination with the department's efforts to verify that the contractor is meeting the minimum and/or maximum engineering parameter values.

Commentary: Agencies are encouraged to consider requirements for RICM operating training/certification when the data will be used as part of the acceptance decision.

- D. Describe how data will be acquired and transferred to the engineer, including method, timing, and personnel responsible. Data transfer shall occur at a minimum once per day or as directed by the engineer. Provide and export the following data in a comma, colon, or space delimited ASCII file format:
 - Machine model, type, and serial/machine number;
 - Roller drum dimensions (width and diameter);
 - Roller and drum weights;
 - File name:
 - Date stamp;
 - Time stamp;

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- RTK-based GPS measurements showing northing, easting, and elevation (e.g., in local project coordinate system);
- Roller travel direction (e.g., forward or reverse);
- Roller speed;
- Vibration setting (i.e., on or off);
- · Vibration amplitude;
- · Vibration frequency;
- RICM MV; and
- Pass count.

4.2 RICM Target Value Determination and Correlation Analysis

- A. For RICM verification and correlation analysis to establish RICM target value, the department (or an independent third-party inspection firm) will conduct in situ testing. Perform RICM roller operations for correlation analysis in the presence of the engineer, unless approved otherwise. The engineer will review all results to set the RICM TV.
- B. The department (or its third-party inspection firm) will prepare reports containing the results of the plate bearing testing and assessment of the RICM TV determination within 24 hours of testing. The test report will include the following:
 - Test identification number,
 - Dates of testing,
 - Names of QC/QA field personnel conducting tests,
 - Description of tests,
 - Tables presenting all data,
 - · Plots of plate bearing test results,
 - · Summary of calculated engineering values,
 - Plot of RICM MV versus independent measurements, and
 - · Plots of RICM proof maps.

4.3 Proof Mapping Roller Operation

To allow comparison of successive roller passes, the roller operations should be consistent between passes. For static (e.g., nonvibratory) rolling operations, maintain relatively constant speed and operate within the manufacturers slope and pitch limits. For vibratory rolling operations, maintain relatively constant vibration frequency and amplitude during roller operations. Permitted variation in vibration frequency is ± 2 Hz. Maintain rolling speed to provide a minimum of 10 impacts per linear foot and within ± 0.5 mph during measurement passes. Record roller operations in forward and reverse directions. Check and validate, if necessary, RICM equipment at the beginning of each workday. Make GNSS calibration checks on a daily basis.

Commentary: Changes in frequency and amplitude can influence RICM MVs. However, the limits for vibration frequency and speed variation can be adjusted if the RICM technology is documented as providing reliable and repeatable measurements outside the noted ranges. Speed fluctuations can also influence the RICM MVs and should not be allowed outside of the specified range during measurement passes. It is anticipated that RICM MVs will be affected by rolling direction, and therefore the output data fields shall indicate rolling direction.

- A. RICM proof mapping shall include two complete passes per lane and one complete pass in shoulder areas. Perform each pass so that a 0% to 10% overlap occurs between passes in the coverage area. The roller operations and rolling patterns for each lift shall be in accordance with the manufacturer guidelines and as proposed in the RICM work plan, subject to approval by the engineer.
- B. Protect completed work before the placement of the subsequent layers and until final acceptance of the project. At any time during construction of aggregate base pavement materials, the engineer may require the contractor to perform RICM proof mapping according to this specification in areas on the project where unstable subgrade is observed. Make corrections to the subgrade even if the engineer previously accepted the areas before they became unstable.
- C. Provide the results of RICM proof mapping to the engineer in printed and electronic form on request or within at least 24 hours of measurement. On approval of the RICM proof mapping, place the subbase, base course, or initial pavement course within 48 hours. If the subbase, base coarse, or initial pavement course is not placed within 48 hours or the condition of the subgrade changes because of weather or other conditions, perform proof mapping and corrective work at the discretion of the engineer and at no expense to the department.

5 PERFORMANCE REQUIREMENTS

The department will consider the roadbed to be unstable if the RICM measurement value is less than the established requirements for the mapping area based on the RICM target value (TV). To establish the RICM TV, the department will perform correlation analysis of the RICM MV to the subgrade bearing capacity, as defined in Section 2. The department will use simple linear regression analysis to establish a correlation between the RICM MV and plate load test values. The department will use a minimum of eight plate load tests to establish the correlation. The department will set the RICM TV as the RICM MV that correlates to a 1-in. plate deflection at a contact pressure of 90 psi (10,178 lbf for 12-in. diameter plate).

RICM MV =
$$b_0 + b_1 \cdot \alpha$$
 (1)

where $b_0 = \text{intercept}$, $b_1 = \text{slope}$, and $\alpha = \text{independent}$ variable.

As an alternative to on-site calibration using simple linear regression analysis, suitable evidence of RICM MV correlations with the selected in situ point measurements (e.g., plate load tests) may be used. Suitable evidence would be unbiased third-party measurements describing and verifying the statistical significance of the determined correlations. The correlations would need to be derived from the same roller machine configuration, operating conditions, and similar soil types.

Note: Relationships between RICM to in situ point measurements can be nonlinear, in which case simple linear regression is not recommended. There are many nonlinear models that can be used to develop correlations. An example of a hyperbolic relationship is provided in Figure C.1.

6 ACCEPTANCE REQUIREMENTS

The department will base acceptance of the RICM proof mapping area on achievement of the RICM TV in the proof mapping area with a minimum of 80% of the RICM MV \geq TV and no contiguous, isolated areas that are larger than 25 ft in length. When proof mapping identifies unacceptable areas in the roadbed, the contractor shall rework the area by scarifying and moisture conditioning the soils as necessary. Reshape and compact the disturbed areas. The engineer may not require retesting of that area by RICM proof mapping if the engineer is satisfied that the corrective actions taken have eliminated the cause of the instability as evidenced by testing and/or visual inspection.

Commentary: The 80% minimum criterion is a suggested value and is expected to vary from about 70% to 90% depending on the desired quality conditions and uniformity. Further, the 25-ft maximum for unstable areas may be adjusted from

 $3\,\rm ft}$ to 50 ft contiguous length. An alternative to the maximum continuous length is to use a maximum area such as the roller footprint (about 150 ft²). Currently, limited information is available to fully understand the impacts of the size of nonconforming areas, and the engineer should use judgment in setting these limits. Areas requiring corrective work, as determined from proof mapping, because of unforeseen conditions may require extra work, in which case the engineer may need to identify the needed remediation. Proof mapping areas are generally on the order of the project width by 200 ft to 1,000 ft in length, but that will depend on the project conditions.

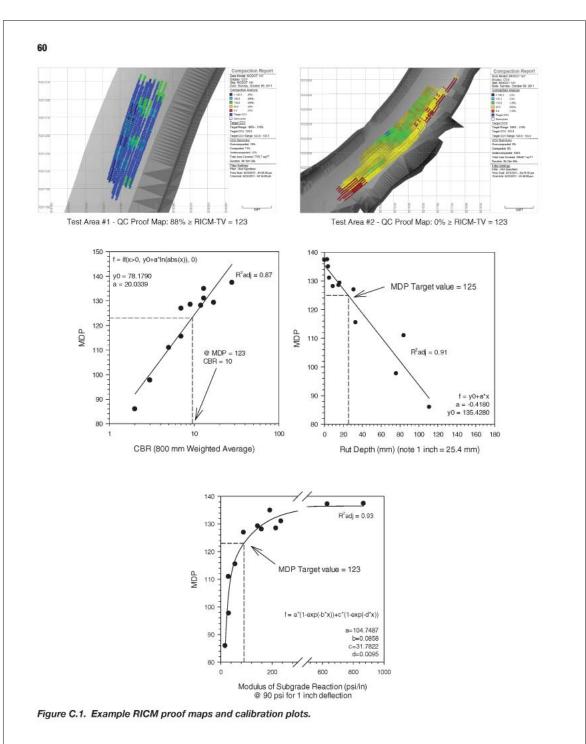
In addition to the RICM mapping described, it may be desirable for the agency to conduct quality assurance plate bearing tests. The number of tests and test locations will be based on assessment of the RICM MVs. In areas of high RICM variability (e.g., coefficient of variation, COV >200%), the test frequency will be about one test per 500 ft. In areas of low RICM variability (e.g., COV <20%), the test frequency will be about one test every 1,000 ft. The test locations could be randomly selected or by inspection of the RICM proof map to identify soft spots. The target numbers for quality assurance testing and RICM variability are related to the materials being tested and the type of RICM measurement technology. Engineering judgment should be used when selecting these limits. Typical values are presented in NCHRP Report 676.

7 BASIS OF PAYMENT

All RICM proof mapping operations are considered incidental to the grading and earthwork. No direct payment will be made to the contractor for RICM proof mapping or corrective work required as a result of the proof mapping.

Commentary: An alternative basis of payment language is as follows: Payment for RICM will be the lump sum contract price. Payment is full compensation for all work associated with providing RICM equipped rollers, transmission of electronic data files, two copies of RICM roller manufacturer software, and training. Delays resulting from GPS satellite reception of signals to operate the RICM equipment or RICM roller breakdowns will not be considered justification for contract modifications or contract extensions. In the event of RICM roller breakdowns, system malfunctions, or GPS problems, the contractor may operate with conventional rolling operations; but RICM proof mapping shall be provided for a minimum 90% of the project surface.

If, because of unforeseen ground conditions and as determined from proof mapping, the engineer determines that corrective construction work is necessary, such corrective work could be paid at the applicable contract unit price or as extra work.



Commentary: This guide specification, developed under the SHRP 2 R07 project, provides a template from which a state highway agency can develop a detailed performance specification for quality control (QC) and quality assurance (QA) of embankment and pavement foundation materials. Implementation of this specification will require investment in new technologies, training, and data management solutions. Traditionally, earthwork specifications are prescriptive, require relatively low test frequency, and/or do not use acceptance testing methods that directly evaluate performance characteristics during construction. To overcome these limitations, this guide specification includes the following key features:

- Acceptance and verification testing using performance measures and parameters—such as elastic modulus testing, modulus of subgrade reaction, and shear strength—that relate to design assumptions;
- Use of real-time roller-integrated compaction monitoring (RICM) technology [i.e., intelligent compaction (IC), continuous compaction control (CCC), compaction documentation system (CDS)] or instrumented proof rolling technology to provide nearly 100% coverage to identify areas needing further work, geospatially referenced data for uniformity analysis, and information to select verification testing locations;
- Protocols for establishing target values for acceptance based on the required engineering parameter values consistent with the design methodology used for the project;
- Quality statements and assessment methods that require achievement of at least some overall minimal value during construction, achievement of a minimum level of uniformity, and identification of contiguous areas of noncompliance that exceed the maximum allowable;
- Protocols for data analysis and reporting such that the construction process is field controlled in an efficient manner to ensure the final product meets design assumptions;
- Assignments of responsibility for field QC/QA, data reporting, and verification testing, and guidance on data interpretation and remediation; and
- A few options for pay adjustments that provide incentives/ disincentives to promote achievement of the specific performance criteria and maximize coverage of the performance verification assessment.

A distinguishing factor for this guide specification, compared with other components of civil infrastructure, is the subterranean nature of the earthworks and pavement foundation projects. If such projects are not built to achieve the intended performance criteria to begin with, maintenance and repair can be costly and difficult, if not impossible. The need to provide technologies and specification guidelines to improve process control and verify as-constructed conditions remains high. A companion performance guide specification was

developed separately from this document and titled, Roller-Integrated Compaction Monitoring (RICM) Proof Mapping Performance Specification for Subgrade. The proof mapping guide specification is a simpler alternative to this specification and achieves many of the key performance criteria.

Implementation of this specification is not envisioned in the short term because of limitations in technology, data analysis/ software, endorsed test/method standards (e.g., AASHTO), and training. A well-planned program needs to be developed to overcome these obstacles. As part of this research, demonstration projects were organized to provide field data to validate parts of this specification. A project report summarizes key findings from the demonstration.

1 GENERAL

This specification presents details on how to evaluate and accept the placement of embankment and pavement foundation materials in terms of performance measures and performance quality statements.

- A. Materials: This specification is applicable to a range of unbound granular and nongranular earth materials, including general embankment fill materials, pavement subgrade materials, unbound aggregate base materials, and chemically and mechanically stabilized materials.
- B. Technologies: Testing technologies that provide rapid measures for increased test frequency are required for quality control (QC) and quality assurance (QA) testing. Many of these technologies are standardized with existing test protocols while some are not standardized and require special protocols for their use as described in this specification.
- C. Performance criteria and assessment: The goal of the specification is to provide a mechanism to ensure that the compacted materials are satisfactory for the intended design purpose. Performance quality assessment is based on achievement of the following quality criteria:
 - Critical design property value(s) over the entire site achieves the specified minimum value;
 - Nonuniformity of the critical design property value(s) over the entire site are no more than the specified maximum amount;
 - Contiguous noncompliance areas are not larger than the specified maximum value; and
 - Moisture contents are greater than the specified minimum values to eliminate postconstruction saturation induced volume and stiffness changes to the acceptable level

Commentary: Traditional end-result earthwork specifications normally address item (1) through infrequent random point

measurements. The point measurements have traditionally been moisture content and density determined from nuclear density tests. The test frequency is such that less than 0.1% of the soil volume is typically tested, making statistical analysis of the data difficult. Geospatially referenced RICM and proof rolling technologies provide the opportunity to address items (2) and (3). Options for enforcing these quality criteria are presented in this guide specification. Generally, moisture control is critical for effective and efficient soil compaction. The specification options address the influence of moisture control through an option to include moisture content as a significant variable in the correlation analysis with stiffness and strength performance criteria and by requiring laboratory testing to select minimum moisture contents to limit postconstruction wetting-induced design property changes to within acceptable limits.

D. Responsibilities and reporting: As part of this specification, the contractor shall develop, implement, and maintain a quality management plan (QMP). The plan shall address selection of the measurement technologies, methods for test strip construction to establish site- and material-specific target values, and electronic data collection and transfer.

2 TERMS AND DEFINITIONS

For the purpose of this specification, the following definitions shall apply:

- A. Roller-integrated compaction monitoring (RICM):

 RICM for earthwork and pavement foundation materials is defined as the generic gathering of data from roller systems involved with the measurement and recording of roller position, date/time, speed, vibration frequency, vibration amplitude, pass count, travel direction, and a compaction measurement value (MV). The RICM system is supplied by either the roller manufacturer or a third party. The RICM monitoring system shall include calibration records of the sensor systems.
- B. Measurement value (MV): Measurement values are calculated from calibrated sensors integrated into rollers that provide information on machine-ground interaction(s). Machine-ground interaction measurements are typically derived from vibration analysis of accelerometers, sensor systems that monitor machine drive power inputs, or direct measures of sinkage/rutting.
- C. Target value (TV): Target values are the established minimum MVs based on in situ correlation analysis to in situ performance point measurements. Correlation analysis requires statistical analysis of geospatially paired independent point measurement values (PMV) linked to MVs

- using global navigation satellite system (GNSS) positioning information.
- D. In situ performance point measurement value (PMV): Point measurement values are in situ measurements used to set TVs for RICM MVs. PMVs suitable for performance measurements include measures of strength and stiffness.
- E. Real-time kinematic (RTK)—based GNSS with base station corrections is used for determining the position of the roller and correlation spot tests. Results from the RICM shall be displayed to the roller operator on a color-coded computer screen in real-time during roller operations, and the data shall be saved for transfer and viewing by the engineer.
- F. RICM repeatability refers to variation observed in the measurement values (also referred to as measurement error) obtained over a test area from consecutive passes under identical operating conditions (i.e., using same operator, amplitude, speed, direction of travel, etc.).
- G. RICM reproducibility refers to the variation in measurements obtained from consecutive passes under changing conditions. The changing conditions may be due to different measurement methods, machines used, operators, or speed and amplitude settings.

3 TEST EQUIPMENT AND METHODS

Commentary: This section should list and describe suitable test equipment and methods to be used in the performance quality assessments. Some of the test methods may not have established AASHTO or ASTM standards and will require listing of state agency standards and/or reference to accepted user manuals. There are many details here, including special focus on RICM and proof rolling/mapping equipment as it is relatively new and not well described in current specifications. The devices for which AASHTO/ASTM standards exist are not described.

3.1 Roller

Provide RICM rollers that comply with the standard specifications for self-propelled vibratory rollers, static rollers, or pneumatic roller. Ensure that RICM equipment can measure roller position, date/time, speed, vibration frequency, vibration amplitude, pass count, travel direction, and a compaction measurement value (MV) with known repeatability and reproducibility. Provide a computer screen in the roller cab for viewing measured results. Ensure that results are stored for transfer to the engineer for viewing on a laptop computer. Provide the engineer with a copy of the RICM data analysis software for viewing results. Ensure that results are displayed as color-coded spatial maps based on GNSS coordinates.

3.1.1 Data Collection, Export, and Onboard Display

Provide and export the following data in a comma, colon, or space delimited ASCII file format:

- 1. Machine model, type, and serial/machine number;
- 2. Roller drum dimensions (width and diameter);
- 3. Roller and drum weights;
- 4. File name;
- 5. Date stamp;
- 6. Time stamp;
- RTK-based global positioning system (GPS) measurements showing northing, easting, and elevation
 [±76 mm in the horizontal and vertical directions
 (RTK GPS)];
- 8. Roller travel direction (e.g., forward or reverse);
- 9. Roller speed (±0.5 km/h);
- 10. Vibration setting (i.e., on or off);
- 11. Machine gear;
- 12. Vibration amplitude (±0.2 mm);
- 13. Vibration frequency (±2 Hz);
- 14. Compaction measurement value (MV); and
- 15. Pass count.

Ensure that the roller onboard display will furnish color-coded GNSS-based mapping showing number of roller passes, vibration frequency, vibration amplitude, and the MV on a computer screen in the roller operator's cab. Provide displayed results to the engineer for review upon request.

3.1.2 Local GNSS Base Station

Provide an RTK GNSS to acquire northing, easting, and elevation data for use in mapping of RICM measurements. Ensure the system has the capability to collect data in an established project coordinate system. Furnish a local base station for broadcasting differential correction data to the rollers with a tolerance less than 25 mm in the vertical and horizontal.

Commentary: If a less accurate system is substituted for RTK GNSS, the quality of correlation analysis from verification testing is reduced and may require increases in the number of in situ tests and/or a higher minimum RICM target value to account for position-induced measurement error. RTK-GNSS position information is recommended to minimize this error.

3.1.3 Roller Operations

Conduct roller operations according to the manufacturer's recommendations to provide reliable and repeatable RICM measurements. To allow comparison of successive roller passes, the roller operations should be consistent between

passes. For static (e.g., nonvibratory) rolling operations, maintain relatively constant speed and operate within the manufacturer's slope and pitch limits. For vibratory rolling operations, maintain relatively constant vibration frequency and amplitude during roller operations. Permitted variation in vibration frequency is ±2 Hz. Maintain rolling speed to provide a minimum of 10 impacts per linear foot and within ±0.5 mph during measurement passes. Record roller operations in forward and reverse directions. If necessary, check and validate RICM equipment at the beginning of each workday. Make GNSS calibration checks on a daily basis.

Commentary: Changes in frequency and amplitude can influence RICM MVs. However, the limits for vibration frequency and speed variation can be adjusted if the RICM technology is documented as providing reliable and repeatable measurements outside the noted ranges. Speed fluctuations can also influence the RICM MVs and should not be allowed outside of the specified range during measurement passes. RICM MVs will likely be affected by rolling direction, and therefore the output data fields shall indicate rolling direction.

3.1.4 Repeatability and Reproducibility Analysis

RICM measurements determined from repeated passes must exhibit reproducible and repeatable results for well-compacted materials. If the results are not repeatable, a test section should be constructed to evaluate the influence of roller operating and changing ground conditions. The procedure for calculating reproducibility and repeatability errors is presented in Attachment A: Repeatability and Reproducibility Analysis Using Two-Way Analysis of Variance (ANOVA).

Commentary: Currently, there are no published acceptable limits of measurement error for roller MVs. However, it is an important element of this specification for evaluating the usefulness of a machine before its use or even periodically during the course of project; this will help build confidence in the measurements. As with any quality assessment device, the measurement values should be both repeatable and reproducible. Variability in roller MVs is one source of scatter in relationships compared with in situ point measurements. The measurement variability is quantified in this specification in a repeatability and reproducibility context. Repeatability refers to variation observed in the measurement values (also referred to as measurement error) obtained over a test area from consecutive passes under identical operating conditions (i.e., using same operator, amplitude, speed, direction of travel, etc.). Reproducibility refers to the variation in measurements obtained from consecutive passes under changing conditions. The changing conditions may result from different measurement methods, machines used, operators, or speed and amplitude settings. The repeatability and reproducibility analysis procedure described is applicable for any RICM technology,

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although the magnitude of measurement error (for the range of MVs) is expected to be different for different RICM technologies. This is important from a specification standpoint as it affects the regression relationships, minimum TVs, and anticipated variability in MVs.

3.2 Test Devices for In Situ Performance Point Measurement Values

The department will establish target values (TVs) for RICM MVs based on material and RICM machine-specific parameters. Select appropriate in situ PMVs from Table C.1.

Maintain current records of calibration and inspection records for the in situ test devices. Submit records to the engineer, on request, before initiating testing.

Commentary: The in situ test technologies listed were selected with the goal of linking design with the as-constructed conditions. Ideally, these measurement technologies will (1) measure characteristics that significantly affect performance, (2) assess quality compaction characteristics that are under the direct control of the contractor, and (3) provide a measurement at or near the time of construction. In some cases no suitable testing technology is available to measure the various

Table C.1. In Situ Point Measurements Property

Measurement	Test Methods/References	Measurement Parameter
Modulus of subgrade reaction (k-value)	AASHTO T222: Nonrepetitive Static Plate Load Test of Soils and Flexible Pavement Components for Use in Evaluation and Design of Airport and Highway Pavements	k-value
Dynamic modulus	ASTM E2583: Standard Test Method for Mea- suring Deflections with a Light Weight Deflectometer (LWD); ASTM WK25932: New Test Method for Measuring Deflections Using a Portable Impulse Plate Load Test Device	ELWD
Dynamic cone penetration (DCP) resistance	ASTM D6951: Standard Test Method for Use of the Dynamic Cone Penetrometer in Shal- low Pavement Applications	DCP Index, California bearing ratio (CBR)
Falling weight deflectometer (FWD) modulus	ASTM D4694-09: Standard Test Method for Deflections with a Falling-Weight-Type Impulse Load Device	E _{FWD}
Clegg impact hammer (CIH) value	ASTM D 5874: Standard Test Method for Determination of the Impact Value (IV) of a Soil	Clegg impact value (CIV)
Rolling wheel deflectometer (RWD) value	ARA. 2005. Rolling Wheel Deflectometer. Bro- chure. Applied Research Associates, Inc., Albuquerque, N.M. http://www.ara.com/ Projects/WWD_brochure.pdf. Accessed November 9, 2009.	δ
Seismic pavement analyzer (SPA) value	Nazarian, S., M. Baker, and K. Crain. 1995. Use of Seismic Pavement Analyzer in Pave- ment Evaluation. In <i>Transportation</i> <i>Research Record 1505</i> , TRB, National Research Council, Washington, D.C., pp. 1–8.	E _{SPA}
Borehole shear test (BST) shear strength parameters	Handy, R. L. 2002. <i>Borehole Shear Test</i> Instruction Manual. Handy Geotechnical Instruments, Inc., Madrid, Iowa.	c', ¢'
Vane shear test (VST) peak and residual shear strength	ASTM D2573: Standard Test Method for Field Vane Shear Test in Cohesive Soil	$S_{u_i} S_{u_{i}}$
Moisture content	Numerous devices can be used to determine moisture content.	w%
Other*	To be determined*	To be determined*

Note: "Other test devices may provide desired performance assessments that are not listed here, and many new technologies are being developed that will serve this purpose.

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functional design properties (e.g., measures that reflect long-term repetitive loading conditions). In addition to these current technology gaps, analysis gaps exist for which there is no known way to collect and process the desired information. Many recent studies (e.g., NCHRP 626) have focused on identifying improved measurement technologies.

4 DESIGN AND PERFORMANCE CRITERIA

Design parameter values for the materials subject to performance quality assessment in this specification were developed on the basis of the procedures identified in Table C.2. The design values establish the performance quality target values to be evaluated in the quality control and quality assessment testing. Table C.2 also lists the project-specific performance criteria.

Commentary: This section lists the project design procedure(s) and elements of the geotechnical system and engineering parameters and mechanisms that control performance attributes. By providing this information, the link is established between the design phase and construction quality assessment phase of the project. The performance parameters determined

from laboratory measurements and the field investigation should be provided.

5 CONSTRUCTION REQUIREMENTS

Commentary: In exchange for providing the contractor flexibility with regard to construction operations to meet the design and performance criteria for embankment and foundation construction, the agency should require the contractor to describe in its QMP how it intends to perform the work and meet the performance requirements. A well-developed plan should help assure the agency that the contractor understands how its own actions (e.g., scheduling, hauling, spreading, finishing, and compaction) will affect the in-place properties and performance of the work and that the contractor has planned the work and allocated its resources accordingly.

6 QUALITY MANAGEMENT

Commentary: The requirements included in this section assume the contract includes a separate provision related to development and implementation of a quality management plan (QMP) that defines general requirements related to the

Table C.2. Example Design and Performance Criteria

Material Components	Design Procedure ¹	Example Performance Criteria ²		
Embankment fill (>3 ft below bottom of pavement layer)	Limit equilibrium slope instability analysis at (failure surface) FS ≥ 1.5	Effective cohesion, c' = 500 psf Effective friction angle, \(\phi' = 25 \) degrees (accounting for geometric factors and ground water table, etc.)		
	Total settlement criteria ≤ 2% of fill height	k-value ≥ 200 pci		
	Differential settlement criteria ≤ 1 in.	w% ≥ strain softening condition for post- saturation and ≲ required to achieve strength/stiffness criteria		
Pavement foundation layers (subgrade, stabilized subgrade, unbound base and fill ≤ 3 ft below bottom of pavement layer)	1993 AASHTO Guide for Design of Pavement Structures/MEPDG	Subgrade k-value = 160 pci Stabilized subgrade, k-value = 300 pci or achievement of 50 psi unconfined com- pressive strength		
	Determine resilient modulus (M,) per AASHTO T307 and estimate k-value = M,/19.4	Unbound k-value = 400 pci (composite k-value based on 30-in. diameter plate load test)		
		In situ <i>M_i</i> = 30,000 psi		
		w% ≥ strain softening condition for post- saturation and ≤ required to achieve strength/stiffness criteria		
Fill materials at identified critical areas (e.g., structural foundations, box culverts)	Total settlement criteria ≤ 1% of fill height	k-value = 500 pci		
(e.g., substalial real idations, DOX Curverts)	Differential settlement criteria ≤ 0.5 in.	w% ≥ strain softening condition for post- saturation and ≤ required to achieve strength/stiffness criteria		

¹ Agency to update design references with applicable FHWA design or agency procedures

² Parameters and values provided as examples only. Actual values are project specific and based on the project design requirements

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contractor's quality management personnel and organizational structure, documentation and reporting requirements, and procedures related to nonconforming work, corrective action, and similar matters. In case such requirements are not otherwise addressed in the contract's general conditions, a sample general provision addressing quality management is included among the guide specifications developed under the SHRP 2 R07 project.

6.1 Contractor's Quality Management Plan (QMP)

Develop and submit a project-specific QMP at the time of the preconstruction meeting that addresses

- Quality control of the compaction materials, including RICM equipment, operations, and coordination with the department's on-site calibration testing. QC may be based on assessment of the RICM MVs according to Section 6 of this specification.
- Process for performing compaction operations during the agency's verification testing to establish RICM target values.
- Data acquisition methods and methods of transmitting data to the engineer.
- Corrective actions to bring areas of noncompliance into compliance per the performance assessment criteria described in Section 6 of this guide specification.
- Development of daily quality compaction report submittals to the engineer.

6.2 RICM Repeatability/Reproducibility Analysis

Perform a repeatability/reproducibility analysis according to the procedures described in Attachment A. Conduct repeatability/reproducibility analyses at the beginning of the project and thereafter as directed by the engineer.

6.3 Correlation Analysis

For correlation analysis, the agency will conduct the in situ PMV testing. Perform RICM roller operations for calibration testing in the presence of the engineer, unless approved otherwise. Conduct roller operations to ensure the results are repeatable and reproducible.

The engineer will evaluate all MV and PMV results to set the RICM TV. The analysis details for correlation analysis are described in Attachment B: Correlation Analysis Between RICM Measurement Values and QA/QC Point Measurements. A test report will be prepared within 24 hours of completing the testing and will include the following:

- Test identification number;
- Dates of testing;
- Names of QC field personnel conducting tests;

- Description of tests;
- Tables presenting all data;
- · Plots of test results;
- · Summary of calculated engineering values;
- Plot of RICM MV versus in situ PMV measurements; and
- Geospatially referenced plots of RICM results (see Attachment C: Geospatial Uniformity Analysis).

7 PERFORMANCE EVALUATION AND ACCEPTANCE CRITERIA

The department will base performance compaction acceptance on four primary quality factors for compacted materials and Type I or Type II performance compaction quality assessment options.

7.1 Primary Quality Factors

The four primary quality factors for compacted materials are as follows:

- The RICM TV (in correlation with the PMV) over the entire site is achieved to at least some specified minimal value during construction (e.g., 80% of the lot area).
- The variability of the RICM MV (in correlation with the PMV) over the entire site is no more than some specified maximum amount [e.g., the coefficient of variation (COV) <30%, distribution of 90% of 90% RICM TV, or geospatial statistical analysis parameters].
- Contiguous areas ("blobs") not achieving the RICM TV (in correlation with the PMV) are no larger than some maximum specified value (e.g., 25 yd² of area, depending on the severity of noncompliance).
- The moisture content is not less that the critical moisture content to ensure postsaturation placement volumetric stability (e.g., prevent collapse/swell, strain softening).

Assessment of these factors is described in Section 7.2, Quality Compaction Performance Acceptance Options.

Commentary: The quality assessment program should provide the ability to measure the design parameters in the field to assess compliance with the design, and to facilitate the setting of suitable target values for in situ measurements that will provide assurance of the quality and performance of the final product. The four primary quality factors in Section 7.1 form the basis of requirements for testing to establish the target values and define responsibilities for the contractor's process control and the agency's verification and acceptance testing. The specification should require that the contractor report the QC from RICM MVs while the agency (or independent agent) performs the in situ performance QA testing. The RICM MVs will be part of the overall data used to inform the agency's acceptance decision.

The department will assess the four primary quality factors using one of the two options described in the following:

 $\it Commentary: Refer to Figure C.2$ and Table C.3 for additional explanation of the two options.

Performance compaction Type I: For this option, the department will use the calibrated RICM-MV maps to target locations for QA PMV testing. The department will use the RICM-MV proof maps to identify areas of possible noncompliance (e.g., too dry/wet, undercompacted, low stabilizer content) to focus QA point measurements.

Use the compaction history of the RICM MVs to control the compaction process. Follow and document proper QC procedures (e.g., controlling moisture content, lift thickness) during compaction operations. Provide the RICM-MV proof maps to the engineer for evaluation and selection of QA test locations. The proof maps are to be assessed in terms of the four primary quality factors described in Section 7.1.

The engineer (or the department's independent QA agent) will select the number of tests and test locations on the basis of

the RICM proof maps. The department will base acceptance on achievement of the RICM-TV requirements and in situ PMVs. If quality criteria are not met, perform additional compaction passes and/or adjust construction operations (e.g., moisture, lift thickness), after which the engineer will retest the area.

Performance compaction Type II: The department will establish RICM TVs from on-site calibration of RICM MVs to QA point measurements. This specification option requires detailed calibration of RICM MVs to in situ QA PMVs from a representative calibration test strip before performing production QA testing. The department will establish the RICM TV from project QA criteria through regression analysis and application of prediction intervals. Correlation test strip construction and testing for this option are discussed in Attachment B: Correlation Analysis Between RICM Measurement Values and QC/QA Point Measurements.

The department will base acceptance of the production area on achievement of MV-TV at the selected prediction interval (e.g., 80%) and achievement of target QA PMVs in the areas with MVs < MV-TV. If quality criteria are not met, perform additional compaction passes and/or adjust construction operations (e.g., moisture, lift thickness), after which the engineer will retest the area.

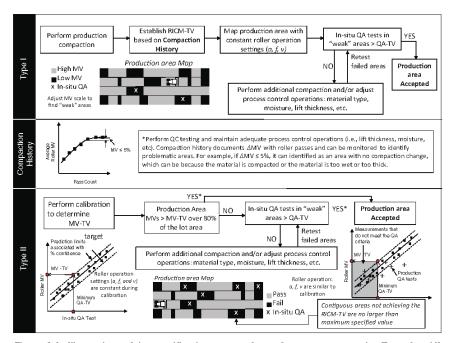


Figure C.2. Illustrations of the specification process for performance compaction Types I and II.

Table C.3. QC/QA Test Guidelines for Performance Compaction Types I and II

Description		Туре І	Type II				
	Subg	rade, subbase/base layers, stabilized layers ≤ 3ft belov	w the bottom of the pavement				
Acceptance criteria	QC	RICM TV is achieved in at least 90% of the lot area; QC TV is achieved in RICM-identified "weak" areas; COV < 30%, or 90% of RICM values fall within 90% of RICM TV or of meeting geostatistical target parameters; and RICM noncompliance areas ("blobs") not achieving the RICM-TV are no larger than 15m².					
	QA	QA TV is achieved in RICM-identified weak areas.					
RICM-TV determination		RICM TV is established by contractor, on the basis of machine-soil specific operations and monitoring compaction curves (e.g., $\Delta MV \le 5\%$).	RICM TV is established from calibration test strips on the basis of a QA-TV point measurement and a desired percentage prediction interval (e.g., 80%).				
Testing frequency	QC	RICM-MV Quality Compaction Reports: Lift thickness, roller pass count, RICM compaction curves					
	QA	1 per 4000 yd²/layer	1 per 8000 yd²/layer				
QA/QC test methods	QC	RICM MV					
	QA	Plate load test (PLT), DCP (for nongranular soils), LWD (for granular and stabilized soils), FWD					
		Embankment fill > 3 ft below the bottom of t	the pavement				
Acceptance criteria	qc	RICM TV is achieved in at least 80% of the test area; QC TV is achieved in RICM-identified weak areas; COV < 40%, or 80% of RICM values fall within 90% of RICM-TV or of meeting geostatistical target parameters; and RICM contiguous noncompliance areas ("blobs") not achieving the RICM TV are no larger than 25m².					
	QA	QA TV(s) are achieved in RICM-identified weak areas.					
RICM-TV determination		RICM TV is established by contractor, on the basis of machine-soil specific operations and monitoring compaction curves (e.g., $\Delta MV \le 5\%$).	RICM TV is established from calibration test strips on the basis of a QA-TV point measurement and a desired percentage prediction interval (e.g., 80%).				
Testing frequency	QC	RICM-MV Quality Compaction Reports: Lift thickness, roller pass count, RICM compaction curves					
	QA	1 per 5000 yd³ (1 per 2000 yd³ in designated critical areas)	1 per 10,000 yd³ (1 per 5000 yd³ in designated critical areas)				
QA/QC test methods	QC	RICM MV					
	QA	PLT, DCP (for nongranular soils), LWD (for granular and stabilized soils), BST, VST					

Commentary: For modulus/strength measurements simple linear regression analysis is generally suitable, while for correlation to dry unit weight/relative compaction measurements, multiple regression analysis including moisture content as a variable may be needed. If underlying layer support conditions are heterogeneous, relationships are likely improved by performing multiple regression analysis with RICM MV or point measurement data from underlying layers. Details of regression analysis are described in Attachment B: Correlation Analysis Between RICM Measurement Values and QC/QA Point Measurements.

Assessment of the required moisture content on the basis of performance parameters values (e.g., strength, stiffness, volumetric stability) has been described in the literature and continues to be part of ongoing research efforts. An example of a method to adjust plate load test k-values is described in AASHTO T222. In that test standard, a saturation correction factor is developed on the basis of the ratio of the deformation of a test specimen at the natural moisture content to the deformation in a saturated specimen under loading. Two specimens of the undisturbed material are placed in a consolidometer or triaxial

chamber. One specimen is tested at the in situ moisture content and the other is saturated after the seating load has been applied. Each specimen is then subjected to the same seating load that was used for the field test (or to account for the desired embankment loading). The seating load is allowed to remain on the in situ moisture content specimen until all deformation occurs, at which time a zero reading is taken on the vertical deformation dial. Without releasing the seating load, additional load is applied to the specimen and allowed to remain until all deformation has occurred. A final reading is then taken on the vertical deformation dial. The other specimen is allowed to soak in the consolidometer or trial cell under the seating load. After the specimen is saturated, a zero dial reading is obtained; then without releasing the seating load, an additional load is applied. The load is allowed to remain on the specimen until all vertical deformation has occurred, and after that a final reading on the dial is obtained. A correction for saturation is then applied.

Determine the target stiffness values as described in ASTM D5874: Standard Test Method for Determination of the Impact Value (IV) of a Soil. The test method involves

8 METHOD OF MEASUREMENT

Measurement for embankment materials furnished and placed in accepted portions of work will be in cubic yards of placed material. Measurement for subgrade materials, stabilized materials, and unbound base material furnished and placed in accepted portions of work will be in square yards for the specified design thickness. The measured area will be based on plan dimensions for the finished surface but will exclude fillets. The department will verify design thickness of the placed materials with spot checks of the grade.

9 BASIS OF PAYMENT AND PAYMENT ADJUSTMENTS

This section describes relationships between payment, pay factors, and performance measurement values.

A. Option 1: The contractor will be paid the contract unit price per square yard for each specified design thickness of subgrade materials, stabilized materials, and unbound base as measured above. This payment shall be full compensation for furnishing all materials, water, preparation of subgrade,

- and for doing all work necessary to complete the material placement in compliance with the contract documents.
- B. Option 2: Payment for RICM will be the lump sum contract price. Payment is full compensation for all work associated with providing RICM-equipped rollers, transmission of electronic data files, two copies of RICM roller manufacturer software, and training. Delays resulting from GPS satellite reception of signals to operate the RICM equipment or RICM roller breakdowns will not be considered justification for contract modifications or contract extensions. In the event of RICM roller breakdowns or system malfunctions/GPS problems, the contractor may operate with conventional rolling operations; but RICM proof mapping shall be provided for a minimum 90% of the project surface. If corrective construction work is necessary, as determined from proof mapping, because of unforeseen ground conditions, the department may pay for the corrective work required at the applicable contract unit price or as extra work.
- C. Option 3: The contractor will be paid according to a pay adjustment to the final quantities on the basis of the final proof map RICM MVs according to the following relationships:

Range of RICM MV≥TV	Pay Factor
80	1.00
85	1.04
95	1.08
100	1.10

Appendix E: Workshop Evaluation Comments

SUMMARY OF EVALUATIONS

Technology Transfer for Intelligent Compaction Consortium (TTICC) September 2–3, 2014 — Harrisburg, PA Total Participants: 22

Attendees rated the following between 1 and 5.

	Very Good		Okay		Needs Improvement	Average Rating
1. Topics covered	1	2	3	4	5	1.31
2. Organization of the program	1	2	3	4	5	1.31
3. Speakers knowledgeable	1	2	3	4	5	1.23
4. Facilities were accommodating	1	2	3	4	5	1.15
5. Program met expectations	1	2	3	4	5	1.31

- 6. What were the most worthwhile parts of this program?
 - States' implementation and limitations (HMA vs. soils, or both).
 - Wednesday was outstanding. This discussions were very helpful. Daniel Clark's presentation on PennDOT's efforts was great at sparking conversation.
 - Status updates.
 - PA project presentation.
 - Discussions.
 - Open discussions.
 - The info from the active and recent project.
 - State updates.
 - PennDot experiences—more members actively engaged. Antonio's attendance.
 - State discussion of IC.
 - Hearing what everyone is looking for in IC and what they want it to do for them.
 - Data discussions and breakout sessions.
 - Hearing about what other states were experiencing with projects.
- 7. What were the least worthwhile parts of this program?
 - Occasional round the room dialog fielded inconclusive debate and understanding. Encourage even stronger facilitation. Nicely done.
 - Everything valuable.
 - None.
 - All was good.
 - All was good.

- 8. What other topics were you hoping would be included in today's program?
 - After separating technology value from acceptance system limitations—e.g., distinguishing validity of a single tier random sampling program from an "info-enhanced" stratified random sampling to better describe (and act on) subpopulations.
 - Verification equipment.
 - None.
 - Met agenda expectations.
 - What is best way to use IC in production?
 - Accuracy of the GPS requirements in the spec's.
 - Working with software. Veda and specific manufacturer software.
- 9. Do you have any suggestions for future workshop topics?
 - Maybe two full days—one day with industry.
 - More field demos if possible.
 - Further idea of real-time decision-making tree (in situ).
 - How to educate people on what IC is and how to use it.
 - More manufacturers involved to discuss more of what their systems can or cannot do.