Intelligent Construction Systems

Innovations in Compaction Control and Testing

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www.fhwa.dot.gov/pavements/
What is “Intelligence?”

– Oxford Dictionary: “…able to vary behavior in response to varying situations and requirements”

– Ability to:
  • Collect information
  • Analyze information
  • Make an appropriate decision
  • Execute the decision
Key Question?

• “Can we make the compaction process work smarter not harder?”
  -- Jim Musselman (FL DOT)
FHWA I C Team

- 12 State Pooled Fund Partners…
- Roller & Test Equipment Manufacturers
- V. Lee Gallivan, HQ/RC
- Michael Arasteh, RC
- Fred Faridazar, RD
- Tom Harman, RC
- John D’Angelo, HQ
- Bob Horan, SaLUT (Support Staff)
We’ve come a long way!
Because we always ask…

How can we do it better?

What’s the next innovation?
Our Visit

- Goal of Roadway Compaction
- Conventional Limitations “Challenges”
- Goal of Intelligent Compaction, IC
- Roadway Compaction 101 “Basics”
- NCHRP IC Project
- Pooled Fund IC Project
- Shared Vision
Roadway Compaction

- Proper in-place density is vital for good performance
- Conventional compaction procedures have some limitations...
- Intelligent compaction technology appears to offer “a better way”
Conventional Limitations

• The Compaction Process...

Limited “On Fly” Feedback

Over or Under-Compaction Can Occur
Conventional Limitations

• Density Acceptance…

Limited Number of Locations

After Compaction is Complete
Intelligent Compaction

Can we make the process...smarter?

Improved Roller Technology

Sophisticated / Clear Documentation Systems

Advanced Hardware & Software
IC – Goals / Benefits

• **Short Term**
  – Improve density… better performance
  – Improve efficiency… cost saving$
  – Increase information… better QC/QA

• **Long Term**
  – Comprehensive Compaction Control (CCC)
  – Estimate pavement moduli?
  – Tie to M-E Design Guide (verify design)?
  – Performance specifications?
Roadway Materials Compaction 101

What are the basics of compaction?
THE IMPORTANCE OF COMPACTION in highway construction has long been recognized. Recent laboratory and field investigation have repeatedly emphasized the value of thorough consolidation in both the base and surfacing courses. Thorough compaction is known to produce the following desirable results:

1. It increases interlocking of the aggregate particles, which is the primary factor in developing a high degree of stability.
2. It retards the entrance of moisture, thus preventing excessive loss of stability under adverse service conditions.
3. It reduces the flow of air and water through bituminous mixtures and is therefore an effective means of lessening damage from weathering and film stripping.

Reference -- "Public Roads, May 1939, authors J.T. Pauls and J.F. Goode"
Effect of In-situ Air Voids on Life

Percent Pavement Voids

Percent Loss Service Life

Washington State
Basics of Compaction

- Effort (Roller) versus Resistance...
Basics of Compaction using Vibratory Rollers

- Constant Mass
- Variables of Vibration
  - Frequency, $f$ (Hz)
  - Amplitude, $A$
  - Roller speed, $v$ (fps)
Basics of Compaction using Vibratory Rollers

Courtesy Bomag America
Vibratory Effort

- Vibration sets aggregates in motion
- Helps aggregates re-orient for better contact
Amplitude

- Amplitude determines impact force
Impact Spacing, $I = f(v, \text{Hz})$
Optimization…

- Amplitude controls force & depth
- Frequency and Speed control Impacts
- Ex. “Best” results when impact spacing is 10 -14 impacts / foot for HMA
Intelligent Compaction, IC
IC TPF / FHWA Definition

1. Vibratory rollers with measurement / control system
   - Measurement system, ex. material stiffness
   - Control system automatically changes parameters (amplitude and possibly frequency) based on measurement…
IC TPF / FHWA Definition

2. GPS-based documentation systems
   - Continuous recordation of materials stiffness
   - Continuous recordation of corresponding roller location
   - Color-coded mapping of stiffness
Ex. Caterpillar

Courtesy of Caterpillar
Ex. Sakai...
Sakai IC Roller Project

• Roller Passes

Shoulder (Supported)

Longitudinal Joint

Paving Direction

Number of roller passes

1 2 3 4 5 6 7 8
Sakai IC Roller Project

- Temperature

Shoulder side (Supported)

Longitudinal Joint

Paving Direction

Intelligent Compaction
Sakai IC Roller Project

• Stiffness

Shoulder side (Supported)

Longitudinal Joint

Paving Direction

Intelligent Compaction
Benefits of IC

- **Maximum productivity** of the compaction process
- **Improved density** of pavement materials
- Measurement and recordation of materials stiffness values
- **Identification** of non-compactable areas
- **Improved depth** of compaction
- Reduction in highway repair **costs**
Bomag America
Generated Stiffness vs. Density

Evib Bomag
Surface temp.
Core temp.
Troxler density

E_{VIB} MN/m², °C

0 1 2 3 4 5 6

0 100 200 300

0 1 2 3 4 5 6

%
Bomag America
Generated Stiffness vs. Density

\[
y = 6x - 300
\]

\[
R^2 = 0.94
\]
Some Critical Research Topics…

- Construction specs on 4 different material types
  - Granular subgrade soil
  - Cohesive subgrade soil
  - Aggregate base and subbase
  - Asphalt pavement material

- Comparison of IC and conventional—Is IC really better?
Some Critical Research Topics…

• Correlation of roller-generated stiffness and in-place density?

• Correlation of roller-generated stiffness and in-situ test methods? (FWD, LWD, DCP, GeoGauge, etc.)
Some Critical Research Topics

- Needed accuracy of GPS
- Best methods of using roller-generated data in agency’s QA and acceptance testing
- Assessment of roller operators ability to understand and utilize more complex equipment
National Research Efforts

• NCHRP 21-09 “Examining the Benefits and Adoptability of Intelligent Soil Compaction”

• Transportation Pooled Fund #954 – “Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base and Asphalt Pavement Material”
NCHRP 21-09 (Soils)

- Study of IC of subgrade soils (limited aggregate base/subbase)

- Objectives: Based on data / information obtained from field studies:
  - Develop generic IC construction specifications for subgrade soils
  - Evaluate the reliability of IC system components
NCHRP 21-09

Two year project in two phases

- Phase 1: One project
- Phase 2: Four projects
  - June, 2006 - June, 2008
  - Allocated Funding: $600,000
  - Awarded 12/05

- Dr. Michael Mooney, Colorado School of Mines, Principal Investigator
- Dr. David White, Iowa State University, Co-Principal Investigator
NCHRP 21-09
Phase One Project

July 2006; MnROAD Research Center

[Image of road construction equipment]
NCHRP 21-09
Phase One Project

Bomag America

Caterpillar

Ammann

Intelligent Compaction
NCHRP 21-09 Phase One Project

Iowa State University Geotechnical Mobile Lab

“Advancing Intelligent Construction”
Mn/DOT Project
In-Situ Testing
Mn/DOT Project
Soils In-Situ Testing Equipment

Lightweight Deflectometer (LWD)

Geo Gauge

Dynamic Cone Penetrometer (DCP)

Question: Can the in-situ test results be correlated to roller-generated output?
Pooled Fund (Soils / HMA)

• 3 year study of IC for all materials
• Solicitation period ended on Dec 2005
• 12 participating states
• Estimate 1 project / State / year ~ 30?
• Close coordination with NCHRP project
• Stated goal to work closely with roller suppliers to increase the number of IC rollers and manufacturers
Accelerated Implementation of IC

Intelligent Compaction
Pooled Fund, Objectives

• Objectives: Based on data obtained from field studies:
  
  – Accelerated development of QC/QA specifications for granular and cohesive subgrade soils, aggregate base and asphalt pavement materials…
Pooled Fund, Objectives

– Develop an experienced and knowledgeable IC expertise base within Pool Fund participating state DOT personnel

– Identify and prioritize needed improvements to and/or research of IC equipment and field QC/QA testing equipment (DCP, FWD, GeoGauge, etc)
Comparison on Pooled Fund and NCHRP Projects

- **Pooled Fund #954**
  - Specification develop.
  - Identify and prioritize needed improvements
  - More projects
  - All pavement materials and entire pavement structure
  - Active participation of state DOT personnel
  - Emphasis on inform./technology transfer

- **NCHRP 21-09**
  - Specification develop.
  - Evaluate existing IC components
  - Detailed research on fewer projects
  - Primarily subgrade soils; some agg. base
  - Research team / NCHRP panel
State DOT IC Research

- Limited number of projects by several State DOTs (MN, NC, MD)
- Mn/DOT has conducted an ongoing research effort over last several years
  - 5 projects complete
  - Subgrade soils only
  - 3 different roller manufacturers
  - Compare roller-generated output to in-situ test methods (DCP, LWD and GeoGauge)
  - Required GPS-based, color coded mapping of roller output and locations
IC Rollers
Current Status

- 5 Roller Manufacturers have announced their intentions to supply IC rollers in US
  - 4 have announced plans to have both single drum soils rollers and tandem drum asphalt rollers
  - 1 has only single drum soils rollers, at this time
- 4 Manufacturers that currently have IC rollers for public display, at this time:
  - Bomag America (both single and tandem drum)
  - Ammann America (single drum)
  - Caterpillar (single drum)
  - Sakai America (tandem drum)
Special Issues for Asphalt IC

• Thin lift construction
• Allowable temperature ranges
• Surface vs. internal temperature measurement
• Non-destructive, in-situ stiffness / modulus companion tests
What have we learned so far?

- IC technology appears to have great potential to improve the compaction process
- Improved and more uniform density should increase pavement service life
- There is a great deal of interest among federal and state DOTs to learn more about it
What have we learned so far?

• Roller manufacturers are responding to this interest by performing R&D, providing rollers and by coordinate efforts with state and national research efforts

• Preliminary findings from studies in US are encouraging
Intelligent Compaction

The Objectives

• Accelerate the development of IC

• Increase awareness and encourage acceptance

• Conduct needed research to clarify the advantages and appropriate uses of the technology

• Provide organizational support for the process of developing intelligent compaction technologies
IC – Goals / Benefits

• Short Term
  – Improve density… better performance
  – Improve efficiency… cost savings
  – Increase information… better QC/QA
Thank you!

Intelligent Compaction Technology

An Innovation in Compaction Control and Testing
Additional Slides
Compaction is the process of compressing HMA into a smaller, denser volume.

Asphalt coated aggregate particles are reoriented and consolidated, which increases the pavement density.
Compaction is the process of compressing material particles into a smaller, denser volume.

Material particles are reoriented and consolidated, which increases the density.
AMPLITUDE
Intelligent Compaction

Optimized compaction process with IC rollers

Density In percent of target

Time, Number of roller passes

Conventional Compaction
Danger of over- or under-compaction

Compaction finished

Courtesy of Ammann America
Roller Correlation
Generated Modulus vs. Density

Marshall density [%]

Temp. [°C], Evib [MN/m²]

Roller Passes

Range: 100 to 260

Evib
Asphalttemperatur
Marshalldichte

Courtesy Bomag America
Roller Correlation
Generated Stiffness vs. Density

Asphalt Layer Stiffness $k_B$ [N/m]

Marshall – Compaction Degree %

ASPHALT

Swiss Federal Institute of Technology, Zurich

Division of Geotechnical Engineering
Roller Correlation
Generated Modulus vs. Density

$E_{\text{VIB}} \text{ [MN/m}^2\text{]}$ vs. Marshall density [%]
Compaction test on asphalt wearing course (SMA)

Perfect correlation:
Evib + Marshall density

Adequate conditions:
• Temperature between (170-120 °C)
• Asphalt layer on solid ground

Courtesy Bomag America
Intelligent Compaction

Depth effect

Comparison:

Rotary exciter
(no infinite variation)

Variomatic
(automatic compaction)

Courtesy Bomag America
Caterpillar
Single Drum Soils Roller
Caterpillar 2-D Mapping

Compaction Viewer
Version 1.2.31.05

Coverage

Scale Max

X: -632
Y: 272

Passes: 7
CMV: 35.96
Evib: 2.00
Energy: 2.24

R²: 0.04
slope: 1
offset: 55

Zoom Actual See All

Log Pt Export Report Export Raw Data Exit

Caterpillar CONFIDENTIAL Please do not distribute

Courtesy of Caterpillar
MnDOT TH 64 Project

Contractor QC using IC Technology
MnDOT Project
Caterpillar Display

CCV Continuously Displayed on Screen

Color-coded mapping shows highest CCV obtained at all locations

Target CCV = 42
MnDOT Project
Caterpillar Display

Roller Icon shows operator roller position

Color-coded map shows total number of roller passes at all locations

Required Number Of Passes = 5

Intelligent Compaction
Bomag America
Single Drum IC Soils Roller
Tandem Drum IC Asphalt Roller and Display Panel

Bomag America
Bomag Operational Panel

- Escape
- Enter

Courtesy of Bomag America
Intelligent Compaction

Bomag Subbase Case Study

Courtesy of Bomag America
Ammann America
Single Drum IC Soils Roller
Ammann America IC Roller Documentation System Display

Courtesy of Ammann America
Bomag BW 190AD Asphalt Manager

- 14 ton vibratory tandem drum roller
- 79” drum width
- Directional amp. (35% higher centrifugal force)
- 3 automatic and 7 manual setting modes
Sakai SW850 IC Roller

- 14 ton vibratory tandem drum roller
- 79” drum width
- Breakdown rolling: Low amplitude (0.013 in) and 4,000 vpm.

Graniterock Company, Watsonville, CA
Sakai IC Roller Measurement Device

- Thermo Gauge
- Accelerometer
- PC Display
- Controller Units
Sakai IC Roller: GPS Measuring, Recording & Mapping System

Intelligent Compaction
Sakai SW850 IC Roller Project

- Number of Roller Passes over each point of the pavement was highly variable
1. Temperature of pavement surface during breakdown rolling.
2. Variation: 270 °F to 140 °F.
1. The stiffness at the final roller pass during breakdown rolling in each location.
2. Variation: 30 to 90 MN/m² (4,350 to 13,055 PSI).

Shoulder side (Supported)

Longitudinal Joint
4,000 vpm, Low Amplitude

Distribution of roller-generated stiffness on final pass of breakdown rolling
1. Fair correlation between stiffness of last breakdown roller pass and core density ($R^2 = 0.5613$)

2. All cores were cut after finishing rolling was done.

3. Coordinates of core locations were measured by GPS with accuracy of 5 ft.
1. No correlation between stiffness and core density measured during finish rolling.
2. All cores were cut after finishing rolling was done.
3. Coordinates of core locations were measured by GPS with accuracy of 5 ft.