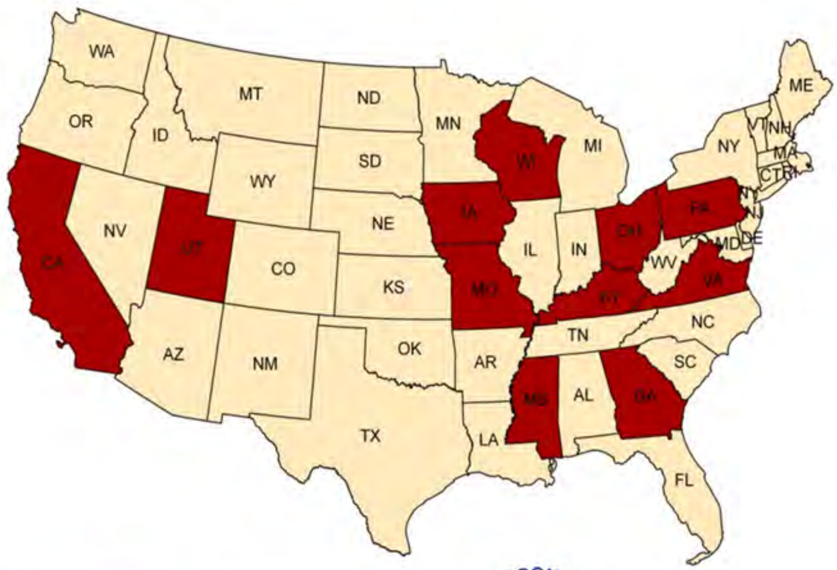
Report of the 2nd Workshop for Technology Transfer for Intelligent Compaction Consortium

June 2012



CEER CENTER FOR EARTHWORKS ENGINEERING RESEARCH

Iowa Department of Transportation

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
pavanv@iastate.edu

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

About the Center for Earthworks Engineering Research

The mission of the Center for Earthworks Engineering Research (CEER) at Iowa State University is to be the nation's premier institution for developing fundamental knowledge of earth mechanics, and creating innovative technologies, sensors, and systems to enable rapid, high quality, environmentally friendly, and economical construction of roadways, aviation runways, railroad embankments, dams, structural foundations, fortifications constructed from earth materials, and related geotechnical applications.

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Table of Contents

Preface

This document summarizes the discussion and findings of the 2nd workshop held on March 6-7, 2012 in Ames, Iowa, 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, Mississippi DOT, Ohio DOT, Pennsylvania DOT, Utah DOT, Virginia DOT, and Wisconsin DOT.

The workshop was hosted 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 brain-storming 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. About 30 attendees representing the state DOTs participating in this pooled fund study, Federal Highway Administration, researchers from Iowa State University, and industry participated in this workshop.

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:

Planning Committee

Sandra Larson, Iowa DOT
Mark Dunn, Iowa DOT
David White, CEER, Iowa State University
Pavana Vennapusa, CEER, Iowa State University
Kelly Miller, CEER, Iowa State University
Heath Gieselman, CEER, Iowa State University

Presenters/Facilitators

Sandra Larson, Iowa DOT
Mark Dunn, Iowa DOT
David White, CEER, Iowa State University
Pavana Vennapusa, CEER, Iowa State University
Johan Smet, Trimble Navigation
Terry Rasmussen, Caterpillar, Inc.
Jim Merchlewitz, Advanced Drainage Systems

State/Federal Agency Participants

Georgia DOT – Ian Rish, Alfred Casteel
Iowa DOT – Stephen Megiven, Jeffrey Schmitt, Mark Dunn, Sandra Larson, Melissa Serio
Missouri DOT – William Stone
Mississippi DOT – Alex Middleton
Ohio DOT – Peter Narsavage
Pennsylvania DOT – Daniel Clark
Utah DOT – Brent Gaschler
Virginia DOT – Edward Hoppe
Wisconsin DOT – Barry Paye
FHWA – Max Grogg, Lisa Rold

Other Workshop Participants

Bomag Americas – Chris Connolly, Larry Keach
Caterpillar, Inc. – Allen DeClerk, Mark Whiting, Terry Rasmussen
Trimble Navigation – Johan Smet
Advanced Drainage Systems – Jim Merchlewitz
Writgen America, Inc. – Mark Blessen
Allender-Butzke Engineers – Milt Butzke
Iowa State University – Kevin Kane, Joseph Gray, James Oliver, Charles Jahren, Terry Wipf, Raj Aggarwal

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 Research/Implementation Needs

1. Data management and Analysis (18*)
2. Intelligent Compaction Specifications/Guidance (14*)
3. Intelligent Compaction and In-Situ Correlations (13*)
4. 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*)
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*)
11. Intelligent Compaction Technology Advancements and Innovations (2*)
12. Intelligent Compaction Research Database (2*)
13. Sustainability (1*)

*total votes are provided in parenthesis

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
2. Define and establish new standards for quality in road building (performance based specifications)
3. Explore alternative contract delivery modes for construction projects that support innovation

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[1,2,3] 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, Mississippi DOT, Ohio DOT, Pennsylvania DOT, Utah 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 on-going 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 2nd TTICC Workshop held on March 6-7, 2012, in Ames, Iowa. The workshop was attended by 13 representatives from state DOTs, 2 representatives from Federal Highway Administration (FHWA), 4 representatives from Iowa State University, and 9 representatives from Industry (Advanced Drainage Systems, Bomag Americas, Caterpillar, Inc., Trimble Navigation Ltd.).

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[1]White 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.
[2]White 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 Moines, Iowa.
[3]White, 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 March 2012

Workshop Objectives and Agenda

The following were the key objectives of this 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 was held over 2 days. The DOT, FHWA, and ISU participants were present on the first day (Figure 2) and the industry participants joined on the second day. The first day 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 1st TTICC workshop; overview of recent IC specifications and demonstration projects; and breakout sessions to review IC research, implementation, and educational needs, and identify action items for TTICC, Industry, and FHWA to accelerate effective implementation of IC technologies.
The second day involved industry participant introductions; presentation of results from the first day breakout sessions; open discussions on the action items identified during the first day; and industry updates/presentations.

This report contains 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. 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 2. Picture showing TTICC participants on Day 1

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 1 sessions.

Ed Hoppe, Virginia DOT: Recently, an HMA overlay project implementing IC was completed in Virginia. Generally, positive feedback was received from the project participants. Questions were raised regarding asphalt compaction with temperature control. VDOT is interested in seeing moisture content measurement capability on rollers for soils and aggregate base material compaction. The technology should be financially viable (with evidence on reduction in construction costs) for contractors to gain more interest. There was no decisive action taken within DOT on next steps.

Peter Narsavage, Ohio DOT: No demonstration project was conducted in Ohio. The contractors were not either interested or aware of the technology. According to current specifications, DOT or independent consultant performs all of the compaction testing on earthwork projects. Modifications are being planned to the specifications where more testing will be required by the contractor. Contractors will hopefully see the benefit in cost savings using this technology when the specifications are changed.

Ian Rish, Georgia DOT: Three new projects with IC specifications are being planned for 2012. Pilot specifications for subgrade, rock base, and asphalt compaction with IC have been developed, and were reviewed by the FHWA.

Daniel Clark, Pennsylvania DOT: PennDOT recently developed a $1M Highways for Life project which includes construction of a four-mile two-lane highway with four types of pavement sections. The project involves using IC for HMA overlay in portions of the project to compare with conventional compaction methods. Not sure how much the project will tell about the success of IC on this particular project.

Bill Stone, Missouri DOT: MoDOT is interested in moving towards performance specifications and away from nuclear gauge density specifications. Recently, a pilot specification with IC on embankment subgrade compaction was implemented on Rt141 reconstruction project, just west of St. Louis. This project was conducted as part of the SHRP R07 research project. The project involved four-lane highway construction with asphalt pavement. The project received green construction credits for using IC. Responsibility of testing on the project included 1 test by DOT for every 10 tests by contractor. DOT recognized the importance of using this technology with 100% coverage on the project. Dr. David White from ISU performed calibration testing by correlating IC measurements with plate load testing and rut depths under test roller. DOT is planning to reduce the number of QC testing by 50% when using IC mapping. IC was also used on MSE backfill compaction. MoDOT is looking forward to implementing the technology on more projects.

Brent Gaschler, Utah DOT: UDOT conducted a trial project in 2009 on US6 on base and subbase materials. The contractor found that the calibration process used was cumbersome; however, liked the color-coded maps. There were some issues with the machine used on the project and there was no timely feedback from the manufacturer. The contractor did not see cost benefits using IC on that project. UDOT attended the recent FHWA workshop held in Utah. UDOT is currently planning for another trial (likely in July 2012) with two rollers using federal funding. The project will require pass coverage as QC requirement. Following are the main concerns moving forward:

- How much it will cost
- Availability of IC machines
- Paying for delays due to any machine issues
- How to analyze lot of machine data in real time
- Integration of construction drawings into roller maps
- How to distinguish between poor versus not-so-poor subgrades from IC maps

UDOT is very concerned about how to identify if the machine is not working properly.

Ian Rish, Georgia DOT Comments: GDOT also had similar issues with machine not working properly. Need some research efforts on calibrating the machine sensors! Manufacturer needs to provide qualification certificates for the machine sensors.

Brent Gaschler, Utah DOT Comments: Paying for delays is an issue. Two rollers are requested on the proposed project to have a backup.

Max Grogg, FHWA Comments: There is a strong need for having a "golden" accelerometer for calibrating the machine sensors. There should be some type of calibration record/routine similar to SHRP calibration for FWD's. Need input from industry on how and when the sensors should be calibrated.

David White, ISU Question to Utah DOT: Is there any credible cost information for IC on the proposed project?

Brent Gaschler, Utah DOT Response: There is no cost information available yet.

Mark Dunn, Iowa DOT: IADOT conducted demonstration projects on one embankment subgrade project on US30, one HMA overlay project on US218, and one grading project on I29 since 2009. On the US30 and I29 projects, ISU operated the machines. On the US218 project, contractor used the machine on a night paving job. Compared pass coverage information with and without viewing the monitors. There was improvement in uniformity of roller pass coverage when the operator was allowed to view the monitor. For HMA projects, contractors can use at least the pass coverage information to save costs and improve efficiency. For soils, IC can at least be used for proof mapping. IADOT conducted demonstration projects with special provisions to specifications on three HMA overlay projects. Another project on cohesive embankment and aggregate base was planned, but did not materialize as equipment meeting the special provisions was not available at the time of the project. The HMA projects required that coverage is needed over at least 80% of the project area. On one HMA project, there was an equipment issue so there was no coverage for one day; however the contractor met the coverage requirement. The data was not used for any QA. Data management and analysis in real time was found to be an issue. Equipment availability is a concern moving forward. The contractors did not see a major benefit right now to invest in the technology; however, they see pass coverage information as a plus (on HMA). Bid costs on the HMA projects varied from about $5,000 to $300,000 to implement the special provisions. ISU recently completed a report with data analysis and summarized project costs and experiences. Project report is available online (http://www.ceer.iastate.edu/research/project/project.cfm?projectID=-225718242)

GADOT Comments: Is it possible to outfit rollers to obtain just roller pass coverage information? That would be less expensive and affordable to contractors.
IADOT Comments: There are systems which can be used to outfit machines with just pass coverage information. This was tried on the Iowa US20 project (findings provided in the report link provide above).

Sid Scott, SHRP R07: SHRP R07 program deals with performance specifications, and how new technologies can be implemented to improve long-term performance and process control during construction. One demonstration project with performance specifications for earthwork construction was recently completed in Missouri (Rt 141 project). Another demonstration project is planned by Louisiana DOT this year using IC for both soils and HMA. Interested in using IC for QC for now and ultimately use it for QA in the future. IC is a great tool to improve uniformity of foundation layers. Attended FHWA workshops on IC – heard similar issues in those meetings as mentioned above with equipment availability and calibration.

Sandra Larson, Iowa DOT Question: Is there any write-up or specification by LaDOT or LTRC on the upcoming project?
Sid Scott, SHRP R07 Response: Will communicate with LTRC to find out information to share.

Group discussion/comments:

- **David White, ISU**: We have not discussed about how the technology will contribute to improving the overall quality.
- **Ian Rish, Georgia DOT**: Having a record to go back and review if there is a problem is a major advantage over current practice with virtually no data. Just having 100% coverage is worth a lot of money. The technology also helps reducing change orders if the contractors use it for QC.
- **Mark Dunn, Iowa DOT**: Uniformity in pass coverage has improved HMA compaction using the technology (as demonstrated on US218 demonstration project in Iowa).
- **Ed Hoppe, Virginia DOT**: Having 100% coverage does not mean that the contractor is responsible for 100% of the area.
- **David White, ISU**: We need to agree that 100% of the area cannot be "good" and it's not economical or practical to hold contractors to that level of responsibility.
- **Peter Narsavage, Ohio DOT**: We need to be realistic in establishing the target value and percent limits.
- **Sid Scott, SHRP R07**: Just documenting the variability is huge with this technology. How do we deal with it in specifications is a major issue.
- **Jeff Schmitt, Iowa DOT**: Iowa DOT recently started a percent within limits (PWL) criterion for HMA field voids with some incentive to the contractor. In 2011, the contractors were only able to meet about 28% of the incentive.
- **Sandra Larson, Iowa DOT**: How does incentive money compare with the initial investment for the contractor? Having such incentives in the specification to meet certain quality might be encouraging for the contractor to invest in the technology!
- **Peter Narsavage, Ohio DOT**: Ohio has an incentive/disincentive specification (for meeting target densities on earthwork projects).
- **Alfred Casteel, Georgia DOT**: Fuel cost savings can be huge for the contractor with the recent increase in fuel prices. How can we show that data?
- **General Comments**: We need to continue to identify advantages, disadvantages, and challenges.

IC 101 Video – Group Discussion

The IC 101 video concept originated during the 2011 workshop[4] discussion among the TTICC participants, as a means to provide executive level overview of the technology. A focused discussion on development of an IC 101 video was held among the participants as part of the Day 1 activities. The objective of this discussion was to identify content and format of the video, its purpose and the targeted audience. Key points resulted from the discussion are as follows:

1. Need to define:
   - Content — Overview, IC for Soils, IC for HMA, Case Studies
   - Length — 4 to 5 minutes
   - Format

2. Audience — Management level personnel from
   - DOT
   - Contractors

3. Need to define value proposition

4. Host on CEER website/DOT links/TRB E-Newsletter/YouTube

5. TTICC team interviews
   - Example video for Accelerated Bridge Construction from Western Iowa (SHRP2 website)

6. Contractor interviews
   - MoDOT IC project contractor for soils
   - HMA?

7. Real Project Story
   - Why picked IC?
   - How it helped?

8. Video purpose
   - Cost savings (during construction and long-term maintenance)
   - People
   - Quality
   - Risk (nuclear gauge regulations)
   - Time/pace of construction
   - Sustainability

[4]White D.J., and Vennapusa, P. (2011). *Report of the 1st Workshop for Technology Transfer for Intelligent Compaction Consortium*, Transportation Pooled Fund Study Number TPF-5(233), Workshop held on December 14-15, 2010, Des Moines, Iowa.

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

On day one, two separate 2 hour long breakout sessions were conducted by separating the workshop participants into two groups. Each group had a facilitator. A brief agenda used to facilitate discussion in the breakout sessions is provided below.

- Review the road map with the 13 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.
- Develop an updated road map by ranking the topic areas using participant voting. Each participant was allowed 7 votes and could apply the votes to any of the topic areas.
- Identify action plans for the TTICC group, FHWA, and industry to move forward on all of the topic areas.

The prioritized list of IC technology research/implementation needs, by combining the results obtained from the two breakout sessions, is presented in Table 1. The revised roadmap elements are presented in Table 2. 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 3 presents the action items identified for the TTTIC group, industry, and FHWA, on each of the roadmap elements.

Table 4 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 1. Prioritized IC technology research/implementation needs – 2012 TTICC workshop

Prioritized IC/CCC Technology Research/Implementation Needs

1. Data management and Analysis (18*)
2. Intelligent Compaction Specifications/Guidance (14*)
3. Intelligent Compaction and In-Situ Correlations (13*)
4. 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*)
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*)
11. Intelligent Compaction Technology Advancements and Innovations (2*)
12. Intelligent Compaction Research Database (2*)
13. Sustainability (1*)

*total votes are provided in parenthesis

Table 2. Revised IC road map research, implementation, and educational elements – 2nd TTICC workshop

IC Road Map Research, Implementation, and Educational Elements

1. **Data Management and Analysis** [3*]. 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 crosscutting with elements 2, 3, 5, 7, 8, 11, and 12.

2. **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 crosscutting with elements 3, 5, 6, 7, and 8.

3. **Intelligent Compaction and In Situ Correlations** [1*]. 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** [6*]. 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 crosscutting with elements 1, 2, and 7.

5. **Standardization of Roller Outputs and Format Files** [7*]. 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** [13*]. 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.

7. **Education Program/Certification Programs** [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 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.

*1st TTICC workshop rating.

Table 2. Revised IC road map research, implementation, and educational elements – 2nd TTICC workshop

8. **Understanding Roller Measurement Influence Depth** [10*]. 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** [4*]. 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** [9*]. 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** [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 sub-elements will need to be developed.

12. **Intelligent Compaction Research Database** [8*]. 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 longterm 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** [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.

*1st TTICC workshop rating.

Table 3. 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	x		
b. Discuss with other state DOTs	x		
c. Enhance Capabilities of Software's		x	
d. Need Real Time Data Processing/Delivery Capabilities		x	
e. Need Improvements in Position Accuracy (vertical)		x	
f. VEDA Software			x
2. IC Specifications/Guidance			
a. Post Examples and Current Specifications Online (Use CEER Website)	x		
b. Establish a Review Committee	x		
c. Develop a Standard Outline	x		
b. Create On-Line Mechanism to Track Document Updates (versions)	x		
e. Be Informed of TTICC Activities (CEER Website)		x	x
f. VEDA Software		x	x
c. Enhance Capabilities of Software's		x	
3. IC and In Situ Correlations			
a. Develop a Standard Calibration Procedure (Non-Nuclear Gauge)	x		
b. Problem Statement to Better Assess Influence of Moisture Content	x		
c. Problem Statement for Roller Measurement Value Relationships with Resilient Modulus for Pavement Layers and Shear Strength Measurements for Embankments	x		
d. Support Research Efforts			x
4. Understanding Impact of Non-Uniformity on Performance			
a. Develop problem statement for ACC/PCC pavements – Accelerated Testing	x		
b. Support Research – In-Kind Contributions		x	
c. Support Research Efforts			x
5. Standardize Roller Outputs and Format			
a. Define and Establish Criteria	x		
b. Refine Software Based on TTICC Recommendations		x	
c. Data Viewing Software Tool			x
6. Standardize Roller Sensor Calibration Protocols			
a. Research to Develop a Standard Calibration Device	x		
b. 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			
a. Produce Technology Transfer Documents	x		
b. Use 2-Layer Elastic Theory to Describe Behavior (new research)	x		

List of Action Items	TTICC	Industry	FHWA
9. Demonstration Projects and Case Histories			
a. Continue Developing IC Briefs	x	x	x
b. Share IC Briefs to Wider Audience through TRB E-News Letter	x		
c. Address Equipment Availability/Serviceability Issues		x	
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		x	
c. Enhancements of Temperature Measurements for HMA [Mat Temperature]		x	
12. Standardize Roller Sensor Calibration Protocols			
a. Continue Developing IC Briefs	x	x	x
13. Sustainability			
a. Develop a Green Value Proposition	x		

Table 4. IC/CCC 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

Open Discussion between TTICC, FHWA, and Industry Participants

On Day 2, the action items identified on Day 1 for the TTICC group, industry, and FHWA, were presented to the participants. The following is a log of discussion between the Day 2 participants and closing thoughts:

Sandra Larson, Iowa DOT: IC briefs/case histories are a good source of information. It can be shared through AASHTO & TRB newsletter.

Open Discussion on Green Value Proposition on Sustainability Topic: TTICC needs to develop a Green Value Proposition – How does IC fit into the "Green Roads Initiative (GRI)"?

Bill Stone, Missouri DOT: Rt. 141 project received green credits because of using bio fuel, no tree cutting, using IC, etc. The contractor received 24 credits, exceeding the DOT minimum requirement of 21.

David White, ISU: Is FHWA endorsing this initiative?

Max Grogg, FHWA: FHWA is aware of the initiative, but there is no official endorsement. It is currently viewed as a score keeping method. Washington State University faculty developed the method (www.greenroads.org). The university offers a green road certification.

David White, ISU: Does TTICC want us to pursue how IC fits into the GRI rating system?

Ian Rish, Georgia DOT: It would be good to know how IC affects the GRI rating.

Improvements in GPS Vertical Accuracy – Industry Action Item:

Caterpillar and Trimble: Vertical accuracy can be improved, but it can be very expensive. Contractors are reluctant to invest in it as they don't see value in high accuracy. DOTs need to define what the criteria are.

Bomag: Bomag recently published a white paper on using elevation data. Will send out an email to the TTICC group.

General Discussion:

TTICC: How is operator training performed by industry?

Caterpillar and Bomag: Currently operator training is being done independently. The challenge is to educate everyone involved in the process.

Ian Rish, Georgia DOT: Is there a minimum level of training time or certification that we could require in the specifications?

Caterpillar: The biggest challenge is to know if DOTs are ready to go for a fundamental change of moving away from nuclear gauge density testing. Top 10 customers want to move away from a method specification to a performance specification.

Caterpillar: Can we have NHI course certification?

SHRPR07: R07 group is currently working on developing a generic guide performance specification for earthworks. The challenge, however, is how to get acceptance from all 50 states.

Bomag: End-results specification developed for HMA really changed the way things are now done on

HMA projects. DOTs need to change their specifications to move IC implementation forward.
Caterpillar: Many countries are now moving away from design-bid- build (DBB) type contracts to build-operate-transfer (BOT) type contracts. This puts responsibility on the contractor to build a quality product and maintain it – this would fundamentally transform how earthwork construction is done and contractors would then really see the benefit in the technology and accept it. Currently, there is no incentive for the contractors to use the technology.
Virginia DOT: For what type of project size would it make sense to invest in this technology for the contractor?
Bomag: One contractor said why not just DOT own the equipment and perform QA?
Trimble: We need to do a better job at explaining it to the contractor on how the technology will pay for itself. Similar to AMG technologies – contractors need to see the benefit. Change in the contract delivery mode will guide the contractors' decision whether or not to use new technologies.
Caterpillar: Australian government is currently building a very large project and planning to use IC system for mapping only. They see a huge field efficiency gain.

Closing Remarks – What are the main things that are going to help state DOTs move forward?
Virginia DOT: Integrating moisture content into roller measurements is key for soils/aggregates. Also moving towards using mechanistic based QC/QA methods is important. We will learn more with experience on demonstration projects.
Georgia DOT: Performance/warranty specifications are the key. Need to have contractor take responsibility for the product, so they can have equipment that suits to build a quality product.
Iowa DOT: There should be a fundamental transformation within DOTs to move away from traditional density testing to implementing performance based specifications. We need to provide contractors an incentive to build quality roads (e.g., with improved uniformity, more stability, etc.). This would attract contractors to invest in the technology.

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 an outline of content for an IC 101 video
4. 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 as shown in Table 5, that need immediate attention to advance and effectively implement IC technology into US construction practice.

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

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

Appendices

Appendix A: Workshop Agenda
Technology Transfer for Intelligent Compaction Consortium (TTICC)
Iowa State University Memorial Union – Campanile Room
Ames, Iowa
March 6-7, 2012

DAY 1

12:00	Lunch (included)
1:05	Welcome and participant introductions – Sandra Larson, P.E., Iowa DOT
1:10	Review TTICC goals, objectives, schedule – Mark Dunn, P.E., Iowa DOT
1:20	State DOT briefings for IC projects and implementation - CA, GA, IA, KY, MO, MS, OH, PA, UT, VA, and WI
2:30	Break
2:45	Overview of new TTICC case history summaries– Pavana Vennapusa, ISU
3:00	Planning for TTICC IC 101 Video – David White, ISU
3:15	Review IC demo projects/SHRP R02 "Compaction Roadeo"/ SHRP R07 MoDOT 141 Demo and draft IC proof mapping specification – David White, ISU
3:45	Review and discuss changes to TTICC IC Road Map and define 2012 action items – Pavana Vennapusa and Kelly Miller, ISU
4:45	Break
5:30	Open discussion and wrap-up
	Dinner (included)

DAY 2

7:30	Continental breakfast (included)
8:15	Review of TTICC Road Map and Problem Statement for Industry Consideration – David J. White, Director of the Center for Earthworks Engineering Research
8:30	Open Discussions - All participants
9:00	Industry Briefings to Technology Transfer for Intelligent Compaction Consortium - Industry participants provide overviews of technologies
10:30	Break
10:45	Industry Briefings (cont.) and Open Discussion – All participants
11:30	Wrap-up TTICC Meeting and Action Items – Pavana Vennapusa, Center for Earthworks Engineering Research (facilitator)
12:00	Lunch (included)

Appendix B: Workshop Attendees

Raj Aggarwal
College of Engineering – ISU
2220C Hoover
Ames, IA 50011
515 294 9824
rka@iastate.edu

Mark Blessen
Wirtgen America, Inc.
6030 Dana Way
Antioch, TN 37013
402 651 3937
mblessen@wirtgenamerica.com

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

Daniel Clark
Pennsylvania DOT
81 Lab Lane
Harrisburg, PA 17110-2543
717 787 3137
danielclar@pa.gov

Chris Connolly
BOMAG Americas
12305 Rockledge Drive
Bowie, MD 20715
301 529 8477
chris.connolly@bomag.com

Allen DeClerk
Caterpillar, Inc.
PO BOX 1875
Peoria, IL 61656
815 878 6867
declerk_allen_j@cat.com

Mark Dunn
Iowa DOT
800 Lincoln Way
Ames, IA 50010
515 239 1447
mark.dunn@dot.iowa.gov

Brent Gaschler
Utah DOT
4501 South 2700 West
Salt Lake City, UT 84114
801 965 3816
bgaschler@utah.gov

Heath Gieselman
CEER - ISU
2711 S Loop Dr Ste 4700
Ames, IA 50010
319 238 3827
giese@iastate.edu

Joseph Gray
CNDE – ISU
Applied Science II
1915 Scholl Road
Ames, Iowa 50011
515 294 9745
jngray@iastate.edu

Max Grogg
FHWA-Iowa
105 6th Street
Ames, IA 50010
515 233 7306
max.grogg@fhwa.dot.gov

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

Charles Jahren
Construction Engineering
Division – ISU
456 Town Engineering Building
Ames, IA 50011
515 294 3829
cjahren@iastate.edu

Kevin Kane
GIS Facility – ISU
219 Durham Center
Ames, IA 50011
515-294-0526
kkane@iastate.edu

Larry Keach
BOMAG Americas
2000 Kentville Road
Kewanee, IL 61443
309 825 9246
larry.keach@bomag.com

Sandra Larson
Iowa DOT
800 Lincoln Way
Ames, IA 50010
515 239 1205
sandra.larson@dot.iowa.gov

Stephen Megivern
Iowa DOT
800 Lincoln Way
Ames, IA 50010
515 239 1936
stephen.megivern@dot.iowa.gov

Jim Merchlewitz
Advanced Drainage Systems
3544 Mulberry Drive
St. Paul, MN 55129
612 387 2413
jim.merchlewitz@ads-pipe.com

Alex Middleton
Mississippi DOT
Research Division 86-01
401 North West Street
Jackson, MS 39215
601 359 7001
amiddleton@mdot.state.ms.us

Kelly Miller
CEER - ISU
2711 S Loop Dr Ste 4700
Ames, IA 50010
515 294 4615
millerdk@iastate.edu

Peter Narsavage
Ohio DOT
1980 W Broad Street
Columbus, OH 43223
614 644 6638
peter.narsavage@dot.state.oh.us

James Oliver
VRAC – ISU
1620 Howe Hall
Ames, IA 50011
515 294 2649
oliver@iastate.edu

Sharon Prochnow
CEER - ISU
2711 S Loop Dr Ste 4700
Ames, IA 50010
515 294 3781
prochnow@iastate.edu

Terry Rasmussen
Caterpillar, Inc.
AB9740, 7915 N Hale Ave
Peoria, IL 61615
309 494 6321
rasmussen_terry@cat.com

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

Lisa Rold
FHWA-Iowa
105 6th Street
Ames, IA 50010
515 233 7307
lisa.rold@fhwa.dot.gov

Johan Smet
Trimble Navigation
10355 Westmoor Dr. Ste. 100
Westminster, CO 80021
720 936 0504
johan_smet@trimble.com

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 Dr Ste 4700
Ames, IA 50010
515 294 2395
pavanv@iastate.edu

David White
CEER - ISU
2711 S Loop Dr Ste 4700
Ames, IA 50010
515 294 1463
djwhite@iastate.edu

Terry Wipf
CCEE – ISU
390 Town Engineering Bldg
Ames, IA 50011
515 294 6979
tjwipf@iastate.edu

Mark Whiting
Caterpillar, Inc.
AB9740, 7915 N Hale Ave
Peoria, IL 61615
309 494 1937
Whiting_Mark_W@cat.com

Trimble


Trimble
Trimble Update
Center for Earthworks Engineering Research
Des Moines, 7 Mar 2012


Trimble
Johan Smet
Financial auditor
Strategy Consultant (Bain)
With Trimble Heavy & Highway since 2004:
Director of Finance (2004-2008)
Director of Marketing (2008-2011)
Director of Technology Consulting and Services


Trimble
What have we been working on?
Compaction Systems: CCSFlex
➔ Making the technology more widely accessible
Making the Connected Site a Reality
➔ Integration of the worksite
➔ Integration along the "construction continuum"
Developing the necessary support networks
➔ SITECH dealership network
➔ Establishment of a technology consulting and services responsibility

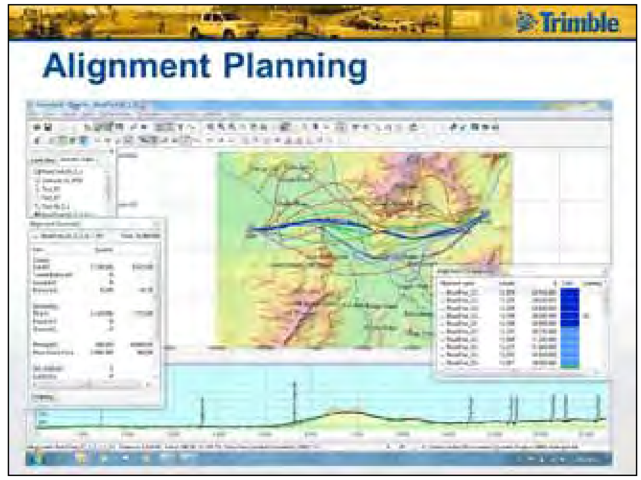

Trimble
CCSFlex
"Non-invasive", system-in-a-case
Asphalt and Soil Compactors
Affordable: $11,995
Pass count system with multiple Add-on options


Trimble
Road Test Results
Without Techonology
With Trimble CCS900
Area of over compaction
• Consistent roll pattern
• Meets target pass count
37% around target pass count (5-7)
51 % around target pass count (5-7)
34% compaction productivity improvement
Paver no longer had to wait for rollers

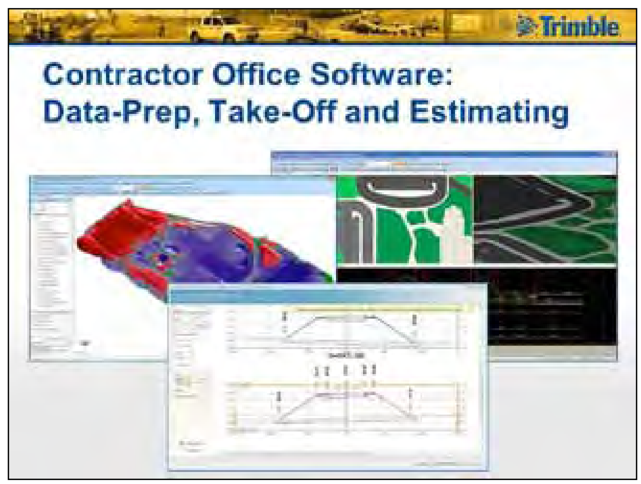

Trimble
Trimble's Connected Site

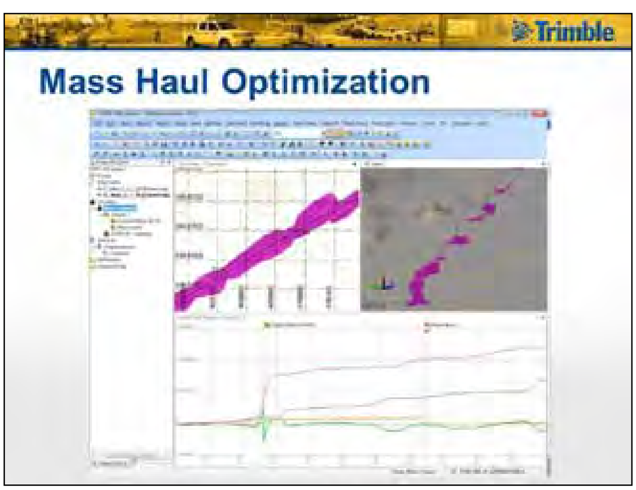
Trimble


Trimble
Connecting the Construction Continuum
PLANNING
DESIGN
ESTIMATE, BID
PAVE, BUILD
Internet based project data:
3D, design, estimates, progress
& management reports
CHECK
FINE GRADE
EARTHWORKS


Trimble
Alignment Planning

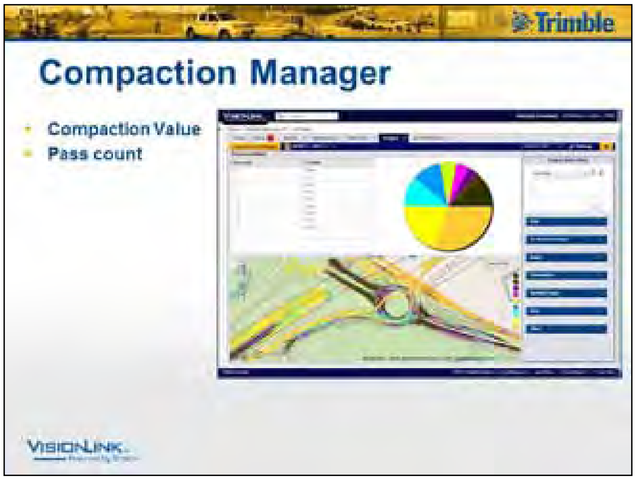

Trimble
Heavy Civil CIM: Tekla Acquisition
Integrated architecture
planning >> design >> construction >> operation
Including earthworks and structures
Site
Civil Construction
Linear Infrastructure
Civil Construction


Trimble
Contractor Office Software:
Data-Prep, Take-Off and Estimating

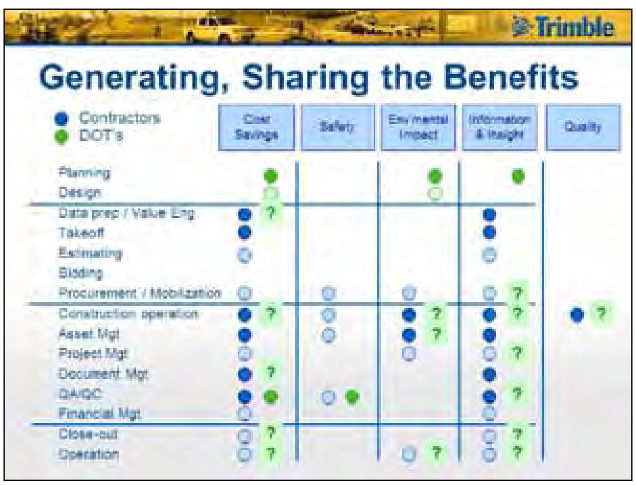

Trimble
Mass Haul Optimization


Trimble
TCC: Connected Site Backbone
Information sharing backbone that allows non-specialists stakeholders to see the information they need
Owners
DOT's
Managers
Suppliers
CONNECTED COMMUNITY
Powered by Trimble

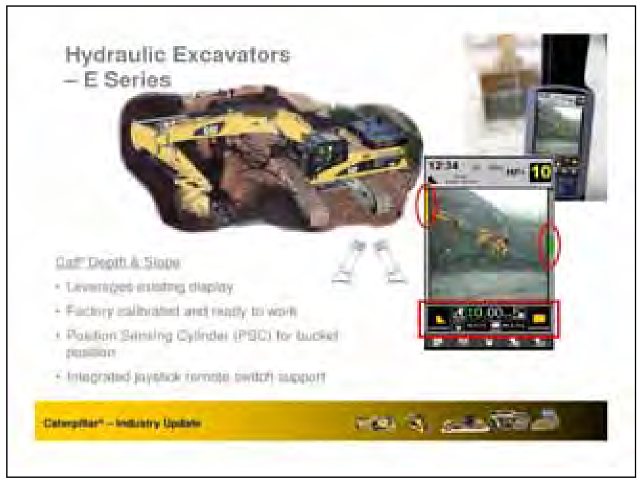
Trimble


Trimble
Compaction Manager
Compaction Value
Pass count
VISIONLINK

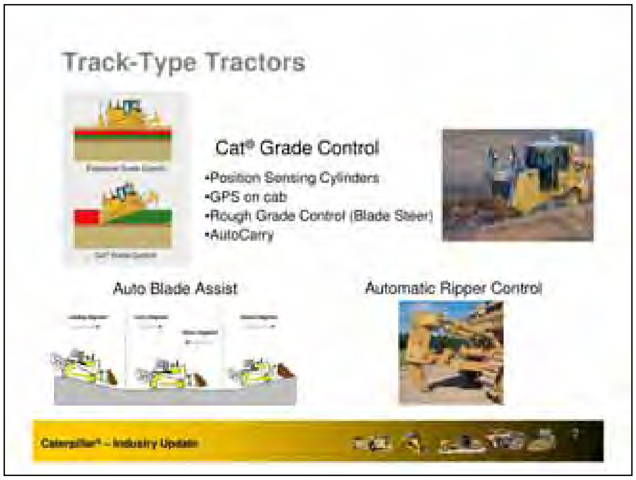

Trimble
Volumes Manager
Coverage maps
Elevation maps
Elevation profiles
Cut/fill maps
Volumes manager
VISIONLINK

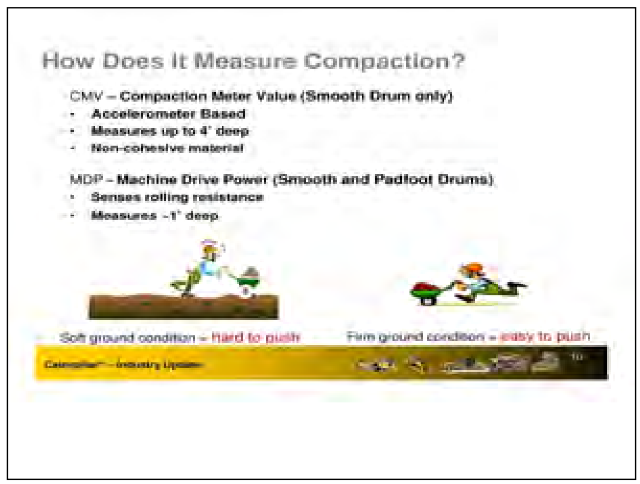

Trimble
Generating, Sharing the Benefits
Contractors
DOT's
Cost Savings
Safety
Env'mental Impact
Information & Insight
Quality
Planning
Design
Data prep / Value Eng
Takeoff
Estimating
Bidding
Procurement / Mobilization
Construction operation
Asset Mgt
Project Mgt
Document Mgt
QA/QC
Financial Mgt
Close-out
Operation

Caterpillar



Caterpillar





ROLLER INTEGRATED SURFACE COVERING DYNAMIC COMPACTION CONTROL MEASURING PRINCIPLE, MEASURING EQUIPMENT AND APPLICATION OF THE METHOD

Dipl.-Ing. Hans-Josef Kloubert and Dipl.-Ing. Wolfgang Wallrath
BOMAG Boppard - GERMANY
Phone +49 6742 100350 – email: hans-josef.kloubert@bomag.com
Phone +49 6742 100172 – email: wolfgang.wallrath@bomag.com

Abstract

Dynamic roller mounted measuring systems for continuous compaction control (CCC) have been available for earthworks and road construction applications for thirty years. The development of these systems is the result of progressively increasing construction outputs, the pressures on financial returns and higher demands for quality assurance.
Conventional testing methods on their own cannot meet these requirements. On large scale construction projects the effect of interruptions to plant utilization schedules caused by conventional test programmes must now be considered. Conventional tests will also only be made at selected locations thus providing only a partial and random verification of the achieved compaction status. Inconsistencies or weak spots may not be identified at all or possibly merely by chance. The verification of the uniformity of bearing capacity which may be of critical importance for certain types of construction is virtually impossible.
Dynamic measuring systems offer the possibility of surface quality assurance adapted to modern construction operations. An indicator provides the roller operator with information about the compaction quality of the soil during rolling.
In Germany, Austria, Swiss and Sweden CCC regulations and recommendations were established and standardized and are used on highway, railway, airfield and dam construction projects.
The paper describes in detail the BOMAG roller integrated measuring method, the components of the system, the way of compaction data collection, data monitoring and data evaluation. The measuring principle enables the determination of the vibration modulus E_{VIB} based on the interrelationship between drum/soil contact force and soil deformation during the compaction process of the vibrating drum. Since E_{VIB} value is a physical measuring magnitude it is directly related to the soil deformation modulus.
Furthermore the paper presents various examples of CCC applications from Germany and Scandinavia.

1 Introduction

Control of the achieved compaction quality is an essential component of compaction technology in earth construction and the construction of traffic routes, alongside the actual compaction itself. This quality of compaction can be assessed via density or load bearing capacity using conventional testing methods. These methods are based on the visual selection of local, potentially weak spots and the application of individual tests, which only allow selective, random quality assessments. Moreover, executing this method is very time

consuming and causes construction downtimes, if detected weak spots need to be reprocessed. This impairs construction progress, which is becoming increasingly significant, and the efficiency of construction operation.
Both beneficial aspects of surface covering and work integrated quality assurance have lead to the development of "Continuous Compaction Control" (CCC). For this purpose some compaction equipment manufacturers developed dynamically working, roller drum mounted measuring systems for direct continuous compaction control, already three decades ago. After years of experience and testing of these systems on large-scale projects in road, railway and airport construction in connection with scientific investigations, the surface covering dynamic compaction control was finally integrated into the national earth works standards of Sweden, Austria, Switzerland and Germany in the nineties.

2 Functional principle of the BOMAG Terrameter

The measuring systems currently offered by the roller manufacturers are based on the interaction between the accelerated roller drum and the stiffness of the soil, as it changes with compaction. Measuring the acceleration of the drum during the compaction process serves as basis for all measuring systems. They differ with respect to the method for analysing the vibration characteristic.
The BOMAG measuring system Terrameter (BTM) uses two acceleration transducers arranged vertically to each other. A force-travel diagram (Fig. 2) stemming from the vertical equilibrium of forces and the vertical oscillating path of the drum (Fig. 1) is created for each eccentric revolution from the acceleration signals measured by the vibrating roller body. The acceleration transducers used pick up the absolute accelerations of the oscillating mass as per the Newtonian axiom in dependence on the time. Since the two acceleration transducer arranged vertically to each other have been turned by 45° from vertical orientation, all courses of motion sequences taking place in the oscillation plane can be analysed.

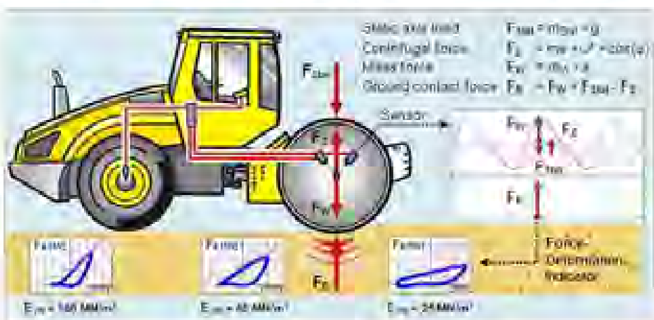


Fig. 1: Equilibrium of forces on the vibrating roller body and temporal course of forces

Besides the mass force of the roller drum, which is proportional to the acceleration, the centrifugal forces of the exciter system, the static axle load comprising the weight force of the vibrating mass plus the statically effective mass of the superstructure and the desired ground contact force, act in vertical direction of oscillation (Fig. 1).
The differential proportion, i.e. the desired ground contact force, result from the temporal course of acceleration of the proportional mass force and the purely sinusoidal centrifugal force. Applying the ground contact force acting between soil and drum above the oscillation path of the roller drum or the deformation of the ground, results in the indicator diagram Fig. 2). The indexed area of the indicator diagram matches the compaction power transferred

into the ground. The inclination of the Force-Path-Characteristic during the compression phase represents a characteristic value k for assessing the stiffness of the soil. It is plausible, that with a low stiffness of the soil the compression curve is flat (flat indicator diagram) and that with increasing stiffness of the soil during the compression phase the resistance against the drum entering into the ground becomes higher (steep indicator diagram) (Fig. 1).

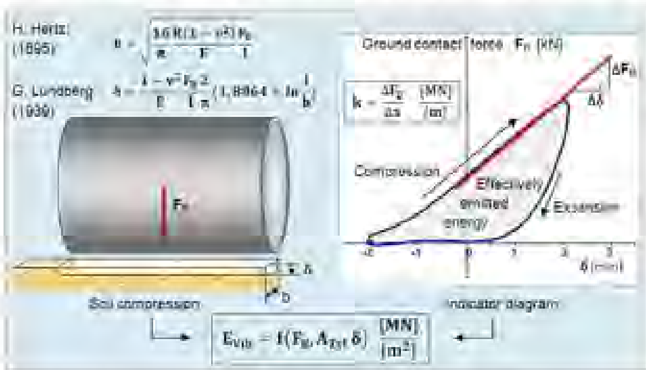


Fig. 2: Soil compression of the drum and indicator diagram

The stiffness k increases with drum width and drum diameter and, in addition to this, depends on the vibrating mass, the statically applied load and the installed unbalance of the machine. In order to obtain a value which is independent from the machine, the so-called "vibration modulus E_{VIB}", which corresponds with the dynamic deformation modulus of the soil, was introduced under due consideration of the contact area and the penetrating depth.
In case of a certain geometry the force-path relation allows conclusions about the properties of the soil. The equations from Hertz (1895) and Lundberg (1939) provide the dependency from geometry, ground force and E-modulus for the linear-elastic-isotropic semi-space. If the soil would fulfil the conditions linearly, elastically and isotropically, the deformation modulus would converge against the E-modulus. Similar to the static load plate test we do not use the term E-modulus for practical evaluation, but, for the purpose of differentiation and with respect to the vibrational excitation, the modulus is named "Vibration modulus E_{VIB}" instead. Compared with previously used indirect non-dimensional measured values this is a physical characteristic of the soil expressed in MN/m², which is directly related to the deformation modulus of the soil.

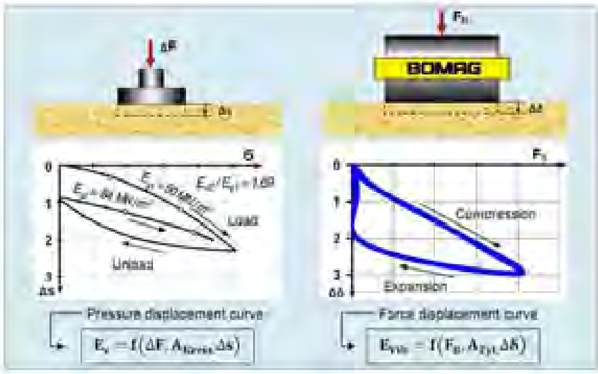


Fig. 3: Analogy of the BOMAG measuring method compared with the static load plate test

The E_{VIB} value is determined in very short timing cycles and in a very tight sequence. The system generates approx. 10-15 values per second, which in fact corresponds with a distance of 6.6 - 10 cm at a typical roller working speed of 3.6 km/h. With continuous compaction this results in an unbroken, surface covering image of the load bearing and compaction status of the soil as well as of the compaction progress.

3 Examination results concerning the vibration modulus E_{VIB}

The following correlations for comparing the vibration modulus E_{VIB} with the static load plate test, the dry density and questions concerning the reproducibility of the measuring value were examined over the past 10 years in the BOMAG Research and Application Center, as well as on international construction sites.
Comparing the Vibration modulus E_{VIB} with the deformation moduli E_{V1} and E_{V2} revealed that at the start of compaction the E_{VIB} value is near the E_{V1} value, because of the high plastic deformation, but will approach the E_{V2} value with increasing compaction. The increase of the E_{VIB} value between two successive passes decreases continuously. The soil reacts increasingly elastically, the compaction potential of the roller decreases. Maximum compaction of the soil is reached when deformation modulus E_{V2} and vibration modulus E_{VIB} are converging.

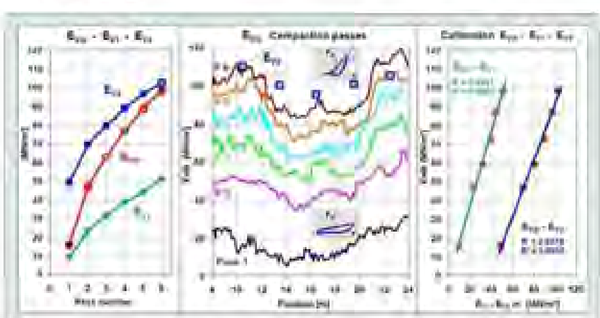


Fig. 4: Comparison and correlation of E_{VIB} with E_{V1}, E_{V2} when compacting silty gravel

Bomag

The E_{VIB} value can be directly used for the qualitative and quantitative assessment of the soil's load bearing capacity.

Comparing the E_{VIB} value with the dry density provides evidence of the excellent correlation potential on silty gravel. The test field was in this case prepared in form of a wedge with a lift height of approx. 0.50 m in the front area (0 - 4 m) ending in 1.50 m in the rear area (16-20 m). A 15 t BW 213 DH-4 BVC with controlled automatically adapting amplitude was used for compaction. While the E_{VIB} values still vary in dependence on the lift height at the beginning of compaction, they increase with progressing compaction and are very uniform at the end of compaction, which also applies for the dry densities. Comparison the mean values of each pass revealed an excellent correlation straight with a correlation coefficient r = 0.99.

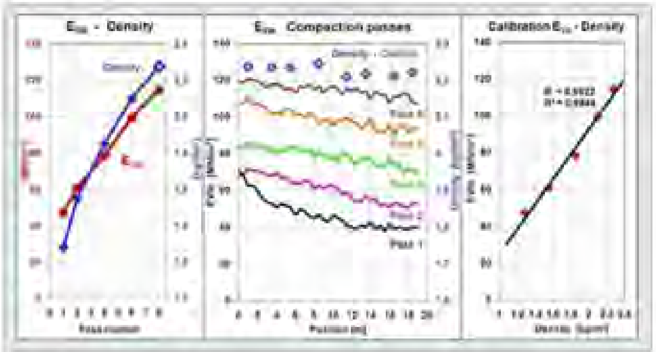


Fig. 5: Comparison of E_{VIB} with the dry density on silty gravel and correlation

As dimensional physical value expressed in MN/m² the vibration modulus, which describes the current soil condition, must be determined in a reproducible way during compaction and during sole control passes. Here the effective and measuring depth of the roller, which to a great extent depends on the dead weight, amplitude and vibration frequency of the excited drum, plays a major role. A soil that is homogeneous over the entire measuring depth must show the same E_{VIB} moduli during compaction measurement, even when changing the equipment specific influencing variables (Fig. 6 and 7). Extensive tests were performed concerning this matter.

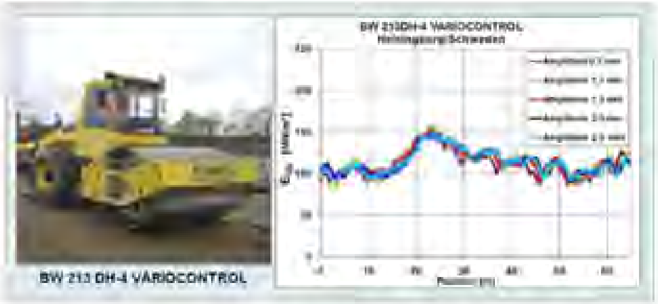


Fig. 6: E_{VIB} control pass with different amplitudes on 40 cm sand gravel layer

Fig. 6 shows the same E_{VIB} values for measuring passes with different amplitudes on a test field in Helsingborg/Sweden.
The comparison of compaction measurements with a 15 t single drum roller BW 213 DH-4 VARIOCONTROL and a 32 t single drum roller BW 332 DI with polygonal drum on a 6 m dam layer of homogeneous soil revealed the same E_{VIB} value under totally different ground contact forces and depth effects (Fig. 7).
Fig. 7 shows that the measuring depth of the CCC systems is determined by the dead weight and the size of the vibration amplitude. Most of the conventional vibratory rollers work with two amplitudes. Further developments, like the BOMAG VARIOCONTROL single drum rollers have 5 amplitudes, which can be set for a certain measuring depth or soil lift height.

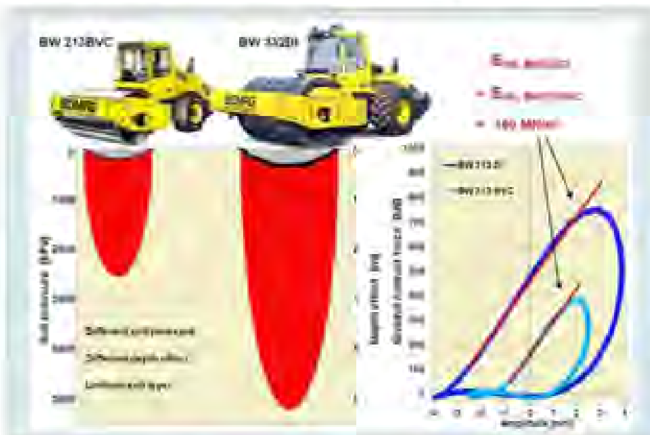


Fig. 7: The same E_{VIB} modulus with different types of equipment and depth effect

4 Roller integrated measuring and documentation system

The Terrameter BTM essentially consists of the recorder unit with two acceleration sensors (which are not arranged on the rotating part of the drum), the electronic unit, a travel sensor, the operating and display unit and a printer. The Terrameter display continuously shows the E_{VIB} value, the working speed, frequency and amplitude. The printer enables printouts to be made directly on-site for paths up to 150 m long. The paper strip documents the recorded E_{VIB} values as a continuous line record and also the operating parameters of the compaction equipment. The measurement printout is particularly helpful on smaller construction measures and for case-by-case control of compaction on larger measures. Weak points and areas with a low bearing capacity can be precisely localized on the measuring route. By comparing the measurement printouts from several passes, you can also identify and document the compaction progress and the maximum compaction level possible with the equipment.

Bomag

Fig. 9: BOMAG compaction measuring and documentation system

The BCM 05 documentation system is indispensable for surface covering observation of the construction site and for exchanging data between roller and site office on medium-sized and large construction measures, like those that occur when building traffic routes or when preparing areas to be ready for the development of commercial and industrial buildings and container terminals. During the compaction process, any measured data coming from the Terrameter is displayed graphically and numerically to the roller driver on the colour display of the BCM 05 system and is analysed, managed and documented on a PC using the evaluation program BCM 05 office. Data transfer between display and PC is by USB memory stick (Figure 8). The BCM 05 software creates meaningful and detailed data summaries with calculations of areas and static examination of the E_{VIB} values for assessing compaction quality both on the BCM display for the roller driver and in the site office for the data evaluator. The graphical representation can optionally be visualized in form of a plan view with colour assignment, or as 2D view.

Fig. 9: Track-bound documentation with the BOMAG BW 213 DH-4 and BCM 05

Without a GPS, documentation is implemented on a track-bound basis using path lengths usually of 100 m. For this purpose, the area to be processed is subdivided into a roller path grid; grid size, positioning within the field by XY coordinates and other data important for

describing compaction work are prepared in the site office using BCM 05 office and saved onto a USB stick.
The documentation system not only offers track-oriented documentation with manual positioning in the section but also a satellite supported documentation solution with the software module BCM 05 positioning developed by BOMAG (Figure 10).
This not only provides continuous, unbroken recording and documentation of the E_{VIB} value, but also of the locational and height-related position of the roller, the operating parameters of the roller and the time of measurement. In principle, all conventional, differential GPS systems with correction signals from reference stations or with satellite supported reference services can be used. Depending on the system and receiver quality, positioning accuracies of 2-5 cm (RTK-GPS) or 10-30 cm can be achieved with solutions using a reference satellite. The BCM 05 positioning software converts the incoming satellite data into UTM or Gauß Krüger coordinates. When entering corresponding transformation parameters, the satellite data can be transformed into other national or local coordinate systems. Axes and outlines can be easily incorporated for orientation within documented areas by recording special points in the construction measure.

Fig. 10: BOMAG BW 213 DH-4 BVC with GPS and BCM 05 equipment as well as surface covering representation of the compaction quality

5 Application possibilities for the surface covering compaction control

Since the introduction of the ZTVE – StB 94/97 (German earthworks regulations) roller integrated measuring and documentation systems can be used in Germany within the scope of self-monitoring and external monitoring of earthwork in road construction. In this case, special emphasis is on the application of CCC as a one hundred percent test based on calibration of the dynamic measured values of the roller to the test features defined in the building contract, compaction degree and deformation module. The procedural method is laid down as the M2 test method in the ZTVE - StB 94/97 and in the German technical test specifications for soil and field in road construction (TP BF – StB) CCC method - Part E 2.
Furthermore, CCC offers a range of other application options which do not require any calibration. A surface covering search for weak points carried out with the BCM 05 by proof rolling can be applied to all types of soil. Weak points with low E_{VIB} values can thus be identified and documented. Compaction can be assessed at these weak points in a targeted way using individual tests. The area can be assessed as a whole by combining the dynamic measured value of the roller and an individual test.
Another important application is the documentation of compaction based on trial compaction and the related determination of a work instruction. To this end, the E_{VIB} values and position of the roller are continuously documented using the BCM 05 system and a GPS connection, which consequently means that the compaction passes are also controlled. The advantages

connected with the different application options with CCC, in respect of increasing compaction performance and improving compaction quality, can be summarized as follows:

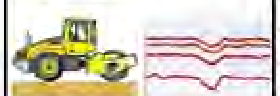
APPLICATION	Recommended roller equipment	Examples	Advantages	Suitability
Weak point analysis 	Small construction: Terrameter BTM Larger Construction: additional BCM 05	Foundation areas, earth-grade and dam fills	Detection of areas with high and low measuring values (weak spot analysis / proof rolling) ⇒ targeted use of conventional testing methods	All soils
Proof of the maximum level of compaction possible 	Small constructions: Terrameter BTM Larger Constructions: additional BCM 05	Dyke fills Frost protection layers Unbound bearing courses	Comparison of measuring values between individual passes Optimized use of equipment	All soils
Determination of work instructions 	BTM and BCM 05 and GPS		Documentation of passes and weak spots	All soils
Proof of compaction by calibration 	Small construction: Terrameter BTM Larger Construction: additional BCM 05	Plane Frost protection layers Unbound bearing courses Dyke fills	Surface covering compaction control	Rock fills Coarse particle soils Mixed soils Mineral mixes
Control of compaction work 	Small construction: Terrameter BTM Larger Construction: additional BCM 05	Dyke fills Frost protection layers Unbound bearing courses	Economy Optimized use of equipment	All soils

Fig. 11: Application possibilities for CCC

6 Construction site applications

6.1 New construction motorway section A33, Germany

The surface covering compaction control acc. to German ZTVE-StB09 was used on the new construction of the 8 km A33 motorway section between Steinhagen and Bielefeld for the purpose of processing dam fills and compaction tests. Slightly gravelly sands with a fine particle component of approx. 8 % by mass were used as dam fill material. A compaction degree of 97% as per table 2 of the ZTVE was demanded for the range 1 m below earth-grade down to the dam sole and 98% for the range from formation level down to a depth of 1 m. In addition requirements concerning the load bearing capacity were placed on the formation, which called for a deformation modulus $E_{V2} \geq 45$ MN/m².

The employment of method M2 always requires calibration of the compaction equipment, for which the measuring value of the compaction machine is correlated with the density or the degree of compaction D_{Pr} and the E_{V2} value on a calibration field with a size arrangement of approx. 10 m x 30 m. The correlation coefficient r thereby must be > 0.7. The sub-base of the calibration field must be re-compacted and documented by a measuring pass.

The compaction equipment used was a BOMAG BW 213 DH-4 BVC equipped with BOMAG Terrameter and BOMAG Compaction Management System BCM 05. On the calibration field three layers of 50 cm each of the dam fill material were arranged in three strips next to each other, also for examining the influence of the sub-soil, and compacted with different numbers of passes (low compaction, medium compaction, high compaction). Finally, measuring passes were run to measure each individual track. In order to determine the degree of compaction and density and to provide evidence of the load bearing capacity of the formation, three field density tests and five static load plate tests were then executed on each track and assigned to the E_{VIB} value of the BW 213 DH-4 BVC. Fig. 12 shows the results.

Fig. 12: Calibration of the E_{VIB} value with the compaction degree and with the E_{V2} value for slightly gravelly sands, dam fill material A33, Germany

For the provision of evidence of compaction this results in an E_{VIB} target value of 80 MN/m² for range 1.0 m below earth-grade down to dam sole and an E_{VIB} target value of 90 MN/m² for the range from earth-grade down to a depth of 1.0 m. The determined correlation coefficient r = 0.9, which is considerably higher than the minimum requirement (r > 0.7) of the German ZTVE-StB09. According to the calibration (Fig. 12) an E_{VIB} value of at least 56 MN/m² is required for providing evidence of the load bearing capacity on the formation. However, the requirement concerning compaction would thereby not be fulfilled. This means that the minimum value of E_{VIB}= 90 MN/m² determined for compaction is decisive as evidence for the load bearing capacity of formation.

6.2 Extension of the air traffic areas on the Kristansund airport, Norway

The runway extension required filling and dam fill work with an overall volume of 2.3 million m³. Blasted granite rock material with good particle distribution and a maximum edge length of 1000 mm was used, which was then compacted in two meter thick layers by two 26 tonne BOMAG single drum rollers type BW 226 DH-4 BVC. The rollers were equipped with Terrameter and the BCM 05 documentation system as well as a GPS system for the purpose of surface covering documentation of compaction work. Before work was started, test compaction took place, during which the settlement was used as a criterion of compaction. During the test compaction the settlement was measured after each pass. The difference in settlement between the last passes being less than 10% of the total settlement served as definition for the end of effective compaction. This was reached after 6 passes. Purpose of the measuring and documentation system was the provision of evidence for the compaction work by surface covering documentation of the 6 passes, while drawing the attention to inhomogeneities and weak spots at the same time.

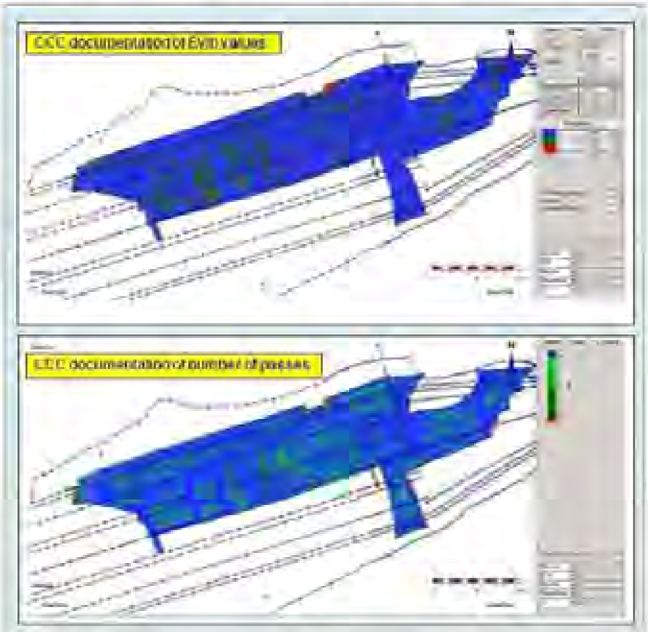


Fig. 13: Documentation of passes (layer no. 10) and the uniformity of compaction, Kristiansund, Norway

6.3 Rotterdam harbour extension – Euromax Container Terminal, Netherlands

For the construction of the Rotterdam Euromax Container Terminal Phase 2 the already existing area, that had been constructed with North Sea sand using the dredging method 30 years ago, had to be excavated down to a depth of 2.70 m and then refilled again in 50 cm layers.

The sand was fine sand with a 10% silt component. The Proctor densities were in the range of 1600-1650 kg/m³ with an optimal water content of 16-17%. For this measure a compaction degree of 100% was demanded and, additionally as proof for the load bearing capacity on formation, a deformation modulus of 120 MN/m². The company Ooms Nederland Holding bv, who was entrusted with earth construction work, used a 15 t BW 213 DH-4 BVC with attachment plates and equipped with measuring and documentation system for compacting the sand. The compaction measuring and documentation system served the purpose of recognizing the maximum possible compaction by monitoring the E_{VIB} increase with each additional pass and to avoid loosening of the highly sensitive sand by further passes. Furthermore, uniform compaction and load bearing capacity should be assured and possible local weak spots should immediately be detected and re-processed. Detailed examinations at the beginning of compaction work showed that E_{VIB} values of 140 MN/m² are required to fulfil the compaction and load bearing requirements (see Fig. 14).

Fig. 14: Evidence and documentation of the maximum possible compaction on the Euromax Terminal area, Rotterdam- Netherlands

7 Further development

The further development at BOMAG currently concentrates on two points of emphasis. On the one hand on the data transfer between several rollers and from the rollers to the construction site office and on the other hand on the elimination of the frequently disadvantageous sub-base influences on the measuring value by determining the layer modulus for the layer to be compacted. Both of these fields of development are of significance for soil compaction, but particularly for asphalt compaction.

All machines involved in the compaction process should have the same level of information by communicating position and compaction data. This should speed up the construction process, make it more efficient and lead to a further improvement of the quality. Fig. 15 shows the data management concept BCM net for asphalt applications targeted by BOMAG. First practical experiences on a large-scale construction have been gathered in 2011.

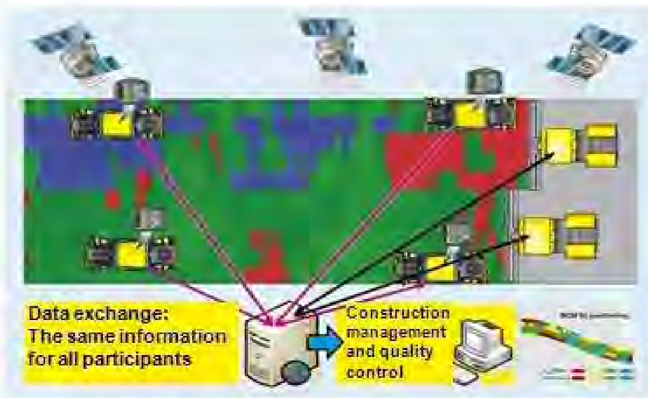


Fig. 15: Exchange of information between compaction equipment and between construction site and site office

With almost homogeneous soil the vibration modulus E_{VIB} converges towards the deformation modulus E_{V2}. Here a value specified by the body of rules serves as standard for sufficient compaction. If this value has not yet been reached, compaction must be continued, irrespective of the fact whether falling short of this value results from the top or the bottom soil layer. When looking at a dam fill or a road structure as a system of layers, the vibration modulus E_{VIB} can be interpreted as an equivalent modulus, which is effective throughout the layer to be compacted, depending on the measuring depth (Fig. 16). This means that the E_{VIB} value detected by the roller is partly determined by the stiffness of the sub-base, depending on the lift height. For surface covering compaction control a preceding calibration on a test field for investigating the influence of the sub-base is therefore required. This work can be minimized by determining the stiffness of the individual layers in addition to the vibration modulus E_{VIB} In this case the compaction process is finished when the layer modulus of the upper layer has reached maximum.

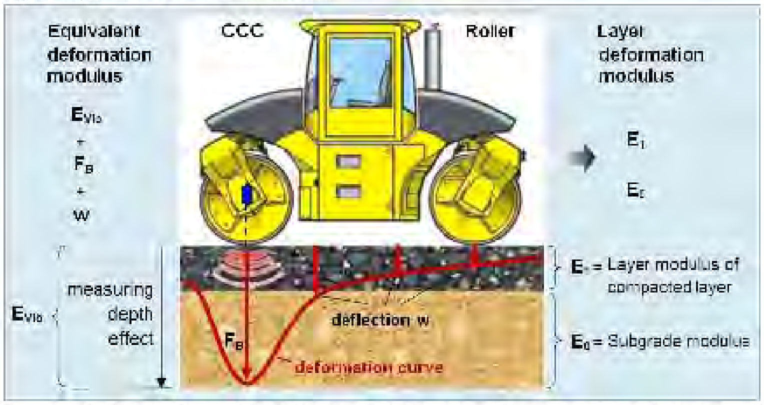


Fig. 16: Determination of the layer moduli for a multi-layer road construction with a BOMAG CCC roller equipped with several sensors for detecting the deformation line

The BOMAG solution is targeted to determine the layer stiffness values using the theory of a multi-layer model as basis by detecting the depression hollow. The stiffness modulus of the sub-base, which is also available, informs about a uniformly bearing sub-base or a sub-base with weak spots and thus completes the surface covering compaction control CCC.

8 Summary

The use of the compaction equipment as measuring and test system is based on the interaction between the acceleration characteristic of the vibrating roller drum and the stiffness of the soil changing with progressing compaction. The advantages of the application lie in the optimization of construction equipment and compaction work as well as in the improvement of the uniformity in the quality of earthwork, in the minimization of the risk of misinterpretation and, last but not least, in the higher reliability of quality assurance. Comprehensive practical experience and scientific findings from numerous construction projects with respect to the assuring subsoil and earthwork quality have led to the development of continuous compaction control method (CCC). In Germany, Austria, Sweden and Switzerland a number of technical regulations and recommendations were published which cleared the path for the general use of CCC in this countries. In the meantime the use of micro-processor controls and the introduction of automatic documentation systems and GPS supported positioning systems paved the path for a compaction management which links the position data from the roller with the compaction data and thus controls and documents the compaction quality and its uniformity as well as the roller passes. The related advantages have led to a further circulation and application of the continuous surface covering compaction control.

With the possibilities of a radio-based online transfer of measuring data to the site office and the linking of rollers, the vision of a process controlled compaction technology has come a whole lot closer.

9 Literature

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Hamm


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Dipl.-Ing. Ralf Schröder
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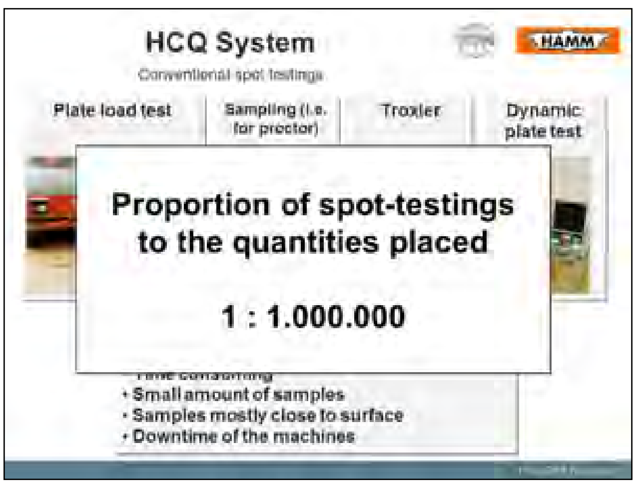
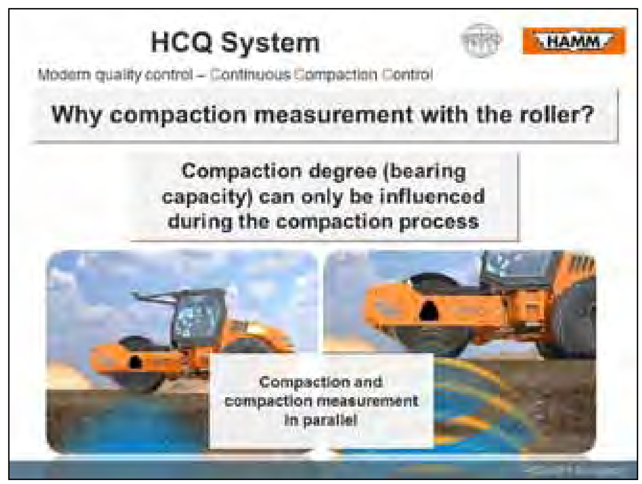
HAMM
HD CompactLine
HD Series
HD+ Series
3000 Series, H Series
DV Series
GRW, Static rollers

Hamm

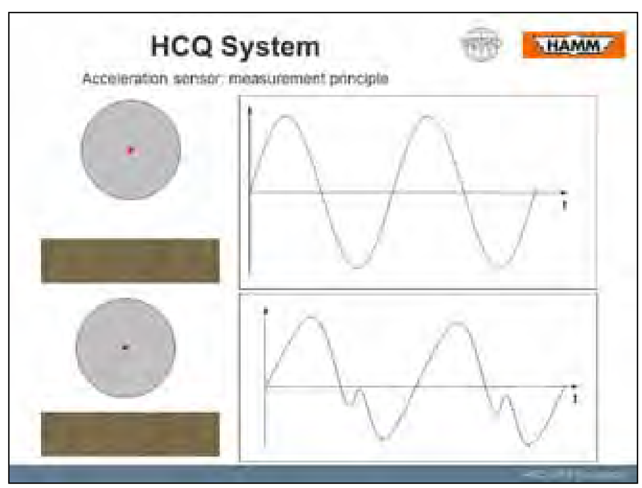

HAMM
HAMM
Compaction
Quality


HCQ System
HAMM
Overview earthwork
HAMM
COMPACTION
QUALITY


HCQ System
HAMM
Conventional spot testings
Plate load test
Sampling (i.e. for proctor)
Troxler
Dynamic plate test
Proportion of spot-testings to the quantities placed
1 : 1.000.000
• Small amount of samples
• Samples mostly close to surface
• Downtime of the machines


HCQ System
HAMM
Modern quality control – Continuous Compaction Control
Why compaction measurement with the roller?
Compaction degree (bearing capacity) can only be influenced during the compaction process
Compaction and compaction measurement in parallel


HCQ System
HAMM
Components: acceleration sensor


HCQ System
HAMM
Acceleration sensor: measurement principle


HCQ System
HAMM
Components: HCQ-Box


HCQ System
HAMM
Components: display unit


HCQ System
HAMM
Components: HCQ-Case
Panel PC
Documentation
GNSS-Receiver
Charger for Panel-PC
Universal travell adapter
Hamm USB flash drive


HCQ System
HAMM
Components: panel PC
• Only one central port
• Lockable mechanical latching
• Full metal body with touchscreen
• Safety class IP65
(dust and water-proof)
• -40 °C bis +70°C (-40 °F to 158 °F)


HCQ System
HAMM
Panel PC – mounting position


HCQ System
HAMM
Panel PC – mounting position

Hamm


HCQ System
HAMM
Panel PC – mounting position


HCQ System
HAMM
Panel PC – mounting position

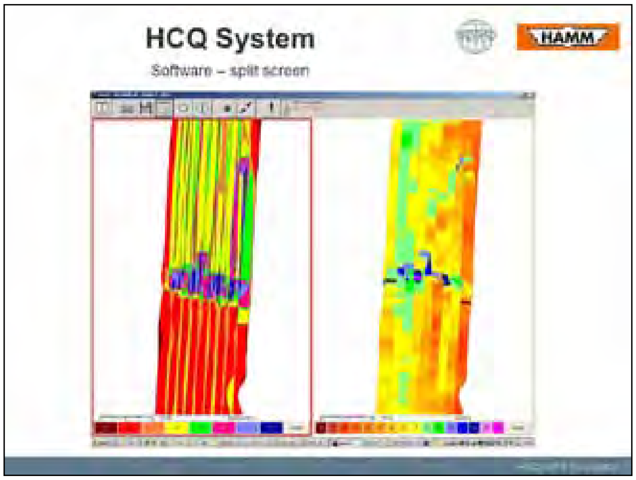

HCQ System
HAMM
Components: D-GPS antenna

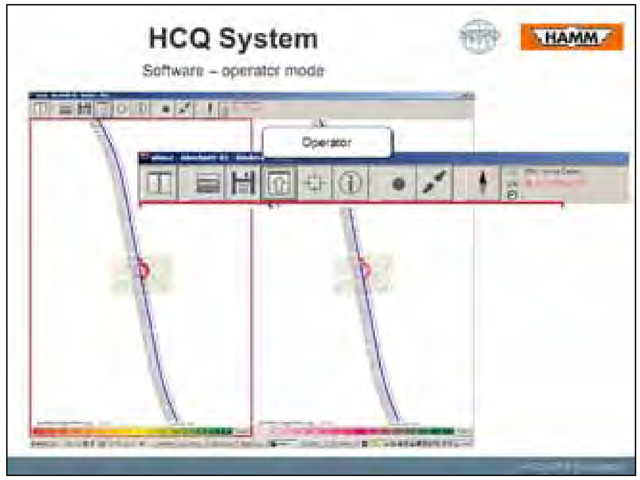

HCQ System
HAMM
GPS accuracy
24 satellites on 6 orbits
Intervisibility of min. 4, ideal 8 satellites required
Accuracy: ~ 20 m


HCQ System
HAMM
D-GPS accuracy
Correction calculation of the GPS-signals via geostationary reference stations.
Correction signal transmitted via communication satellites to D-GPS-receiver (rover).
Accuracy: 5 – 10 cm


HCQ System
HAMM
Documentation – compaction data and position

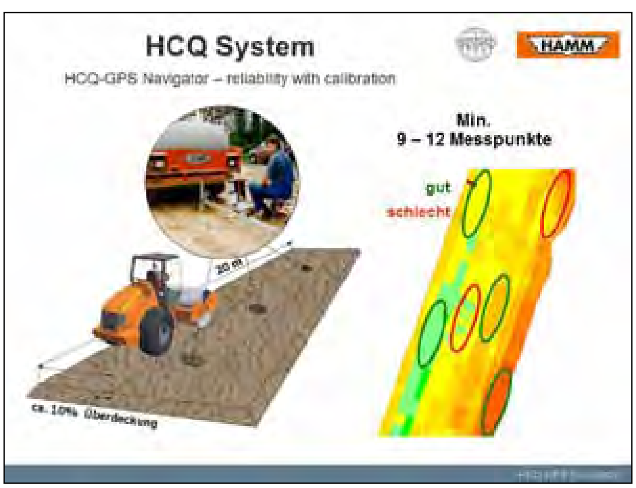
Hamm


HCQ System
Software – split screen
HAMM


HCQ System
Software – operator mode
Operator
HAMM


HCQ System
HCQ-GPS Navigator – quality control for earthwork
HAMM


HCQ System
HCQ-GPS Navigator – quality without calibration
HAMM
HCQ Bodenqualität

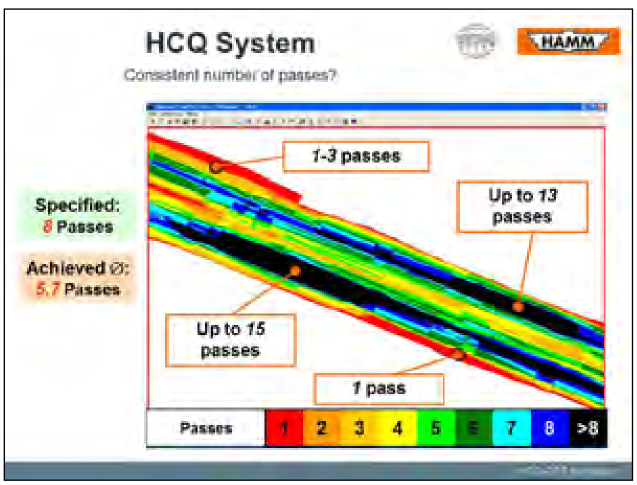

HCQ System
HCQ-GPS Navigator – reliability with calibration
HAMM
Min.
9 – 12 Messpunkte
gut
schlecht
30 m
ca. 10% Überdeckung


HCQ System
HCQ-GPS Navigator – reliability with calibration
HAMM
HCQ Erdbau Kalibrierung

Hamm

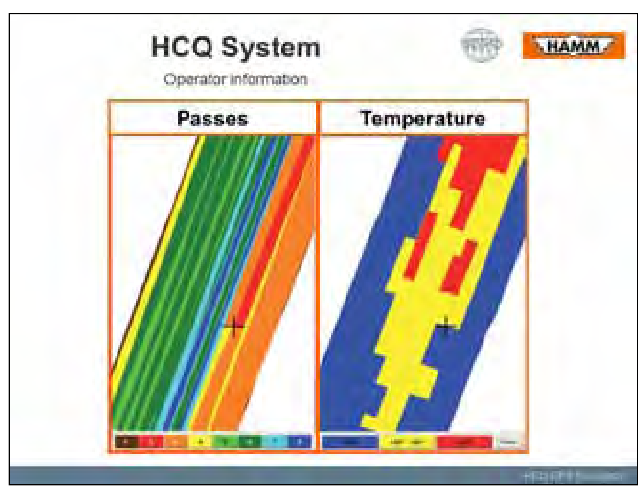

HAMM
Asphalt?


HCQ System
HAMM
Difference between earthwork and soil
MN/m²
%


HCQ System
HAMM
Consistent number of passes?
Specified:
8 Passes
Achieved Ø:
5,7 Passes
1-3 passes
Up to 13
passes
Up to 15
passes
1 pass
Passes
1
2
3
4
5
6
7
8
>8


HCQ System
HAMM
Documentation – passes, temperature and position


HCQ System
HAMM
Vibratory, Oscillatory and static rollers


HCQ System
HAMM
Operator information
Passes
Temperature


HCQ System
HCQ-Asphalt Navigator – quality by consistency
HAMM
HAMM
HCQ - Asphalt-Navigator


Thank you!

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. Report of the 1st Workshop for Technology Transfer for Intelligent Compaction Consortium (available for download from www.ceer.iastate.edu)

3. List of Potential Intelligent Compaction Briefs – By Pavana Vennapusa and David White

4. Intelligent Compaction Briefs:
   i. Iowa I-29 Pavement Foundation Layer Construction Summer 2009 [Draft]
   ii. Minnesota TH64 – Unbound Materials – Summer 2006 [Draft]
   iii. Minnesota TH14 – Unbound Materials – Fall 2005 [Draft]
   iv. Iowa US218 – HMA Resurfacing – Aug-Sept 2009 [Draft]
   v. Mississippi US84 – Untreated and Cement Treated Granular Materials – July 2009 [Draft]
   vi. Iowa US30 – Cohesive Embankment – July 2009 [Draft]
   vii. Iowa US30 – Hot-Mix Asphalt Overlay – July 2010 [Draft]
   viii. Texas FM156 – Untreated and Lime Treated Cohesive Mateirals and Granular Baser Materials – July 2008 [Draft]
   ix. North Dakota US12 – Embankment Subgrade and Geogrid Stabilized Base Materials – August 2010 [Draft]
   x. Minnesota Route 4 – HMA Overlay – June 2008 [Draft]

5. Roller-Integrated Compaction Monitoring (RICM) Proof Mapping Guide Specification

6. Research Article – Field Assessment and Specification Review for Roller-Integrated Compaction Monitoring Technologies, By David J. White, Pavana K.R. Vennapusa, and Heath H. Gieselman, Advances in Civil Engineering Journal, Volume 2011.

7. MoDOT Hwy 141 Proposed RICM Proof Mapping for Pavement Subgrade – RICM Target Value Determination and Specification Update [Presentation Slides]

8. Compaction Roadeo Field Demonstration – Hwy 9, Jacksonville, FL [Presentation Slides]

9. List of Intelligent Compaction Technical Publications

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

1

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.

2

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
Technical Contact
Steve Megivern, P.E.
Soils Design Section
Iowa DOT
800 Lincoln Way
Ames, Iowa 50010
515-239-1936
stephen.megivern@dot.iowa.gov

Lead State
Administrative Contact
Sandra Q. Larson, P.E.
Director, Research & Technology Bureau
Iowa DOT
800 Lincoln Way
Ames, Iowa 50010
515-239-1205
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

TTICC Problem Statement

Table 1. Intelligent Compaction Road Map for Research and Training

IC Road Map Research and Educational Elements

1. **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.

2. **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.

3. **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.

4. **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.

5. **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, 8, 9, and 10.

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.

7. **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.

8. **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.

9. **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 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 research element will contribute to research elements 1, 2, 6, 9.

*2008 Workshop Ranking

4

List of Potential Intelligent Compaction Briefs

Technology Transfer Intelligent Compaction Consortium (TTICC) – TPF-5(233)
List of Potential Intelligent Compaction Briefs
Updated March 4, 2012, By Pavana Vennapusa and David White

		Materials						Drum		Manufacturer						
#	Project Location	Granular	Non Granular	Chemically Treated Granular	Chemically Treated Non Granular	Mechanically Stabilized Materials	Hot Mix Asphalt	Smooth Drum	Padfoot	Bomag	Caterpillar	Case/Ammann	Dynapac	Sakai	Trimble	Volvo
1	Iowa – I29, Monona County*	x						x							x	x
2	Iowa – US218, Coralville*						x	x						x		
3	Minnesota – TH64, Akeley**	x						x			x					
4	Mississippi – US84, Waynesboro*	x		x				x	x		x	x		x		
5	Iowa – US30, Colo*		x						x		x					
6	Minnesota – TH14, Janesville*		x					x				x				
7	Minnesota – Rt4, Kandiyohi County*						x	x						x		
8	Texas – FM156, Roanoke*	x	x		x			x	x			x	x			
9	North Dakota – US12, Marmarth*	x	x			x		x	x		x					
10	Iowa – US30, Harrison County**						x	x						x		
11	Minnesota – MnROAD, Albertville*	x	x					x	x	x	x	x				
12	Australia – JRAC, Northern Territory*		x			x		x			x					
13	Minnesota – TH60, Bigelow**		x						x		x					
14	Minnesota – US10, Staples**	x						x			x					
15	Minnesota – TH36, North St. Paul**	x	x					x			x					
16	Colorado – I25, Longmont*	x	x					x		x	x		x			
17	Maryland – I70, Frederick*	x	x					x	x	x			x	x		
18	North Carolina – High Point*	x	x					x		x		x				
19	Florida – I10, Jacksonville*	x						x				x	x			
20	Minnesota – Olmstead County**		x						x		x					
21	Kansas – US69*		x					x	x		x			x		
22	Indiana – SR25, West Lafayette*	x						x			x					
23	Florida – Hwy 9, Jacksonville*	x						x			x					

*Research/Demonstration Projects
** Projects with IC Specifications

List of Potential Intelligent Compaction Briefs

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:

____

Intelligent Compaction Briefs

INTELLIGENT COMPACTION BRIEF February 2012

Iowa I-29 Pavement Foundation Layer Construction Summer 2009

PROJECT DATE/DURATION
Aug. 31 to Sep. 2 and Sep. 9, 2009

RESEARCH PROJECT TITLE
Iowa DOT Intelligent Compaction Research and Implementation – Phase I

SPONSOR
Iowa Department of Transportation

RESEARCH TEAM
David J. White, Ph.D.
Pavana KR. Vennapusa, Ph.D.
Heath Gieselman, M.S.

PRINCIPAL INVESTIGATOR
David J. White, Ph.D.
Assoc. Prof., Civil, Construction, and Environmental Engineering Dir., Earthworks Engineering Research Center
Iowa State University
515-294-1463
djwhite@iastate.edu

AUTHORS
David J. White, Ph.D.
Pavana KR. Vennapusa, Ph.D.
Heath Gieselman, M.S.

MORE INFORMATION
http://www.iowadot.gov/research/pdf/newsnovember2010.pdf

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

CENTER FOR CEER EARTHWORKS ENGINEERING RESEARCH

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Objectives

The objective of this field demonstration project was to evaluate the compaction meter value (CMV) roller integrated compaction monitoring (RICM) system on the Volvo SD116DX smooth drum vibratory roller for use in quality control (QC) and quality assurance (QA) during construciton of pavement foundation layers.

The following research tasks were established for the study:

- Develop correlations between CMV and various conventionally used in situ point measurement values (point-MVs) in earthwork QC/QA practice.
- Evaluate the advantages of using the technology for production compaction operations.
- Obtain data to evaluate future RICM specifications.
- Develop content for future educational and training materials for Iowa DOT and contractor personnel.

Project Description

This demonstration project was one of three projects conducted as part of this research (White et al. 2010) and was located on I-29 in Monona County, Iowa. The project involved reconstructing the pavement foundation layers (base, subbase, and subgrade) of the existing Interstate highway on the northbound and southbound lanes on I-29 in Harrison and Monona Counties from just south of county road F-20 to just north of I-75. The existing subgrade layer was undercut to about 0.30 to 0.60 m below the existing grade. The exposed subgrade in the excavation was scarified and recompacted. The excavation was then replaced with a 0.30 to 0.45 m thick recycled asphalt ("special backfill subgrade treatment") subbase layer and a 0.15 m thick recycled portland cement concrete (RPCC) base layer. Crushed limestone material was also used for the subbase layer in some areas.

The Volvo SD116DX smooth drum vibratory roller used on this project was equipped with a compaction meter value (CMV) system and global positioning system (GPS) outfitted by Trimble, Inc.

INTELLIGENT COMPACTION BRIEF

February 2012

The onboard display unit on the machine consisted of a Trimble® CB430 unit for real-time display of RICM measurements (Figure 1). A total of 11 test beds were constructed and tested as part of this project. Compaction on the test beds was achieved using the Volvo IC roller. Three in situ testing methods (Figure 2) were used in this project to evaluate the in situ soil compaction properties and obtain correlations with CMV: (a) Humboldt nuclear gauge (NG) to measure soil dry unit weight (γ_d) and moisture content, (b) Zorn light weight deflectometer (LWD) setup with 300 mm plate diameter to measure elastic modulus (E_{LWD-Z3}), and (c) dynamic cone penetrometer (DCP) to determine California bearing ratio (CBR).

Figure 1. Volvo SD116DX smooth drum vibratory roller (top), and the on-board Trimble CB430 display (bottom) (from White et al. 2010)

Figure 2. Nuclear gage (top left), dynamic cone penetrometer (top right), light weight deflectometer (bottom) (from White et al. 2010)

The Volvo machine consisted of low amplitude and high amplitude settings. In low amplitude setting the theoretical amplitude was a = 1.50 mm at frequency f = 34 Hz. In high amplitude setting the theoretical amplitude was a = 1.85 mm at frequency f = 30 Hz. the actual amplitude was measured and reported in the output. The data output contained the following information: (a) GPS position (i.e., northing/easting/ elevation), (b) machine speed, (c) CMV, (d) resonant meter value (RMV), (e) frequency and amplitude, (f) machine gear (forward/reverse), and (g) vibration setting (on/off).

Test Results and Analysis

Calibration Test Beds

One calibration test bed each for each material (subgrade, subbase, and base) was constructed as part of this project (Figure 3). CMV and in situ point-MVs obtained from multiple roller passes on subgrade, recycled asphalt subbase, and RPCC base layer test beds were used to develop compaction curves, as shown in Figure 4. Results indicated that the CMV, E_{LWD-Z3}, CBR, and γ_d measurements on the subbase layer are higher than on the subgrade layer.

Figure 3. Preparation of calibration test beds (from White et al. 2010)

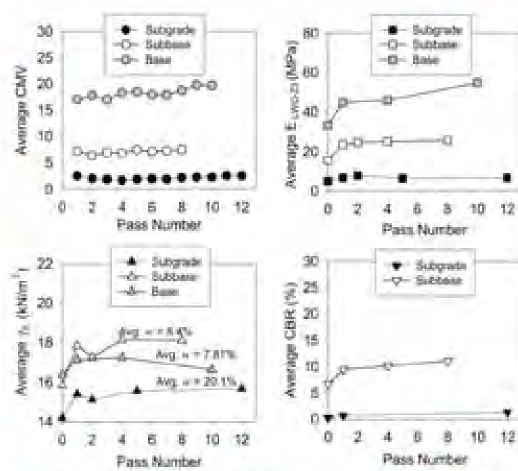

Figure 4. Average (per pass) CMV, E_{LWD-Z3}, γ_d, and CBR compaction curves for subgrade, subbase, and base layers (from White et al. 2010)

The CMV and E_{LWD-Z3} values on the base layer were higher than on the subbase layer. The γ_d measurements were slightly lower on the base layer than on the subbase layer. The average CMV did not change considerably with increasing pass number on the three layers. The average E_{LWD-Z3} values on the subgrade and subbase layers increased up to pass 2 and then remained constant up to the final compaction pass. The average E_{LWD-Z3} on the base layer increased from pass 0 to 1, remained constant up to pass 4, and

INTELLIGENT COMPACTION BRIEF

February 2012

then increased up to pass 10. The average γ_d on all three layers increased from pass 0 to 1 and then generally remained at the same level up to the final pass. Correlations from these calibration test beds yielded correlations with $R^2 < 0.5$ due to the narrow range of the measurements. The correlations calculated by combining results from multiple test beds are presented below.

Production Test Beds

A total of seven production area test beds were constructed and tested as part of this study. Production area maps were obtained by creating two to three roller maps (Figure 5) at different amplitude settings (i.e., low and high amplitude). The in situ point-MV locations were selected based on the roller map, i.e., at locations with relatively high, medium, and low CMV. Figure 6 shows an example of production test bed data (CMV in low and high amplitude settings) from subgrade and overlying special backfill subbase layers with DCP-CBR profiles at three selected locations.

Results indicate that the CMV measurements are influenced by vibration amplitude. CMV measurements on the subgrade were on average about 1.1 to 1.3 times greater at high-amplitude setting (i.e., a = 2.00 mm) than at low-amplitude setting (i.e., a = 1.50 mm). Similarly, CMV measurements of the subbase and base layers were on average about 1.2 to 1.5 times greater at high-amplitude setting than at low-amplitude setting. This is likely due to potential differences in the magnitude of stresses applied to the materials by the roller drum under different amplitude settings. Figure 7 shows a CMV map on an on-board display highlighting a box culvert location with a high CMV.

Regression Analysis Results

Based on data obtained from multiple test beds on this project, regression relationships between CMV (in low- and high-amplitude settings) and point-MVs were developed, as shown in Figure 8. Nonlinear exponential relationships showed the best fit for CMV vs $E_{LWD\text{-}Z2}$ MVs with $R^2 = 0.66$ to 86. Relatively weak regression relationships with $R^2 = 0.12$ to 0.18 was observed for CMV vs CBR. No statistically significant relationship was found for CMV vs. γ_d.

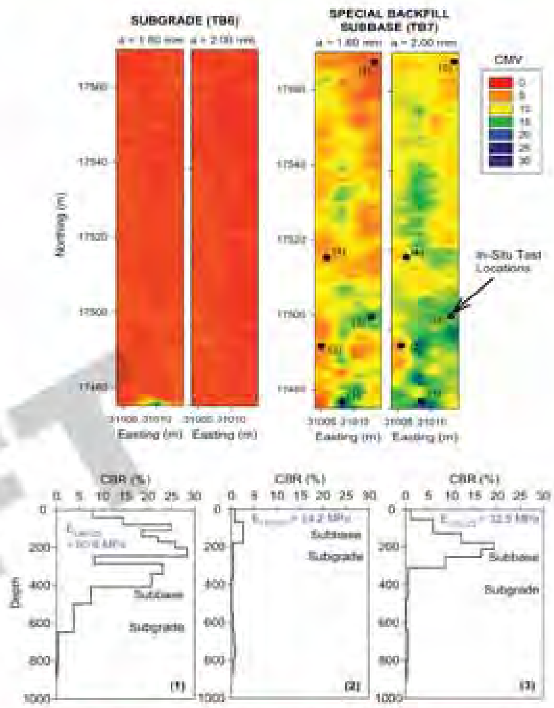

Figure 6. Spatial comparison of a subgrade layer CMV map overlain by a special backfill subbase layer CMV map and DCP-CBR profiles at three selected locations (from White et al. 2010)

Figure 5. Mapping operations on a production base layer test production test bed (from White et al. 2010)

Figure 7. CMV map on an on-board display highlighting a box culvert location with a high CMV (from White et al. 2010)

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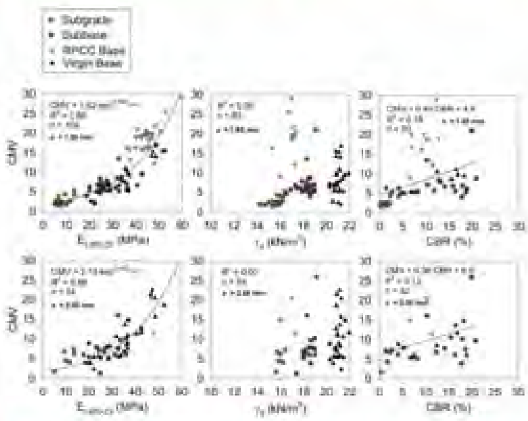

Figure 8. Empirical correlations between CMV and in situ point-MVs (from White et al. 2010)

Repeatability Analysis Results

The error associated with the repeatability of IC is believed to be one source of scatter in relationships with in situ point-MVs. One challenge for evaluating the repeatability of IC measurements is that the data points obtained from different passes are not collected at the exact same location. To overcome this problem on this project, the data were processed in such a way that an average data point was assigned to a preset grid point along the roller path. The grid point was set at 0.3 m along the roller path, which represented an average of IC-MVs that falls within a window of size 0.15 m in the forward and backward directions (the actual data were reported every 0.15 to 0.3 m). Repeatability analysis was performed on measurements obtained from compaction passes on subgrade, subbase, and base layer calibration beds (Figure 9) under identical operating conditions (i.e., same amplitude, nominal speed, and direction). The CMV measurement error was quantified by taking pass count and measurement location into account as random effects in a two-way analysis of variance (ANOVA). For this data set, the CMV measurement error was about ≤ 1.1 for low-amplitude settings at a nominal operation speed of about 4 km/h.

Summary of Key Findings

- Data from calibration strips indicated that the CMV, E_{LWD-Z3}, CBR, and γ_d measurements on the recycled asphalt subbase layer were relatively higher than on the subgrade layer. The CMV and E_{LWD-Z3} values on the RPCC base layer were higher than on the subbase layer. The γ_d measurements were slightly lower on the RPCC base layer than on the recycled HMA subbase layer.
- Correlations developed from this project yielded nonlinear exponential relationships between CMV and E_{LWD-Z3} with R^2 = 0.66 and 0.86 for low- and high-amplitude settings, respectively. Relatively weak regression relationships with $R^2 < 0.2$ were observed between CMV and CBR. No statistically significant relationship was found between CMV and γ_d.

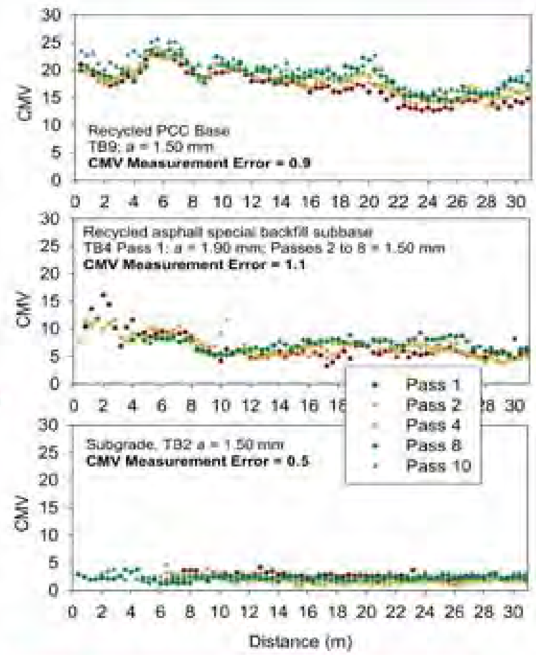

Figure 9. CMV measurements from multiple passes on subgrade, subbase, and base layers (from White et al. 2010)

- CMV maps obtained on the subbase and the overlaid RPCC base layers indicate that "soft" and "stiff" zones in the subbase layer maps are reflected on the RPCC base layer maps.
- CMV maps were able to effectively delineate "soft" and "stiff" zones effectively.
- CMV measurements were on average about 1.1 to 1.5 times greater at high-amplitude setting than at low-amplitude setting. This is likely due to potential differences in the magnitude of stresses applied on the materials by the roller drum under different amplitude settings.
- The CMV measurement error was about ≤ 1.1 for low-amplitude settings at a nominal machine speed of about 4 km/h.

Reference

White, D.J., Vennapusa, P., and Gieselman, H. (2010). *Iowa DOT Intelligent Compaction Research and Implementation—Phase I.* Final Repoart ER10-06, Iowa State University, Ames, Iowa.

INTELLIGENT COMPACTION BRIEF February 2012

Minnesota TH64–Unbound Materials–Summer 2006

PROJECT DATE
Summer 2006

RESEARCH PROJECT TITLE
Field Validation of Intelligent Compaction Monitoring Technology for Unbound Materials

SPONSOR
Minnesota Department of Transportation
Federal Highway Administration

PRINCIPAL INVESTIGATOR
David J. White, Ph.D.
Assoc. Prof. and holder of Wegner Professorship, Civil, Construction, and Environmental Engineering,
Iowa State University
515-294-1463
djwhite@iastate.edu

RESEARCH TEAM
David J. White, Ph.D.
Pavana KR. Vennapusa, Ph.D.
Mark J. Thompson, Ph.D.

AUTHORS
David J. White, Ph.D.
Pavana KR. Vennapusa, Ph.D.
Department of Civil, Construction, and Environmental Engineering
Center for Earthworks Engineering Research

MINNESOTA DOT CONTACT
John Siekmeier, P.E.
Minnesota Department of Transportation
Office of Materials and Road Research,
MS 645 1400 Gervais Ave., Maplewood, MN 55109-2044
651-366-5417
john.siekmeier@state.mn.us

MORE INFORMATION
http://www.ceer.iastate.edu/research/project/project.cfm?projectID=72483391

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

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Introduction

This document summarizes the intelligent compaction (IC) specification and field results from the TH 64 reconstruction project near Akeley, Minnesota in summer 2006. Full details of this project are presented in White et al. (2007, 2008). To the authors' knowledge, this was the first earthwork project in the United States to require IC technology (White et al. 2008). In this study, in-situ point measurement values (point-MVs) of dry unit weight, moisture content, dynamic cone penetration index (DCP Index), and light weight deflectometer (LWD) modulus are compared with the roller-integrated compaction meter value (CMVs) obtained from a Caterpillar CS-563 vibratory smooth drum roller. Except for measuring soil moisture content, the IC technology applied to the roller was the principal method for quality control (QC). Test rolling on proof sections was used for final quality acceptance (QA). In the end, the IC specification was successfully implemented and all sections of the project passed the final QA test rolling criteria. Beyond the requirements for the specification, IC and point-MVs were collected and compared to assess the relationships between the various measurements and also to examine the variation observed for the measurement parameter. Further, a geodatabase using ArcGIS modules was created for demonstrating the approach of managing large quantities of IC and point-MVs. Applying geostatistical methods in the analysis of IC data was also investigated.

Project Details

The project comprised of widening and reconstructing 10 km of an existing alignment south of Akeley, MN. Compaction was performed using the CS-563 vibratory smooth drum roller with CMV technology that incorporated variable feedback amplitude control. Several in-situ tests were performed beyond that required by the specification to generate a data set for analysis. Fill material comprised of poorly graded to well-graded sand with silt (classified as A-1-b to A-3).

INTELLIGENT COMPACTION BRIEF February 2012

IC Specification Summary

The pilot specification implemented on this project was written to require use of IC technology as the primary quality control (QC) tool (Mn/DOT 2006). The contractor was required to develop and detail a QC procedure (i.e., anticipated number, pattern and speed of roller passes, potential corrective actions for non-compliant areas, etc.) that incorporated IC-MVs gathered from control (or calibration) strips. Following control strip construction, proof layers (production areas) were constructed. For proof layers, the engineer observed the final IC recording pass, reviewed and approved the QC data, performed companion and verification moisture content testing, and observed test rolling results to ensure compliance (less than 50 mm rut under wheel of 650 kPa (95 lb/in2) tire pressure). The following key attributes are included in the pilot specification: (a) equipment specifications, (b) control strip construction, (c) QC/QA requirements, (d) and documentation requirements.

Each control strip was at least 100 m (300 ft) x 10 m (32 ft). Thickness was equal to that of the planned granular treatment thickness being constructed (maximum 1.2 m (4.0 ft)). One control strip was constructed for each different type/source of grading material used on the construction site. Optimum compaction on control strips was reached when the engineer determined that additional compaction passes did not result in a significant increase in IC-MVs. IC target values (IC-TV) for all proof layers were obtained from a control strip representative of the proof section. All proof areas were to be compacted such that at least 90% of the IC-MVs were at least 90% of the IC-TV prior to placing the next lift. If localized areas had IC-MVs of less than 80% of the IC-TV, the areas were to be re-compacted. If a significant portion of the grade was more than 30% in excess of the selected IC-TV, the engineer re-evaluated the IC-TV. Moisture content was specified to be 65%–100% of standard Proctor optimum. Control strips constructed at moisture content extremes were allowed to be used to develop a linear IC-TV correction trend line.

Caterpillar CS563 IC System

Caterpillar used a Geodynamik compaction measurement device that measures compaction meter value (CMV) and resonance meter value (RMV). CMV technology uses accelerometers installed on the drum of a vibratory roller to measure roller drum accelerations in response to soil behavior during compaction operations. CMV can be calculated as (Sandstrom and Pettersson 2004):

where C = constant (normally about 300), A1 = acceleration of the first harmonic component of the vibration, and A0 = acceleration of the fundamental component of the vibration. The RMV gives a measurement of the degree of double jump that the vibratory drum is experiencing and provides a means for automatic feedback control (AFC) of amplitude. The RMV is calculated as (Sandstrom and Pettersson 2004):

where A0.5 = amplitude of half the fundamental vibration frequency. As a means to prevent double jump which can decompact the soil, the roller for this project was programmed by the manufacturer to decrease amplitude of the vibrating drum when roller RMVs approached 17. After the roller RMV was reduced to a sufficiently low level, the amplitude was increased until the roller RMV approached 17 at which time the amplitude was decreased. In this way, the compactor was always attempting to operate at a high amplitude. A secondary means of amplitude control was setting a maximum amplitude value and operating in the manual mode. Frequency was not changed with the amplitude.

Analysis and Comparison of IC and Point-MVs

Establishing IC-TVs from Control Strips

Prior to production soil compaction, control sections were constructed to determine target values for CMV. Separate control sections were constructed and tested for the different types of fill sections of the project (e.g., 0.25 m or 1.1 m subcut). A total of five control strips were constructed for this project with IC-TVs of 35, 42, 45, 52, and 60. For establishing the IC-TVs based on CMV data, an iterative method was adopted. Following each roller pass over the control section, the data were grouped into the following pre-defined tolerance bins: < 70%, 70 to 80%, 80 to 90%, 90 to 130%, and >130% of the trial IC-TV. The target value was adopted as quality criteria when the distribution of the data in the five bins met the specification criteria of 90% of the data exceeding 90% of the target value. An example of this process with results from a control strip constructed to establish the target value for a 1.1 m subcut section is shown in Figure 1a. The CMV compaction curve for this control section is shown as a box plot. Based on the distribution of CMV, little compaction was observed following the third roller pass. At seven roller passes, the target value was set at 42. For another control strip with a 0.25 m subcut, significantly high CMV distributions with IC-TV = 60 (Figure 1b) at 11 roller passes. It was determined that this value was unreasonably high compared to a similar section which showed IC-TV = 35 but was not subjected to the extensive off road dump truck and scraper traffic. This experience provided evidence of the benefit of managing the equipment fleet to aid in the compaction process that largely goes undocumented without the application of IC. Measurement and documentation provides a significant benefit to contractor interested in process control and optimizing fleet management.

Analysis of IC Measurement Variability and Influence of Vibration Amplitude

To understand the influence of different operating conditions on IC-MVs and to document variability over a longer distance (2.7 km) the roller was operated over several proof areas previously test rolled and accepted. The roller was operated in manual mode at nominal amplitude of 0.7 mm while heading north. The AFC mode was used from STA 178.5 to 179.7 and from STA 230.8 to 232.2. The roller was also operated in manual mode with nominal amplitude of 1.1mm while heading south along the same travel path. The AFC mode was used from STA 178.2 to 180.1 and from STA 197.9 to 198.7 and higher amplitude of 1.4 mm from STA 240 to 250. The roller data for this test section are shown in Figure 2.

INTELLIGENT COMPACTION BRIEF

February 2012

that of the calibration area (94 m) should meet the spatial statistics established from the calibration. This means that the sill values in the production area should be equal to or lower than the sill values achieved in the calibration area and likewise the range values in the production area should be equal to or higher than the range values achieved in the calibration area. Kriged surface maps of the original and mathematically adjusted CMV data are presented in Figure 7. For this exercise, CMV data was adjusted to one of the following:

CMV < 45 = 45, CMV < 48 = 48, or CMV > 52 = 52. The semivariograms associated with each adjusted CMV data set are presented in Figure 7 along with the semivariogram of the calibration strip. Comparatively, the semivariogram for the CMV < 48 = 48 adjusted dataset with sill = 29 closely follows the semivariogram of the target calibration strip with sill = 30. The semivariogram of the CMV < 52 = 52 adjusted dataset shows greater uniformity with a lower sill value, relative to the calibration strip, which would exceed the baseline uniformity criteria established from the calibration strip. This approach provides an optimized solution to target areas that need additional compaction. It also provides quantitative parameters to establish uniformity based on spatial statistics criteria.

Summary and Key Findings

- IC technology was successfully used as the principal QC tool on a grading project on TH 64 in MN.
- Control sections were constructed and tested to establish appropriate quality criteria, which were then applied to production areas. Compaction curves observed with control section CMV data showed that little compaction occurred after the initial roller passes. This highlights the importance of GPS location and pass information provided to the operator. Target values were selected form the control sections to be applied to proof sections.
- Roller and in-situ measurements values were collected on proof sections and analyzed with the objectives of correlating CMV with measures of dry unit weight, DCP index, and LWD modulus. Variation parameters were also investigated, as intelligent compaction technology may be effective in indicating uniformity of compacted materials. CMV and in-situ test results are correlated at the project scale using average values for different proof sections. Dry unit weight and DCP index were predicted from CMV with R2 values of 0.52 and 0.79, respectively. Scatter was still observed for ELWD and attributed to different measurement influence depths of this compaction control device and the roller.
- IC technology provides opportunity to collect and evaluate information for 100%of the project area, but it also produces large data files that create analysis, visualization, transfer, and archival challenges. An approach for managing large quantities of data is to create a "geodatabase" using ArcGIS modules. A geodatabase of the TH 64 project IC data and in-situ spot test measurements was briefly described to demonstrate this application.
- Applying geostatistical methods in the analysis of IC data has the advantage of quantifying spatial variability, which is not possible with univariate statistical analysis. A semi-variogram model can be used to characterize uniformity of the IC data.
- To demonstrate the application of geostatistics, IC data collected for a proof section and a reference control section were analyzed and compared with the specification quality control criteria. The proof section "passed" the specification acceptance criteria but failed to meet an alternatively proposed "sill" criterion that establishes a uniformity criterion.

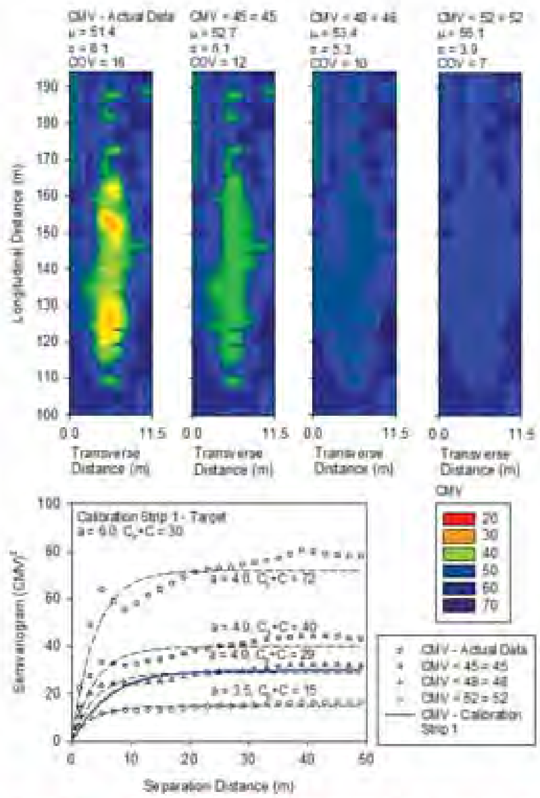


Figure 7. Kriged surface maps and semivariograms of a selected portion of the proof showing variations with modifications in the actual CMV data (from Vennapusa et al. 2010)

- The approach of using geostatistics provided an optimized solution to target areas that need additional compaction along with quantitative parameters to establish uniformity based on spatial statistics criteria. Geostatistical analysis and spatially referenced roller-integrated compaction monitoring represent a paradigm shift in how compaction analysis and specifications could be implemented in the future.

INTELLIGENT COMPACTION BRIEF

February 2012

Comparing results of CMV (Figure 2) obtained in the manual mode at different amplitude settings shows that the CMV values were dependent on amplitude setting (CMVavg = 63 @ 0.7 mm amplitude and CMVavg = 67 @ 1.1 mm amplitude). For the section operated at 1.4 mm vibration amplitude the average CMV value dropped to 52, but in this case RMVs were variable and high indicative of double jump and rocking conditions. For the sections operated in AFC mode, the CMV measurements averaged 58 and the RMV measurements averaged 18 (close to the controller setting of 17). In-situ measurements were collected at 91 m (300 ft) intervals (every three stations) starting at STA 160. These in-situ measurements are overlain by CMV data in Figure 3.

Comparison of IC and In-situ Measurement Values

For investigating the relationships at the project scale, average CMV and point-MVs for different proof sections were compared. Scatter plots are shown in Figure 4. Average dry unit weight and DCP index are predicted from average CMV with R2 values of 0.52 and 0.79, respectively. Considerable scatter was still observed for surface light weight deflectometer elastic modulus (ELWD) with the 200 mm plate diameter measurements. Additional testing was performed to investigate the effects of performing tests at depths of 110 to 170 mm below the surface. These subsurface tests showed that the average ELWD increased by a factor of about 1.7. Future correlation studies should investigate LWD testing below the surface for fine sand materials. Relationships between coefficients of variation (Cv) for CMV and in-situ point-MVs show that Cv are similar to DCP and LWD compaction test data (Figure 4). This is of consequence as it relates to developing uniformity criteria for compaction. The Cv for density measurements is generally much less than LWD and DCP index measurements.

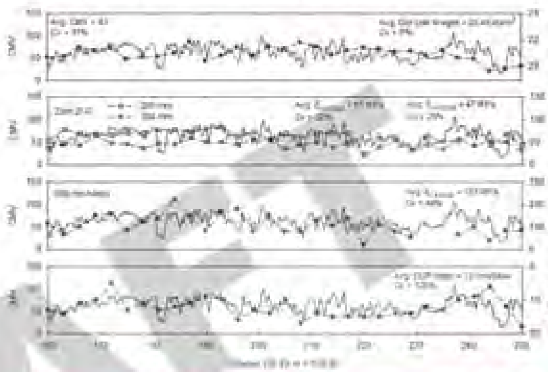


Figure 3. CMV (0.7 mm amplitude) and in-situ measurement data (from White et al. 2008)

Figure 1. CMV compaction curves control strips (a) 1.1m subcut (left) and (b) 0.25m subcut (right) (from White et al. 2008)

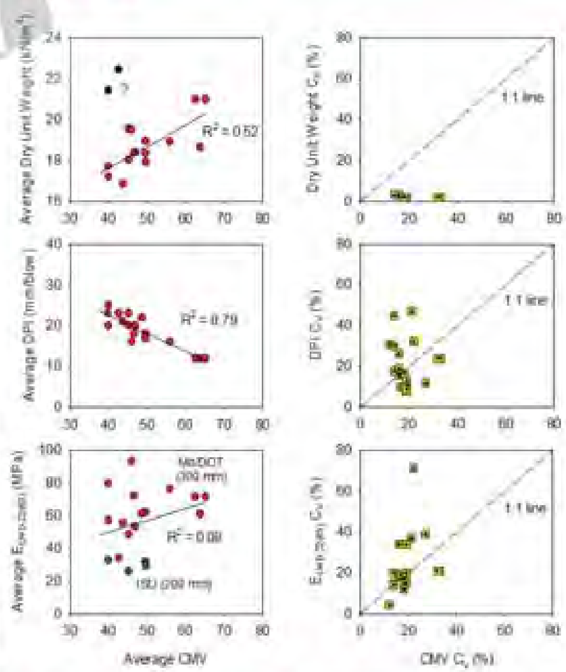


Figure 4. Correlation of average CMV and average in-situ measurements and coefficients of variation (combined proofs) (from White et al. 2008)

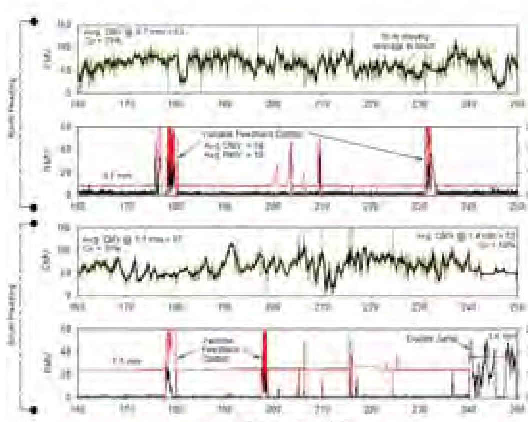


Figure 2. CMV, RMV, and amplitude data for 2.7 km test section after acceptance of all proof layers (from White et al. 2008)

INTELLIGENT COMPACTION BRIEF February 2012

Data Management using GIS

IC technology provides the opportunity to collect and evaluate information for 100 percent of the project area, but it also produces large data files that create analysis, visualization, transfer, and archival challenges. As part of this project, an approach for managing the data was developed consisting of "geodatabase" using ArcGIS/ArcInfo modules. IC data archived in this manner is spatially referenced, which is useful for state agencies as it relates to data management, and mapping. IC output files usually contain unessential data (e.g. data collected when roller is reversing, etc.) which can be filtered before importing into a database. A personal geodatabase was created using ArcCatalog and ArcMap by importing tables into the geodatabase. The imported attribute tables were converted to a feature class using the Hubbard County, MN co-ordinate system projections. Data visualization and analysis such as creating histogram plots, semivariogram models, geostatistical analysis can be performed using ArcGIS. Figure 5 shows kriged CMV data obtained from a proof area overlaid with point-MVs from ArcMAP.

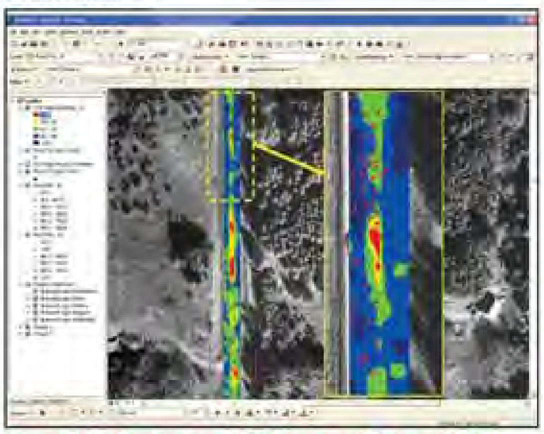


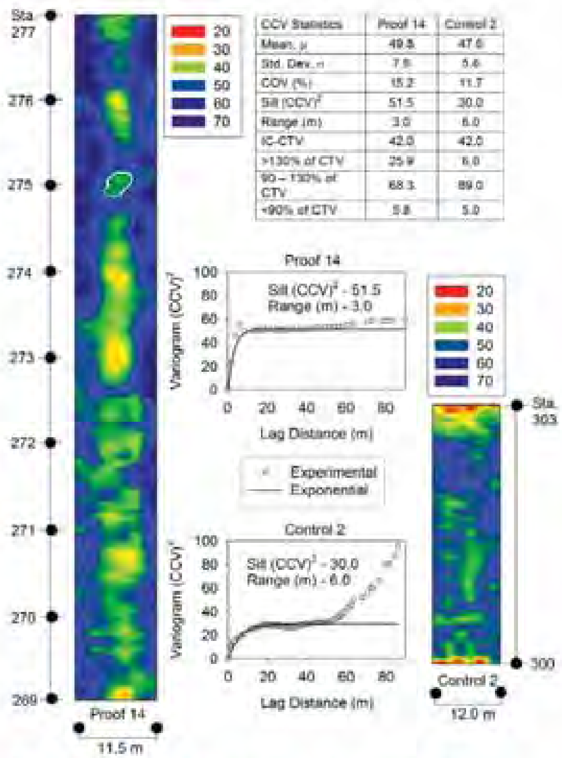
Figure 5. Kriged surface map of CMV from a proof area overlaid with point-MVs (in red circles)–created using ArcMap (from White et al. 2008)

Geostatistical Analysis

Univariate statistics of IC measurements alone do not characterize the spatial variability and specifically do not address the issue of uniformity from a spatial viewpoint. Mn/DOT implemented a tolerance acceptance criterion for the TH 64 project such that a proof area should meet at least 90% of the target value established from a calibration strip for 90% of the area. This approach has the advantage of being relatively simple and easy to implement. However, it should be emphasized that the proof areas may have identical distributions of the data as control strip, but may not be spatially similar. A semi-variogram model in combination with univariate statistics could potentially be utilized to effectively address the issue of uniformity. From a semi-variogram model, a low "sill" and longer "range of influence" can represent best conditions for uniformity, while the opposite represent poor conditions for uniformity.

To demonstrate this application, IC-TV's established from a control section was used as reference for QA in a proof section.

Comparison of the univariate statistics of CMV measurements and acceptance criteria is presented in Figure 6. Results indicate that this proof area "passed" the quality acceptance criterion of achieving 90% of IC-TV in 90% of the evaluated area. However, if spatial statistics between the proof and the calibration strip are compared, the proof area failed to achieve the "sill" and "range" values achieved in the referenced calibration strip. The production area consisted of localized areas of soft ground conditions or "hot spots" that have CMV < 30, especially along the centerline of the alignment. These locations generally match with the locations of grade stakes in the field and were not subjected to construction traffic like the outside lines. Although the proof area meets the acceptance criteria specified for the project based on average values, geostatistical spatial analysis reveals localized areas that perhaps could benefit from additional compaction to improve spatial uniformity.



CCV Statistics	Proof 14	Control 2
Mean, μ	49.5	47.6
Std. Dev., σ	7.5	5.6
COV (%)	15.2	11.7
Sill (CCV)²	51.5	30.0
Range (m)	3.0	6.0
IC-CTV	42.0	42.0
>130% of CTV	25.9	6.0
90 – 130% of CTV	68.3	89.0
<90% of CTV	5.8	5.0

Figure 6. Comparison of a proof section with a control section using CMV surface maps, semi-variograms, and univariate statistics (from White et al. 2007)

Figure 7 illustrates a mathematical exercise to select localized areas within the proof area to target for additional compaction or other treatment that would contribute to improved uniformity. Ideally, any given portion of the production area with dimensions equal to

Intelligent Compaction Briefs

INTELLIGENT COMPACTION BRIEF — February 2012

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PRINCIPAL INVESTIGATOR
David J. White, Ph.D.
Assoc. Prof. and holder of Wegner Professorship, Civil, Construction, and Environmental Engineering
Iowa State University
515-294-1463
djwhite@iastate.edu

RESEARCH TEAM
David J. White, Ph.D.
Mark J. Thompson, Ph.D.
Heath Gieselman, M.S.

AUTHOR
David J. White, Ph.D.
Department of Civil, Construction, and Environmental Engineering
Center for Earthworks Engineering Research

MINNESOTA DOT CONTACT
John Siekmeier, P.E.
Minnesota Department of Transportation
Office of Materials and Road Research, MS 645 1400 Gervais Ave., Maplewood, MN 55109-2044
651-366-5417
john.siekmeier@state.mn.us

MORE INFORMATION
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CENTER FOR CEER EARTHWORKS ENGINEERING RESEARCH

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INTRODUCTION

This document summarizes test results from a field study conducted on TH14 in Janesville, Minnesota, using Ammann AC110 vibratory smooth drum roller equipped with roller-integrated stiffness (k_s) measurement value with automatic feedback control (AFC). Some highlights of this project are presented in this document. Full details of this project and results are presented in White et al. (2007) and Thompson et al. (2008). The study focused on: (1) relationships between k_s and various in-situ point measurement values (point-MVs), (2) performance of AFC of amplitude and frequency, and (3) comparison of k_s with rut depth from test rolling. Point-MVs used in this study included dry unit weight, moisture content, dynamic cone penetration index (DCP index), light weight deflectometer (LWD) modulus, Clegg impact value, and static plate load test modulus.

AMMANN RICM SYSTEM

The Ammann RICM system is called the Amman Compaction Expert (ACE) system. It provides a continuous measurement and display of roller-integrated k_s measurement value, which is based on drum vibration amplitude and applied force, and also on-the-fly AFC of vibration amplitude and frequency. The AFC works in parallel with k_s measurement using a closed-loop feedback control algorithm, which increases the vibration amplitude and reduces the vibration frequency when operated on soft material, or vice-versa when operated on stiff material. The anticipated benefits of operating the roller in AFC mode include (1) more efficient soil compaction, (2) improved uniformity of compacted materials, (3) prevention of over-compaction, and (4) reduced vibration amplitudes in the vicinity of sensitive structures (Anderegg and Kaufmann 2004).

INTELLIGENT COMPACTION BRIEF February 2012

MATERIALS

Soils tested in this study included a subgrade soil classified as sandy lean clay (CL; A-6), and a base material classified as poorly graded sand with silt and gravel (SP-SM ; A-1-b).

COMPARISON BETWEEN k_s AND IN-SITU MEASUREMENTS

An example subgrade test strip, shown in Figure 1, was constructed perpendicular to the highway alignment through the soft median to capture a wide range in soil stiffness conditions. The roller was operated in AFC mode. Following roller passes, point-MVs were obtained from 7 to 30 test locations. k_s and point-MVs obtained along this test strip are shown in Figure 2. Mean (μ) and coefficients of variation (CV) values are also provided in Figure 2 for all point-MVs. Along the test strip, all point-MVs follow closely the k_s. Further deviation from k_s was observed in the median with Clegg impact and DCP index values.

To better identify the relationships between k_s and in-situ point-MVs, the compaction measurements are plotted against spatially-nearest k_s values in Figure 3. Linear relationships were observed for all measurements except for DCP index, which was highly influenced by a single observation. Measurements were collected over a range of soil characteristics (i.e., roadbed versus median), and correlation R^2 values ranged from 0.30 to 0.80. As expected, highest correlation was seen with static plate load test modulus (shown as E_{V1}). k_s was also highly correlated with moisture content, which demonstrates the sensitivity of soil stability to moisture content.

Similar comparison measurements were obtained on a base material test strip with relatively uniform conditions, which did not show any statistically significant relationship between k_s and point-MVs due to narrow measurement range (Figure 4). Additional details are provided in Thompson et al. (2008).

EVALUATION OF AFC

The benefits of AFC have not been thoroughly investigated and supported with quantitative compaction data. In this study, the ability of AFC systems to produce compacted material with higher uniformity than material compacted with constant amplitude and frequency was investigated.

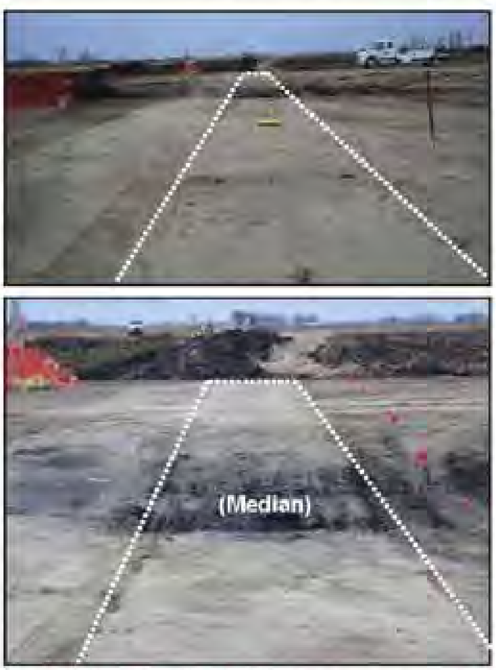

Figure 1. Test strip (outlined with dashed lines) comprised of subgrade material with testing locations spaced at 1.5-m intervals (from Thompson et al. 2008)

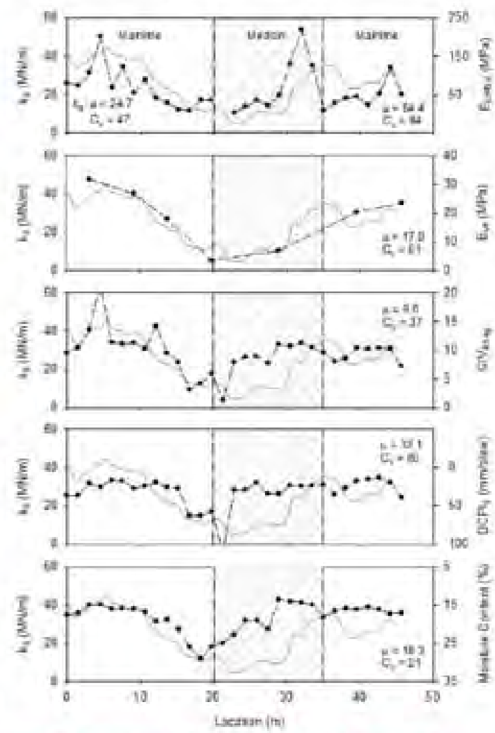

Figure 2. Comparison of k_s (solid line) and in-situ compaction measurements on a test strip comprised of subgrade material (from Thompson et al. 2008)

INTELLIGENT COMPACTION BRIEF February 2012

A 90-m long test strip with granular base material placed by the contractor, solely as subgrade cover for the winter months, was selected for compaction. The test strip was compacted using three roller passes in AFC mode at the high force setting. Even though the roller used in this study did not output vibration amplitude and frequency with k_s, changing operational parameters through the AFC algorithm was apparent during roller operation.

Figure 5 provides the k_s histograms and summary statistics for the three compaction passes. Average soil stiffness decreased slightly from the first to the second roller pass. Further, CVs for the first, second, and third roller passes were 5, 7, and 9%, respectively. Therefore, these admittedly limited compaction data do not support AFC systems as capable of improving the uniformity of compacted materials. It is also worth noting that the base material was initially placed with relatively uniform conditions. Increasing compaction was unlikely to produce more uniform soil. The performance of AFC must be further investigated, quantified, and documented in future studies.

COMPARISON WITH TEST ROLLING

A two-dimensional test area was established as four adjacent test strips, each 60 m in length and the width of the roller drum. The subgrade material was compacted with three roller passes. For the first and second lanes, the roller was operated in the manual mode with amplitude set to 80% of maximum. The roller was operated in the third and fourth lanes in the variable feedback control mode at the high force setting. k_s data for the first and third roller passes are shown in Figure 6. The comparatively soft areas (e.g., first and second lanes from 35 to 45 m) and stiff areas (e.g., third and fourth lanes from 25 to 50 m) are observed for both passes to demonstrate measurement repeatability.

Test rolling per Minnesota DOT specifications was performed using a pneumatic-tired roller with gross mass of 27.2 metric tons and tire pressure of 650 kPa towed by tractive equipment (see Figure 7). Two passes were made over each test area. The roadbed was considered to be suitable if, under the operation of the roller, the surface shows yield or rutting of less than 50 mm measured from the top of the constructed grade to the rut bottom. As the subgrade material was placed without compaction by the contractor at the location of the two-dimensional test area (by request of the investigators), considerable rutting was observed (see Figure 7).

Figure 8 shows k_s comparison to rut depth measurements, which indicates that the rut depth measurements track well with roller k_s data. The principal advantages of using RICM technology over testing rolling include (1) more efficient construction process control and QC/QA practice, (2) documentation of subgrade stability, and (3) ability to map 100% of the test area.

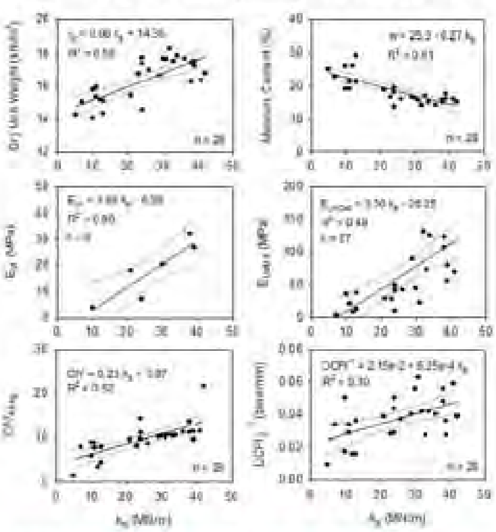

Figure 3. Relationships between k_s and in-situ compaction measurements for a test strip comprised of subgrade material (from Thompson et al. 2008)

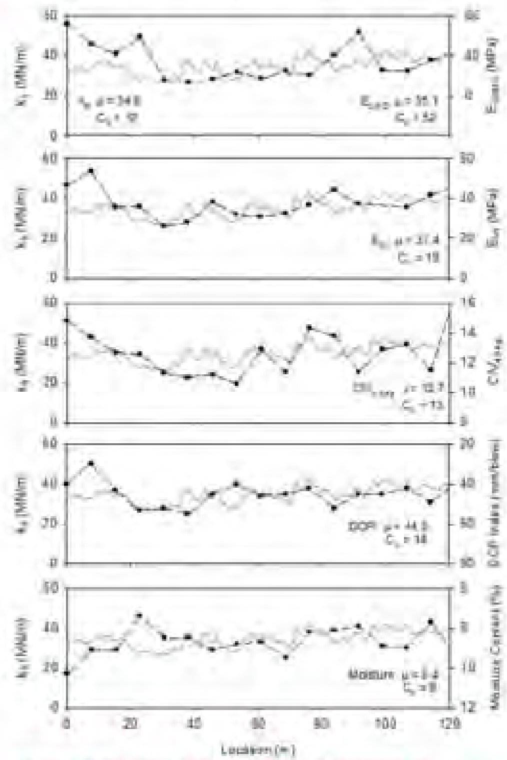

Figure 4. Comparison of k_s (solid line) and in-situ compaction measurements on a test strip comprised of granular material (from Thompson et al. 2008)

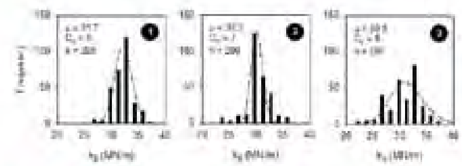

Figure 5. Distribution of k_s for three consecutive roller passes on Class 5 using variable feedback control operation (from Thompson et al. 2008)

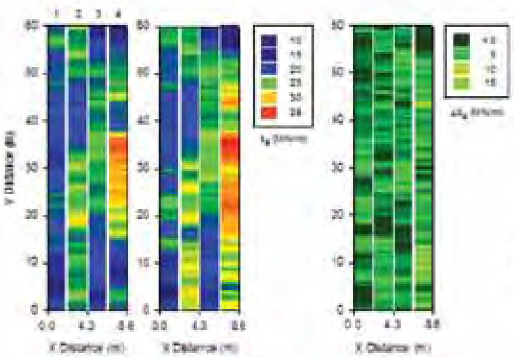

Figure 6. Ammann k_s (MN/m) for Pass 1 (left) and Pass 3 (middle), change in k_s (right) on test strip of subgrade material (from Thompson et al. 2008)

Figure 7. Test roller and subgrade rutting observed following test rolling (from Thompson et al. 2008)

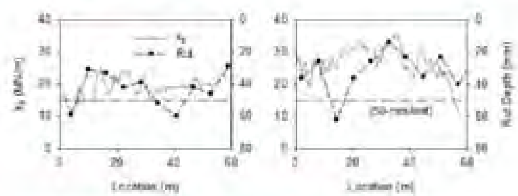

Figure 8. Comparison of k_s and rut depth along adjacent test strips of subgrade material (from Thompson et al. 2008)

KEY FINDINGS

- Subgrade stability measurements from in-situ testing devices follow closely roller-measured stiffness.
- Roller-measured stiffness is highly correlated with moisture content, which clearly shows that interpretation of k_s must consider soil moisture conditions.
- Ammann k_s is empirically related to in-situ compaction measurements through linear relationships with R^2 values ranging from 0.49 to 0.80 (for this study). The relationships are heavily influenced by the range of values over which the measurements are taken.
- The RICM measurements collected in AFC mode during this study alone did not support the process being capable of improving the uniformity of compacted materials. Future studies should more thoroughly investigate these systems to verify the intended benefits of the technology.
- The RICM system used in this study effectively identified areas of unstable subgrade material similar to test rolling.

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PRINCIPAL INVESTIGATOR
David J. White, Ph.D.
Assoc. Prof. and Holder of Wegner Professorship, Civil, Construction, and Environmental Engineering
Iowa State University
515-294-1463
djwhite@iastate.edu

RESEARCH TEAM
David J. White, Ph.D.
Pavana KR. Vennapusa, Ph.D.
Heath Gieselman, M.S.

AUTHORS
David J. White, Ph.D.
Pavana KR. Vennapusa, Ph.D.
Department of Civil, Construction, and Environmental Engineering,
Center for Earthworks Engineering Research

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This document was developed as part of the Federal Highway Administration (FHWA) transportation pooled fund study TPF-5(233)—Technology Transfer for Intelligent Compaction Consortium (TTICC).
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CENTER FOR CEER EARTHWORKS ENGINEERING RESEARCH
IOWA STATE UNIVERSITY
Institute for Transportation

Objectives

The objective of this field demonstration project was to evaluate Sakai's roller-integrated compaction measurement (RICM) system on a SW880 dual smooth drum vibratory roller for use in hot-mix asphalt (HMA) construction. The following research tasks were established for the study:

- Evaluate the effectiveness of the compaction control value (CCV) RICM values in assessing the compaction quality of HMA materials.
- Develop correlations between CCV, temperature, and in-situ point test measurements such as nuclear gauge total density, and falling weight deflectometer (FWD) modulus.
- Evaluate the advantages of using the technology for production compaction operations (e.g., uniformity in pass coverage).
- Obtain data to evaluate future RICM specifications.
- Develop content for future educational and training materials for Iowa DOT and contractor personnel.

Project Description

This demonstration project was one of the three projects conducted as part of this research (White et al. 2010) and was located on US218, south of I-80 in Coralville, Iowa. The project involved construction of HMA overlay over the existing PCC surface.

The HMA base course layer was compacted using two Sakai dual drum rollers in the breakdown position. Of the two rollers, one Sakai roller was equipped with the RICM system. The compaction monitoring system involved recording roller pass coverage, surface temperature, CCV, vibration settings, etc., and displaying data in real time on the on-board display monitor located in front from the roller operator.

All the measurements were linked to a real-time kinematic (RTK) global positioning system (GPS) to provide a continuous record of the data. The ISU research team was present on-site periodically during paving operations for three days (08/31/2009 to 09/02/2009). A photo of construction operations is shown in Figure 1.

INTELLIGENT COMPACTION BRIEF February 2012

Figure 1. Paving operations on US218 project (from White et al. 2010)

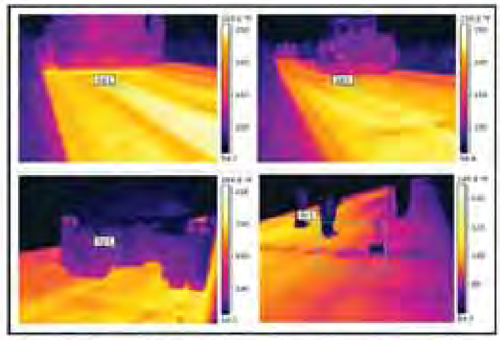

Figure 2. FLIR thermal images: in front of paver (top left), in front of break down roller (top right), behind water truck during finish rolling (bottom left), and nuclear gauge testing on the final compacted surface (bottom right) (from White et al. 2010)

On day 1, the compaction monitoring system on the roller was switched on but the on-board display monitor was closed for viewing by the operator. On days 2 and 3, the roller operator was allowed to use the on-board display to aid in "uniform" roller pass coverage. The roller operator was instructed to perform four passes (two forward and two reverse passes). The two Sakai rollers on the project were generally following each other resulting in a total of eight roller passes (note that compaction monitoring was available on only one roller).

On day 3, in-situ relative compaction using nuclear density gauge, Kuab FWD modulus testing, and asphalt surface temperature measurements using a thermal imaging camera (FLIR) and a infrared camera mounted on the FWD trailer, were obtained. Measurements were obtained on mainline and paving over the existing shoulder lane. Correlations between CCV measurements and in-situ relative compaction and FWD modulus E_{FWD} values have been developed.

Test Results and Analysis

FLIR thermal images showing spatial variation in the asphalt surface temperatures are presented in Figure 2. Example roller pass coverage maps from days 1 and 2 are presented in Figure 3 and example CCV coverage maps for days 1 and 2 are presented in Figure 4. Histogram plots of roller pass coverage data, temperature, and CCV data obtained from days 1, 2, and 3 are presented in Figure 5. The histogram plots did not reveal any significant differences in the number of roller passes, temperature, and CCV from the three days. To further analyze any differences in the "uniformity" of pass coverage between days 1 to 3, geostatistical semivariograms of number of roller passes are developed as shown in Figure 6. The semivariograms indicate improved uniformity in pass coverage on day 3 compared to day 1. This is a significant finding which provides quantitative evidence of improvement in compaction operations by viewing the data in real time.

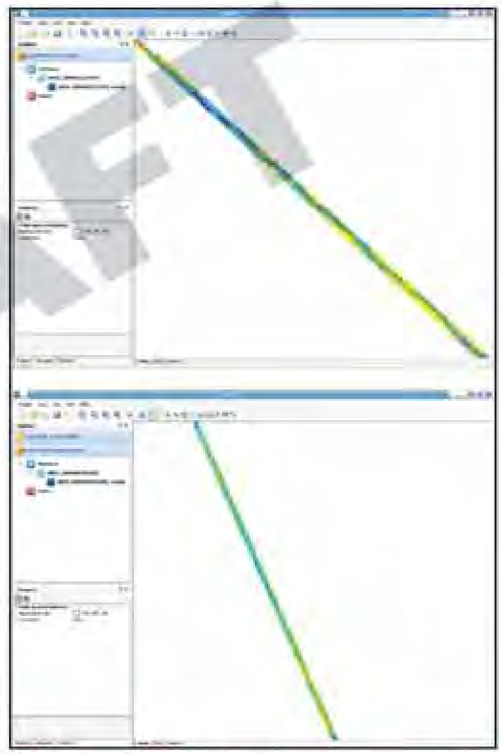

Figure 3. Pass coverage maps from day 1 (top—between mile posts 95 and 97) and day 2 (bottom—between mile posts 92 and 95) (from White et al. 2010)

Intelligent Compaction Briefs

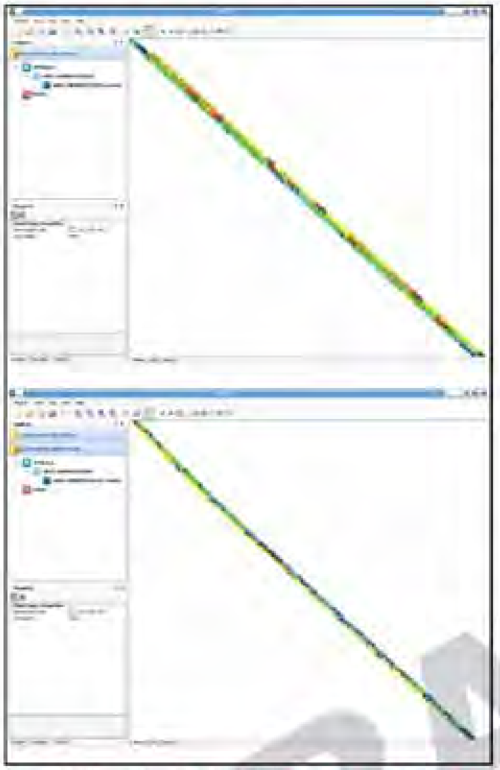

Figure 4. CCV maps from day 1 (top—between mile posts 95 and 97) and day 2 (bottom—between mile posts 97 and 95) (from White et al. 2010)

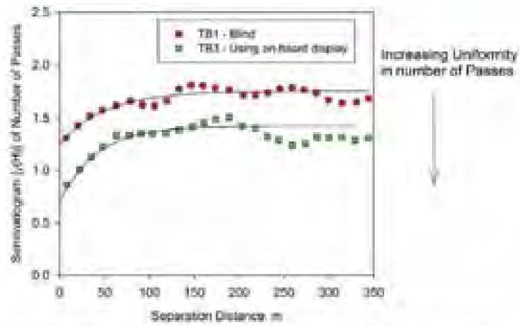

Figure 6. Comparison of semivariogram of number of roller passes from day 1 (TB1—blind study) and day 3 (TB3—with aid of on-board monitor) assessing uniformity in pass coverage (from White et al. 2010)

FLIR temperature (T_{FLIR}) and relative compaction measurements were obtained at two locations with several measurements across the pavement width (including mainline and shoulder) at each location. These results are presented in Figure 7 along with the CCV map at one test location.

Relative compaction, E_{FWD}, and T_{FLIR} in-situ test measurements obtained at several locations along a stretch of about 1.3 km on mainline and shoulder lane are compared with roller CCV measurements in Figure 8. Results presented in Figures 7 and 8 indicate that the density, modulus, and CCV were all lower on the shoulder lane compared to the mainline. This is likely because of comparatively weak support conditions under the shoulder lane compared to the mainline.

Correlations between CCV, relative compaction, and E_{FWD} are presented in Figure 9. Correlation between CCV and E_{FWD} showed strong linear regression relationship with $R^2 = 0.8$ compared to correlation between CCV and relative compaction with $R^2 = 0.4$. This is expected as CCV is a result of drum response under vibratory loading which is a measure of the stiffness and not necessarily related to the density of the material. In addition, various other factors influence both roller and in-situ test measurements which include: (a) differences in underlying support conditions; (b) differences in measurement influence depths of each device; (c) temperature at the time of the measurement; and (c) direction of roller travel.

The influence of differences in underlying support conditions is clearly reflected with data groupings in the correlations Figure 9. Further analysis revealed that CCV and E_{FWD} measurements are influenced by temperature – note that these temperature measurements are obtained at the time the in-situ test measurements were obtained while CCV were obtained at a different time.

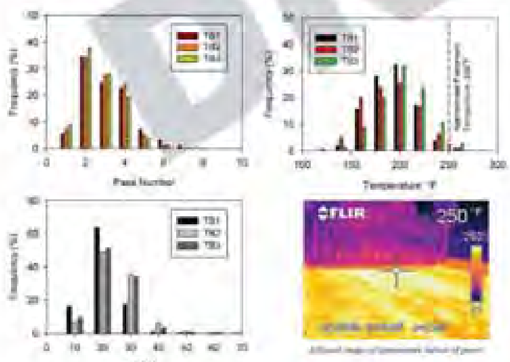

Figure 5. Histogram plots of number of passes, measured temperature, and CCV measurements from the IC rollers from TBs 1, 2, and 3 (from White et al. 2010)

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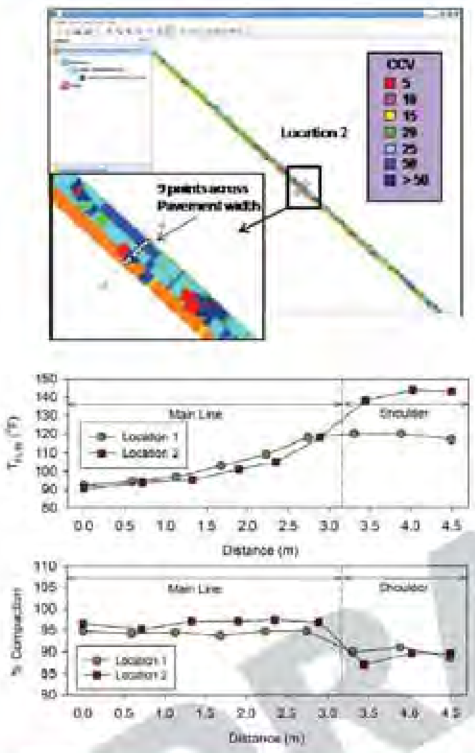

Figure 7. Comparison of semivariogram of number of roller passes from day 1 (TB1—blind study) and day 3 (TB3—with aid of on-board monitor) assessing uniformity in pass coverage (from White et al. 2010)

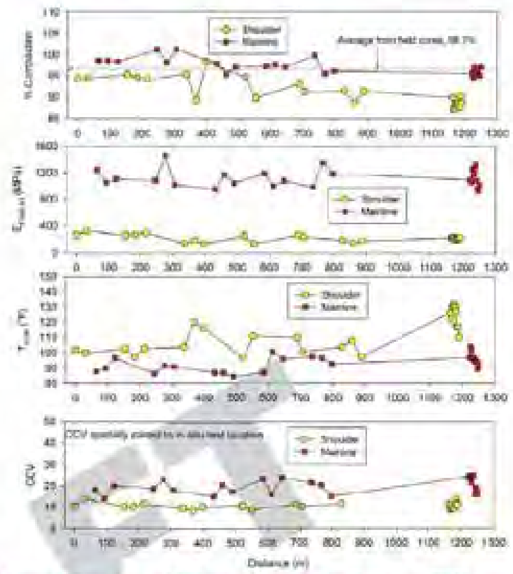

Figure 8. Comparison of CCV, percent compaction, E_{FWD-K3}, and TFUR along shoulder and mainline (from White et al. 2010)

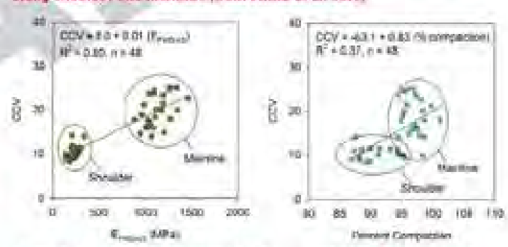

Figure 9. Correlations between CCV, E_{FWD-K3}, and percent compaction (from White et al. 2010)

Summary of Key Findings

- Univariate statistics of pass count information on each day did not reveal any differences between day 1 (blind study) and days 2 and 3. Geostatistical semivariogram analysis of pass count information revealed quantitative evidence of improved spatial uniformity in pass coverage on day 3 compared to on day 1.
- Due to greater HMA layer thickness on the shoulder compared to the mainline, the surface temperature of HMA on the shoulder lane was on average about 19°F warmer than the temperature of the HMA on the mainline. The RC of the HMA layer was on average about 6% lower on the shoulder compared to the mainline.
- FWD modulus and CCV measurements on the shoulder lane were lower than on the mainline. This is likely because of weaker support conditions under the shoulder lane compared to the mainline.
- Correlation between CCV and FWD modulus showed a relatively strong linear regression relationship with $R^2 = 0.8$ compared to correlation between CCV and relative compaction with $R^2 = 0.4$. This should be expected as CCV is a result of drum response under loading which is a measure of material stiffness and not necessarily related to the density of the material. The regression relationships are influenced by differences in underlying support conditions as it was clearly reflected with data groupings (with separate groups for shoulder lane and mainline measurements) in the correlations. Results indicated that the CCV, RC, and FWD modulus measurements are influenced by temperature.

Reference

White, D.J., Vennapusa, P., and Gieselman, H. (2010). *Iowa DOT Intelligent Compaction Research and Implementation—Phase I.* Final Repoart ER10-06, Iowa State University, Ames, Iowa.

INTELLIGENT COMPACTION BRIEF February 2012

Mississippi US 84—Untreated and Cement Treated Granular Materials—July 2009

PROJECT DATE
July 13 to 17, 2009

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

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PRINCIPAL INVESTIGATOR
George Chang, Ph.D., P.E.
Project Manager
The Transtec Group, Inc.
512-451-6233

RESEARCH TEAM
David J. White, Ph.D.
Pavana KR. Vennapusa, Ph.D.
Heath Gieselman, M.S.
Bradley Fleming, M.S.
Stephen Quist
Luke Johanson

AUTHORS
Pavana KR. Vennapusa, Ph.D.
David J. White, Ph.D.
Department of Civil, Construction, and Environmental Engineering, Center for Earthworks Engineering Research

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

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Introduction

This demonstration project was conducted on US84 highway in Waynesboro, Mississippi. The machine configurations and roller-integrated compaction measurement (RICM) systems used on this project included (Figure 1): a Caterpillar CP56 padfoot roller equipped with machine drive power (MDP) and compaction meter value (CMV) measurement systems, a Sakai SW880 dual vibratory smooth drum roller equipped with compaction control value (CCV) measurement system, and a Case/Ammann SV212 smooth drum vibratory roller equipped with roller-integrated stiffness (k_s) measurement system with automatic feedback control (AFC). All the machines were equipped with real time kinematic (RTK) global positioning system (GPS) and on-board display and documentation systems. The project involved constructing and testing nine test beds with untreated and cement treated granular base and granular subgrade materials. The RICM values were evaluated by conducting field testing in conjunction with a variety of in-situ testing devices measuring density (γ_d) or relative compaction (RC), moisture content (w), California bearing ratio (CBR), dynamic elastic modulus using a 300 mm diameter plate light weight deflectometer (E_{LWD}) and a 300 mm diameter plate falling weight deflectometer (E_{FWD}), and static initial and reload modulus (E_{V1} and E_{V2}) using a 300 mm diameter static plate load test. The goals of this field investigation were to:

- develop correlations between RICM values and traditional in-situ point measurement values (point-MVs),
- evaluate usefulness of using RICM maps for selection of QC/QA test locations,
- explore geostatistical methods to quantify and characterize spatial non-uniformity of embankment materials,
- evaluate AFC mode operations in comparison with manual mode operations,
- compare RICM values on untreated and treated subgrade and base layers (shortly after compaction and after 2 days of curing).

Figure 1 – Caterpillar CP56 (top left) padfoot roller equipped with MDP technology, Case SV212 (above) smooth drum roller equipped with k_s technology, and Sakai SW880 (bottom left) dual smooth drum roller equipped with CCV technology (from White et al. 2010)

INTELLIGENT COMPACTION BRIEF February 2012

Materials

Two granular subgrade materials and one granular base material were evaluated on the project. The subgrade materials consisted of light red silty sand classified as A-4 to white poorly graded to silty sand classified as A-3. The granular base material consisted of light red silty sand classified as A-2-4. All the materials were non-plastic.

Test Results

A total of nine test beds were constructed and tested as part of this project. A few highlights are presented in this document for brevity. Additional information is provided in White et al. (2010).

CCV map on a test bed consisting 5-day cured 150 mm thick cement treated granular base layer is presented in Figure 2. Following the mapping pass, in-situ point MVs (E_{LWD}, E_{FWD}, RC, E_{V1}, E_{V2} and DCP-CBR profiles) were obtained from 20 test locations. Results from three selected locations with low, medium, and high CCVs are presented in Figure 2. The average CCV on this test bed was about 2 times higher than on an untreated base layer test bed (TB1) located adjacent to this test bed. Similarly, the average point-MVs (E_{LWD}, E_{FWD}, RC, E_{V1}, E_{V2} and DCP-CBR) on this test bed were about 1.3 to 2.6 times higher than on TB1. The RC was however greater on TB1 (93%) than on TB2 (89%). Geostatistical analysis on CCV revealed that this test bed was comparatively more non-uniform (sill = 28, standard deviation = 6) than the untreated base layer (sill = 6, standard deviation = 1.3).

Results from TB7 consisting an untreated subgrade layer are presented in Figure 3. The subgrade material was variable across the test bed with portions of it containing white and red subgrade sand. White sand contained 8% fines (A-3) while the red sand contained about 37% fines passing the # 200 sieve (A-4). The portion of the test bed with white sand was unstable under construction traffic due to lack of confinement at the surface. The area was mapped in three roller lanes with Case/Ammann smooth drum roller for one pass each in manual mode and in AFC mode settings, and Caterpillar padfoot roller for one roller pass. In-situ point-MVs (E_{LWD}, E_{FWD}, RC, E_{V1}, E_{V2}, and DCP-CBR) were obtained at 10 test locations along one roller lane. The color-coded spatial RICM maps and linear plots along one lane are presented in Figure 3. DCP-CBR profiles at 6 selected locations (i.e., with high, low, and medium RICM values) are also presented in Figure 3. These results indicate that both point-MVs and RICM values tracked well together with relatively soft conditions in the area with white subgrade sand compared to the area with red subgrade sand.

Figure 4 compares k_s and measured amplitude (a^*) measurements obtained in manual and AFC modes in all three roller lanes. During AFC mode operation, the k_s measurements varied from 15 to 50 MN/m and the a^* measurements varied from 0.4 to 1.8 mm. The frequency (f) measurements remained relatively constant at about 30 Hz. Analysis of k_s and a^* measurements indicated that the a^* is reduced with increase in k_s. Comparison between k_s and a^* for different response distances (i.e., 0, 1, 2, and 3 m) indicated that the response distance for altering the amplitude and frequency was

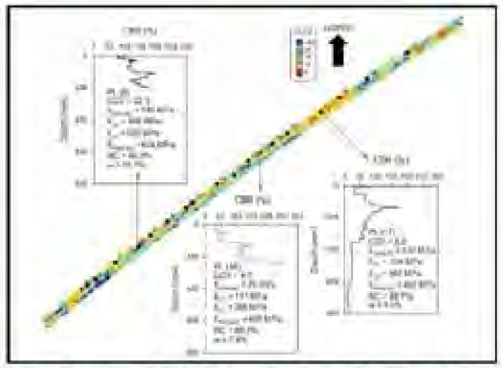

Figure 2. CCV map and point-MVs at three select locations with low, medium, and high CCV values – TB2 treated base material (amplitude (a) = 0.30 mm, frequency (f) = 55 Hz, speed (v) = 4 km/h nominal settings) (from White et al. 2010)

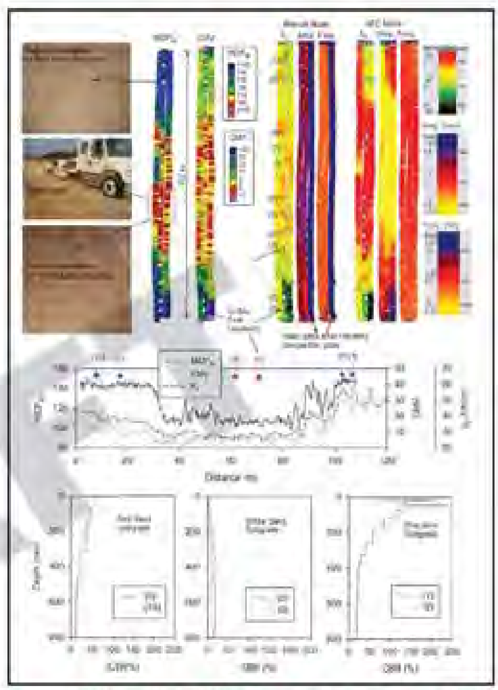

Figure 3. RICM spatial maps, MDP_{40}, CMV, and k_s measurements along the middle lane, and DCP-CBR profiles at selected locations—TB7 granular subgrade material (from White et al. 2010)

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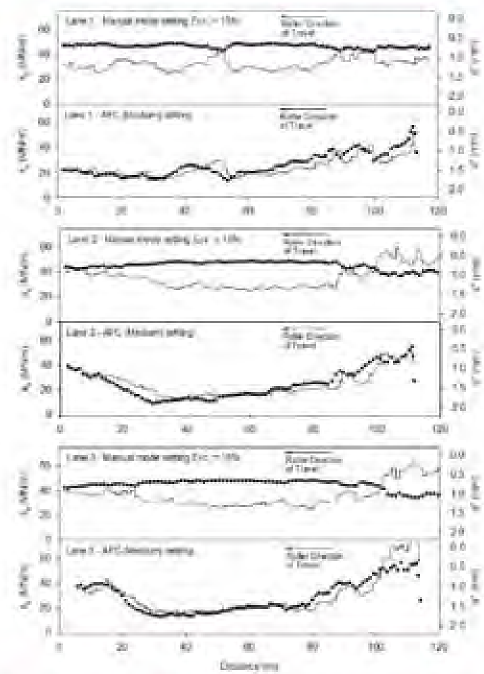

Figure 4. k_s (solid line) and a (black circles) measurements in manual and AFC mode settings—TB7 granular subgrade (from White et al. 2010)*

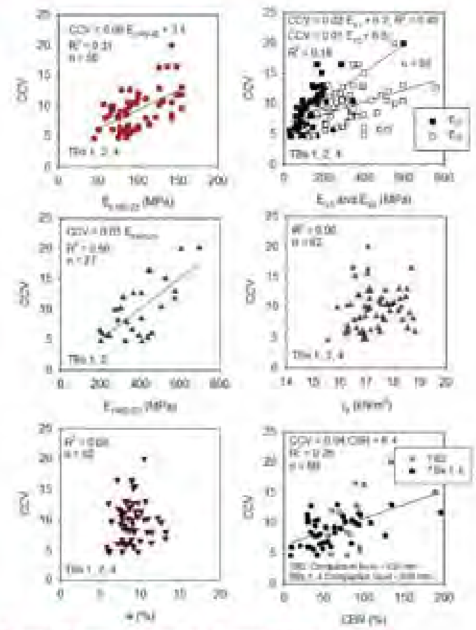

Figure 5. Regression analyses between CCV and point-MVs (from White et al. 2010)

In the range of 1 to 2 m (for variation in travel speed = 3.8 to 4.2 km/h) (note that the roller data was reported approximately every 1 m).

Regression Analysis

The data obtained from multiple test beds are combined to develop site wide correlation results as some of the test bed results represented only a narrow range of measurement values. Combining results provided a perspective of more general trends and associated variability.

Relationships between CCV and point-MVs based on the data obtained from TB1 (granular base), TB2 (treated granular base after 5-day cure), and TB4 (granular subgrade) are presented in Figure 5. Correlation with E_{FWD} showed the best relationship with $R^2 = 0.50$ compared to other point-MVs. Correlations with E_{V1} and E_{LWD} yielded $R^2 = 0.40$ and 0.31, respectively. Relationships with E_{V2} and CBR were relatively weak with $R^2 < 0.30$. No trend was observed in relationship with γ_d.

Relationships between MDP_{40} and point-MVs based on the data obtained from TBs 4 and 7 (granular subgrade) are presented in Figure 6. Non-linear exponential relationships were observed in correlations between MDP_{40} and all point-MVs. R^2 values for relationships with E_{LWD}, E_{V1}, E_{V2} and CBR_{300} point-MVs varied from 0.49 to 0.76. R^2 values for relationships with γ_d and w varied from 0.49 and 0.69, respectively. MDP_{40} values tend to reach an asymptotic value of 150, which is the maximum value programmed in the machine. This observed non-linearity has practical implications, for example, the MDP_{40} values are relatively insensitive (from about 140 and 150) to a change in E_{V1} from about 70 to 200 MPa while the MDP_{40} values are very sensitive (from about 100 to 140) to change in E_{V1} from about 10 to 70 MPa. The MDP settings on future projects could be adjusted for the measurement range of plate load test modulus values to provide the desired sensitivity for very stiff materials.

Relationships between k_s and point-MVs based on data obtained from TB3 (treated granular base-no cure), TB4 (granular subgrade), TB5 (treated granular subgrade-no cure), TB7 (granular subgrade), and TB8 (treated granular base-2 day cure) are presented in Figure 7. Correlation with E_{FWD} showed the best relationship with $R^2 = 0.74$ compared to other point-MVs. Correlations with E_{V1}, E_{V2}, and E_{LWD} yielded $R^2 = 0.68$, 0.52, and 0.49, respectively. Relationship with γ_d was relatively weak with $R^2 = 0.30$. Some influence of w was noted with $R^2 = 0.22$.

The effect of compaction time delay on cement stabilized red sand subgrade and base materials (5.5% of cement by dry weight) were studied in the laboratory, with standard Proctor test specimens compacted at 0, 30, 60, 120, and 240 minutes after mixing.

INTELLIGENT COMPACTION BRIEF   February 2012

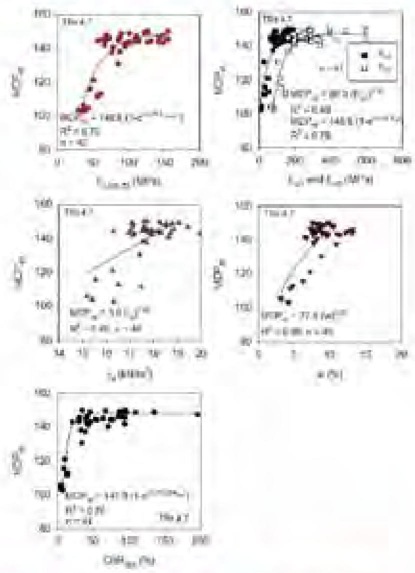

Figure 6. Regression analyses between MDP_{80} and point-MVs (from White et al. 2010)

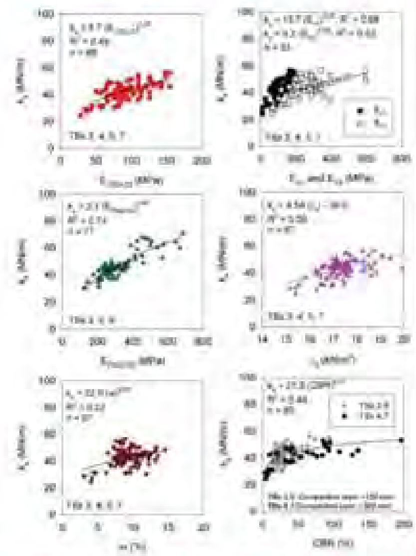

Figure 7. Regression analyses between k_s and point-MVs (from White et al. 2010)

Effect of Compaction Delay Time on Cement Treated Soils

Results obtained from this study indicated that the dry density of the treated materials decreased with increasing compaction delay time after mixing. Similar results have been demonstrated by Arman and Saifan (1967) and indicated that a delay of two or more hours in compaction after mixing results in reduced durability, compressive strength, and density of the soil-cement mixture. Project specifications indicated that the soil-cement mixture should be compacted within two hours after mixing.

Summary of Key Findings

- Empirical correlations between RICM values and different point-MVs sometimes showed weak correlations when evaluated independently for each test bed, because of the narrow measurement range. The correlations improved when data are combined for site-wide correlations with a wide measurement range.
- RICM values generally correlated better with modulus based point-MVs ($E_{LWD\text{-}Z2}$, $E_{FWD\text{-}K3}$, E_{V1}, and E_{V2}) and CBR point MVs than with dry density point-MVs. Correlations with E_{FWD} and E_{V1} showed the strongest correlation coefficients (R^2 values).
- AFC mode operations using different performance settings were evaluated in this study. In high performance setting, the amplitude was decreased and the frequency was increased with increase in k. In low and medium performance settings, the amplitude was decreased with increase in k, while the frequency remained constant. The response distance for altering the amplitude and/or frequency was about 1 to 2 m at a travel speed of about 4 km/h.
- Geostatistical analysis indicated that the spatial non-uniformity is higher on the treated subgrade/base layers after curing compared to shortly after compaction and untreated layers. Many factors contribute to this increased non-uniformity including non-uniform application of cement, water content, compaction delay time, and compaction energy over a given area. This is an important finding and has not been well documented. This finding is in contrary to the common presumption that stabilization creates a more "uniform" working platform. More research is warranted to further investigate this topic.

References

White, D.J., Vennapusa, P., Gieselman, H., Fleming, B., Quist, S., Johanson, L. (2010). *Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials: US 84 Waynesboro, Mississippi.* Final ER10-03, Submitted to the Transtec Group and FHWA by Iowa State University, Ames, IA, April 2010.

Arman, A., and Saifan, F. (1967). "The effect of delayed compaction on stabilized soil-cement." *Highway Research Board* No. 198, Washington, D.C., 30-38.

INTELLIGENT COMPACTION BRIEF February 2012

Iowa US30—Cohesive Embankment—July 2009

PROJECT DATE/DURATION
July 5 to 8, 2009

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Iowa DOT Intelligent Compaction Research and Implementation – Phase I

SPONSOR
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PRINCIPAL INVESTIGATOR
David J. White, Ph.D.
Assoc. Prof. and Holder of Wegner Professorship, Civil, Construction, and Environmental Engineering
Iowa State University
515-294-1463
djwhite@iastate.edu

RESEARCH TEAM
David J. White, Ph.D.
Pavana KR. Vennapusa, Ph.D.
Heath Gieselman, M.S.

AUTHORS
Pavana KR. Vennapusa, Ph.D.
David J. White, Ph.D.
Department of Civil, Construction, and Environmental Engineering
Center for Earthworks Engineering Research

MORE INFORMATION
http://www.iowadot.gov/research/pdf/newsnovember2010.pdf
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Objectives

The objective of this field demonstration project was to evaluate the machine-drive power (MDP) based Caterpillar compaction value roller-integrated compaction measurement (RICM) system on CP56 padfoot roller for use in embankment construction with cohesive soils. The following research tasks were established for the study:

- Evaluate the effectiveness of the RICM values in assessing the compaction quality of cohesive subgrade materials.
- Develop correlations between RICM values and in situ test measurements such as dry density, moisture content, elastic modulus, and shear strength.
- Evaluate the advantages of using the technology for production compaction operations.
- Obtain data to evaluate future RICM specifications.
- Develop content for future educational and training materials for Iowa DOT and contractor personnel.

Project Description

This demonstration project was one of three projects conducted as part of this research (White et al. 2010) and was located on US30 between Colo, Iowa and State Center, Iowa. The project involved adding two lanes to the existing highway to make it a four-lane divided highway. Grading work typically included construction of embankment and subgrade layers with "select clay" subgrade treatment in the top 0.76 m (2.5 ft) of the final subgrade elevation. The soils on site consisted of dark clays at the surface underlain by sandy to silty clay soils derived from glacial deposits (Figure 1). Fill materials were obtained from on-site borrow and cut areas along the project alignment. Fill materials were classified as sandy clay (SC) and lean clay to silt (CL-ML). Project specifications required that the moisture content of the material be within ±2% of standard Proctor optimum moisture content.

The project involved construction and testing of one calibration test bed (TB), two spatial areas TBs and one production

INTELLIGENT COMPACTION BRIEF February 2012

Figure 1. Construction operations and in situ soil conditions (from White et al. 2010)

TB with multiple lifts wherein MDP-based RICM values (hereafter referred to as MDP_{40}; see White et al. 2010 for description) and in situ point-MVs were obtained. Compaction on the TBs was mostly achieved using the CP56 padfoot roller equipped with the RICM system. Compaction was also achieved using pull-behind sheepsfoot rollers and construction traffic in production areas. In situ light weight deflectometer (LWD), dynamic cone penetrometer (DCP), and nuclear gauge (NG) tests were conducted on each TB. LWD and DCP tests are shown in Figure 2. Correlations between MDP_{40} and in situ point-MVs were developed for each TB by matching the GPS referenced in situ point-MV locations with the spatially nearest GPS-referenced MDP_{40} measurements. Data obtained from each TB were analyzed separately to develop correlations. In the end, data obtained from all the test beds were combined to develop site-wide correlations over a wide measurement range.

Figure 2. Light weight deflectometer test (left) and dynamic cone penetrometer test (right) (from White et al. 2010)

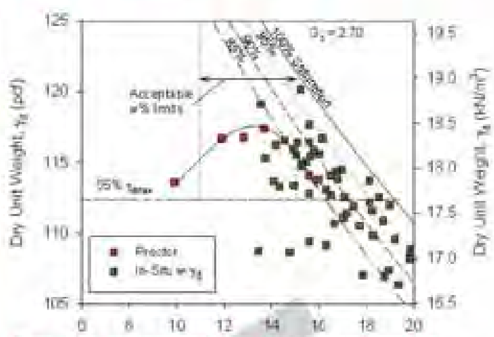

Figure 3. In situ moisture and dry unit weight measurements in comparison with laboratory standard Proctor test data (from White et al. 2010)

Summary of Key Findings

The moisture content of the subgrade materials was generally wet of optimum (about 5% wet of standard Proctor optimum moisture content) and the relative compaction of the materials varied on average (per test bed) from 90% to 97% of standard Proctor maximum dry unit weight (γ_{dmax}) (Figure 3). The material was in wet conditions due to frequent rain events at the time of project demonstration. MDP_{40} compaction curves were affected by roller "off-tracking", i.e., roller operator not maintaining the same track as the previous pass.

MDP_{40} data were able to delineate soft and stiff areas as verified by in situ point-MVs (Figure 4).

Spatial visualization of MDP_{40} maps from multiple lifts in a production area TB indicated that a "soft" zone with relatively low MDP_{40} values on lift 1 reflected through the successive lifts 2, 3, 4, and 5 with similarly low MDP_{40} values in that zone (Figure 5). Geostatistical semivariogram analysis on MDP_{40} measurements on lifts 1 to 5 indicated that the variability reduced and the spatial continuity of the measurements improved from lifts 1 to 5, as demonstrated by a decrease in the sill and an increase in the range values (Figure 6).

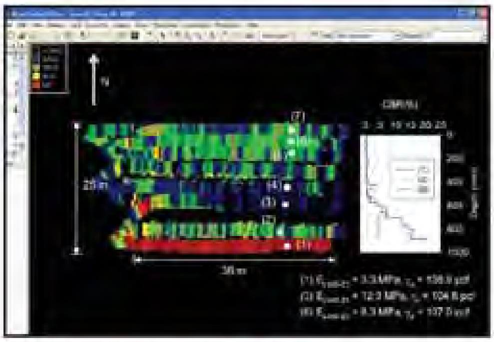

Figure 4. MDP40 final pass map from TB2 with in situ test results at selected point test locations (from White et al. 2010)

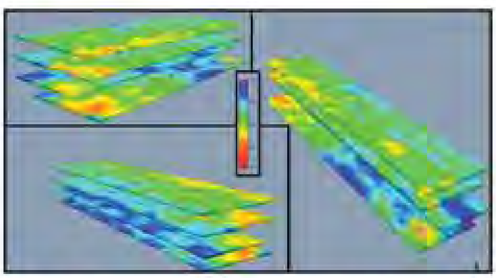

Figure 5. Three-dimensional spatial visualization of MDP measurements on lifts 2 to 5 (note: vertical elevation between each lift exaggerated for clarity) (from White et al. 2010)

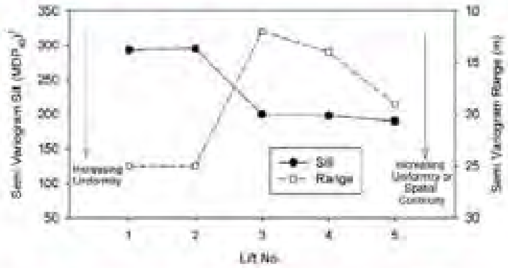

Figure 6. Semi variogram sill and range values on lifts 1 to 5 (from White et al. 2010)

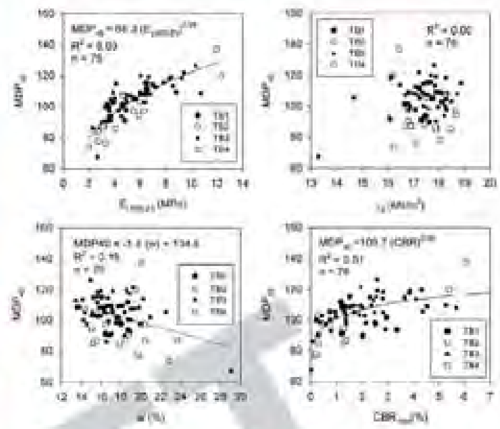

Figure 7. Correlations between MDP$_{40}$ and point-MVs from all test beds (from White et al. 2010)

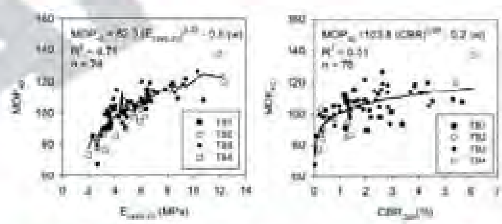

Figure 8. Multivariate non-linear regression analysis results (from White et al. 2010)

Regression analysis results indicated better correlations between MDP$_{40}$ and LWD modulus and California bearing ratio (CBR) determined from DCP compared to dry density measurements. Combining data from all test beds, MDP$_{40}$ vs. LWD modulus and CBR yielded a non-linear power relationship with $R^2 > 0.50$ (Figure 7). MDP$_{40}$ vs. dry density did not yield a statistically significant relationship (Figure 7). MDP$_{40}$ measurements were somewhat sensitive to moisture content (MDP$_{40}$ decreased with increasing moisture content). Correlation between MDP$_{40}$ and moisture content yielded a linear relationship with $R^2 = 0.20$.

Multivariate non-linear regression analysis was performed to assess the influence of including a moisture content parameter in predicting MDP$_{40}$ from LWD modulus measurements (Figure 7). This analysis showed $R^2 = 0.71$, which is a slight improvement over the simple regession model without the moisture content parameter ($R^2 = 0.63$). A similar analysis was performed to predict MDP$_{40}$ from CBR measurements, but it did not show any improvement in the R^2 value (Figure 8). The MDP$_{40}$ vs. dry density dataset combined with moisture content did not show a statistically significant relationship.

Reference

White, D. J., Vennapusa, P., and Gieselman, H. (2010). Iowa DOT Intelligent Compaction Research and Implementation—Phase I. Final Report ER10-06, Iowa State University, Ames, Iowa.

INTELLIGENT COMPACTION BRIEF February 2012

Iowa US30—Hot-Mix Asphalt Overlay—July 2010

PROJECT DATE/DURATION
July 12 to 27, 2010

RESEARCH PROJECT TITLE
Iowa DOT Intelligent Compaction Research and Implementation – Phase II

SPONSOR
Iowa Department of Transportation

PRINCIPAL INVESTIGATOR
David J. White, Ph.D.
Assoc. Prof. and holder of Wegner Professorship, Civil, Construction, and Environmental Engineering
Iowa State University
515-294-1463
djwhite@iastate.edu

RESEARCH TEAM
David J. White, Ph.D.
Pavana KR. Vennapusa, Ph.D.
Justin Harland
Stephen Quist

AUTHORS
Pavana KR. Vennapusa, Ph.D.
David J. White, Ph.D.
Department of Civil, Construction, and Environmental Engineering,
Center for Earthworks Engineering Research

MORE INFORMATION
http://www.ceer.iastate.edu/research/project/project.cfm?projectID=-225718242

This document was developed as part of the Federal Highway Administration (FHWA) transportation pooled fund study TPF-5(233) – Technology Transfer for Intelligent Compaction Consortium (TTICC).
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CENTER FOR CEER EARTHWORKS ENGINEERING RESEARCH

IOWA STATE UNIVERSITY
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Project Summary

The US30 project is about 8.1 miles long and is located between Dunlap, Iowa and Dow City, Iowa (between mile posts 38.38 and 46.12). A special provision (SP) was developed to implement roller-integrated compaction monitoring (RICM) technology on this project: "Intelligent Compaction–HMA, Harrison County, NHSN-030-1(12)--2R-43 (Effective January 20, 2010) [SP-090048]." The project involved milling the existing pavement to about 38 mm (1.5 in.), and resurfacing with 51 mm (2 in.) of hot-mix asphalt (HMA) intermediate course and 51 mm (2 in.) of HMA surface course layers. HMA resurfacing was performed in the mainline over a width of about 24 feet and over the shoulder extending about 4 feet on each side.

Compaction of the HMA layers was achieved using a Sakai SW990 smooth-drum roller in the breakdown position, followed by Hamm GRW18 pneumatic rubber-tire roller, and a Caterpillar CB-634D smooth-drum roller for final passes. Only the Sakai SW990 smooth-drum roller was equipped with a RICM system. Sakai's RICM system recorded and displayed the spatial position of the roller (i.e., GPS northing, easting, and elevation), roller pass coverage, surface temperature, compaction control value (CCV), vibration mode, etc. in real time to the roller operator through an on-board display unit. Compaction using the SW990 roller was achieved in vibratory mode using a low amplitude setting (0.33 mm) and a frequency setting of 50 Hz (3000 vpm). Screen shots of roller pass coverage, temperature, and CCV maps from the RICM software are shown in Figures 1 to 3, respectively.

Beyond the quality control (QC) or quality assurance (QA) testing required in the project specifications, a total of fourteen production test sections (PSs) were tested

INTELLIGENT COMPACTION BRIEF February 2012

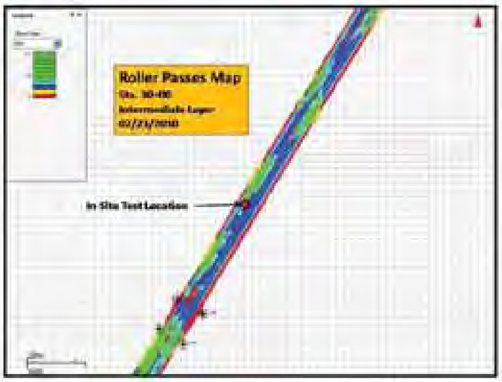

Figure 1. Roller pass coverage map at Sta. 30+00 intermediate course layer (from White et al. 2010)

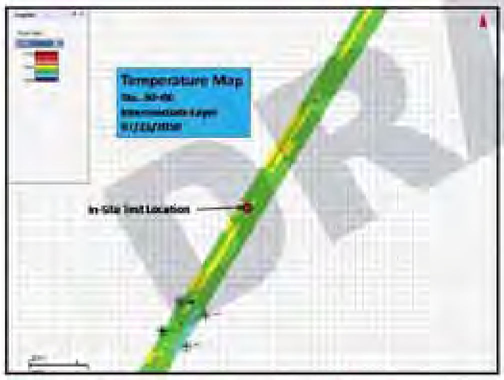

Figure 2. Surface temperature coverage map at Sta. 30+00 intermediate course layer (from White et al. 2010)

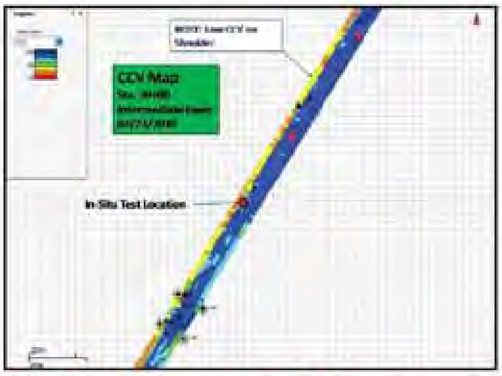

Figure 3. Roller CCV coverage map at Sta. 30+00 intermediate course layer (from White et al. 2010)

on the project site. A Troxler nuclear gauge was used to obtain percent compaction measurements on the HMA layers. HMA surface temperature measurements were obtained using a FLIR thermal camera (T_{FLIR}) and the infrared camera mounted on the RICM roller (T_{Roller}). Density and surface temperature measurements were obtained before and after multiple roller passes (e.g., 0, 1, 2, 3, etc.) to evaluate their changes with increasing passes and time. In addition, FWD tests were obtained on the existing milled asphalt base layer prior to and after placement of the intermediate layer at few test locations. FWD tests were performed to evaluate the influence of support conditions on the roller-integrated CCV measurements, which presumably have deeper influence depths (e.g., up to > 1 m).

Project Special Provisions and Costs

The SP090048 described the contractor's responsibilities to furnish the RICM rollers, data acquisition, and other key attributes related to equipment and materials, construction, data acquisition and submittals, method of measurement, and basis of payment. As part of the SP, the contractors were required to collect the RICM data for research purposes, and the data were not used for QC or QA. However, the SPs required that the RICM data be collected over a minimum of 80% of the project intermediate and surface course layers to request full payment.

Contract bid costs submitted for this project are summarized in White et al. (2011). The bid item cost (for all bidders) for implementing the SP on this project varied from about 0.7% to 3.6% of the total project cost, while the bid unit cost/mile (for all bidders) varied from about $494 to $18,541.

INTELLIGENT COMPACTION BRIEF

February 2012

Summary of Key Findings

- The RICM-HMA SP-090048 was successfully implemented on the US30 Harrison County pilot project. Evaluation of RICM data coverage information indicated that the RICM data were collected over 85% of the project area on the intermediate course layer and over 95% of the project area on the surface course layers, thus conveniently exceeding the minimum 80% requirement in the SP.
- Field core density results indicated that 115 out of 117 samples exceeded the target minimum 95% compaction requirement.
- Percent compaction curves indicated that 95% compaction was generally achieved within 1 to 2 break-down roller passes at most locations, with exceptions at few locations where up to four passes or more were required (for an example, see Figure 4).
- Roller surface temperature measurements with pass generally indicated that the pass 2 measurement was lower than pass 3 (note that the rolling pattern included forward, reverse, and forward directions of travel for passes 1, 2, and 3). The temperature sensor on the roller was located on the front drum of the roller, and water sprayed on to the roller drum likely caused a reduction in the surface temperature values when the roller traveled in the reverse direction.
- Asphalt temperature cooling rate (Cy) was modeled using an exponential statistical model from surface temperature with time measurements (see Figure 5). For cases where data up to a maximum of 35 minutes were considered, the Cy values ranged from about -0.0090 to -0.0157 with an average of about -0.0135 and standard deviation of 0.0022.
- Correlations between CCV and asphalt density or percent compaction measurements yielded relatively low R^2 values in the range of 0.1 to 0.7 (see Figure 6). However, if the measurements for each TS were viewed separately, there was generally a trend of increasing CCV with increasing percent compaction in most sections.
- Poor correlations between density and CCV are to be expected when data are combined over multiple sections, because CCV provides a measure of ground stiffness and is strongly influenced by the conditions of the layer underneath the HMA layer and not necessarily the density of the surface layer. FWD test measurements obtained from the intermediate course layer and the underlying existing base layer confirmed that variable support conditions exist at different test locations. Correlations between the FWD modulus on intermediate course layer and base layer and CCV on the intermediate course layer yielded R^2 values in the range of 0.5 to 0.9 (Figure 7). Results presented during Phase I of this

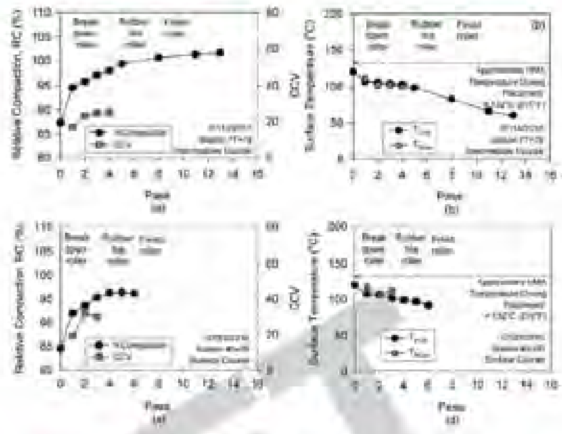

Figure 4. (a) Relative compaction versus pass count on intermediate course layer at Sta. 77+79, (b) Surface temperature versus pass count on intermediate course layer at Sta. 77+79, (c) Relative compaction versus pass count on surface course layer at Sta. 40+00, and (d) Surface temperature versus pass count on surface course layer at Sta. 40+00 (from White et al. 2010)

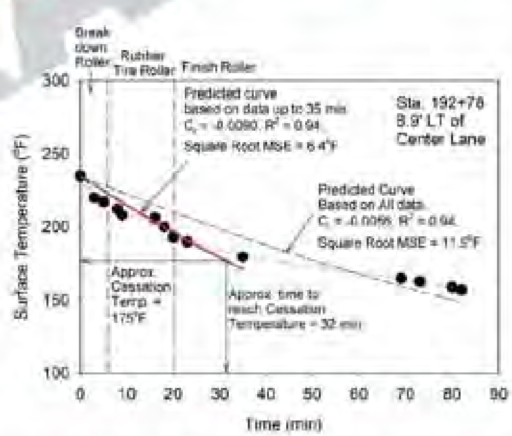

Figure 5. Surface temperature and percent compaction measurements with time at four test locations – US30 Harrison county project surface course layer (from White et al. 2010)

research (White et al. 2010) also corroborate this finding. This research finding is critical to understand, as it has practical consequences in terms of how roller-integrated CCV data can be used for QC or QA in future specifications.

- Correlation between T_{Roller} and T_{IR} indicated that there was no statistically significant correlation between the two measurements; however, about 29 of the 35 measurements were close to the 1:1 line, and the measurements were, on average, comparable to each other.

INTELLIGENT COMPACTION BRIEF February 2012

- Based on field observations and conversations with the roller operator, it was understood that the roller operator targeted 3 to 4 roller passes using the breakdown roller. Roller coverage data indicated that the average number of breakdown roller passes on the project was about 3, with a standard deviation of about 1 to 2. Geostatistical analysis of pass count indicated that the sill values varied from about 2.4 to 3.6 and the range values varied from about 9 to 20 m (see Figures 8 and 9). These sill values were higher than observed in Phase I on the US218 project (~1.3) described in White et al. (2010) and on the US20 project (~0.6) described in White et al. (2011). The high sill values on the US30 project compared to the US218 and US20 projects indicates that the pass coverage was more variable on the US30 project. Field observations indicated that the number of passes made by the breakdown roller was governed heavily by the pace of the paver ahead of the breakdown roller.
- Average CCV ranged from 20 to 30 on intermediate course and 22 to 33 on surface course layers. Average surface temperature at the end of breakdown roller pass ranged from about 215°F to 225°F on surface and intermediate course layers.

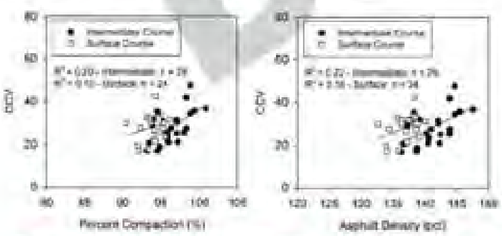

Figure 6. Correlations between in-situ HMA compaction measurements and CCV (from White et al. 2010)

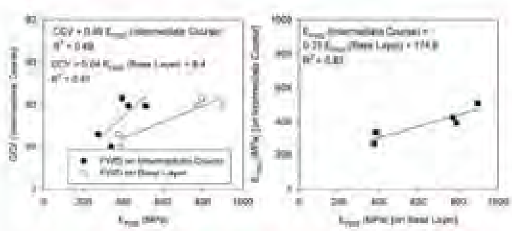

Figure 7. Correlations between CCV on intermediate course layer and FWD modulus (left) and FWD modulus on intermediate course layer and underlying base layer – US30 Harrison county project (from White et al. 2010)

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White, D.J., Vennapusa, P., Harland, J., and Quist, S. (2011) "Iowa Roller Integrated Compaction Monitoring Technology Research and Implementation—Phase II," ER11-01, Iowa State University, Ames, Iowa, June.

White, D.J., Vennapusa, P., and Gieselman, H. (2010). Iowa DOT Intelligent Compaction Research and Implementation—Phase I. Final Report ER10-06, Iowa State University, Ames, Iowa.

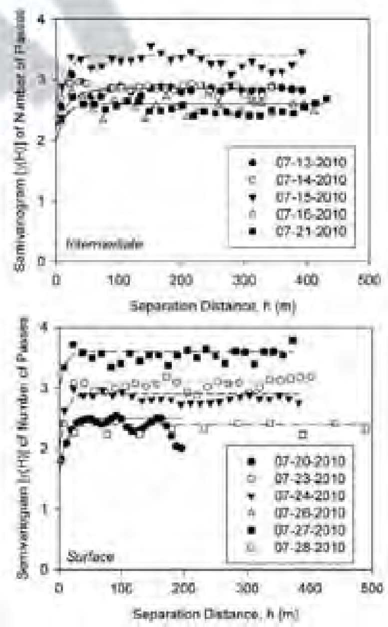

Figure 8. Semivariograms of number of roller passes on intermediate and surface course layers for each day (from White et al. 2010)

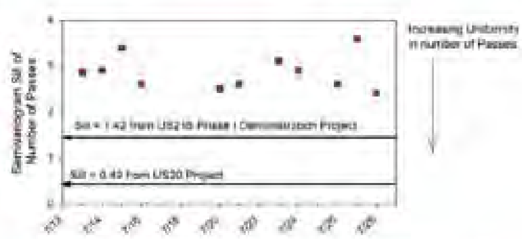

Figure 9. Variation in semivariogram sill of number of roller passes for each day (from White et al. 2010)

INTELLIGENT COMPACTION BRIEF — February 2012

Texas FM156—Untreated and Lime Treated Cohesive Materials and Granular Base Materials—July 2008

PROJECT DATE/DURATION
July 20 to 25, 2008

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

SPONSOR
Federal Highway Administration

PRINCIPAL INVESTIGATOR
George Chang, Ph.D., P.E.
Project Manager
The Transtec Group, Inc.
512-451-6233

RESEARCH TEAM
David J. White, Ph.D.
Pavana KR. Vennapusa, Ph.D.
Heath Gieselman, M.S.
Luke Johanson
Rachel Goldsmith

AUTHORS
David J. White, Ph.D.
Pavana KR. Vennapusa, Ph.D.
Center for Earthworks Engineering Research, Department of Civil, Construction, and Environmental Engineering

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

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

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CENTER FOR CEER EARTHWORKS ENGINEERING RESEARCH

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INTRODUCTION

This demonstration was conducted on the FM156 project in Roanoke, Texas. The machine configurations and roller-integrated compaction measurement (RICM) systems used on this project included (Figure 1): a Case SV212 12-ton padfoot roller and a smooth drum roller equipped with roller-integrated stiffness ks measurement system with automatic feedback control (AFC), and a Dynapac CA362 15-ton smooth drum roller equipped with compaction meter value (CMV) measurement system with AFC. All the machines were equipped with real time kinematic (RTK) global positioning system (GPS) and on-board display and documentation systems. The project involved constructing and testing seven test beds with fine grained cohesive subgrade clay soils, lime treated cohesive subgrade clay soils, and granular base materials (flex base). The RICM systems were evaluated by conducting field testing in conjunction with a variety of in situ testing devices measuring: dry density (γd), moisture content (w), California bearing ratio (CBR), dynamic elastic modulus using a 200 mm plate light weight deflectometer (E_{LWD-Z2}) and a 300 mm plate falling weight deflectometer (E_{FWD}), initial (E_{V1}) and re-load modulus (E_{V2}) using a static plate load test with 300 mm diameter plate, and dynamic seismic pavement analyzer (D-SPA) low strain elastic modulus (E_{SPA}). The goals of this field study were to:

- Evaluate the effectiveness of the RICM values from padfoot and smooth drum rollers in assessing the compaction quality of the three material types encountered on the project.
- Develop correlations between RICM values from padfoot and smooth drum rollers and various conventionally used in-situ point measurement values (MVs) in QC/QA practice, and
- Assess comparisons between smooth drum and padfoot roller RICM values.

Figure 1. (left) Case SV212 padfoot roller, (right) Case SV212 smooth drum roller, and (bottom) Dynapac CA362 smooth drum roller

INTELLIGENT COMPACTION BRIEF February 2012

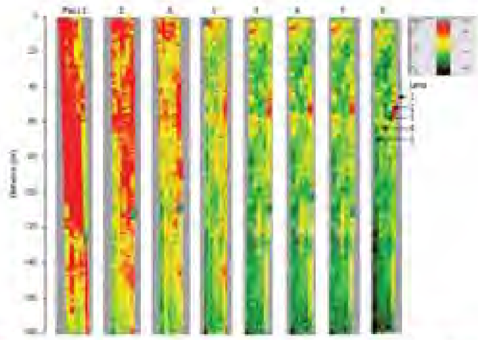

Figure 2. Screen shots of k_{SEV} maps for different passes on TB 1 – cohesive subgrade soil (from White et al. 2008)

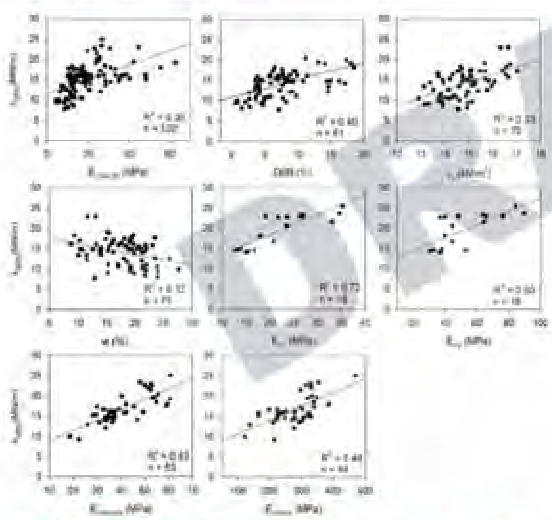

Figure 3. Simple linear regression relationships between k_{SEV} and in-situ point measurements (TB 1 – cohesive subgrade clay material) (from White et al. 2008)

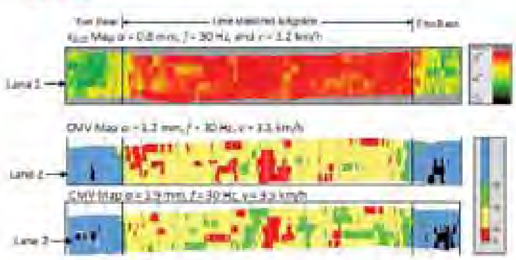

Figure 4. Comparison between k_{SEV}, CMV maps– TB2 flex base and lime-stabilized subgrade (from White et al. 2008)

MATERIALS

The cohesive subgrade material was classified as lean clay (CL) and A-7-6(24) soil, the lime treated subgrade material was classified as silt with gravel (SM) and A-2-7 soil, and the flex base material was classified as poorly-graded gravel to silty gravel with sand (GP-GM) and A-1-a soil.

SUMMARY OF KEY FINDINGS

- Both padfoot and smooth drum roller-integrated k_s values (k_{sPD} and k_{sSD}) reliably indicated the compaction quality of the subgrade clay material with good repeatability. Correlations with E_{FWD-K3} and E_{V1} values (with $R^2 > 0.6$) produced better R^2 values compared to E_{LWD-Z2}, γd, and CBR (of the compaction layer) measurements (e.g., Figure 3). Poorer correlations with E_{LWD-Z2}, γd, and CBR compaction layer values is attributed to the limitation of shallow measurement influence depth of these measurements (< 250 mm). CBR profiles up to 1 m generated from DCP tests identified "soft" zones below the compaction layer which affected the k_s values. The E_{V1} and E_{FWD-K3} are believed to have influence depths that extend below the compaction layer due to higher applied contact stresses at the surface.
- Both RICM values and in-situ point measurements captured the wide variation in stiffness of the compacted lime stabilized and flex base materials (Figure 4). A box-culvert located beneath the lime stabilized subgrade was identified with high roller MVs in that location (Figure 5). Linear regression relationships generally indicate separate linear trends for the lime stabilized and flex base materials. E_{FWD} measurements produced better correlations than other point measurements. Hyperbolic regression relationships were developed for E_{FWD} and E_{DSPA} measurements which showed strong correlations with ks and CMV measurements but additional data is needed to validate the relationships. The CMV measurements at this location were highly repeatable.
- The ks measurements effectively identified poor backfill compaction conditions along the edge of a box culvert located in this test bed and the results were confirmed from CBR profiles (Figure 6). Regression relationships between ks and different in-situ point measurements show positive correlations with varying degree of uncertainty in the correlations (as assessed by the R^2 values), however. Better correlations were observed with E_{FWD}, E_{V1}, E_{V2}, and E_{LWD} values (with $R^2 > 0.5$) compared to E_{DSPA} and γd. Relationships with E_{DSPA} show encouraging trends in the data, however. The ks values were sensitive to moisture content of the compaction layer material.
- The roller-integrated CMV measurements showed good repeatability on the flex base material. Results from compaction passes did not show considerable increase in compaction with increasing passes. In some areas, the

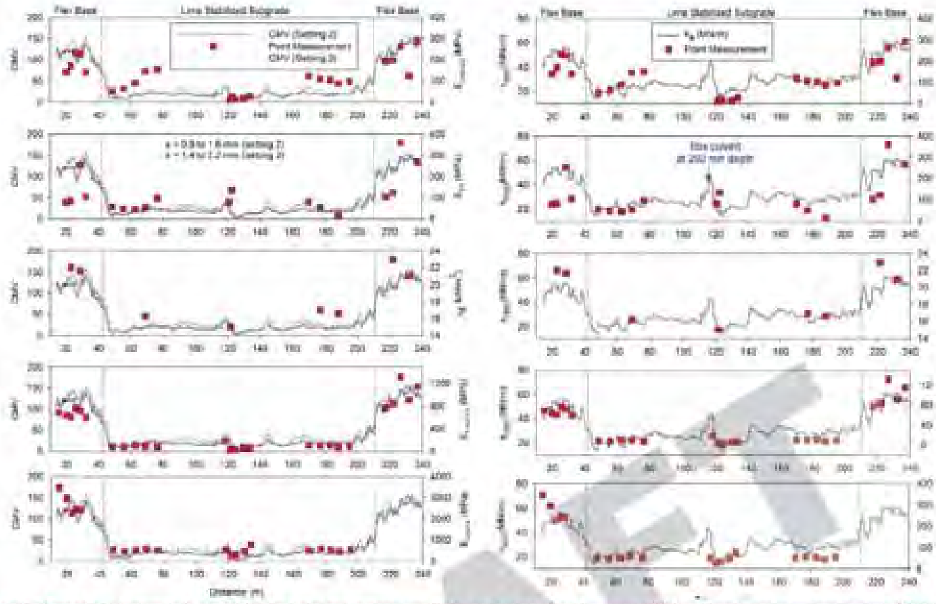

Figure 5. Comparison between k_{s02} and in situ point measurements (left) and comparison between CMV and in situ point measurements (right) – TB2 flex base and lime-stabilized subgrade (from White et al. 2008)

material was wet and "spongy" during compaction passes. The CMV measurements obtained from this test bed were in the range of 20 and 70. The CMV measurements on TB2 flex base material which was very dry were greater than about 100. This indicates that the material gains significant strength over time as the material is subjected to several days of compaction under construction equipment and as it becomes drier.

- The CMV measurements are influenced by the vibration amplitude and show that increasing amplitude generally causes an increase in CMV on this material. Comparison between CMV and E_{FWD} measurements showed that the point measurements tracked well with the variability in CMV in some cases and in some cases it did not. The CMV measurements however were well correlated with variations in moisture content (within 4% to 6%) as evidenced by a decrease in CMV with increasing moisture content. E_{LWD}, E_{V1}, and CBR tracked well with the variations in CMV measurements. The reason for poorer correlation with E_{FWD} measurements in some locations is attributed to the possible influence of heterogeneity observed in the material across the drum width due to moisture segregation. Only one point measurement was obtained at the center of the drum while the roller value is an integrated response over the full drum width.

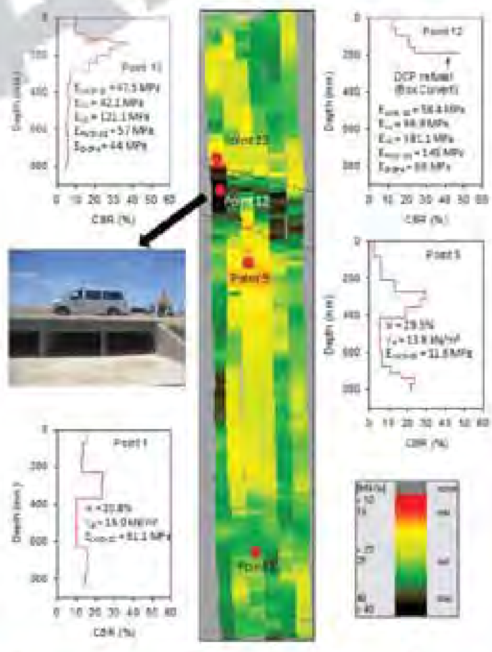

Figure 6. k_{s02} map and DCP profiles at select locations on TB5 lime stabilized material (from White et al. 2008)

INTELLIGENT COMPACTION BRIEF

February 2012

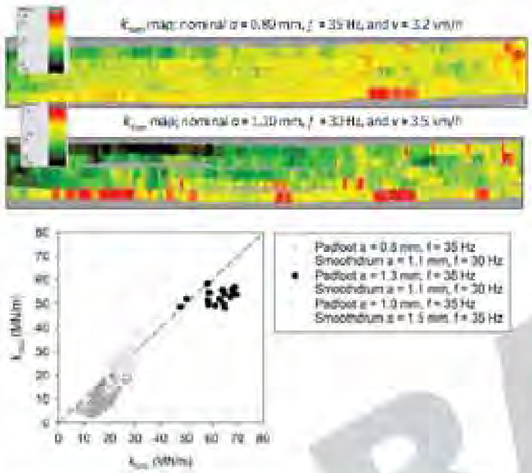

Figure 7. Relationship between k_{SPD} and k_{SPD} measurements (from White et al. 2008)

- Comparison between k_{SPD} and k_{SPD} show that k_{SPD} values are generally greater than k_{SPD} (Figure 7). Note that the values were obtained at different amplitude settings. Future studies may focus on obtaining correlations from the two measurements at similar amplitude settings. Comparison padfoot penetration depth measurements in conjunction with k_{SPD} and k_{SPD} measurements in future studies may help provide additional insights into the correlations between k_{SPD} and k_{SPD} values. Nevertheless, the trends observed between k_{SPD} and k_{SPD} are encouraging and the padfoot roller measurements demonstrate similar advantages as the smooth drum roller measurements.

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White, D.J., Vennapusa, P., Gieselman, H., Johanson, L., Goldsmith, R. (2008). Accelerated Implementation of Intelligent Compaction Monitoring Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials TPF-5(128) - Texas IC Demonstration Field Project, Report submitted to The Transtec Group, FHWA, November

INTELLIGENT COMPACTION BRIEF February 2012

North Dakota US12—Embankment Subgrade and Geogrid Stabilized Base Materials—August 2010

PROJECT DATE/DURATION
August 9 to 12, 2010

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

SPONSOR
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PRINCIPAL INVESTIGATOR
George Chang, Ph.D., P.E.
Project Manager
The Transtec Group, Inc.
512-451-6233

RESEARCH TEAM
David J. White, Ph.D.
Pavana KR. Vennapusa, Ph.D.
Heath Gieselman, M.S.
Jiake Zhang, M.S.
Michael Eidem

AUTHORS
David J. White, Ph.D.
Pavana KR. Vennapusa, Ph.D.
Department of Civil, Construction, and Environmental Engineering
Center for Earthworks Engineering Research

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

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CENTER FOR CEER EARTHWORKS ENGINEERING RESEARCH

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Figure 1. Caterpillar CS56 smooth drum with padfoot shell kit (left) and Caterpillar CS563E smooth drum (right) rollers (from White et al. 2010)

INTRODUCTION

This demonstration was conducted on the US Highway 12 in Marmarth, North Dakota. The machine configurations and roller-integrated compaction measurement (RICM) systems used on this project included (Figure 1): a Caterpillar CP56 smooth drum roller with a padfoot shell kit (hereinafter referred to as padfoot roller) equipped with machine drive power (MDP), and a Caterpillar CS563E vibratory smooth drum roller equipped with MDP and compaction meter value (CMV) measurement technologies. (Note: MDP* values are reported as MDP*; see White et al. (2010) for description of MDP*). The machines were equipped with real time kinematic (RTK) global positioning system (GPS) and on-board display and documentation systems. The project involved construction and testing of seven test beds (TBs). Four of these TBs included silty subgrade materials and the remaining three included salvage base materials. The TBs with salvage base materials varied in terms of their underlying support conditions. One TB was reinforced with two layers of geogrid in the base layers, one TB was partially treated with over excavation and replacement due to soft subgrade conditions, and the other TB served as a control section with no special treatments.

The RICM values were evaluated by conducting field testing in conjunction with different point measurements: in situ dry density (γ_d) and moisture content (w) determined from nuclear gauge, California bearing ratio (CBR) determined from dynamic cone penetrometer (DCP) test, drained shear strength parameters from borehole shear test (BST), and dynamic modulus determined from falling weight deflectometer (FWD) and light weight deflectometer (LWD). The goals of this field study were to accomplish the following:

- Document machine vibration amplitude influence on compaction efficiency.
- Develop correlations between RICM values to traditional in-situ point measurements (point-MVs).
- Evaluate the impact of geogrid reinforcement in the base layers on RICM values and point-MVs in comparison with sections without reinforcement.
- Compare RICM results to traditional compaction operations.
- Study RICM values in production compaction operations.
- Evaluate RICM values in terms of alternative specification options.

INTELLIGENT COMPACTION BRIEF February 2012

MATERIALS

The silty subgrade material in the TBs was classified as silty sand (SM) and A-2-4 soil, and the salvage base material was classified as poorly graded sand with gravel (GM) and A-1-a.

SUMMARY OF KEY FINDINGS

Subgrade Test Beds Compacted with Padfoot Roller

Four subgrade test beds (TBs 1 to 3, and 7) were constructed and tested in this study. TB1 consisted of three side-by-side calibration lanes compacted in static, low amplitude (a = 0.90 mm), and high amplitude (a = 1.80 mm) modes. TB2 consisted of a one-dimensional test strip with visible rutting areas at the surface. TBs 3 and 7 consisted of production areas. Following are some key findings and conclusions from these TBs:

- MDP* data are influenced by the vibration amplitude settings used during compaction. Results from TB1 indicated that on average, MDP* generally increased with increasing number of passes when compacted in static and low amplitude mode, while in high amplitude mode the compaction growth curve yielded inconsistent results between passes (Figures 2 and 3). This is attributed to de-compaction of the material at the surface and possibly deeper compaction when high amplitude setting is used for compaction.
- The average MDP* values from TB1 obtained in low amplitude mode were either similar or slightly lower (by about 1.02 to 1.05 times) than the MDP* values obtained in static mode. The average MDP* values from TB3 production area in low amplitude mode were about 1.06 times lower than the MDP* values obtained in static mode.
- The average MDP* values from TB1 obtained in high amplitude mode were lower (by about 1.19 to 1.25 times) than the average MDP* values in static and low amplitude modes.
- The average LWD modulus and CBR were lower on low and high amplitude mode lanes, compared to the lanes compacted in static mode. In contrary, the average γ_d was greater on low and high amplitude mode lanes than on static mode lane (Figure 3).
- Regression analysis results between static MDP* and different point-MVs showed R^2 values ranging from 0.15 to 0.54. Static MDP* values were better correlated with LWD modulus (R^2 = 0.54) than with CBR (R^2 = 0.17) and γ_d (R^2 = 0.15) (Figure 4). This observation is generally consistent with findings from several previous case studies that the RICM values correlate better with stiffness or modulus measurements compared to density measurements. Correlations with low and high MDP generally showed weak relationships because of limited and narrow range of measurements.
- MDP* and LWD point-MVs obtained from TB2 effectively identified the soft/rutting areas observed at the surface (Figure 5).
- Geostatistical analysis on production area MDP* values indicated nested spherical variogram structures with short- and long-range spatial structures (Figure 6). The long-range spatial structures are

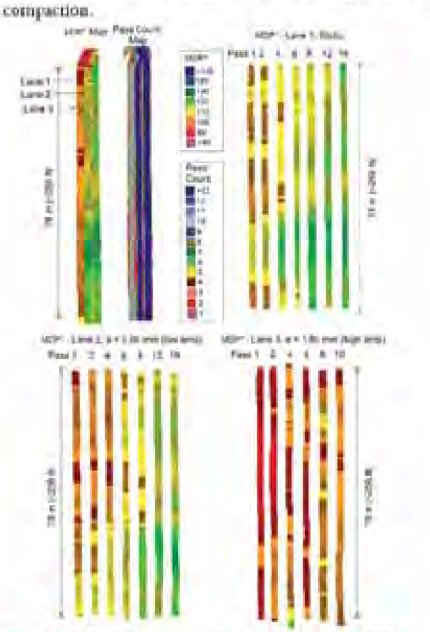

Figure 2. MDP and elevation maps of lanes 1 to 3, and MDP* spatial maps for multiple padfoot roller passes on lanes 1 to 3 – TB1 (from White et al. 2010)*

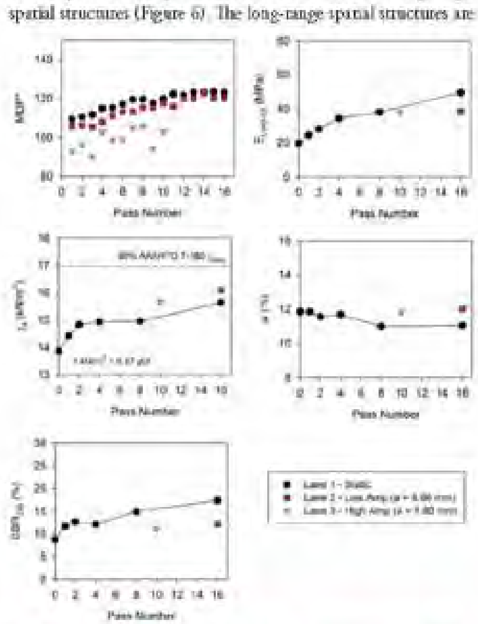

Figure 3. Average MDP and in-situ point measurement values with increasing roller passes on lanes 1 to 3 – TB1 (from White et al. 2010)*

INTELLIGENT COMPACTION BRIEF February 2012

likely linked to the spatial variation in the underlying support conditions while the short-range spatial structures are a result of soil properties close to the surface.

- The static MDP*values in TB3 production area showed more variability with high sill values compared to low amplitude MDP*. This was also evident with a slightly higher standard deviation (σ) value for static MDP* over low amplitude MDP* (Figure 6).

Salvage Base Materials (Control, Geogrid Reinforced, and Partial Core-out and Replace Sections) Compacted with Smooth Drum Roller

Three test beds were constructed and tested with salvage base material. TB4 consisted of two salvage base layers reinforced with two TX5 geogrid (Figure 7) layers, and were placed over compacted mixed subgrade+base. TB6 was partially treated with core-out and replacement with salvage base due to soft subgrade conditions. TB5 served as a control section with no treatments. On TB4, tests were conducted on the mixed subgrade+base layer, and the two salvage base layers. On TBs 5 and 6, tests were mostly conducted on the final surface of the salvage base layer. Following are the key findings from these test beds:

- CMV data showed relatively high variability (COV = 28 to 87%) compared to MDP* data (COV = 2%) on TB4 mixed subgrade+base layer. The LWD modulus and CBR point-MVs showed COV ranging between 30% and 64%. Variations observed in the point-MVs corroborated well with the variations in CMV while MDP* did not capture these variations.
- MDP* values were repeatable for forward passes but were affected by variable machine speed for reverse passes.
- Results on TB4 indicate that the MDP* and the point-MVs are relatively high and less variable on salvage base layer 1 than on the underlying mixed subgrade layer. On salvage base layer 2, the point-MVs are on average higher on base layer 2 than on the underlying base layer 1 and the mixed subgrade layer. The average MDP* and COV of MDP* were about the same on base layers 1 and 2.
- Variations observed in DCP-CBR profiles corroborated well with variations observed in the BST effective shear strength measurements (i.e., cohesion c' and effective angle of internal friction ϕ') with depth in the base and subgrade layers.
- The average MDP* from TB6 control section (i.e., outside the core-out area) was lower (by about 1.06 times) and the COV of MDP* was greater than on TB4 (1% on TB4 and 4% on TB6) (Figure 8). The LWD and FWD modulus values in the control section were also on average lower (by about 1.1 to 1.6 times) than on TB4. However, it must be noted that only a limited number of point-MVs (1 to 4) were obtained in this area.
- MDP* values were slightly lower (by about 1.04 times) on TB5 control section than on the TB4 geogrid reinforced section. The FWD modulus values were also on average slightly lower (by about 1.1 times) on TB5 than on TB4, while the average the LWD modulus values were about the same. The COV of MDP* and point-MVs on TBs 4 and 5 were quite similar.

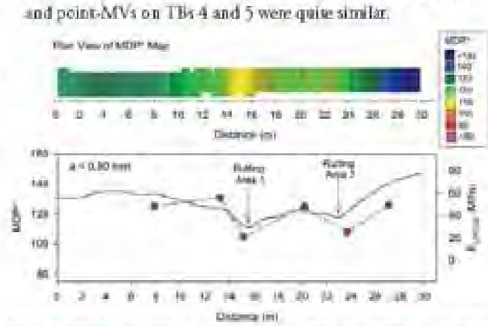

Figure 5. MDP* and LWD measurements on TB2 (from White et al. 2010)

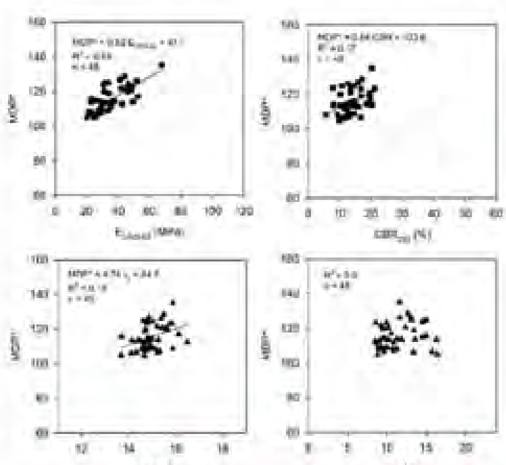

Figure 4. Correlations between MDP* and in-situ point measurements on lane 1 (static) – TB1 (from White et al. 2010)

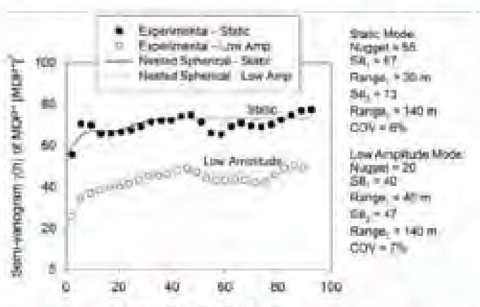

Figure 6. Histograms and geostatistical semivariograms of MDP* from static and low amplitude mapping passes – TB3 production area

- Although the relationships generally showed correct trends, they were weak ($R^2 < 0.5$) for all MDP* correlations with point-MVs (Figure 9). The primary reason for such weak correlations is attributed to the narrow MDP* measurement range (varied between 135 and 149). Also, different trends were observed for TB4 and TB5 for MDP* vs. E_{LWD-Z2} and MDP* vs. E_{FWD-K3} relationships. This is likely because of differences in underlying support conditions. No information was available from TB5 to assess those conditions.

Figure 7. TX5 geogrid used in TB4 (from White et al. 2010)

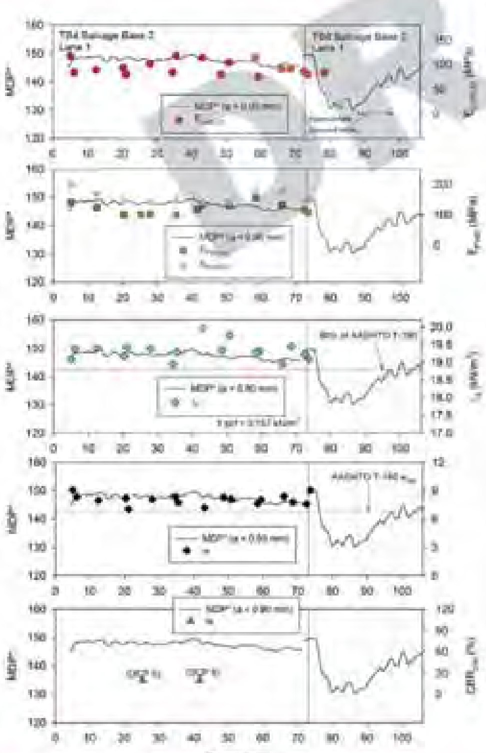

Figure 8. Comparison of MDP measurements and in situ point measurements on salvage base layer 2 lane 1 – TBs 4 and 6*

- CMV correlations with E_{FWD-K3} and CBR yielded $R^2 > 0.5$, while correlations with E_{LWD-Z2} yielded $R^2 = 0.35$ (Figure 10). No statistically significant relationship was observed between CMV and E_{FWD-DY}.

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White, D.J., Vennapusa, P., Gieselman, H., Johanson, L., Goldsmith, R. (2010). Accelerated Implementation of Intelligent Compaction Monitoring Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials TPF-5(128) – US12 Marmarth, North Dakota, Report submitted to The Transtec Group, FHWA, November.

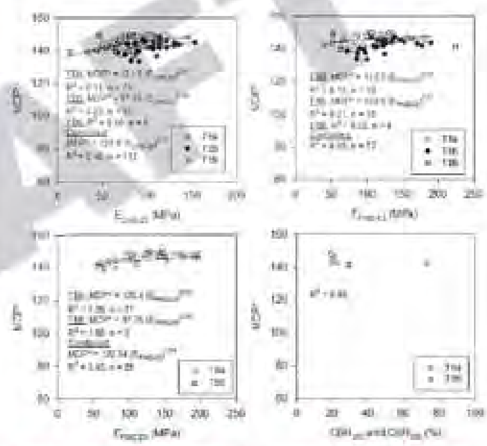

Figure 9. Correlations between MDP (a = 0.90 mm and f = 30 Hz) and point-MVs – TBs 4, 5, and 6 (from White et al. 2010)*

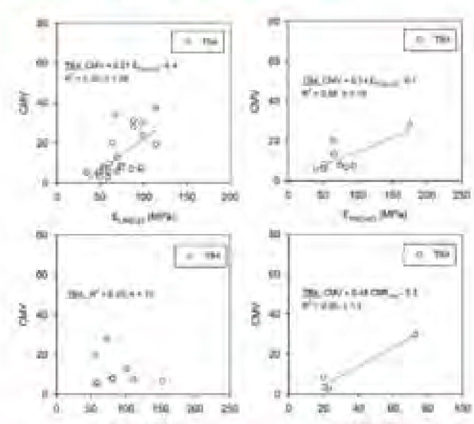

Figure 10. Correlations between CMV (a = 0.90 mm and f = 30 Hz) and point-MVs - TB 4 (from White et al. 2010)

INTELLIGENT COMPACTION BRIEF — February 2012

Minnesota Route 4—HMA Overlay—June 2008

PROJECT DATE/DURATION
June 14 to 17, 2008

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

SPONSOR
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PRINCIPAL INVESTIGATOR
George Chang, Ph.D., PE
Project Manager
The Transtec Group, Inc.
512-451-6233

RESEARCH TEAM
David J. White, Ph.D.
Pavana KR. Vennapusa, Ph.D.

AUTHORS
Pavana KR. Vennapusa, Ph.D.
David J. White, Ph.D.
Department of Civil, Construction, and Environmental Engineering
Center for Earthworks Engineering Research

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

The sponsors of this research are not responsible for the accuracy of the information presented herein. The conclusions expressed in this publication are not necessarily those of the sponsors.

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Figure 1. Sakai SW880 smooth drum roller

INTRODUCTION

This demonstration was conducted on Route 4 in Kandiyohi County, Minnesota. A Sakai SW880 double drum roller (Figure 1) equipped with the Compaction Control Value (CCV) roller-integrated compaction measurement (RICM) system was used in this study. The machine was equipped with real time kinematic (RTK) global positioning system (GPS) and on-board display and documentation systems. The project involved mapping the existing subbase layer and the hot mix asphalt (HMA) overlay non-wearing and wearing course layers. The main goal of this study was to evaluate the influence of the subbase layer support conditions on the HMA layer CCV measurements.

SITE CONDITIONS

The project area consisted of approximately 1 to 3 m (3 to 10 ft) thick compacted subgrade material placed over the previous grade of Route 4. Reportedly, the subgrade layer over a portion of the project area "failed" under test rolling during construction in summer 2007. Later, the subgrade layer was capped with 150 mm (6 in.) of class 5 aggregate subbase material (Minnesota aggregate subbase classification). Since installing the subbase layer, the aggregate surface road has been open for traffic.

Kandiyohi County soil survey information (NRCS 2008) indicated that the majority of natural soils in the project area are derived from glacial till and glacial outwash materials. Portions of the project area consisted of muck herbaceous organic materials of Houghton muck and Palms muck soil series. These soils are very poorly drained with the water table at surface and typically have natural moisture contents in the range of 40% to 100%.

The approximate location of the area that "failed" under test rolling is highlighted on the soil survey map presented in Figure 2. The natural soils in this area consist of Palms muck soil series with sandy substratum which contained muck to a depth of about 0.7 m (27 in.) underlain by clay loam and sandy soils to a depth of about of 1.5 m (60 in.), below natural grade. A review of project drawings indicates that approximately 1 m to 2 m (3 ft to 6 ft) of new subgrade fill was placed over the previous grade in this region.

SUBBASE LAYER AND HMA LAYERS MAPPING

The granular subbase layer was mapped in five roller lanes which included three roller lanes to cover the north bound (NB) and south bound (SB) pavement lanes, and two roller lanes to cover the NB and SB shoulders. The front drum was in vibration mode while the rear drum was in static mode during the mapping process. The vibration settings used were as follows:

- Subbase map 1: frequency, f = 2500 vpm, amplitude, a = 0.6 mm (high amp), v = 4.8 km/h (3.0 mph)
- Subbase map 2: frequency, f = 3000 vpm, amplitude, a = 0.3 mm (low amp), v = 4.8 km/h (3.0 mph)

The HMA non-wearing course layer was compacted using a = 0.3 mm and f = 4000 vpm in a few areas of the project, but most areas were compacted using a = 0.6 mm and f = 3000 vpm settings. Compaction was performed using two vibratory roller passes with both front and rear drums in vibration mode. (Note that only the front drum was instrumented with CCV system).

RESULTS AND ANALYSIS

Results indicated that CCVs on the shoulder lanes were lower compared to CCVs on the mainline. Average CCV on the pavement lanes was about 1.5 times greater than average CCV on shoulder lanes. Field observations indicate that the shoulders were not subjected to traffic, as vehicles were predominantly driven within the pavement lanes.

Figure 3 shows CCV maps of the HMA non-wearing course layer and the underlying subbase layer for a 210 m (700 ft) long section with heterogeneous subbase. Figure 3 also shows locations of high CCV and low CCV areas on the subbase layer reflecting on CCV measurements on the HMA layer. Regression relationships in Figure 4 indicate a statistically strong relationship between CCV measurements obtained on the HMA non-wearing course layer and subbase layer at a = 0.6 mm setting with R^2-value of about 0.7. CCV measurements obtained on the subbase layer at a = 0.3 mm showed relatively poor correlation to CCV measurements on the HMA layer.

Figure 2. Aerial image with soil survey information of the project area (modified from NRCS 2008)

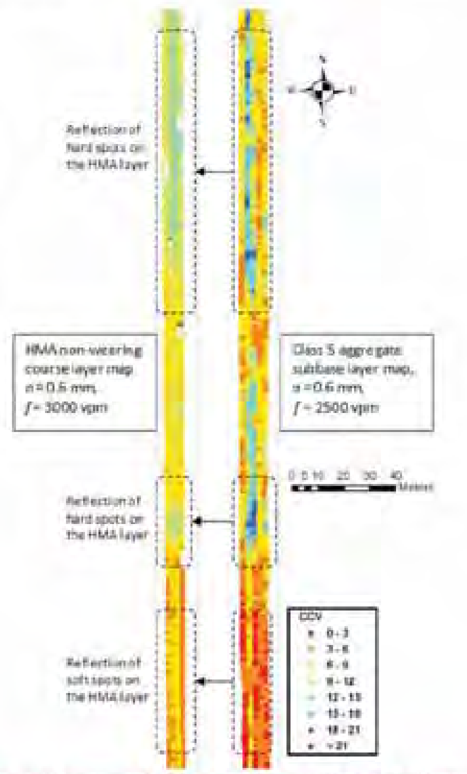

Figure 3. Comparison of HMA non-wearing course layer and subbase layer map showing the influence of underlying layer heterogeneity (from White and Vennapusa 2008)

INTELLIGENT COMPACTION BRIEF

February 2012

Following compaction operations on the HMA non-wearing course layer on the SB lane, premature "failure" cracks were observed over a 200-ft long section on the HMA layer under construction traffic (Figure 5). To further evaluate the condition, the CCV measurements on the HMA wearing course layer and the subbase layer in this area were compared as shown in Figure 6. The data in Figure 6 show average CCV = 2.5 for the subbase layer, which is considerably lower than the project average CCV = 7.5. Average CCV on the HMA wearing course in the same area was about 5.2, which was also lower than the project average of about 6.9. This area is located within the area where the subgrade layer reportedly "failed" under test rolling in summer 2007. Again, the underlying natural soils in this section were identified in the soil survey as consisting of peat/muck soil deposits (see Figure 2).

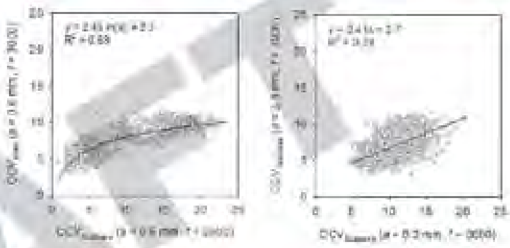

Figure 4. Simple regression relationships between CCV measurements on subbase and HMA non-wearing course layer (from White and Vennapusa 2008)

Figure 5. Premature failure observed in the HMA non-wearing course layer between Sta. 140+12 and Sta. 142+61 (from White and Vennapusa 2008)

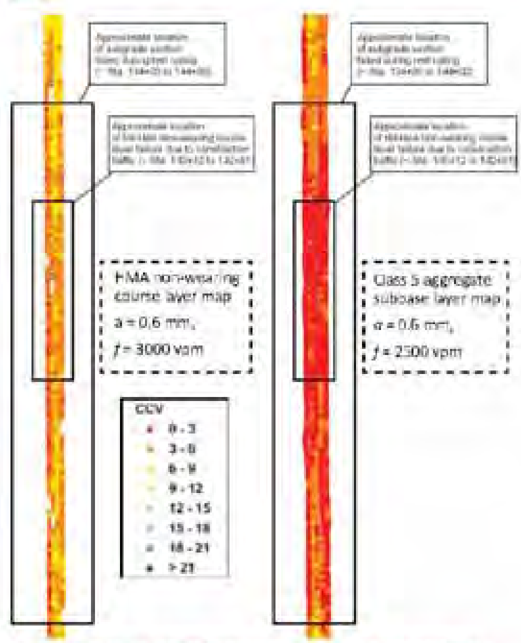

Figure 6. Comparison of HMA non-wearing course layer and subbase layer maps (from White and Vennapusa 2008)

SUMMARY OF KEY FINDINGS

- CCV measurements on the subbase layer at $a = 0.3$ mm setting were on average about 1.5 times greater than CCV measurements at $a = 0.6$ mm setting.
- Comparison between CCV maps on the HMA non-wearing course layer and subbase layer showed several locations of high and low CCV that reflected on the HMA layers. Regression relationships between CCV measurements on the subbase layer on the HMA layer showed strong correlation. This demonstrates the importance of the knowledge of the underlying layer in interpreting CCV measurements at the surface, which has not been well documented in the literature.
- CCV measurements obtained on the subbase layer at 0.6 mm amplitude setting better distinguished the hard/soft spots compared to CCV measurements obtained at 0.3 mm amplitude setting.
- Following compaction and mapping of the HMA non-wearing course layer on the SB lane, premature "failure" cracks were observed over a 200-ft long section on the HMA layer. This area was located within the area where the subgrade layer reportedly "failed" under test rolling in summer 2007 and is an area underlain by peat/muck soils.

REFERENCES

White, D.J., and Vennapusa, P. (2008). Accelerated Implementation of Intelligent Compaction Monitoring Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials TPF-5(128) – Minnesota Rc4 Project, Report submitted to The Transtec Group, FHWA, June.

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Roller-Integrated Compaction Monitoring (RICM) Proof Mapping Guide Specification

Title: Roller-Integrated Compaction Monitoring (RICM) Proof Mapping Guide Specification

DRAFT v_(7)_DJW

Updated March 5, 2012

The goal of this guide specification is to provide a more efficient quality verification measurement with improved documentation to assure that pavement subgrade bearing capacity is satisfactory. The specification provides a provision to substitute traditional proof rolling with Roller-Integrated Compaction Monitoring (RICM) proof mapping. This specification was drafted as part of the SHRP R07 research effort to develop guide performance specifications. The Missouri Department of Transportation provided guidance in the development of this specification and field tested an early version of this guide specification. An example of the output is provided with this document.

MMM. Subgrade RICM Proof Mapping

1.0 Description. In addition to the regular nuclear moisture density testing requirements specified in the Inspection and Testing Plan (ITP), this work shall consist of testing the support conditions of the prepared roadbed subgrade prior to paving by proof mapping with a Roller-Intergraded Compaction Monitoring (RICM) equipped compactor. RICM proof mapping will be performed on all prepared subgrade including mainline, outer roadways, ramps, and all side streets.

Note 1: As an alternate to nuclear moisture density testing, moisture content testing in addition to dynamic cone penetration (ASTM 6951), plate load testing (ASTM D1196), or light weight deflectometer testing (ASTM E2583 or ASTM E2835) can be considered. Target value determination for these other methods is beyond the scope of this test standard.

2.0 Terms and Definitions.

- Roller-Integrated Compaction Monitoring (RICM) is the recording and color coded real-time display of integrated measurement parameter values on rollers including, but not limited to, roller operation parameters (i.e., speed, frequency, amplitude), global positioning system (GPS) based position, roller-ground interaction parameter values (e.g., ground stiffness), temperature, and/or moisture content.
- Measurement Value (MV) is defined as the roller-ground interaction parameter values being reported from the compactors RICM system (e.g. compaction meter value, machine drive power, dynamic modulus, etc.).
- Target Value (TV) is defined as the minimum acceptable RICM MV, and is determined from calibration testing in-situ.
- Subgrade bearing capacity is the plate load test contact pressure required to induce 1 inch of plate deflection (25.4 mm) for a 12 inch (300 mm) diameter plate.

Roller-Integrated Compaction Monitoring (RICM) Proof Mapping Guide Specification

3.0 Test Capabilities. The RICM equipped compactor(s) shall 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 general accordance with ASTM 1196. The subgrade bearing capacity is defined herein as the plate load test contact pressure required to induce 1 inch of plate deflection (25.4 mm) for a 12 inch (300 mm) diameter plate.

Note 2: An alternate to defining subgrade bearing capacity based on 1 inch of plate deflection if is to use a target minimum modulus of subgrade reaction (e.g., k-value used for design purposes) at a defined plate contact stress (ASTM D1196). Modulus of subgrade reaction is defined as the plate contact stress divided by the average plate deflection. Common plate contact stress values used to define modulus of subgrade reaction are 10 pounds per square inch for subgrade and 30 pounds per square inch for stabilized subgrade and aggregate base.

The RICM system shall have the capability to immediately display and provide a permanent electronic record of the proof map and data as follows:

a) Integrated, color-coded, real-time computer display viewable by roller operator showing RICM MV, percent RICM MV with reference to RICM TV, and roller pass coverage,
b) Electronic data file in ASCII (American Standard Code for Information Interchange) format with time stamp, real-time kinematic (RTK) GPS position in state DOT standard coordinate system, roller operation parameters (speed, gear, and forward/reverse machine travel direction), and the RICM MV and RICM TV.

4.0 RICM Quality Management Plan

Note 3: 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 Contractor's quality management personnel and organizational structure, documentation and reporting requirements, and procedures related to non-conforming work, corrective action, and similar matters. If 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 SHRP2 R07 project.

The Quality Management Plan (QMP) submittal shall include a detailed plan for quality control (QC) of the pavement subgrade layer including the tests to be performed, test methods to be used, and minimum and/or maximum property requirements which must be met to ensure that the desired subgrade bearing capacity is acheived. This QMP shall describe the Contractor's responsibilities for furnishing RICM equipped rollers, data acquisition, and transmitting data to the Engineer.

QC will be based on assessment of the RICM MVs according to Section 5.0 of this specification. The RICM MV results will be used as a guide to conduct quality assurance (QA) testing by the contractor's testing agent and Engineer.

2

As part of the QMP, submit to the Engineer a RICM work plan. Describe in the RICM work plan including the following:

- Roller vendor,
- Roller model,
- Roller dimensions and weights,
- Description of RICM measurement system(s),
- Roller data collection methods including sampling rates and intervals,
- RTK GPS capabilities,
- Documentation system and data file types, and
- Data viewing and analysis software
- Documenting demonstrating that the RICM MV are reliable, reproducible, and repeatable

Transfer of data to the Engineer including method, timing, and personnel responsible shall be described in the RICM work plan. 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
- RTK-GPS measurements showing Northing, Easting, and Elevation
- Roller Travel Direction (e.g., forward or reverse)
- Roller Speed
- Vibration Setting (i.e., On or Off)
- Vibration Amplitude
- Vibration Frequency
- RICM MV

Ensure that the roller's onboard display will furnish color-coded GPS based mapping, showing number of roller passes and the RICM MV on a computer screen in the roller operators cab. Provide displayed results to the Engineer for review upon request. Provide RTK-GPS to acquire northing, easting, and elevation data used in mapping of RICM measurements. Ensure the system has the capability to collect data in an established project coordinate system. Furnish a local GPS base station used for broadcasting differential correction data to the rollers with a tolerance less than 0.1 ft in the vertical and horizontal.

For RICM roller calibration, an independent testing agency shall be used. Calibration tests shall be performed in the presence of the Engineer, unless approved otherwise. All results will be evaluated by the Engineer in order to set the RICM TV. Test reports for the subgrade plate

3

bearing test results shall be submitted to the Engineer within 48 hours of completion the calibration testing. The test report shall include:

- Test identification number
- Test locations
- Subgrade classification
- Subgrade moisture content
- Date of testing
- Names of 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 (vertical axis) versus subgrade bearing capacity (horizontal axis)
- Plots of RICM proof maps

RICM operations shall be performed according to manufacturer's recommendations to provide reliable, reproduciable, and repeatable measurements. For vibratory roller operations, vibration frequency and amplitude shall be maintained relatively constant during roller operations for comparing successive passes. Changes in frequency and amplitude can influence RICM MVs. Unless documented by the roller manufacturer, permitted variation in vibration frequency is ± 125 vibrations per minute. Further, maintain rolling speed to provide a minimum of 10 impacts per linear foot and within ± 0.5 miles per hour during measurement passes. Speed fluctuations can also influence the RICM MVs and are not permitted outside this range during measurement passes. Record roller operations forward and reverse directions. It is anticipated that RICM MVs will be affected by rolling direction and therefore the output data fields shall indicate rolling direction. Check and validate, if necessary, RICM equipment at the beginning of each workday.

Note 4: The values provided in this statement are approximate and should be validated by each manufacture "...permitted variation in vibration frequency is ± 125 vibrations per minute. Further, maintain rolling speed to provide a minimum of 10 impacts per linear foot and within ± 0.5 miles per hour during measurement passes."

5.0 Performance Requirements. RICM proof mapping shall include two complete passes per lane and one complete pass in shoulder areas. Each pass shall be performed in a manner so that not more than 10% overlap occurs between passes in the coverage area. The roller shall be operated to provide reliable results in accordance with the manufacturer's guidelines. The roller operations and rolling patterns shall be proposed by the Contractor, and is subject to approval by the Engineer.

The Contractor is fully responsible for protection of competed work prior to placement of the subsequent layers and until final acceptance of the project. Therefore, at any time during construction of aggregate base pavement materials, if the Engineer believes that an unstable grade exists, he/she may at his/her discretion require the Contractor to perform RICM proof mapping according to this specification in any areas on the project. Where areas of yielding grade are noted, the Contractor shall perform correction of the grade even though the Engineer may have accepted the areas before they became unstable.

Establishment of the RICM TV requires calibration of the RICM MV to the subgrade bearing capacity. The subgrade bearing capacity is defined herein as the contact pressure required to induce 1 inch of plate deflection (25.4 mm) for a 12 inch (300 mm) diameter plate performed in general accordance with ASTM 1196. Simple linear regression analysis shall be used to establish a correlation between the RICM MV plate load test values. A minimum of eight plate load tests will be required to establish the correlation. The RICM TV will be set as the RICM MV that correlates to a 1-inch plate deflection at a contact pressure of 90 psi (10,178 pounds of force for 12 inch diameter plate).

Note 5: Simple linear regression analysis involves developing a relationship between independent and dependent variables using an intercept and a slope coefficient. This analysis is simple enough to be performed on a hand calculator. For each linear, univariate regression model the coefficient of determination R^2 provides a measure of how well the regression model describes the data. In this specification the correlation is considered acceptable if $R^2 \geq 0.5$. The regression relationships will be developed by considering the "true" independent variables (in this specification, plate bearing test measurements or modulus of subgrade reaction) and the RICM MV as the dependent variable using the model shown in Eq.1.

$$\text{RICM MV} = b_0 + b_1 \cdot \alpha \qquad (1)$$

where: b_0 = intercept, b_1 = slope, and α = independent variable.

Note 6: As an alternate to on-site calibration using simple linear regression analysis, suitable evidence of RICM MV correlations with the selected in-situ point measurements 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.

Acceptance of the RICM proof mapping area is based on achievement of the RICM TV in the proof mapping area with a minimum of 80% of the RICM MVs ≥ RICM TV and no contiguous, isolated areas (25 ft long x the roller lane width). When proof mapping identifies unstable areas in the roadbed, the Contractor shall perform a plate bearing test at locations selected by the Engineer, unless approved otherwise, to demonstrate that the minimum bearing capacity has been achieved, or the Contractor shall rework the area by scarifying and moisture conditioning the soils as necessary or by using chemical or mechanical stabilization solutions. The disturbed areas shall be reshaped and compacted. Retesting of that area by RICM proof mapping will not be required 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.

Note 7: The 80% minimum criterion is a suggested value and is expected to vary depending on the desired quality conditions, uniformity, and RICM technology. Further, the 25ft maximum for unstable *areas may be adjusted from 3ft to 50 ft contiguous length x the roller lane width. 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 judgment should be used by the Engineer in setting these limits.*

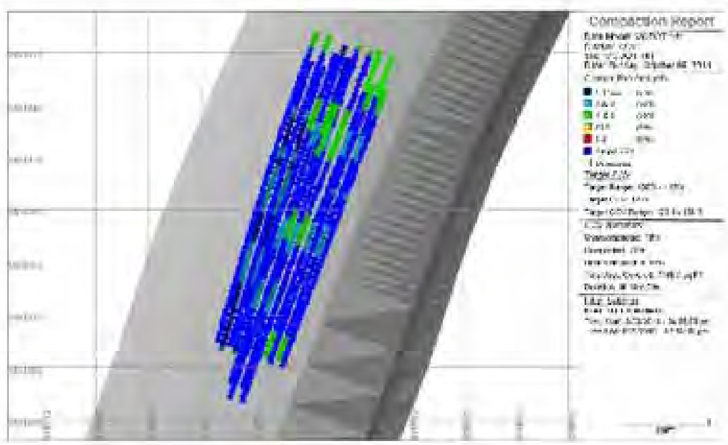
Note 8: In addition to the testing described, it may be desirable to contact QA plate bearing tests. The number of tests and test locations will be based on assessment of the RICM MVs. In areas of high RICM variability (COV = greater than 20%), the test frequency will be about 1 test per 500ft. In areas of low RICM variability (COV = less than 20%), the test frequency will be about 1 test every 1000 ft. The test locations could be randomly selected or by inspection of the RICM proof map to identify soft spots. The target numbers for QA 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 NCHPR Report 676.

The results of RICM proof mapping shall be provided to the Engineer in printed and electronic form upon request or within at least 24 hours of measurement. Upon approval of the RICM proof mapping, the subbase, base course or initial pavement course shall be placed within 48 hours. If the Contractor fails to place the subbase, base coarse or initial pavement course within 48 hours or the condition of the subgrade changes due to weather or other conditions, proof mapping and correction shall be performed again at discretion of the Engineer and at no expense to the agency.

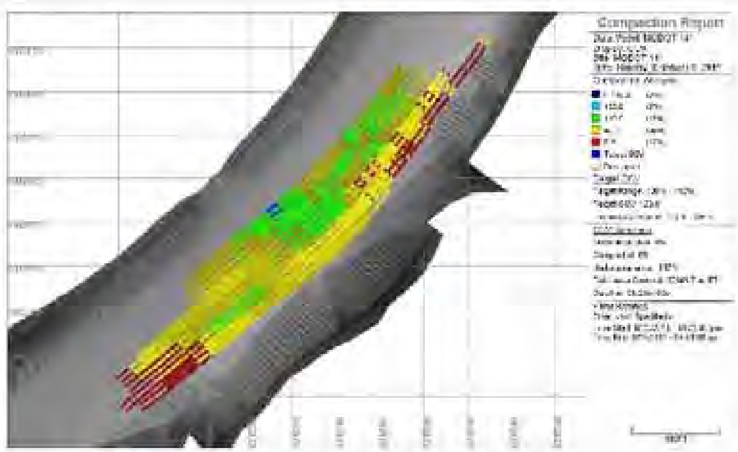
Note 9: If the pavement contract is responsible the aggregate subbase layer placement prior to paving under a separate contract than the subgrade/earthwork contract, the RICM proof mapping could be applied to the paving contractors contract.

6.0 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 any corrections required as a result of the proof mapping.

Note 10: An alternative basis of payment 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 due to GPS satellite reception of signals to operate the 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/GPS problems, the Contactor may operate with conventional rolling operations, but RICM proof mapping shall be provided for a minimum 90% of the project surface.



Test Area #1 - QC Proof Map: 88% ≥ RICM-TV = 123



Test Area #2 QC Proof Map: 0% ≥ RICM-TV = 123

Figure 1A. Examples of RICM Proof Maps: (top) passes RICM TV proof mapping compliance requirement; and (bottom) fails RICM TV proof mapping compliance requirement

7

Roller-Integrated Compaction Monitoring (RICM) Proof Mapping Guide Specification

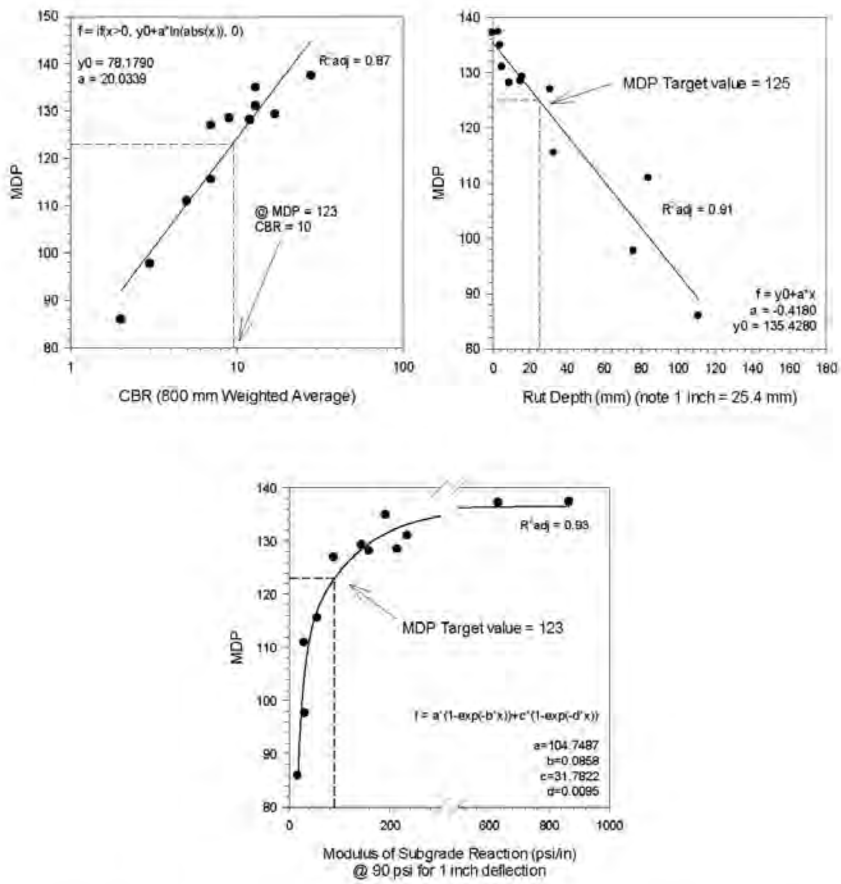


Figure 2A. Examples of RICM MV calibration plots base don California bearing ratio (CBR), traditional proof rolling rut depth, and plate load test modulus of subgrade reaction

8

As part of the QMP, submit to the Engineer a RICM work plan. Describe in the RICM work plan including the following:

- Roller vendor,
- Roller model,
- Roller dimensions and weights,
- Description of RICM measurement system(s),
- Roller data collection methods including sampling rates and intervals,
- RTK GPS capabilities,
- Documentation system and data file types, and
- Data viewing and analysis software
- Documenting demonstrating that the RICM MV are reliable, reproducible, and repeatable

Transfer of data to the Engineer including method, timing, and personnel responsible shall be described in the RICM work plan. 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
- RTK-GPS measurements showing Northing, Easting, and Elevation
- Roller Travel Direction (e.g., forward or reverse)
- Roller Speed
- Vibration Setting (i.e., On or Off)
- Vibration Amplitude
- Vibration Frequency
- RICM MV

Ensure that the roller's onboard display will furnish color-coded GPS based mapping, showing number of roller passes and the RICM MV on a computer screen in the roller operators cab. Provide displayed results to the Engineer for review upon request. Provide RTK-GPS to acquire northing, easting, and elevation data used in mapping of RICM measurements. Ensure the system has the capability to collect data in an established project coordinate system. Furnish a local GPS base station used for broadcasting differential correction data to the rollers with a tolerance less than 0.1 ft in the vertical and horizontal.

For RICM roller calibration, an independent testing agency shall be used. Calibration tests shall be performed in the presence of the Engineer, unless approved otherwise. All results will be evaluated by the Engineer in order to set the RICM TV. Test reports for the subgrade plate

Roller-Integrated Compaction Monitoring (RICM) Proof Mapping Guide Specification

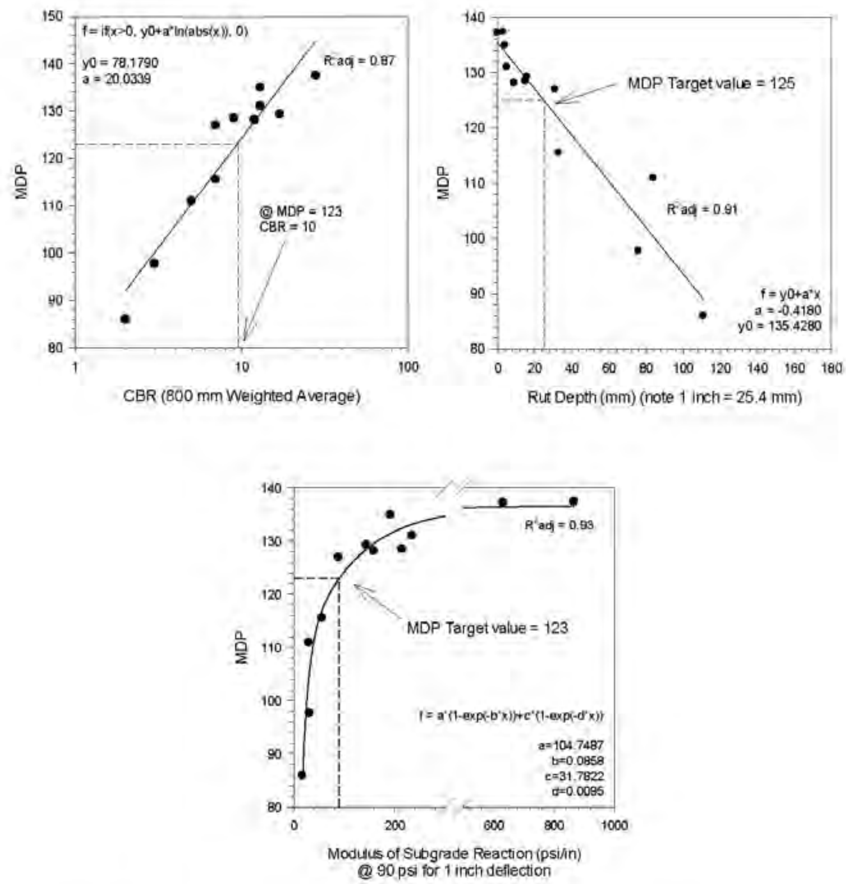


Figure 2A. Examples of RICM MV calibration plots base don California bearing ratio (CBR), traditional proof rolling rut depth, and plate load test modulus of subgrade reaction

8

Roller-Integrated Compaction Monitoring
(RICM) Proof Mapping Guide Specification

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Research Article

Field Assessment and Specification Review for Roller-Integrated Compaction Monitoring Technologies

David J. White, Pavana K. R. Vennapusa, and Heath H. Gieselman

Department of Civil, Construction, and Environmental Engineering, Center for Earthworks Engineering Research, Iowa State University of Science and Technology, Ames, IA 50011-8664, USA

Correspondence should be addressed to Pavana K. R. Vennapusa, pavanv@iastate.edu

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Roller-integrated compaction monitoring (RICM) technologies provide virtually 100-percent coverage of compacted areas with real-time display of the compaction measurement values. Although a few countries have developed quality control (QC) and quality assurance (QA) specifications, broader implementation of these technologies into earthwork construction operations still requires a thorough understanding of relationships between RICM values and traditional in situ point test measurements. The purpose of this paper is to provide: (a) an overview of two technologies, namely, compaction meter value (CMV) and machine drive power (MDP); (b) a comprehensive review of field assessment studies, (c) an overview of factors influencing statistical correlations, (d) modeling for visualization and characterization of spatial nonuniformity; and (e) a brief review of the current specifications.

1. Introduction

Roller-integrated compaction monitoring (RICM) technologies refer to sensor measurements integrated into compaction machines. Work in this area was initiated over 30 years ago in Europe for smooth drum rollers compacting granular soils and involved instrumenting the roller with an accelerometer and calculating the ratio of the fundamental frequency to the first harmonic [1, 2]. Modern sensor technologies, computers, and global positioning system (GPS) technologies now make it possible to collect, transmit, and visualize a variety of RICM measurements in real time. As a quality assessment tool for compaction of earth materials, these technologies offer tremendous potential for field controlling the construction process to meet performance quality standards. Recent efforts in the United States (US) have focused attention on how RICM technologies can be used in road building [3–5] and relating selected RICM parameters to mechanistic pavement design values.

Several manufactures currently offer RICM technologies on smooth drum vibratory roller configurations for compaction of granular materials and asphalt, and nonvibratory roller configurations for compaction of cohesive materials. The current technologies calculate: (1) an index value based on a ratio of selected frequency harmonics for a set time interval for vibratory compaction [1, 2], (2) ground stiffness or dynamic elastic modulus based on a drum-ground interaction model for vibratory compaction [6–8], or (3) a measurement of rolling resistance calculated from machine drive power (MDP) for vibratory and nonvibratory compaction [9]. When the accelerometer-based measurement system provides automatic feedback control for roller vibration amplitude and/or frequency and/or roller speed control, it is referred to as "intelligent" compaction and offers the advantage of reducing the potential for drum "bouncing". The MDP approach has the advantage of working in both vibratory and static modes [9] and has its origin in the discipline of terramechanics. Recent finding from the Mars Exploratory Rover (MER) mission demonstrated that the MDP approach can be applied to determine Martian regolith cohesion and friction angle by monitoring the electromechanical work expended [10]. Future RICM technologies may provide information on soil mineralogy and moisture content but are currently only a subject of research.

Regardless of the technology, by making the compaction machine a measuring device and insuring that compaction requirements are met during construction, the compaction process can be better controlled to improve quality, reduce rework, maximize productivity, and minimize costs [11]. Recent advancements with global positioning systems (GPS) add a significant benefit with real time spatial viewing of the RICM values. Some of these technologies have recently been implemented on full-scale pilot earthwork and asphalt construction projects in the US [12–18], and its use is anticipated to increase in the upcoming years. Effective implementation of this technology needs proper understanding of the relationships between RICM values and traditional in situ point test compaction measurements (e.g., static or dynamic plate load test modulus, density, etc.). This builds confidence in the technology and provides insight into the key parameters affecting the machine measurement values.

The purpose of this paper is to provide: (a) an overview of two technologies—compaction meter value (CMV) and machine drive power (MDP); (b) a summary of field evaluation studies, (c) an overview of factors influencing the statistical correlations, (d) modeling for visualization and characterization of spatial nonuniformity, and (e) a brief review of the current specifications.

2. Overview of CMV and MDP Technologies

Compaction meter value (CMV) is a dimensionless compaction parameter developed by Geodynamik that depends on roller dimensions, (i.e., drum diameter and weight) and roller operation parameters (e.g., frequency, amplitude, speed) and is determined using the dynamic roller response [19, 20]. CMV is calculated using (1), where C is a constant (used as 300 for the results presented in this paper), and $A_{2\Omega}$ = the acceleration of the first harmonic component of the vibration, A_{Ω} = the acceleration of the fundamental component of the vibration [8]:

$$\text{CMV} = C \cdot \frac{A_{2\Omega}}{A_{\Omega}}. \qquad (1)$$

According to Geodynamik [21], CMV at a given point indicates an average value over an area whose width equals the width of the drum and length equal to the distance the roller travels in 0.5 seconds. At least two manufactures have used the CMV technology as part of their RICM systems (Figure 1). The Geodynamik system also measures the resonant meter value (RMV) which provides an indication of the drum behavior (continuous contact, partial uplift, double jump, rocking motion, and chaotic motion). RMV is not discussed in detail here, but it is important to note that the drum behavior affects the CMV measurements [6] and therefore CMV must be interpreted in conjunction with RMV [22].

Machine drive power (MDP) technology relates the mechanical performance of the roller during compaction to the properties of the compacted soil. The use of MDP as a measure of soil compaction is a concept originated from study of vehicle-terrain interaction [23]. The basic premise of determining soil compaction from changes in equipment response is that the efficiency of mechanical motion pertains not only to the mechanical system but also to the physical properties of the material being compacted. More detailed background information on the MDP system is provided in [9]. The basic formula for MDP is

$$\text{MDP} = P_g - WV\left(\sin\alpha + \frac{a}{g}\right) - (mV + b), \qquad (2)$$

where P_g = gross power needed to move the machine (kJ/s), W = roller weight (kN), a = machine acceleration (m/s²), g = acceleration of gravity (m/s²), α = slope angle (roller pitch from a sensor), V = roller velocity (m/s), and m (kJ/m) and b (kJ/s) = machine internal loss coefficients specific to a particular machine [9]. The second and third terms of (2) account for the machine power associated with sloping grade and internal machine loss, respectively. MDP is a relative value referencing the material properties of the calibration surface, which is generally a hard compacted surface (MDP = 0 kJ/s). Positive MDP values therefore indicate material that is less compact than the calibration surface, while negative MDP values would indicate material that is more compacted than the calibration surface (i.e., less roller drum sinkage). In some recent field studies [13], the MDP output value has been scaled to MDP_{80} or MDP_{40} depending on the modified settings which are recalculated to range between 1 and 150 using (3) and (4), respectively,

$$\text{MDP}_{80} = 150 - 1.37\ (\text{MDP}), \qquad (3)$$

$$\text{MDP}_{40} = 150 - 2.75\ (\text{MDP}). \qquad (4)$$

For the MDP_{80} calculation, the calibration surface with MDP = 0 kJ/s is scaled to MDP_{80} = 150, and a soft surface with MDP = 108.47 kJ/s (80000 lb-ft/s) is scaled to MDP_{80} = 1. For the MDP_{40} calculation, the calibration surface with MDP = 0 kJ/s is scaled to MDP_{40} = 150 and a soft surface with MDP = 54.23 kJ/s (40000 lb-ft/s) is scaled to MDP_{40} = 1.

Effective use of RICM technologies is aided by the integration of GPS position information and an on-board computer monitor (Figure 1) which displays the roller location, machine measurement values (i.e., CMV or MDP), vibration amplitude and frequency, and roller speed. Thus, the technology enables a roller operator to make judgments regarding the condition of the compacted fill material in real time. If real-time kinematic (RTK) GPS systems are used, those systems reportedly have position accuracies of about ±10 mm in the horizontal plane and ±20 mm in the vertical plane [24].

3. Field Evaluation of CMV and MDP Technologies

Field evaluation studies beginning in about 1980 have documented correlations between RICM measurements and various traditionally used point measurements. A summary of key findings from these different studies, types of rollers used, and materials tested is provided in Table 1. A variety of QC/QA measurements have been used in the documented correlation studies, which include:

(a)

(b)

Figure 1: Photographs of on-board display units by Caterpillar (a) and Dynapac (b).

(a) nuclear gauge (NG), electrical soil density gauge (SDG), water balloon method, sand cone replacement method, radio isotope method, "undisturbed" shelby tube sampling, and drive core samples to determine moisture content and dry unit weight,

(b) light weight deflectometer (LWD), soil stiffness gauge (SSG), static plate load test (PLT), falling weight deflectometer (FWD), Briaud compaction (BCD), dynamic seismic pavement analyzer (D-SPA), and Clegg hammer to determine stiffness or modulus,

(c) dynamic cone penetrometer (DCP), cone penetration testing (CPT), "undisturbed" shelby tube sampling, and rut depth measurements under heavy test rolling to determine shear strength or California bearing ratio (CBR).

Most of the field studies involved constructing and testing controlled field test sections for research purposes and correlation development, while a few studies were conducted on full-scale earthwork construction projects where RICM was implemented as part of the project specifications [12, 13].

Based on the findings from a comprehensive correlation study conducted on 17 different soil types from multiple project sites as part of the National Cooperative Highway Research Program (NCHRP) 21-09 project [25], the factors that commonly affect the correlations are as follows:

(1) heterogeneity in underlying layer support conditions,

(2) high moisture content variation,

(3) narrow range of measurements,

(4) machine operation setting variation (e.g., amplitude, frequency, speed, and roller "jumping"),

(5) nonuniform drum/soil contact conditions,

(6) uncertainty in spatial pairing of point measurements and roller MVs,

(7) limited number of measurements,

(8) not enough information to interpret the results,

(9) intrinsic measurement errors associated with the RICM and in situ point measurements.

In general, results from controlled field studies indicate that statistically valid simple linear or simple nonlinear correlations between RICM values and compaction layer point-MVs (e.g., modulus or density) are possible when the compaction layer is underlain by a relatively homogenous and stiff/stable supporting layer. For example, Figure 2 presents simple linear regression relationships between CMV and in situ LWD modulus and dry density point-MVs obtained from a calibration test strip with plan dimensions of 30 m × 2 m. The test strip consisted of silty sand with gravel base material underlain by a very stiff fly ash stabilized subgrade layer. For this case, correlations between CMV and both LWD modulus and dry density measurements showed $R^2 > 0.8$.

On the contrary, many field studies summarized in Table 1 indicate that modulus- or stiffness-based measurements (i.e., determined by FWD, LWD, PLT, etc.) generally correlate better with the RICM measurements than compaction layer dry unit weight or CBR measurements. This is illustrated in Figures 3 and 4. Data presented in Figure 3 was obtained from several calibration and production test areas with lean clay subgrade, recycled asphalt subbase, recycled concrete base, and crushed limestone base materials compacted with a vibratory smooth drum roller. Data presented in Figure 4 was obtained from several calibration and production test areas with lean clay subgrade compacted using a nonvibratory padfoot roller. CBR measurements presented herein are obtained from DCP tests using empirical correlations between DCP index values and CBR [38]. Figures 3 and 4 clearly indicate that CMV correlates better with LWD modulus point-MVs compared to dry unit weight or CBR point-MVs. One of the primary reasons for this is that modulus measurements represent a composite layered soil response under an applied load which simulates vibratory drum-ground interaction. The density and CBR measurements are average measurements of the compaction layer and do not directly represent a composite layered soil response under loading. Although DCP-CBR measurements did not correlate well in the two cases presented in Figures 3 and 4, many field studies [13, 25, 34] have indicated that DCP tests are effective in detecting deeper "weak" areas (at depths > 300 mm) that are commonly identified by

Table 1: Summary of field correlations studies on CMV and MDP technologies documented in the literature.

Reference; project location	Roller drum type; RICM; soil types	QC/QA point-MVs	Key findings and comments
Forssblad [1]; Sweden	Dynapac SD; CMV; fine and coarse rock fill.	Water balloon, PLT, FWD, and surface settlement	Linear correlations are observed between CMV and point-MVs. Moisture content should be considered in correlations for fine-grained soils. Roller results in a composite value in a layered soil condition. CMV is affected by roller speed (higher speeds result in lower CMV)
Hansbo and Pramborg [20]; Sweden	Dynapac SD; CMV; gravelly sand, silty sand, and fine sand	Sand cone, pressure-meter, PLT, CPT, and DCP	Compaction growth curves showed improvement in CMV and other mechanical properties (i.e., modulus and cone resistance) with increasing pass. Relative percent compaction (or density) was not sensitive to changes in CMV
Floss et al. [26]; Munich, Germany	Dynapac dual SD; CMV; sandy to silty gravel fill	Water balloon and sand cone, PLT, and DCP	Correlations with modulus and DCP measurements are generally better than density. CMV measurements are dependent on speed, vibration frequency and amplitude, soil type, gradation, water content, and strength of subsoil
Brandl and Adam [6]; not provided	Bomag SD; CMV	PLT	Correlation between CMV and PLT modulus (initial) showed different regression trends for partial uplift and double jump operating conditions. Regressions in partial uplift and double jump conditions yielded $R^2 = 0.9$ and 0.6, respectively
Nohse et al. [27]; Tomei, Japan	Sakai SD; CMV; clayey gravel	Radio-isotope	Dry density and CMV increased with increasing roller pass on a calibration test strip. Linear regression relationships with $R^2 > 0.9$ are observed for correlations between dry density and CMV
White et al. [9, 28], Edwards, Ill, USA	Caterpillar PD; MDP; lean clay	NG, Drive core, DCP, and clegg hammer	Correlations between MDP and in situ test measurements using simple and multiple regression analyses are presented. MDP correlated better with dry density ($R^2 = 0.86$) than with DCP ($R^2 = 0.38$) or Clegg impact value ($R^2 = 0.46$). Including moisture content via multiple regression analysis improved the R^2 values for DCP and Clegg impact value ($R^2 > 0.9$). Results are based on data averaged 20 m long strip per pass
L. Petersen and R. Peterson [29]; TH53, Duluth, Minn, USA	Caterpillar SD; CMV and MDP; fine sand	LWD, DCP, and SSG	Weak correlations are obtained on a point-by-point basis comparison between in situ test measurements and roller measurements, likely due to the depth and stress dependency of soil modulus and the heterogeneity of the soils. Good correlations are obtained between CMV values and DCP measurements for depths between 200 and 400 mm depth
White et al. [11, 30]; Edwards, Ill, USA	Caterpillar SD; MDP; well-graded silty sand	NG and DCP	Average MDP values showed a decreasing trend on a log scale, and dry unit weight and DCP index values showed an asymptotic decrease with increasing roller pass. Correlations between MDP and point-MVs showed good correlations ($R^2 = 0.5$ to 0.9). Incorporating moisture content into analysis is critical to improve correlations for dry unit weight

Table 1: Continued.

Reference; project location	Roller drum type; RICM; soil types	QC/QA point-MVs	Key findings and comments
Thompson and White [31]; Edwards, Ill, USA	Caterpillar PD; MDP; silt and lean clay	NG, DCP, Clegg Hammer, and LWD	Correlations between MDP and point-MVs are presented using simple and multiple regression analysis. Averaging the data along the full length of the test strip (per pass) improved the regressions. Multiple regression analysis by incorporating moisture content as a regression parameter further improved the correlations
White et al. [12]; TH64, Ackley, Minn, USA	Caterpillar SD; CMV; poorly graded sand and well-graded sand with silt	LWD, DCP, and NG	Project scale correlations by averaging data from different areas on the project are presented, which showed R^2 values ranging from 0.52 for density and 0.79 for DCP index value. Correlations with LWD showed poor correlations due to the effect of loose material at the surface. The variability observed in the CMV data was similar to DCP and LWD measurements but not to density measurements
White et al. [32], Edwards, Illinois, USA	Caterpillar PD; MDP; sandy lean clay	NG and DCP	Based on average measurements over the length of the test strip (~20 m); correlations between MDP and point-MVs showed $R^2 = 0.87$ for density and 0.96 for DCP index values
Vennapusa et al. [33], Edwards, Ill, USA	Caterpillar PD; MDP; crushed gravel base	DCP and LWD	Correlations were obtained on a test bed with multiple lifts placed on a concrete base and a soft subgrade base. Correlations between MDP and point-MVs yielded $R^2 = 0.66$ to 0.85 for spatially nearest point data, and $R^2 = 0.74$ to 0.92 for averaged data (over the length of concrete or soft subgrade)
White et al. [13, 34], TH60, Bigelow, Minn, USA	Caterpillar PD-MDP_{80} and SD-CMV; sandy lean clay to lean clay with sand	Heavy test roller, DCP, LWD, and PLT	Correlations are presented from multiple calibration test strips and production areas from the project. MDP_{80} and LWD modulus correlation showed two different trends ($R^2 = 0.35$ and 0.65) over the range of measurements as the MDP_{80} reached an asymptotic value of about 150 which is the maximum value on the calibration hard surface. CMV correlation with LWD modulus produced $R^2 = 0.70$, and with rut depth produced $R^2 = 0.64$
White et al. [13], TH36, North St. Paul, Minn, USA	Caterpillar SD; CMV; granular subbase and select granular base	DCP, SSG, Clegg Hammer, LWD, PLT, FWD, and CPT	Correlations between CMV and point-MVs from calibration and production test areas based on spatially nearest point data are presented. Positive trends are generally observed with $R^2 > 0.5$ (for LWD, FWD, PLT, SSG, and Clegg) with exception of one test bed (FWD, LWD, and CPT) with limited/narrow range of measurements

Table 1: Continued.

Reference; project location	Roller drum type; RICM; soil types	QC/QA point-MVs	Key findings and comments
White et al. [13], US10, Staples, Minn, USA	Caterpillar SD; CMV; poorly graded sand with silt to silty sand	LWD, PLT, and DCP	Correlations between CMV and point-MVs from calibration and production test areas based on spatially nearest point data are presented. Correlations between CMV and point-MVs showed R^2 value ranging from 0.2 to 0.9. The primary factors contributing to scatter are attributed to differences in measurement influence depths, applied stresses, and the loose surface of the sandy soils on the project. Correlations between CMV and LWD or DCP measurements improved using measurements at about 150-mm below the compaction surface
White et al. [13], CSAH 2, Olmsted County, Minn, USA	Caterpillar PD; MDP_{80}; sandy lean clay	LWD	MDP_{80} values are influenced by the travel direction of the roller due to localized slope changes and roller speed. Correlations between MDP_{80} and LWD generally showed $R^2 > 0.6$ (with exception of one case) when regressions are performed by separating data sets with different travel directions and speed. Data was combined by performing multiple regression analysis incorporating travel speed and direction which showed correlations with $R^2 = 0.93$
Mooney et al. [25]; Minnesota, Colorado, Maryland, North Carolina, Fla, USA	Caterpillar PD-MDP and SD-CMV, Dynapac SD-CMV; two types of cohesive soils, eleven types of granular soils	NG, DCP, LWD, FWD, PLT, Clegg hammer, SSG	Simple and multiple regression analysis results are presented. Simple linear correlations between RICM and point-MVs are possible for a compaction layer underlain by relatively homogenous and a stiff/stable supporting layer. Heterogeneous underlying conditions can adversely affect the correlations. A multiple regression analysis approach is described that includes parameter values to represent underlying layer conditions to improve correlations. Modulus measurements generally capture the variation in RICM values better than dry unit weight measurements. DCP tests are effective in detecting deeper "weak" areas that are commonly identified by RICM values and not by compaction layer point-MVs. High variability in soil properties across the drum width and soil moisture content contribute to scatter in relationships. Averaging measurements across the drum width, and incorporating moisture content into multiple regression analysis, can help mitigate the scatter to some extent. Relatively constant machine operation settings (i.e., amplitude, frequency, and speed) are critical for calibration strips and correlations are generally better for low amplitude settings (e.g., 0.7 to 1.1 mm)

Table 1: Continued.

Reference; project location	Roller drum type; RICM; soil types	QC/QA point-MVs	Key findings and comments
White et al. [35]; FM156, Roanoke, Tex, USA	Dynapad SD; CMV; granular base and lime stabilized subgrade	NG, LWD, PLT, FWD, D-SPA	CMV measurements showed good repeatability but are influenced by vibration amplitude. High amplitude (i.e., >1.5 mm) caused drum bouncing and affected the CMV measurements. Increasing amplitude generally showed an increase in CMV. Results showed that FWD modulus point measurements tracked well with variations in CMV in some cases and in some cases it did not. The reason for poor correlations with FWD measurements in some cases is attributed to the possible influence of heterogeneity observed in the material across the drum width due to moisture segregation. The CMV measurements however were well correlated with variations in moisture content as evidenced by a decrease in CMV with increasing moisture content. D-SPA, PLT, and DCP measurements tracked well with the variations in CMV
White et al. [36]; US219, Springville, NY, USA	Caterpillar SD; CMV and MDP_{40}; well-graded gravel	DCP, LWD, FWD, PLT, BCD, NG, and SDG	Nonlinear power, exponential, and logarithmic relationships are observed between RICM and point-MVs. Correlations between RICM values and different point-MVs are generally weak when evaluated independently for each test bed due to narrow range of measurements. When data are combined for site wide correlations with a wide measurement range, the correlations improved. RICM values generally correlated better with modulus/stiffness and CBR point-MVs than with dry density point-MVs. Correlations between RICM values and FWD measurements showed the strongest correlation coefficients
White et al. [37]; US84, Waynesboro, Miss, USA	Caterpillar PD; MDP40; poorly graded to silty sand	DCP, LWD, FWD, NG, and PLT	

Notes: SD: smooth drum, PD: padfoot drum.

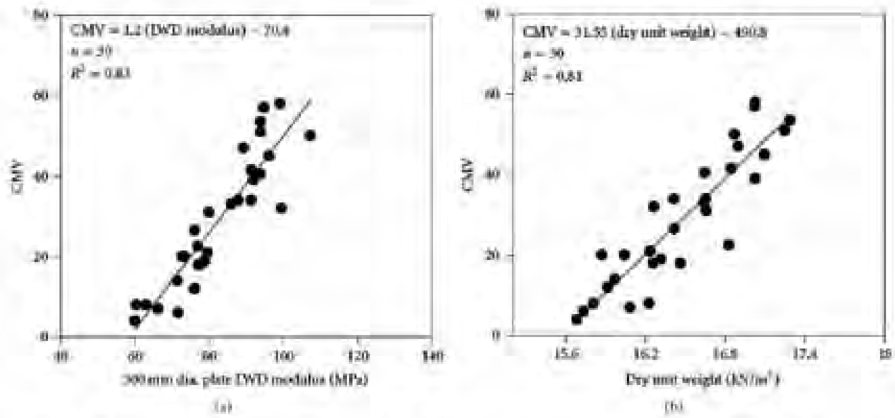

Figure 2: Simple linear regressions between CMV (amplitude = 1.00 mm) and in situ point measurements (LWD modulus and dry unit weight)—silty sand with gravel underlain by fly ash stabilized subgrade.

RICM measurements and not by point-MVs obtained on the surface. This is primarily because of the differences in measurement influence depths. Accelerometer based roller measurements have measurement influence depths ranging from 0.8 m to 1.5 m depending on soil layering, drum mass, and excitation force [25, 39–41], while machine drive power based measurements range from 0.3 to 1.3 m depending on the heterogeneity in subsurface conditions [33]. On the other hand, most point-MVs have influence depths <0.5 m [41]. Statistical multiple regression analysis techniques can be used to account for heterogeneity in the underlying layers if the underlying layer RICM or in situ point MV measurements have been demonstrated [25].

High variability in soil properties across the drum width and soil moisture content also contribute to scatter in relationships. Averaging point measurements across the drum width, and incorporating moisture content into multiple regression analysis, when statistically significant, can help mitigate the scatter to some extent. An example of multiple regression analysis by incorporating moisture content into the analysis is shown in Figure 5 based on the data described in Figure 4. Results indicate that the correlation between MDP_{40} and LWD modulus improved from R^2 value = 0.03 to 0.71, when moisture content is incorporated in to the regression analysis. MDP_{40} versus CBR dataset did not show much improvement when moisture content is incorporated, although it was found to be statistically significant (as assessed by t and F statistics).

4. Spatial Analysis of In situ and RICM Measurements

RICM technologies offer a unique advantage of quantifying and characterizing "nonuniformity" of compaction measurement values. This topic presumably should be of considerable interest to pavement engineers. Vennapusa et al. [22] demonstrated the use of variogram analysis in combination with conventional statistical analysis to effectively address the issue of nonuniformity in QC/QA during earthwork construction. A variogram is a plot of the *average* squared differences between data values as a function of separation or lag distance and is a common tool used in geostatistical studies to describe spatial variation. Three important features of a variogram include *sill*, *range*, and *nugget*. *Sill* is defined as the plateau that the variogram reaches. *Range* is defined as the distance at which the variogram reaches the sill, and *Nugget* is defined as the vertical height of the discontinuity at the origin which mostly represents sampling error or short scale variations [42]. From a variogram model, a low "sill" and longer "range of influence" can represent best conditions for uniformity, while the opposite represents an increasingly nonuniform condition.

To evaluate the application of spatial analysis, a test section was created for comparison analysis of CMV and MDP with DCP index values. The comparisons are shown using theoretical and experimental variogram models, and Kriged surface maps were generated for in situ compaction measurements using the theoretical (exponential) variogram model. The theoretical variograms were fit to the experimental variograms by checking for its "goodness" using the modified Cressie goodness of fit approach suggested by Clark and Harper [43]. A lower Cressie "goodness" factor indicates a better fit. The study area was comprised of a compacted subgrade material (Edwards glacial till material, USCS classification: CL) and a scarified portion (to a depth of 200 mm) in a "Z" shape. The scarified portion was prepared intentionally to represent a common condition in earthwork construction resulting from utility trench

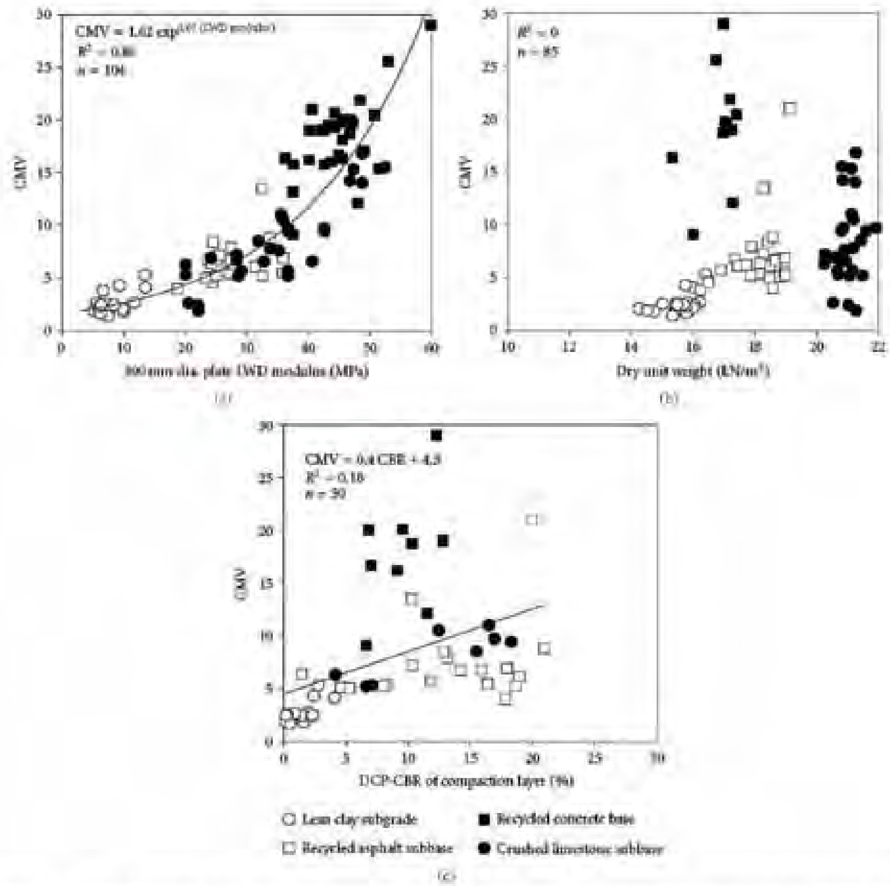

Figure 3: Relationships between CMV (theoretical amplitude = 1.50 mm) and in situ point measurements (LWD modulus, dry unit weight, and CBR determined from DCP).

construction where the backfill may not be as compact as the neighboring unexcavated materials. After subgrade preparation, the area was mapped using a smooth drum machine in seven lanes using a vibration amplitude = 2.1 mm and frequency = 29 Hz. DCP tests were performed at 144 locations in the upper 200 mm (shown in gray circles on Figure 6) following roller mapping passes. The DCP test locations were strategically spaced such that the boundaries of compacted and uncompacted areas were captured during Kriging interpolation.

CMV and MDP spatial data along with experimental and theoretical variogram models are shown in Figure 6. Log transformation of CMV was required to detrend the experimental variogram (details on detrending is explained in detail in Vennapusa et al. [22]). Kriged surface map and variogram model generated for the DCP Index values are also presented in Figure 6. The univariate statistics (mean (μ), standard deviation (σ), and coefficient of variation (COV)) of the measurement values are also provided on the figure for reference. The compacted and uncompacted areas were generally well captured by the CMV/MDP and DCP index measurements; however, they were more clearly delineated by the DCP Index measurements.

Univariate statistics show that the COV of the MDP (89%) and DCP index (86%) measurements are comparable and are also significantly higher compared to that of CMV (59%). Similarly, the exponential variogram models of MDP and DCP Index exhibit significantly lower *range* values than

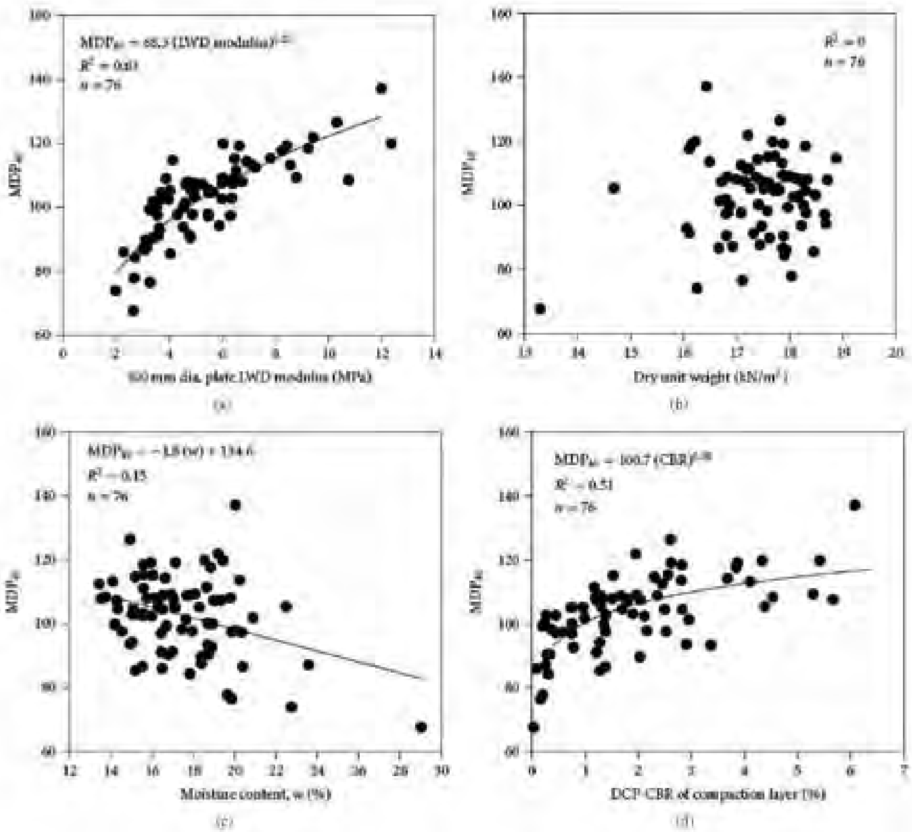

Figure 4: Example 3: Relationships between MDP_{40} (obtained in static mode) and in situ point measurements (LWD modulus, dry unit weight, moisture content, and CBR determined from DCP)—Sandy clay to silty clay subgrade.

CMV. This suggests that the MDP and DCP index measurements have less spatial continuity and higher variability compared to CMV measurements. This high variability is likely due to differences in the measurement influence depths of these measurements as discussed earlier in this paper. DCP index values presented in Figure 6 are based on average values in the top 300 mm of the surface.

In addition to using spatial analysis for visualization purposes, analysis from some field studies by the authors [36] has indicated that experimental semivariograms of RICM values sometimes show nested structures with distinctively different long- and short-range components. The nested structures are very likely linked to spatial variation in the underlying layer support conditions. These observations are new, have not been fully evaluated, and warrant more research. Further, a field study by White et al. [35] reported that variograms developed for two different spatial areas with similar univariate statistics (i.e., mean and standard deviation) showed distinctly different shapes of variograms with different spatial statistics, which illustrate the importance of spatial modeling to obtain better characterization of "nonuniformity" compared to using univariate statistics. This emphasizes the importance of dealing with "nonuniformity" in a spatial perspective rather than in a univariate statistics perspective.

5. Implementation of RICM Technology

A few countries and governmental agencies have developed specifications to facilitate implementation of RICM technologies into earthwork and hot mix asphalt (HMA) construction practices [44]. The international society of soil

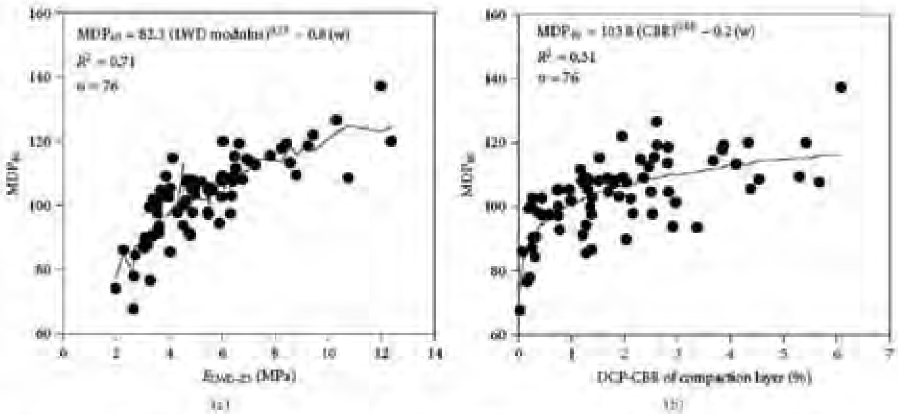

Figure 5: Example 4) Multivariate non linear regression analysis between MDP and in situ point measurements (LWD modulus and CBR determined from DCP) using moisture content—Sandy clay to silty clay subgrade.

mechanics and geotechnical engineering (ISSMGE) [39], Minnesota department of transportation (DOT) [45, 46], Austrian [47], German [48], and Sweden [49] specifications require performing either static or dynamic plate load tests on calibration strips to determine average target values (typically based on 3 to 5 measurements) and use the same for QA in production areas. The ISSMGE, Austrian, and German specifications suggest performing at least three static plate load tests in locations of low, medium, and high degree of compaction during calibration process. Further, it is specified that linear regression relationships between roller compaction measurement values and plate load test results should achieve a regression coefficient, $R \geq 0.7$. Although it is not clear yet what the right number of test measurements is to develop a field calibration, the experience of the authors shows that by increasing the number of measurements to 10–15 points, this substantially increases the statistical significance of the predictions.

One of the major limitations of the existing RICM specifications is that the acceptance requirements (i.e., percent target value limits, acceptable variability, etc.) are technology specific and somewhat based on local experience. This limitation hinders widespread acceptance of these specifications into practice as there are currently at least ten different RICM technologies. Significant efforts are being made in the US in developing widely acceptable and technology independent specifications [3–5]. Based on feedback obtained from various state and federal agency personnel in recent national level workshops conducted on this topic, White and Vennapusa [4] documented the following as the key attributes of RICM specification:

(1) descriptions of the rollers and configurations,

(2) guidelines for operations (speed, vibration frequency and amplitude, and track overlap),

(3) records to be reported (time stamp, operational mode, soil type, moisture content, layer thickness, etc.),

(4) repeatability and reproducibility measurements for RICM values,

(5) ground conditions (smoothness, levelness, isolated soft/wet spots),

(6) calibration procedures for rollers and selection of calibration areas,

(7) regression analysis between RICM values and point measurements,

(8) number and location of quality control (QC) and quality assurance (QA) tests,

(9) operator training/certification, and

(10) acceptance procedures/corrective actions based on achievement of minimum RICM target values and associated variability.

Several new and innovative specification concepts have been proposal by researchers in the past few years [4, 13, 25]. These concepts primarily vary in the way the item number 10 listed above is dealt in the specification, that is, in the required level of upfront calibration work and data analysis which consequently leads to differences in the level of confidence in the quality of the completed work. A few of those concepts have been beta tested on demonstration level projects [25] but have never been fully evaluated on full scale projects to explore their limitations and advantages. More coordination between researchers and practitioners is needed to carefully evaluate those concepts and is a high-priority step forward to successfully implement the RICM technologies in practice. Further, integrating advanced analytical methods discussed in this

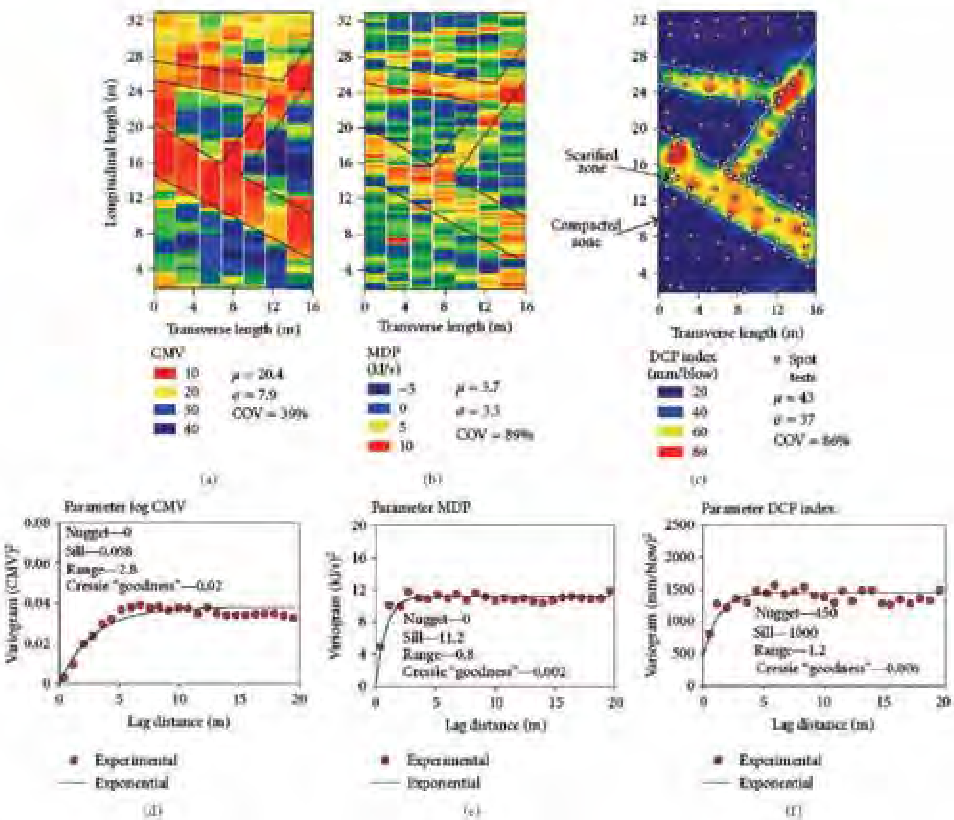

Figure 6: Spatial comparison of dynamic cone penetration (DCP) index and roller integrated CMV and MDP measurements on compacted and scarified Edwards glacial till subgrade soil.

paper (such as simple and multiple regression analysis to develop correlations and target values and spatial analysis to address nonuniformity) into a specification along with development of simple and ready-to-use software tools is much necessary to help advance the technology.

6. Concluding Remarks

RICM technologies with real-time display capabilities and 100% coverage of compaction data offer significant advantages to the earthwork construction industry. Integration of these technologies into practice requires proper understanding of the correlations between RICM values and compaction measurements (e.g., density, modulus) and factors that influence these correlations. This paper provided an overview of two technologies (i.e., CMV and MDP) and a review of field correlation studies documented in the literature. Review of the literature revealed correlations between the RICM measurements and various in situ tests used to measure density, modulus or stiffness, shear strength, and CBR. Results from field studies indicated that simple linear or nonlinear correlations between any of these measurements are possible if the compaction layer is placed over a "stable" and "homogenous" underlying layer. If the underlying layer is not stable or homogenous, correlations are adversely affected. For these cases, in general, relationships between RICM and modulus based measurements (e.g., LWD or FWD or PLT modulus) are better compared to RICM and dry density or CBR measurements. Multiple regression analysis can be performed incorporating properties of the underlying layers and moisture content to improve correlations. Other important factors that affect the correlations include narrow range of measurements, variations in machine settings, nonuniform conditions across the drum width, limited number of measurements, and measurement error associated with both RICM and in situ point measurements.

Geostatistical spatial modeling techniques can be utilized for data visualization and characterization of spatial nonuniformity using spatially referenced RICM data. To demonstrate the application of spatial analysis for visualization, an example CMV and MDP data set over a spatial area was used in comparison with DCP index measurements. Analysis results indicated that the compacted and uncompacted areas over the spatial area were well captured by all the measurements. Some field studies documented in the literature indicate that geostatistical semivariograms of RICM measurements can be used for construction process control and also to analyze variations in the underlying support conditions. These observations are new, have not been fully evaluated, and warrant more research.

Review of current RICM specifications revealed a potential limitation with the acceptance requirements (i.e., percent target value limits, acceptable variability, etc.) being technology specific and somewhat based on local experience. This limitation hinders widespread acceptance of these specifications into practice as there are currently at least ten different RICM technologies. Several new specification concepts have been recently documented in the literature with variations in the way calibration work is performed and acceptance requirements are established. These concepts require detailed field evaluation to explore their limitations and advantages. Integration of advanced analytical methods discussed in this paper (such as simple and multiple regression analysis to develop correlations and target values, and spatial analysis to address nonuniformity) into a specification along with development of simple and ready-to-use software tools are much necessary to help advance the technology.

Acknowledgments

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Report Update October 9, 2011
By David J. White, Ph.D.
Sponsored by SHRP R07

MoDOT HWY 141 Proposed RICM Proof Mapping for Pavement Subgrade - August 23, 2011

RICM TARGET VALUE DETERMINATION & SPECIFICATION UPDATE

Key Findings

- RICM Target Value (MDP) = 123.
- Recommend changing the criteria from 90% of coverage area ≥ RICM-TV to 80% ≥ RICM-TV.
- k-values determined from plate load test provide highest degree of correlation to RICM-MVs (R^2 = 0.93).
- RICM-TV analysis for plate load testing and actual rut depth measurements produced similar results.
- MDP = 123 is correlated to CBR = 10 based on 800 mm (32 inch) weighted average.
- The RICM-MVs are not well correlated to percent relative compaction or moisture content.

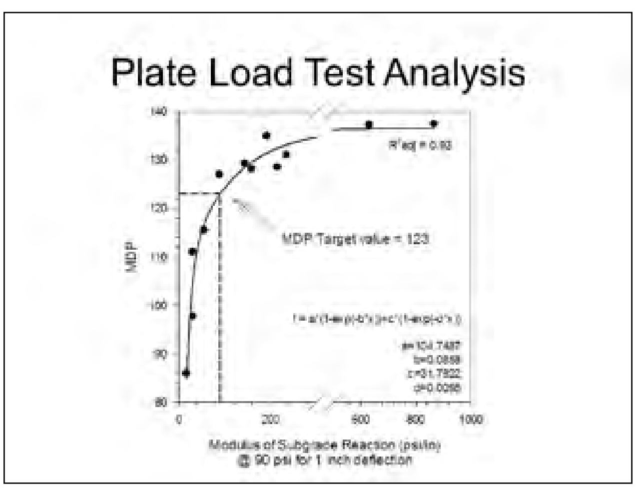
QA/QC operations to conduct nuclear density tests

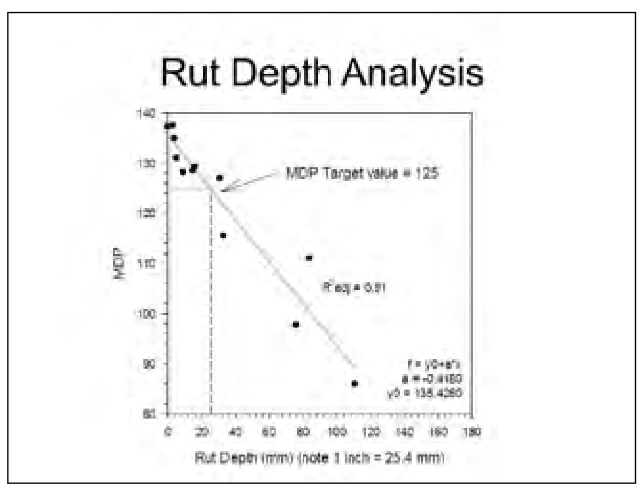
Caterpillar 815F RICM Equipped Roller

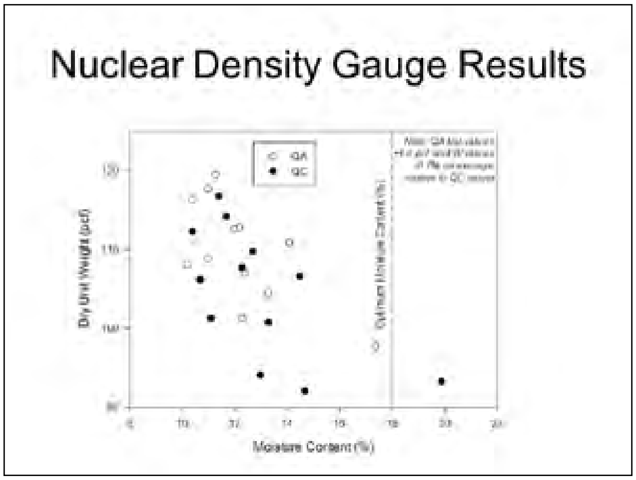
RICM Target Value Determination and Specification Update

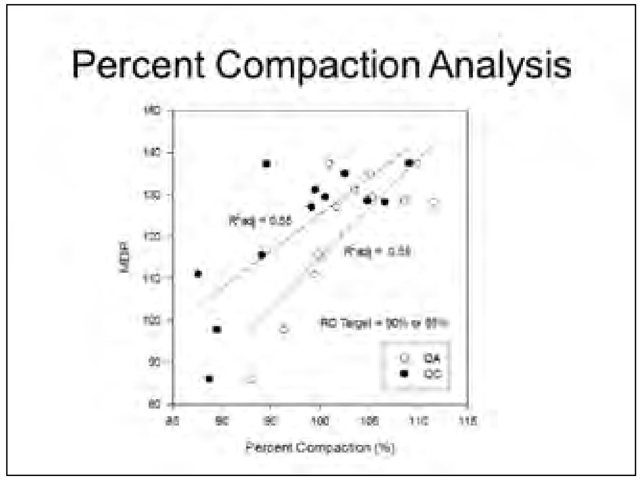
Loaded dump truck for traditional proof roll to determine rut depth

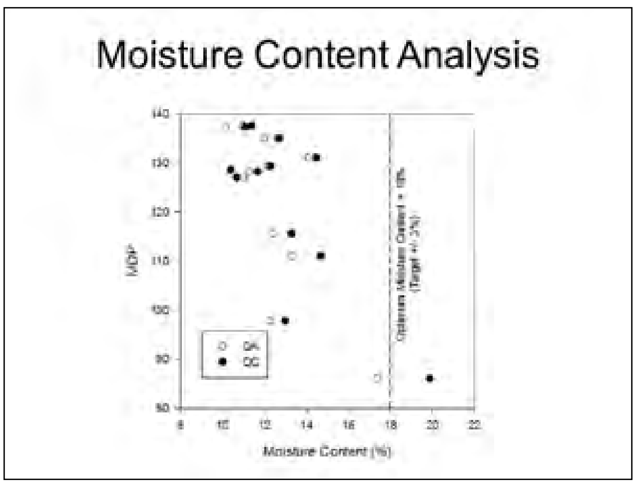
Test Area #2 – significant rutting

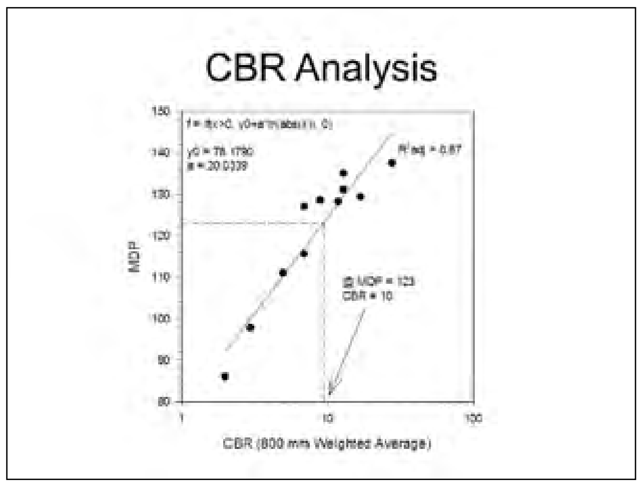


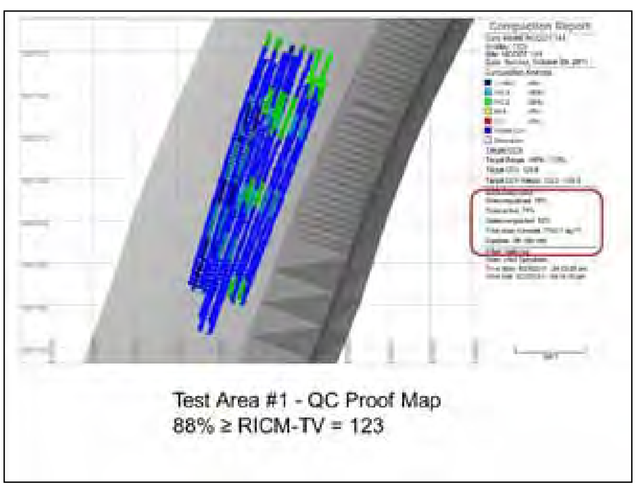


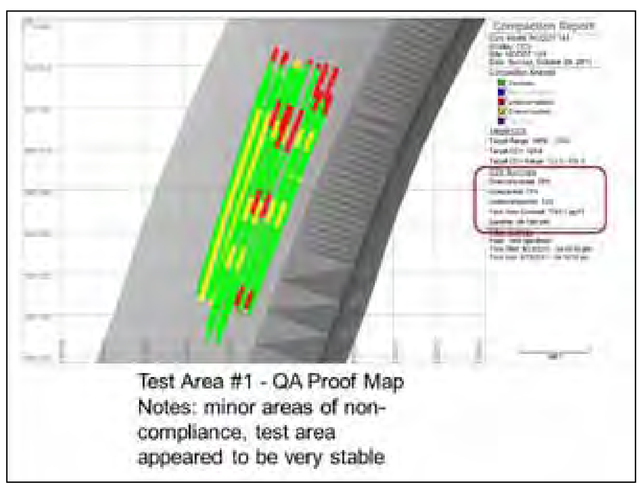

Nuclear Density Gauge Results
QA
QC
Dry Unit Weight (pcf)
Moisture Content (%)
Optimum Moisture Content (%)

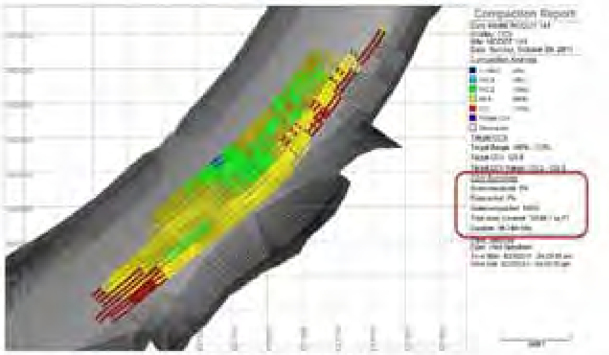

Percent Compaction Analysis
MDP
Percent Compaction (%)
QA
QC


Moisture Content Analysis
MDP
Moisture Content (%)
QA
QC

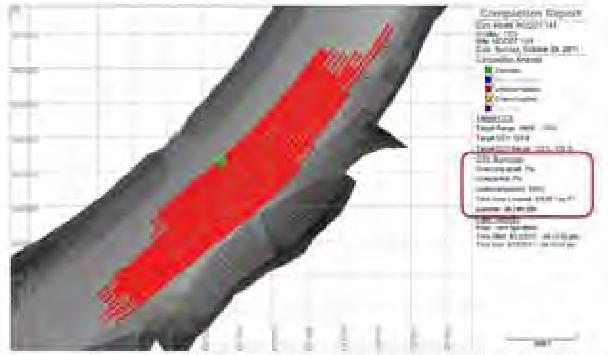

CBR Analysis
MDP
CBR (800 mm Weighted Average)
@ MDP = 123
CBR = 10


Compaction Report
Test Area #1 - QC Proof Map
88% ≥ RICM-TV = 123

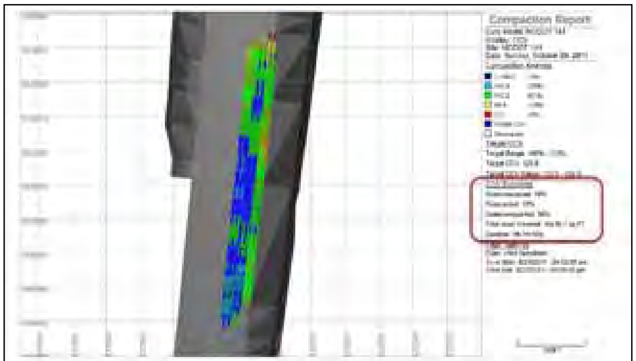

Compaction Report
Test Area #1 - QA Proof Map
Notes: minor areas of non-compliance, test area appeared to be very stable



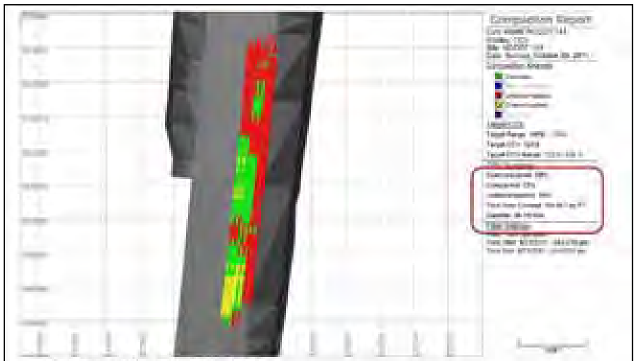
Test Area #2 QC Proof Map
0% ≥ RICM-TV = 123



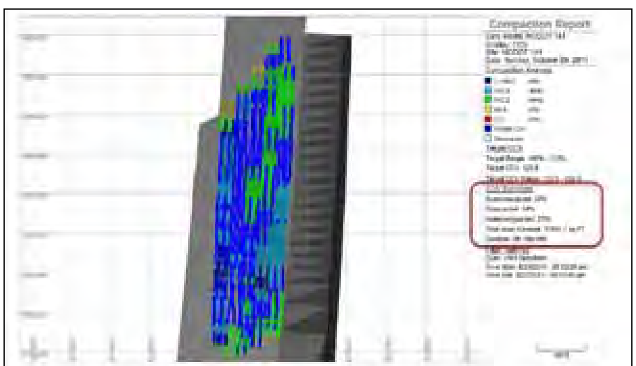
Test Area #2 QA Proof Map
Notes: Large area of unstable material. Still in process of being compacted. Rut of +4 inches. May require drying



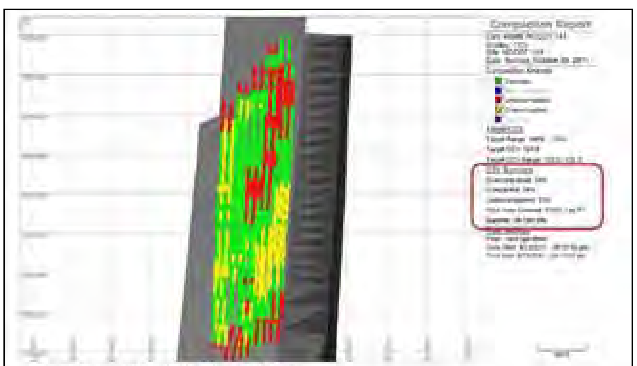
Test Area #3 - QC Proof Map
42% ≥ RICM-TV = 123



Test Area #3 QA Proof Map
Notes: Section was becoming stable, still needs work on north end and east side

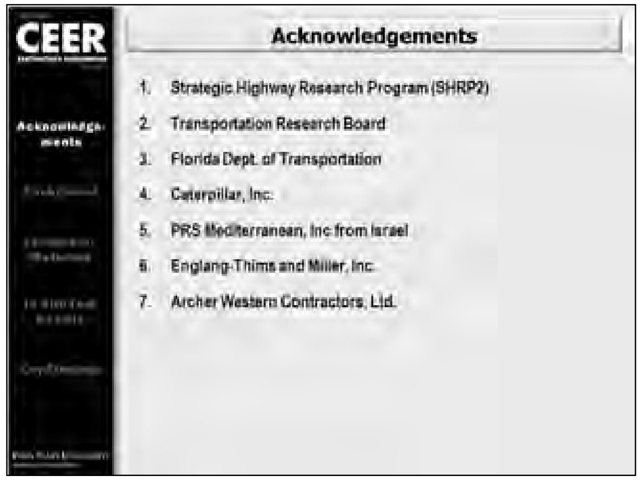


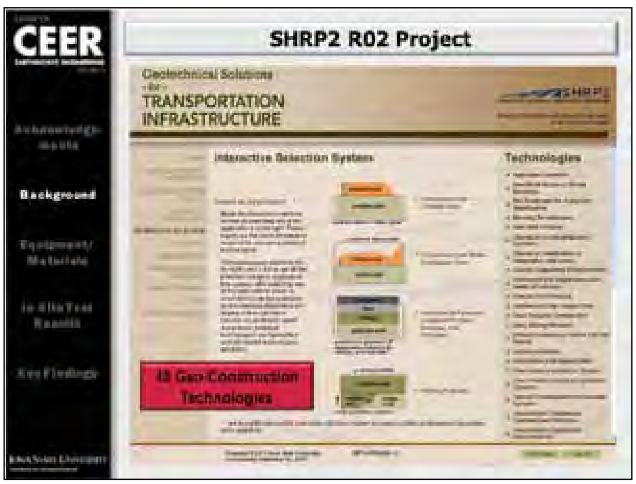
Test Area #4 - QC Proof Map
77% ≥ RICM-TV = 123

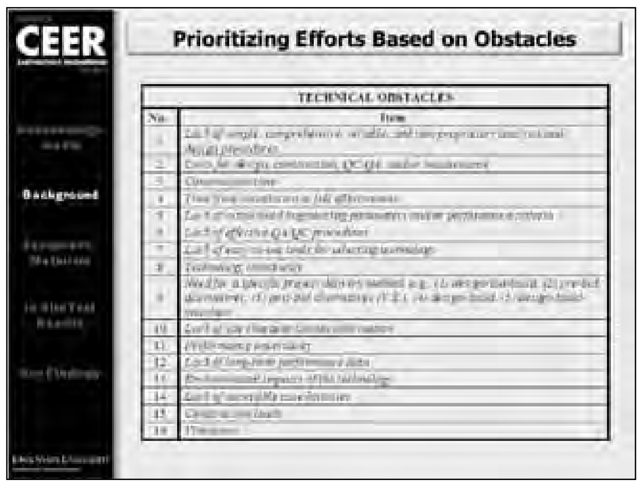


Test Area #4 - QA Proof Map
Notes: Area was generally stable, but a few areas of rough ground and may need additional passes


CEER
Compaction Roadeo Field Demonstration
Hwy 9, Jacksonville, FL
By
David J. White, Ph.D.
Associate Professor
CEER
SHRP2
IOWA STATE UNIVERSITY
KU


CEER
Acknowledgements
1. Strategic Highway Research Program (SHRP2)
2. Transportation Research Board
3. Florida Dept. of Transportation
4. Caterpillar, Inc.
5. PRS Mediterranean, Inc from Israel
6. Englang-Thims and Miller, Inc.
7. Archer Western Contractors, Ltd.

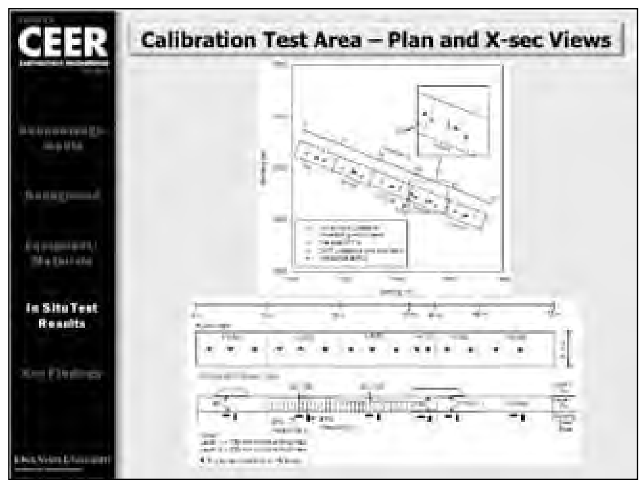

CEER
SHRP2 R02 Project
Geotechnical Solutions for TRANSPORTATION INFRASTRUCTURE
Interactive Selection System
Technologies
46 Geo-Construction Technologies
Background

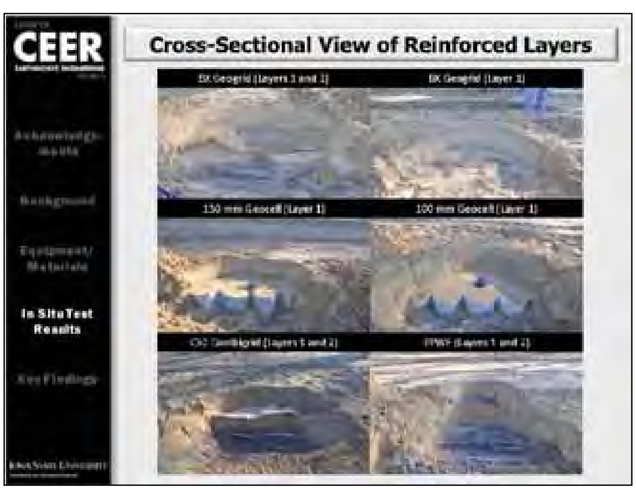

CEER
Prioritizing Efforts Based on Obstacles
TECHNICAL OBSTACLES
No.
Item
Background

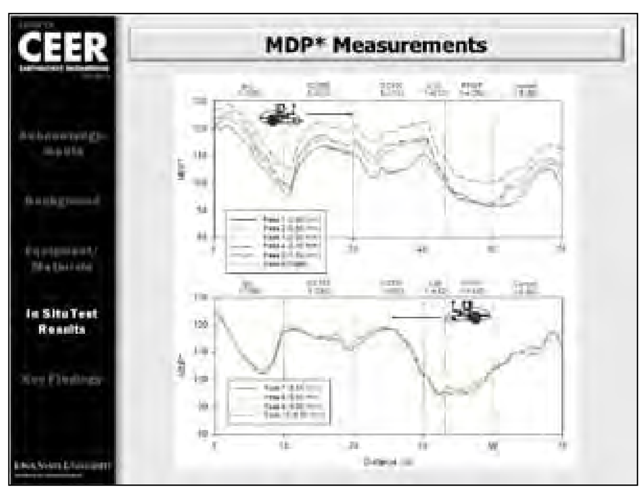

CEER
Compaction Roadeo Field Demonstration
Background

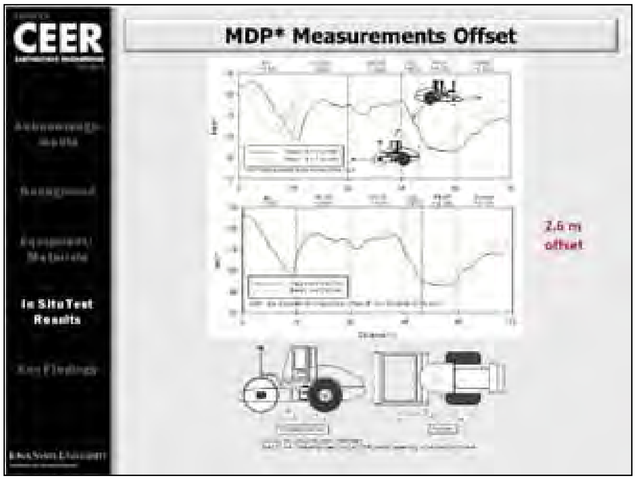

CEER
In Situ Testing Equipment
Equipment/ Materials

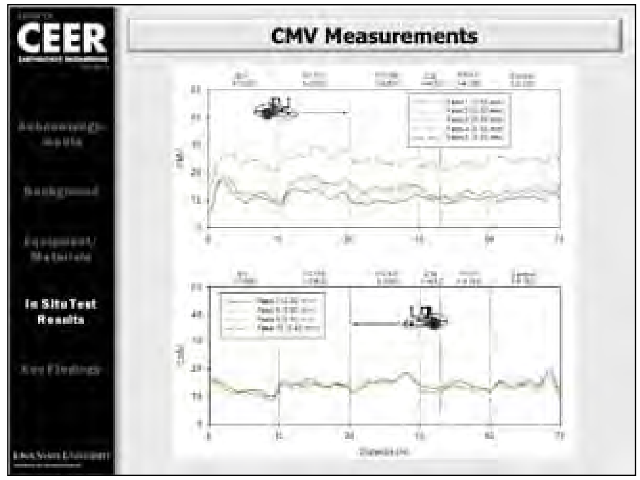
Compaction Roadeo Field Demonstration

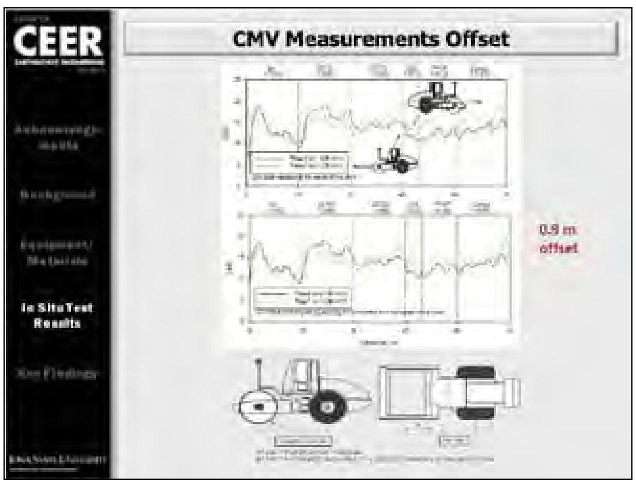


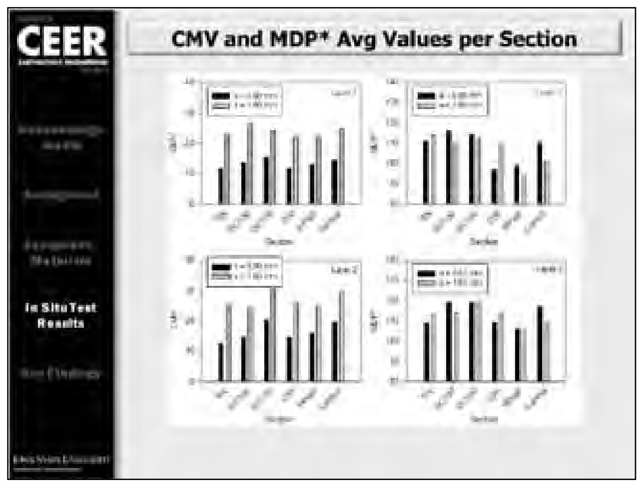


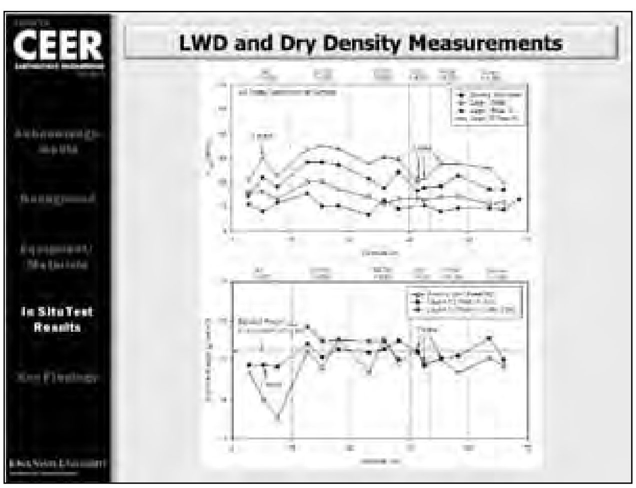


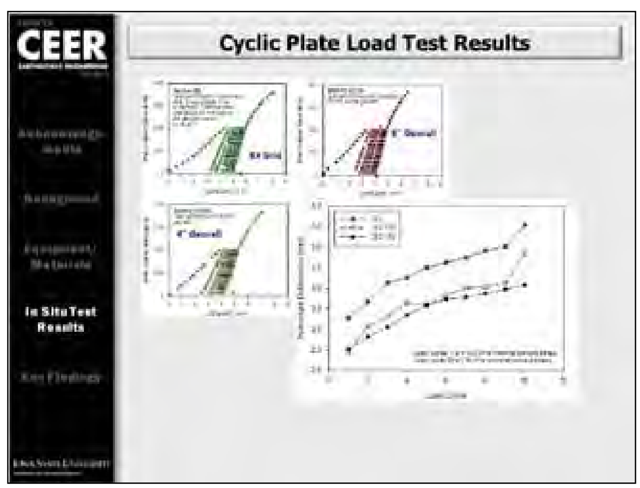

CEER
MDP* Measurements Offset
In Situ Test Results
2.6 m offset

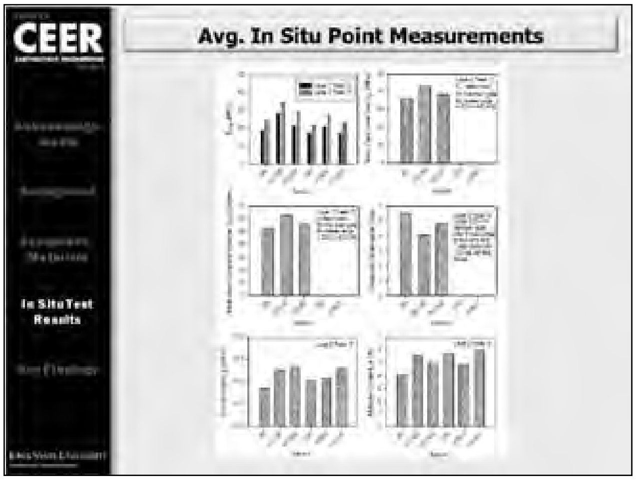

CEER
CMV Measurements
In Situ Test Results

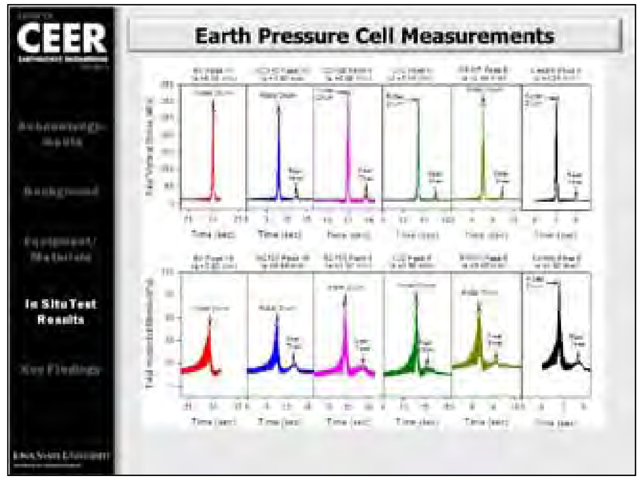

CEER
CMV Measurements Offset
In Situ Test Results
0.9 m offset


CEER
CMV and MDP* Avg Values per Section
In Situ Test Results


CEER
LWD and Dry Density Measurements
In Situ Test Results


CEER
Cyclic Plate Load Test Results
In Situ Test Results


CEER
Avg. In Situ Point Measurements
In Situ Test Results


CEER
Earth Pressure Cell Measurements
In Situ Test Results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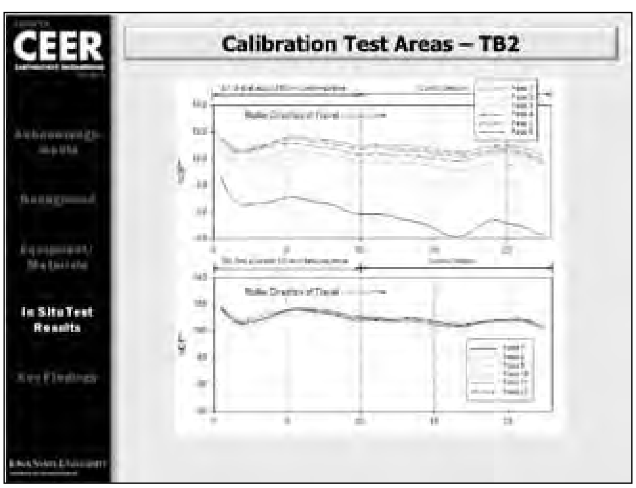
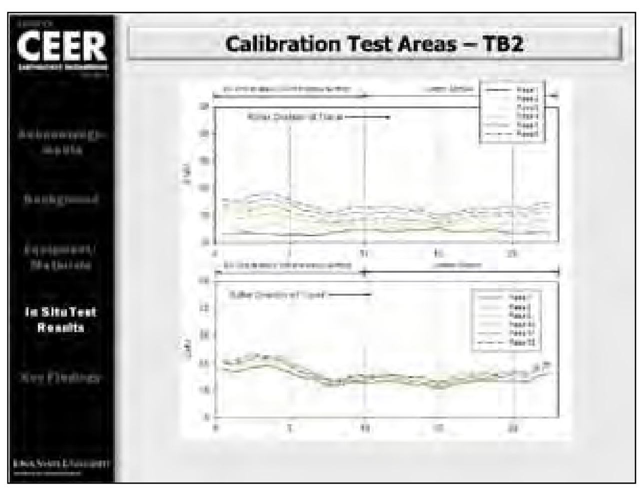
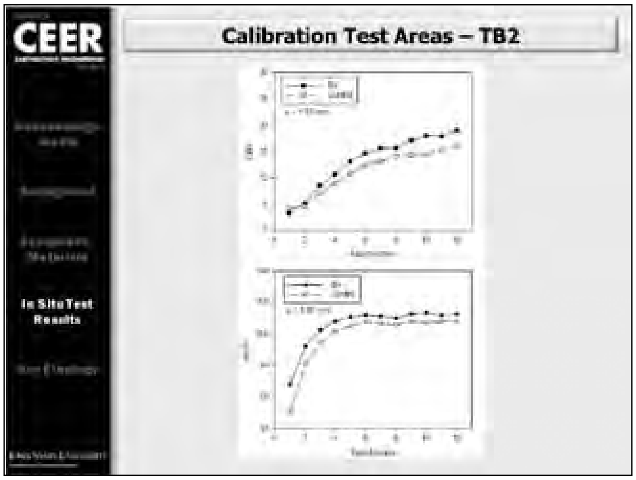
Calibration Test Areas – TB2
In Situ Test Results


CEER
Calibration Test Areas – TB2
In Situ Test Results


CEER
Calibration Test Areas – TB2
In Situ Test Results


CEER
Calibration Test Areas – TB2
In Situ Test Results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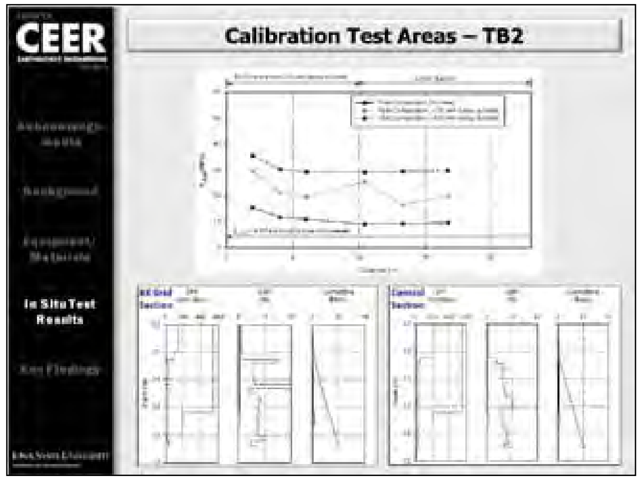
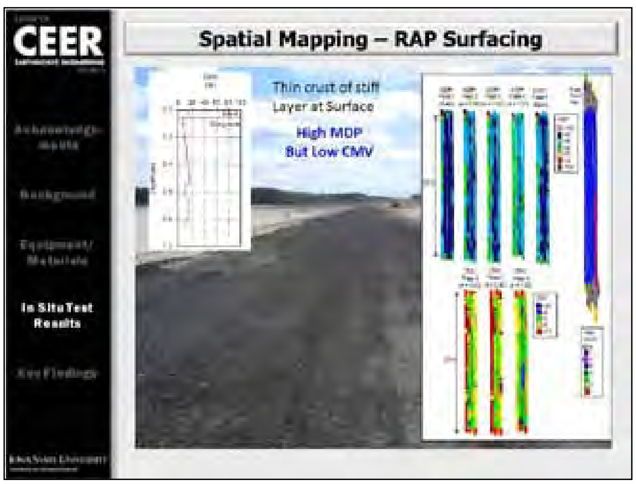
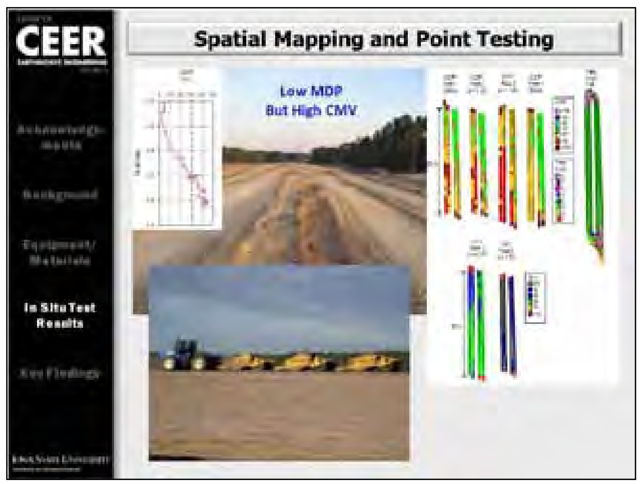
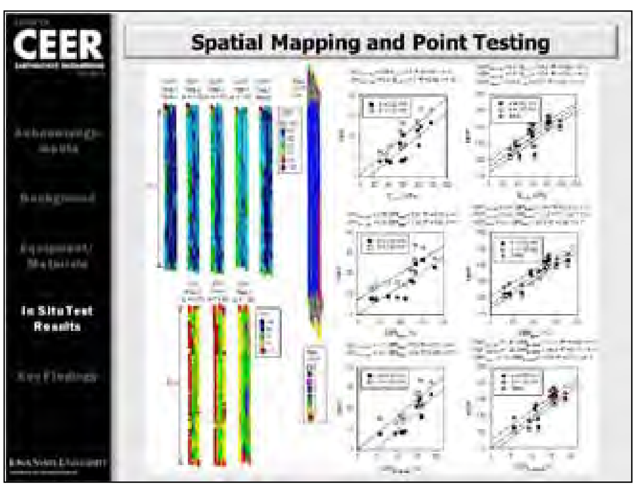
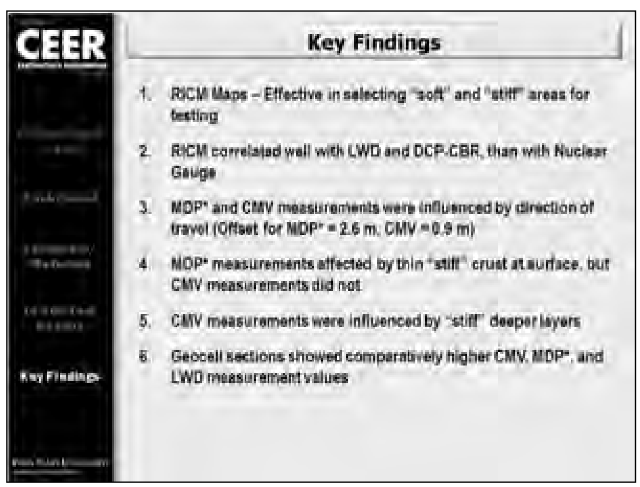
Calibration Test Areas – TB2
In Situ Test Results


CEER
Calibration Test Areas – TB2
In Situ Test Results


CEER
Spatial Mapping – RAP Surfacing
Thin crust of stiff Layer at Surface
High MDP But Low CMV
In Situ Test Results


CEER
Spatial Mapping and Point Testing
Low MDP But High CMV
In Situ Test Results


CEER
Spatial Mapping and Point Testing
In Situ Test Results


CEER
Key Findings
1. RICM Maps – Effective in selecting "soft" and "stiff" areas for testing
2. RICM correlated well with LWD and DCP-CBR, than with Nuclear Gauge
3. MDP* and CMV measurements were influenced by direction of travel (Offset for MDP* = 2.6 m, CMV = 0.9 m)
4. MDP* measurements affected by thin "stiff" crust at surface, but CMV measurements did not
5. CMV measurements were influenced by "stiff" deeper layers
6. Geocell sections showed comparatively higher CMV, MDP*, and LWD measurement values
Key Findings

Intelligent Compaction Technical Publications
Prepared by David White and Pavana Vennapusa
Center for Earthworks Engineering Research, Iowa State University

Intelligent Compaction Technical Publications

Journal and Conference Papers (organized by publication date)

1980

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List of Intelligent Compaction Technical Publications

Intelligent Compaction Technical Publications
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Center for Earthworks Engineering Research, Iowa State University

14. Thurner, H. (1993). " Continuous compaction control - specifications and experience." *Proc., XII IRF World Congress*, 951-956, Madrid.
15. Watts, K.S. and Charles, J.A. (1993). "Initial assessment of a new rapid impact ground compactor." Proceedings of the Conference on Engineered Fills, London, Paper No. 32.

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Page 2 of 22 (Updated March 3, 2012)

List of Intelligent Compaction Technical Publications

29. Nohse, Y., Uchiyama, K., Kanamori, Y., Kase, J., Kawai, Y., Masumura, K., and Tateyama, K. (1999). "An attempt applying a new control system for the vibratory compaction using GPS and CMV in the embankment construction (Part 1)." *Proc. of the 13th Intl. Conf. of the ISTVS: Okinowa*, Japan, 295-300.

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List of Intelligent Compaction Technical Publications

Intelligent Compaction Technical Publications
Prepared by David White and Pavana Vennapusa
Center for Earthworks Engineering Research, Iowa State University

2002

42. Kloubert, H. (2002). "Asphalt manager with high efficient compaction system for better roads," *Proc., Intl. Conf. on Bituminous Mixtures and Pavements*, Thessaloniki, Greece.
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Page 7 of 22 (Updated March 3, 2012)

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Page 12 of 22 (Updated March 3, 2012)

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Prepared by David White and Pavana Vennapusa
Center for Earthworks Engineering Research, Iowa State University

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Page 14 of 22 (Updated March 3, 2012)

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Page 16 of 22 (Updated March 3, 2012)

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Page 17 of 22 (Updated March 3, 2012)

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Center for Earthworks Engineering Research, Iowa State University

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54. *US84, MISSISSIPPI FHWA IC POOLED FUND STUDY DEMONSTRATION [White, D.J., Vennapusa, P.., Gieselman, H., Fleming, B., Quist, S., Johanson, L. (2010). *Accelerated Implementation of*

Intelligent Compaction Monitoring Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials TPF-5(128) – *Mississippi IC Demonstration Field Project*, ER10-03, Report submitted to The Transtec Group, FHWA, January.]

55. *I29, Monona County, Iowa – Pavement Foundation Layer Construction** [White, D.J., Vennapusa, P., Gieselman, H. (2010). *Iowa DOT Intelligent Compaction Research and Implementation – Phase I*, ER-10-06, Final Report, Earthworks Engineering Research Center, Iowa State University, Ames, Iowa, December.]
56. ***US30, Colo, Iowa – Embankment Construction** [White, D.J., Vennapusa, P., Gieselman, H. (2010). *Iowa DOT Intelligent Compaction Research and Implementation – Phase I*, ER-10-06, Final Report, Earthworks Engineering Research Center, Iowa State University, Ames, Iowa, December.]
57. ***US218, Coralville, Iowa, Colo, Iowa – HMA Overlay Construction** [White, D.J., Vennapusa, P., Gieselman, H. (2010). *Iowa DOT Intelligent Compaction Research and Implementation – Phase I*, ER-10-06, Final Report, Earthworks Engineering Research Center, Iowa State University, Ames, Iowa, December.]
58. ***Geosynthetic Stabilized Subbase Test Sections, Weirton, West Virginia** [White, D.J., Gieselman, H., Douglas, S., Zhang, J., Vennapusa, P. (2010). *In-Situ Compaction Measurements for Geosynthetic Stabilized Subbase: Weirton, West Virginia*. ER10-05, Prepared by the Earthworks Engineering Research Center at Iowa State University, Report submitted to Tensar, Inc.

2010

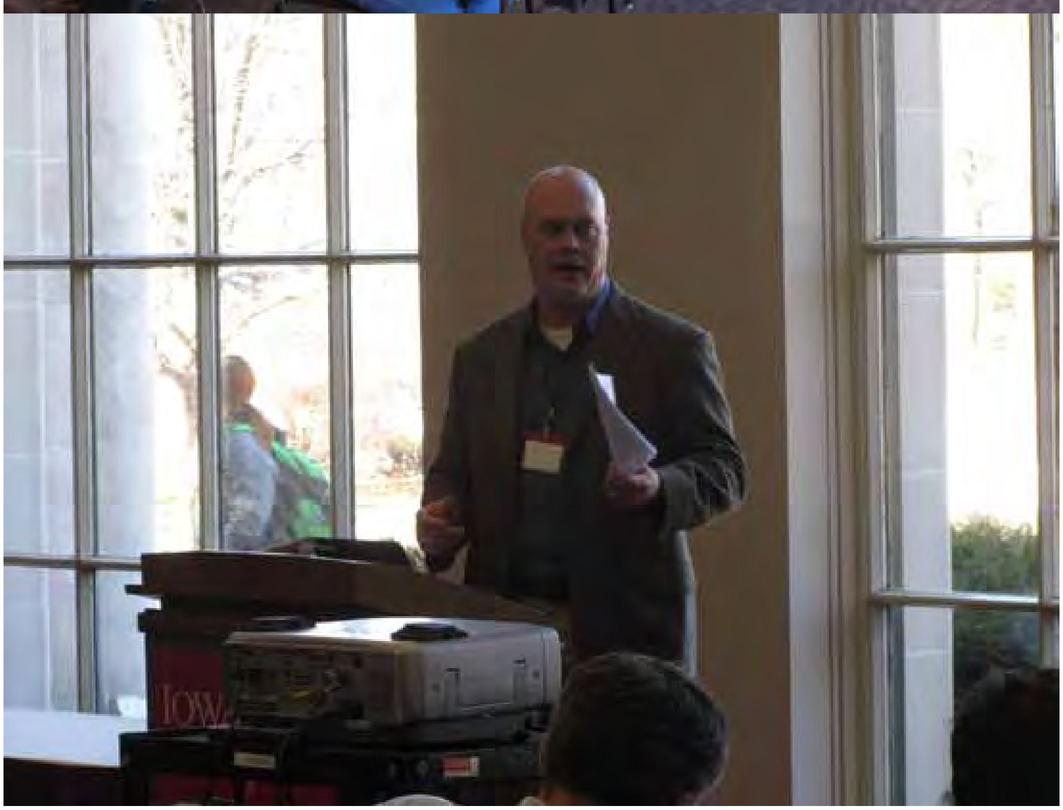
59. ****Hwy 9, Kossuth County, Iowa – HMA Overlay Construction** [White, D.J., Vennapusa, P., Gieselman, H., Harland, J., Quist, S. (2011). *Iowa DOT Intelligent Compaction Research and Implementation – Phase I*, Final Report, Earthworks Engineering Research Center, Iowa State University, Ames, Iowa, (in preparation).]
60. ****Hwy 30, Harrison County, Iowa – HMA Overlay Construction** [White, D.J., Vennapusa, P., Gieselman, H., Harland, J., Quist, S. (2011). *Iowa DOT Intelligent Compaction Research and Implementation – Phase I*, Final Report, Earthworks Engineering Research Center, Iowa State University, Ames, Iowa, (in preparation).]
61. ****Hwy 20, Ida County, Iowa – HMA Overlay Construction** [White, D.J., Vennapusa, P., Gieselman, H., Harland, J., Quist, S. (2011). *Iowa DOT Intelligent Compaction Research and Implementation – Phase I*, Final Report, Earthworks Engineering Research Center, Iowa State University, Ames, Iowa, (in preparation).]
62. ***US12, Marmarth, North Dakota FHWA IC Pooled Fund Study Demonstration** [White, D.J., Vennapusa, P., Gieselman, H., Zhang, J., Eidem, M. (2010). *Accelerated Implementation of Intelligent Compaction Monitoring Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials* TPF-5(128) – *North Dakota IC Demonstration Field Project*, ER10-08, Report submitted to The Transtec Group, FHWA, November.]
63. ***SR-25, West Lafayette, Indiana FHWA IC Pooled Fund Study Demonstration** [White, D.J., Vennapusa, P., Gieselman, H., (2010). *Accelerated Implementation of Intelligent Compaction Monitoring Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials* TPF-5(128) – *Indiana IC Demonstration Field Project*, Report submitted to The Transtec Group, FHWA (in preparation)].
64. ***US52 HMA IC Field Demonstration, West Lafayette, Indiana** [Chang, G., Xu, Q., Horan, B., Michael, L. (2010). *Accelerated Implementation of Intelligent Compaction Monitoring Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials TPF-5(128) – US52 West Lafayette, Indiana HMA IC Demonstration*, Report submitted to FHWA, March.]
65. ***FM1281 HMA IC Field Mini Demonstration, El Paso, Texas** [Chang, G., Xu, Q., (2010). *Accelerated Implementation of Intelligent Compaction Monitoring Technology for Embankment*

List of Intelligent Compaction Technical Publications

Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials TPF-5(128) – FM1281, El Paso, Texas, HMA IC Demonstration, Report submitted to FHWA, June.]

66. *IH39 HMA IC **FIELD DEMONSTRATION, MOSINEE, WISCONSIN** [Chang, G., Xu, Q., Horan, B., Michael, L. (2010). *Accelerated Implementation of Intelligent Compaction Monitoring Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials TPF-5(128) – IH39, Mosinee, Wisconsin HMA IC Demonstration*, Report submitted to FHWA, June.]
67. ***US219 HMA IC FIELD DEMONSTRATION, SUMMERHILL, PENNSYLVANIA** [Chang, G., Xu, Q., Horan, B., Michael, L. (2010). *Accelerated Implementation of Intelligent Compaction Monitoring Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials TPF-5(128) – US219, Summerhill, Pennsylvania HMA IC Demonstration*, Report submitted to FHWA, October.]
68. ***I-66 HMA IC FIELD DEMONSTRATION, FAUQUIER COUNTY, VIRGINIA** [Chang, G., Xu, Q., Horan, B., Michael, L. (2010). *Accelerated Implementation of Intelligent Compaction Monitoring Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials TPF-5(128) – I-66, Fauquier County, Virginia HMA IC Demonstration*, Report submitted to FHWA, October.]
69. ***STH80 SUBGRADE, BASE, AND HMA RECONSTRUCTION AND WIDENING PROJECT, NORTH OF HIGHLAND, WISCONSIN** [Quintus, V.L.H., Rao, C., Bhattacharya, B., Titi, H., English, R. (2010). *Evaluation of Intelligent Compaction Technology for Densification of Roadway Subgrades and Structural Layers*, WHRP Project No. 0092-08-07 (Draft Final Report), Prepared by Applied Research Associates and University of Wisconsin at Milwaukee, November.]
70. ***STH18 SUBGRADE AND BASE RECONSTRUCTION PROJECT, WEST OF JEFFERSON, WISCONSIN** [Quintus, V.L.H., Rao, C., Bhattacharya, B., Titi, H., English, R. (2010). *Evaluation of Intelligent Compaction Technology for Densification of Roadway Subgrades and Structural Layers*, WHRP Project No. 0092-08-07 (Draft Final Report), Prepared by Applied Research Associates and University of Wisconsin at Milwaukee, November.]
71. ***US45 HMA OVERLAY PROJECT, NEAR EDEN, WISCONSIN** [Quintus, V.L.H., Rao, C., Bhattacharya, B., Titi, H., English, R. (2010). *Evaluation of Intelligent Compaction Technology for Densification of Roadway Subgrades and Structural Layers*, WHRP Project No. 0092-08-07 (Draft Final Report), Prepared by Applied Research Associates and University of Wisconsin at Milwaukee, November.]

Appendix E: Workshop Photos




What have we been working on?

Appendix F: Workshop Evaluation Comments

EVALUATION
Technology Transfer for Intelligent Compaction Consortium (TTICC)
Iowa State University
Ames, Iowa

March 6-7, 2012

Did the TTICC meeting meet your expectations?

- Yes. Wish more states had participated
- Yes. Exceed expectations (3 responses)

What was the most useful part of the meeting?

- Day 2 discussions with industry (2 responses)
- Input/issues from other DOTs
- Industry's new developments and technologies
- Discussion/breakout groups
- Industry

What was the least useful part of the TTICC meeting?

- "Reorganizing priorities" discussion (dragged)
- DOT updates
- Nothing. Everything had a purpose. All useful (3 responses)

What suggestions would you make to improve the next TTICC meeting?

- Hard to say; other than to have progress on various needs/problems/solutions to discuss
- Try to get more DOTs involved
- Industry involved every time!
- Continue dialogue with industry

Additional comments:

- Enjoyed the venue and meals
- Logistics were excellent. Well organized.