Intelligent Compaction – Improved Construction Technologies For Hot Mix Asphalt That Benefits Agencies And Contractors

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ABSTRACT: Practitioners in roadway construction have known for over a century that compaction of Hot Mix Asphalt (HMA) is critical to obtaining long-term performance of pavements. Currently used compaction equipment, operational procedures and density measurement protocols do not consistently result in desired compaction/density levels throughout the pavement. The use of Intelligent Compaction (IC) in the United States provides for greater control and oversight of the compaction process, which results in higher and more uniform densities. IC activities are also being utilized on in-situ or subgrade materials to establish a good working platform for HMA pavements. The Federal Highway Administration (FHWA) is managing a project to develop construction specifications and materials acceptance procedures using the IC technology. This program encourages the study and implementation of IC through cooperation with equipment manufacturers, highway contractors, state highway agencies and academia. FHWA has sponsored and is participating in state and national research to demonstrate the technology throughout the country. Data is being collected to evaluate the process and specifications are being developed to advance the technology for standard use. Field data has demonstrated the capabilities and benefits of Intelligent Compaction technology by demonstrating a significant improvement in the compaction process. IC is an innovative technology that can provide real time quality control data by evaluating the response of the supporting materials to determine the needed compaction levels. Contractors have benefited from IC by the optimization of their resources and the acceleration of activities. This paper covers the findings from the completed projects.

KEY WORDS: Intelligent Compaction, Hot Mix Asphalt, Benefits.

1 INTRODUCTION

Practitioners in roadway construction have known for almost a century that compaction of pavement materials is critical to obtaining long-term performance of the roadway. Currently used compaction equipment, operational procedures and density measurement protocols do not consistently result in desired compaction/density levels in all areas of the pavement. (Pauls, et al., 1930) Intelligent compaction (IC) is a technology that is being used in Europe and Asia that provides for greater control and oversight of the compaction process, resulting in better and more uniform compaction.

The FHWA is supporting the advancement of technology in America and has defined intelligent compaction as a process that includes vibratory rollers equipped with a measurement / control system that can automatically control compaction parameters in response to materials stiffness measured during the compaction process. The roller must also be equipped with a documentation system that allows for continuous recording of the roller location and corresponding density-related output. (Horan, et al., 2005)

According to the Oxford Dictionary, Intelligence is defined as: "…able to vary behavior in response to varying situations and requirements". The question is whether or not intelligence can be applied to compaction/density activities. Twelve State Agencies and technical experts from Industry believe that intelligent equipment can be developed to collect, analyze, make an appropriate decision regarding the information and then execute the decision 3000 to 4000 times a minute on various types of materials. (Gallivan, et al., 2007, 2008, 2010) This paper represents the evaluation of field demonstrations in multiple states in the US.

The Federal Highway Administration is working with State Agencies through a pooled fund project TPF-5(128) to accelerate the implementation of Intelligent Compaction Technology in Soils, Aggregates and Hot Mix Asphalt pavement materials. (Gallivan, et al., 2008)

2 IC CASE STUDIES

A summary of the findings from six (6) case studies for various hot mix asphalt (HMA) construction projects are described in this paper and more details can be found on the US FHWA/TPF IC website: www.IntelligentCompaction.com. A summary of the case studies is presented in Table 1.

Table 1: Summary of IC Case Studies.

Location	Dates	Materials/Construction	IC Rollers
Minnesota	June, 2008	HMA overlay & new construction	Sakai
New York	May, 2009	HMA new construction	Sakai
Mississippi	July, 2009	HMA new construction	Sakai
Maryland	July, 2009	SMA overlay	Sakai and Bomag
Georgia	Sept, 2009	New HMA construction	Sakai
Indiana	Sept, 2009	HMA overlay	Sakai and Bomag

The Sakai and Bomag tandem IC roller used in the case studies are shown in Figure 1. The features of this roller are described in Table 2. The Sakai roller measurement value (RMV) is called Compaction Control Value (CCV) while the Bomag's RMV is called Vibration Modulus values, (E_{vib}). (Sakai, 2000) (Scherocman, et al., 2007)

Figure 1: Sakai (left) and Bomag (right) Tandem Drum IC Rollers.

Table 2: Features of the Sakai and Bomag Tandem IC Rollers.

Manufacturer	Sakai America, Inc.	Bomag America, Inc.
Model Name	Exact Compact System (ECS)	VarioControl
Model Number	SW880	BW 278AD-4
Drum Width	79”	78’’(front) and 48”(rear) dia. x 78” wide
Machine Weight	29,560 lbs (~ 14 tons)	25,000 lbs. (~ 13 tons)
Amplitude Settings	0.13”, 0.25” (3.3 to 6.4 mm)	0.019’’ (low) and 0.029’’(high)
Frequency Settings	2520, 3000, 4020 vpm	3,400, 4,000 vpm
Auto-Feedback	No	Yes
Measurement System	CCV with temperature and passes mapping	E_{vib} with temperatures and passes mapping
Measurement Value	Compaction control value (CCV)	Vibration Modulus E_{vib}
Measurement Unit	Unit less	MN/m^2
GPS Capability	Yes	Yes
Documentation System	Compaction Information System (CIS)	BCM 05 Office and Mobile

IC rollers are dependent on the operation of a Global Positioning System (GPS) to track the roller position during operations in order to understand real-time compaction operations. The GPS system allows for the color-coded display of roller-integrated measurement values (RMV), roller pass counts, infrared temperature sensor readings for surface temperatures and a laptop computer for real time computations and analysis. (Gallivan, et al., 2008, 2010)

The Universal Transverse Mercator (UTM) Coordinate system has been used successfully for the research project in the US. A real-time kinematic RTK GPS base station that acquires northing, easting, and elevation data and broadcasts updated correction data to the rollers is a key element for mapping operations. The GPS system for the IC field demonstrations has also included hand-held rover units for the identification of the locations of traditional testing for subsequent correlations to the IC roller RMV data. All of the field demonstrations to date have utilized the Trimble GPS system. (Chang, et al., 2007, 2009, 2010) The field demonstrations have had a survey GPS tolerance of less than 40 mm in both horizontal and vertical directions. The GPS system has been found to be sufficiently rugged and accurate for IC HMA operations. Alternative GPS manufacturers are also going to be evaluated as part of the research project.

2.1 Field Demonstration Findings

IC field demonstrations have been completed on six (6) HMA pavement projects in the US and have demonstrated an improvement in the compaction process on all of them. The HMA portion of the projects have been constructed using either a 9.5 mm, 19 mm, 25.0 mm HMA mixtures or a 9.5 mm SMA mixture. Mixture designations are based on the AASHTO Nominal Maximum Aggregate Sizes (NMAS). (AASHTO, 2009) The mixtures have included up to 30% of Reclaimed Asphalt Pavements (RAP), with and without milling of the existing surfaces, and/or placed on a stabilized granular base material.

The research has shown that IC technology can be used to obtain improved and more consistent rolling operations. This is especially valuable during night time paving where the operator does not have any visual references of previously rolled areas. The IC display provides for real-time coverage of the operation since the operator can locate the roller position and count the number of passes completed over a given part of the pavement. The IC display can also show the surface temperatures in real-time.

Training of field personnel should be considered as two categories, i.e., roller operator, and field superintendent. IC rollers have similar functions to activate the amplitude or frequency controls on non-IC rollers and as a result the training of the operator has been nominal. In-addition, the understanding of the display operations has also been nominal. Training for the field superintendents regarding the capabilities of the IC roller has not been an issue.

2.2 Significant findings from the various IC field demonstrations include:

2.2.1 Pavement Structure Evaluations (Chang, et al., 2007, 2009, 2010)

a. RMV is affected by the vibration frequency, roller pass, amplitude, and material temperatures.
b. A pavement section with premature failure of the asphalt base course was verified to be within a weak spot identified during mapping of the subbase using lower frequency (2,500 vpm) and higher amplitude (0.6 mm). This area is located within the area where the subgrade layer reportedly "failed" under the test rolling in summer 2007, and is an area identified on NRCS soil survey maps consisting of peat/muck soils. This finding is significant and meaningful for both agencies and contractors.
c. The measurement values between different pavement layers correlated well, which indicates that a stiff or soft layer underneath could significantly affect the compaction results for the upper layers reflected by the RMV.
d. The Geostatistics of semi-variogram analysis indicates that the HMA base course has higher compaction uniformity than that of the subbase layer, which sounds reasonable since the compaction was improved from the lower subbase course to the upper HMA base course to achieve a more uniform compaction. Semi-variogram is anticipated to be included in standard IC reports to assess uniformity.
e. The compaction uniformity, indicated by the RMV semi-vairogram, has significantly improved from the existing HMA pavements to the fresh SMA overlay.

2.2.2 Roller Operations/Mapping (Chang, et al., 2007, 2009, 2010)

a. The Sakai IC double drum roller was used to successfully map the existing prime-coated cement-stabilized subbase at different cured stages. Relatively soft spots were easily identified with the IC maps. The strength gain of cement-stabilized subbase was reflected on the IC maps after the compaction was performed.

b. The IC rollers effectively track the roller passes, HMA surface temperature, and the RMV which provides useful information for operators to control and adjust compaction efforts toward a more uniform compaction.
c. The Sakai CCV displayed on the screen allowed the operator to see in real time the relatively softer and stiffer areas of the entire roadway during compaction. The rolling patterns were drastically improved after the operator was trained to use the IC features.
d. Using IC rollers for night paving during the Maryland demonstration project was very successful. The IC technologies, such as tracking roller passes and coverage, were exceptionally useful under low visibility. This demonstrates significant benefits for both agencies and contractors to maintain consistent rolling patterns for night-time paving.
e. The Sakai double-drum IC roller and Bomag double-drum IC roller were used successfully to map the existing HMA surface prior to the SMA overlay at the Maryland demonstration. Both the IC rollers can be used to map the milled asphalt pavements prior to paving the HMA overlay.
f. The Bomag IC mapping of the existing asphalt shoulders at the Maryland demonstration showed lower vibration amplitude settings which results in higher vibration modulus values (E_{vib}).
g. The Bomag E_{vib} values on the milled HMA surface are higher than that of the HMA shoulder, indicating that the former is a stronger pavement structure.
h. Sakai and Bomag IC mappings of the existing HMA pavements have indicated relatively lower RMV on the shoulder than those of the pavement lane. RMV from both IC machines can also identify soft or stiff support consistently.
i. The Georgia project successfully demonstrated the ability of the IC roller to map the existing granular subbase and the compaction of HMA.
j. The moisture of graded aggregate base (GAB) at the Georgia project was found to have significantly affected the CCVs based on the mapping data. Therefore, it is recommended to pave the HMA layer when the GAB is in “drier” condition.

2.2.3 Testing Operations (Chang, et al., 2007, 2009, 2010)

a. The RMVs and nuclear/non-nuclear gauge test results of asphalt density have inconsistent trends. The trends may have been the result of multiple variables including the effective temperature variation, roller passes, vibration amplitude and frequency. Note that the factors affecting HMA density may also include the mixture properties, construction machines and compaction.
b. The RMVs and nuclear gauge test results of HMA density seem to have linear relationships with a relatively low correlation. There are many potential causes of this poor correlation including the influence zone of RMV (the whole pavement system rather than a single HMA layer), effective temperature variation, roller passes, vibration amplitude and frequency. Note that the factors affecting HMA density may also include the mixture properties, construction machines and compaction, and improperly maintained nuclear gauges.
c. At the Georgia project the densities of HMA core samples correlated to CCVs.

d. The Sakai CCV on the existing HMA pavements correlates satisfactorily with the Falling Weight Deflectormeter (FWD) deflections and back-calculated layer moduli of the existing HMA pavements.
e. The HMA modulus values measured by the Portable Seismic Property Analyzer (PSPA) did not appear to have a linear relationship with the FWD back-calculated layer moduli or the Sakai CCVs.
f. The nuclear density gauge readings and non-nuclear density gauges measurement values did not correlate with each other or with the IC roller.
g. With the use of both Bomag and Sakai IC rollers, the non-nuclear density gauge measurements increase with increasing roller pass numbers.
h. Low Sakai CCVs on the GAB reflected on low CCVs on the HMA layer.
i. The FWD measured deflection and modulus correlate well with the RMVs of HMA base course, indicating the reflective effect of the lower layers on the overall stiffness of the multiple layers.
j. The measured LWD deflections and derived CBR did not correlate with the CCVs on the HMA layer.
k. The FWD deflections and back-calculated moduli of the GAB layer are correlated to CCVs at some test beds but not at others. Further investigation is warranted.
l. The measured Light Weight Deflectometer (LWD) deflections and derived CBR values do not correlated to CCVs on the HMA layer.
m. The FWD deflections at HMA surfaces corresponding to the underlying concrete slab joints are higher than those at HMA surfaces corresponding to slab centers. The weaker support at the concrete slab joints and the FWD deflections on milled HMA are higher than those at the HMA surface overlay.

2.3 Correlation of IC Data to Standard Testing Data

Bomag America, Inc., and Sakai America, Inc. have two different dimensionless measurement methods to evaluate the “stiffness” of the substrate materials. Intelligent Compaction demonstrations on HMA have confirmed that the RMVs are only computed values based on the accelerometer data obtained from the roller drum and the roller configuration using various algorithms. (Furuya, et al., 2010) It is important to understand that the RMVs represent a relative value of the stiffness computed from the acceleration data and is not an absolute value.

One of the variables in stiffness correlation that has to be considered is the influence depth of the IC rollers. Typical HMA density measurements, whether determined from core tests or nuclear density gauges, have an influence depth of 0.3 m or less whereas the IC roller influence depth exceeds 2.0 m. The IC RMV for any particular HMA layer includes the accelerator response(s) from the subgrade, subbase and/or previous HMA layers into a single value. This value is a different single value obtained either by coring or nuclear testing devices that we understand to be the “density” of the HMA layer. For example, a Sakai CCV value of 4 and a Bomag E_{vib} value of 20 and a maximum theoretical density value of 92 percent could be equal. These single values only represent what the material is at the time of the reading.

Another variable that has to be understood is the IC RMV data itself and what it represents. This data is obtained from the single average value obtained from full width of the roller i.e., 200 cm to that of a core diameter of 1.50 cm. With the IC roller, an improved understanding of the stiffness of the material(s) is achieved as more material is being represented. Again, the result from an IC roller is a computed value and is not an absolute value.

Lastly, another factor that has to be considered is the temperature of the mixture at the time of compaction. Current temperature technologies are recording the surface reading from a single point on the roller. It would be more desirable to measure or at least estimate the internal temperature. Research efforts continue to develop and to evaluate alternative processes to understand and monitor the mixtures internal temperatures during rolling operations.

2.4 Benefits to Contractors

Contractors benefit from Intelligent Compaction technology with the optimization of resources (equipment and personnel) to achieve the specified density, real time knowledge of the status of roller operations, improved process control documentation that includes vibration frequency, roller passes, amplitude, and material surface temperatures. The contractor also gains knowledge of the stiffness of the underlying pavement materials as well as easy tools for the roller operator to use, especially at night. Training of field operators has been shown to be successful without extensive learning curves due to the ability to "visually" show the capabilities of the equipment. (Horan, 2010)

The evidence of immediate benefits for contractors is in the improvement of rolling patterns. Significant differences between the rolling patterns "Before" and "After" using IC technologies have occurred on all field demonstrations. In Figure 2, the "Before" represents the number of passes on the pavement before the utilization of the IC information. The graphing displays inconsistent and incomplete number of roller passes on the full width of the pavement. The "After" represents the number of passes on the pavement by the same roller operator after training on the operation of the IC roller and represents significant improvements in the roller consistency of the passes.

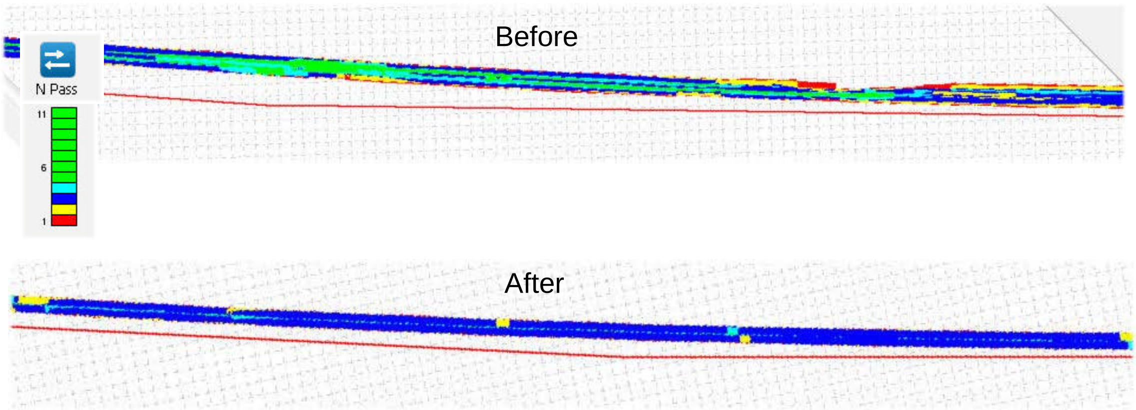

Figure 2: Improvement of rolling patterns using the IC technologies.

Minimal or inconsistent rolled areas are easily identified in the top portion of Figure 2 when the IC roller is set to display the number of passes. Consistent rolling as shown in the lower portion resulted in an improvement in the specified compaction.

2.5 Benefits to Agencies

The agencies benefit from IC technology with improved densities on HMA mixtures. IC operations have been demonstrated to be valid for different aggregate sizes of HMA base, intermediate or surface mixtures of traditional hot mix or warm mix, or stone mastic asphalt mixtures. IC operations have also been demonstrated to work with or without RAP or milling operations. IC technology can provides agencies the knowledge that 100% of the materials placed by the contractor meet an RMV that correlates to a target stiffness value for the project instead of a random spot check for density. (Xu, et al., 2010)

The IC roller can effectively track the location of the rollers in real time and identify subsurface weak spots giving the agency the opportunity to minimize future problems which leads to longer pavement performance.

IC technology may lead to the reduction of Quality Assurance (QA) acceptance testing using traditional testing methods due to the improved knowledge of the actual rolling operations and coverage by the contractor. Research efforts continue to evaluate the reliability of IC data for potential use in the acceptance process through wireless protocols.

2.6 Future of Intelligent Compaction

IC is an innovation that will transform the industry in the next five years. Contractors are adopting IC technology due the benefits achieved in the compaction process without agencies specifying it.

3 CONCLUSION AND RECOMMENDATIONS

Intelligent compaction field demonstrations on HMA in the US have shown to be successful in achieving improved compaction which leads directly to higher and more uniform pavement densities, improved payment with less penalties to the contractors, and improved long-term performance of the pavements. IC with GPS technology has also been successful in improving the roller operator's ability to provide full roller coverage of the pavement in addition to the added benefit of knowing where the roller during nighttime operations. Mapping of the underlying materials prior to asphalt pavement placement has demonstrated the ability to identify weak areas which allows for timely remediation prior to paving. On all field projects, roller operators have readily learned how to operate IC rollers and have recognized that IC technology provides them a valuable tool that they can use effectively to improve the compaction process. Nuclear and non-nuclear density gauge measurements of HMA overlay do not correlate with IC technologies. IC technology is also being evaluated on in-situ or subgrade materials as part of the FHWA efforts and has been found to be very successful.

Intelligent Compaction processes for Hot Mix Asphalt have been successful on multiple mixture types, new construction projects, rehabilitation and resurfacing type construction projects and in daylight and nighttime working conditions using multiple manufacturers' equipment.

3.1 Recommendations

a. Validation of the IC Global Positioning System (GPS) setup prior to the compaction operation using a survey grade GPS hand-held unit is crucial to providing precise and correct measurements. The process should require IC rollers moving forward and backward to validation locations.
b. A RTK GPS base station that acquires northing, easting, and elevation data and broadcasts updated correction data to the rollers is a key element for the mapping operations.

c. Wireless transmission of the RMVs needs to be advanced as the final step of IC to facilitate contractor’s process control monitoring of the roller operations and agencies acceptance procedures.
d. To correlate in-situ tests with IC data, in-situ test locations must be established using a hand-held GPS “rover” unit that is tied into the project base station and offers survey grade accuracy.
e. It is highly recommended to perform IC measurements (mapping) of the underlying layers prior to the paving of upper layers in order to identify possible weak spots and facilitate the interpretation of the measurements on the asphalt surface layers.
f. Long-term pavement performance monitoring is recommended in order to identify performance trends that may relate to RMVs.
g. Indicators of undesirable IC measurement conditions (such as bouncing, sudden start/stop, etc.) are strongly recommended to be stored in order to filter out invalid IC data.
h. Standardization of procedures related to IC data collection, data analysis and data management is strongly recommended to accelerate the implementation IC for State agencies. The recommended items include: a standard IC data storage format, an independent viewing/analysis software tool, and detailed data collection plan (include any in-situ/lab test results).
i. Further investigation on a global scale (e.g., segment-by-segment analysis of entire paved sections) is recommended to provide guidance of usage of IC mapping data on existing pavement layer with subsequent IC measurements during HMA paving. This would include: setting a target RMV value from test trip data based on the onsite support condition and asphalt job mix formula.

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