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Intelligent Compaction of Soils and Flexible Pavements

Prepared for
Wisconsin Highway Research Program
Flexible Pavements and Geotechnics Technical Oversight Committees

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Transportation Literature Searches are prepared for WisDOT staff and principal investigators to heighten awareness of completed research in areas of current interest. The citations below are representative, rather than exhaustive, of available English-language studies on the topic. Primary online resources for the literature searches are OCLC's WorldCat and TLCat, U.S. DOT's TRIS Online, the National Transportation Library (NTL), TRB's Research in Progress (RiP) and other academic, engineering and scientific databases as appropriate. Links to online copies of cited literature are noted when available. Hard copies may be obtained through the WisDOT Library at library@dot.state.wi.us or 608-264-8142.

SUMMARY

In our search of the above databases, we found 22 reports or articles pertaining to the intelligent compaction of soils and asphalt pavements, and another four projects in progress.

Of these, two trade news articles focus on **Geotechnics and Flexible Pavements** applications of intelligent compaction. Fourteen studies and articles pertain to **Geotechnics** alone, and six pertain only to **Flexible Pavements**.

Intelligent compaction is clearly in its infancy in the United States; all relevant citations date from 2002 to 2006. We found two each in 2002 (one focused on soils, one on asphalt pavement) and 2003 (both on soils), four from 2004 (one on both pavement and soils, two on soils only, one on pavement only), three from 2005 (two on soils, one on pavement), and 11 from 2006 (one on both soils and asphalt pavement, seven on soils only, and three on asphalt only).

Of the 14 geotechnics-only citations, three are from federal documents, six from state transportation agency and university reports (three from Minnesota, two from Iowa and the Center for Transportation Research and Education, and one from Texas A&M University), and five from conference proceedings or academic journals.

Of the six flexible pavements citations, one comes from a federal publication, one from a conference proceeding, and the remaining four from trade news sources.

Three of the four **Research in Progress** projects have state-specific sources—the Virginia Transportation Research Council and Virginia DOT, CTRE and Iowa DOT, and Kansas DOT. The remaining project has a nationwide scope, and is driven by the National Cooperative Highway Research Program.

KEYWORDS

Intelligent, compaction, soil, asphalt, flexible, pavement.

CITATIONS – GEOTECHNICS and FLEXIBLE PAVEMENTS

Title: Intelligent compaction: The next big thing?
Author(s): Dick Kronick
Date: Fall 2006
Doc ID/URL: *Technology Exchange* (Newsletter of the Minnesota Local Technical Assistance Program), Vol. 14 (4), Fall 2006: 1, 4. http://www.mnltap.umn.edu/publications/exchange/2006-4/2006-4-1-1.html
Description: 2 pp.
Contents: This article describes three methods and equipment for intelligent compaction of soil and asphalt at sites in Minnesota, and its information is drawn from pages 12-13 of *Minnesota Pavement Conference: Session*

Summaries (St. Paul, Minn.: University of Minnesota, LTAP, Feb. 16, 2006), which can be viewed at http://www.mnltap.umn.edu/pdf/2006PaveConSummary.pdf.

Title: Never guess again: Intelligent compaction making precision commonplace at the jobsite
Author(s): B. Wilson
Date: August, 2004
Doc ID/URL: *Roads and Bridges*, Vol. 42 (8): 22-25.
http://www.roadsbridges.com:80/rb/index.cfm/powergrid/rfah=|cfap=/CFID/3211407/CFTOKEN/89068603/fuseaction/showArticle/articleID/5396
Description: 4 pp.
Contents: This article focuses on intelligent compaction systems that take the guesswork out of soil or asphalt compaction. These systems automatically measure and control the energy output of a roller's drum. Although each manufacturer's system has its own specific method of execution, they all generally function in the same way by measuring and reacting to the changing stiffness of the material being compacted. The compaction systems use devices such as accelerometers to measure both the horizontal and vertical reaction of the drum to the material it is compacting. The systems then actually control the output of the drum. The process, which is known as vectoring, involves a microprocessor that calculates the accelerometer's gathered data and then redirects the energy of the drum to avoid over-compaction. Several of these intelligent compaction systems also include an asphalt mat temperature sensing capability that help (sic) in achieving error-free applications. Additional benefits associated with intelligent compaction systems include a longer service life for equipment, increased efficiency, and the documentation of jobsite results through on-board printers.

CITATIONS – GEOTECHNICS

Title: Field Evaluation of Compaction Monitoring Technology, Phase II
Author(s): David J. White, Mark J. Thompson, Kari Jovaag, Edward J. Jaselskis, Vernon R. Schaefer, E. Thomas Cackler
Date: March 2006
Doc ID/URL: CTRE Project 04-171, Final Report. http://www.ctre.iastate.edu/reports/compaction_2.pdf
Description: 209 pp.
Contents: This report documents an extensive field program carried out to identify the relationships between soil engineering properties, as measured by various in situ devices, and the results of machine compaction monitoring using prototype compaction monitoring technology developed by Caterpillar Inc. Primary research tasks for this study include the following: (1) experimental testing and statistical analyses to evaluate machine power in terms of the engineering properties of the compacted soil (e.g., density, strength, stiffness) and (2) recommendations for using the compaction monitoring technology in practice. The compaction monitoring technology includes sensors that monitor the power consumption used to move the compaction machine, an on-board computer and display screen, and a GPS system to map the spatial location of the machine. In situ soil density, strength, and stiffness data characterized the soil at various stages of compaction. For each test strip or test area, in situ soil properties were compared directly to machine power values to establish statistical relationships. Statistical models were developed to predict soil density, strength, and stiffness from the machine power values. Field data for multiple test strips were evaluated. The R2 correlation coefficient was generally used to assess the quality of the regressions. Strong correlations were observed between averaged machine power and field measurement data. The relationships are based on the compaction model derived from laboratory data. Correlation coefficients (R2) were consistently higher for thicker lifts than for thin lifts, indicating that the depth influencing machine power response exceeds the representative lift thickness encountered under field conditions. Caterpillar Inc. compaction monitoring technology also identified localized areas of an earthwork project with weak or poorly compacted soil. The soil properties at these locations were verified using in situ test devices. This report also documents the steps required to implement the compaction monitoring technology evaluated.

Title: Intelligent Compaction: A Minnesota Case History
Author(s): F. Camargo, B. Larsen, B. Chadbourn, R. Roberson, J. Siekmeier
Date: February 2006
Doc ID/URL: *54th Annual University of Minnesota Geotechnical Conference*, February 17, 2006.
http://www.mrr.dot.state.mn.us/research/mnpave/MnGeotechIC011006final.pdf
Description: 20 pp.
Contents: Intelligent Compaction (IC) uses an instrumented roller to provide continuous, real time verification of in situ soil properties over the entire compaction area. Ammann, Bomag and Caterpillar compactors were used on three trunk highway projects in Minnesota during 2005. The objective of this study was to compare quality control data

from an IC roller with quality assurance data collected from several hand-held field-testing devices. The results demonstrate the potential of IC technology for use as quality control during construction. This case history discusses the field study results and makes recommendations for IC implementation in 2006.

Title: Intelligent compaction control
Author(s): M. Hossain, J. Mulandi, L. Keach, M. Hunt, S. Romanoschi
Date: 2006
Doc ID/URL: *Proceedings of the 2006 Airfield and Highway Pavement Specialty Conference*, Vol. 2006: 304-316.
Description: 13 pp.
Contents: The Intelligent Compaction Control (ICC) consists of continuous compaction control/monitoring compaction using rollers with adjustable compaction energy (amplitude, frequency, and roller speed). In ICC, a number of parameters are measured: displacements/amplitude of the roller (up and down) using the drum mounted accelerometer, frequency, roller speed, and various relative bearing capacity or equivalent stiffness/density values. This paper gives an introduction to ICC and application of ICC for highway embankment projects in Kansas. Three test sections on two routes were compacted using a Bomag Variocontrol (BVC) intelligent roller that produces real time stiffness values of compacted soil. Traditional compaction control measurements included density testing using a nuclear gage, moisture measurements using a speedy moisture tester, and soil bearing capacity measurements using a Dynamic Cone Penetrometer (DCP). The results showed that the intelligent compaction (IC) roller continuously measured the stiffness of soil under compaction and thus, was able to identify locations with lower stiffness in the spatial direction. In general, density increased with multiple passes of the IC roller. The IC roller stiffness was fairly sensitive to the moisture content and the percent compaction obtained in the field. Poor correlation was observed between the BVC stiffness and the CBR values calculated from the DCP results.

Title: Intelligent compaction and in-situ testing at Mn/DOT TH53
Author(s): D. Lee Petersen, Ryan Peterson
Date: 2006
Doc ID/URL: MN-RC-2006-13, Final Report. http://www.lrrb.org/PDF/200613.pdf
Description: 50 pp.
Contents: This report describes an intelligent compaction demonstration project on Mn/DOT TH 53 in Duluth, MN, and the associated field and laboratory testing. The project was conducted during September 2005, using a Caterpillar Model CS-563E vibratory soil compactor, equipped with Intelligent Compaction (both Compaction Meter Value (CMV) and energy or power) and global positioning system (GPS) technology. A Prima light-weight deflectometer (LWD), dynamic cone penetrometer (DCP) and Humboldt GeoGauge were used to collect in situ companion test data at 42 locations. Mn/DOT conducted gradation, moisture content and Procter tests. Location and Compaction Meter Value (CMV) were downloaded for comparison with the in situ testing. CMV data was compared to the in situ data on a point-by-point basis and on the basis of the overall distribution. In general, poor correlations were obtained on a point-by-point basis, likely due to the depth and stress dependency of soil modulus, and the heterogeneity of the soils. Good correlations were obtained between CMV values and DCP measurements for depths between 8-inches and 16-inches deep. The Caterpillar Compaction Viewer software, although still in development at the time of testing, is functional and is well integrated with GPS. It is easy to extract data and do more sophisticated analyses. Surface-covering documentation adds value by identifying potential problem areas where compaction is limited by material, moisture or subgrade deficiencies. LWD testing protocol must be followed to obtain useful results, since measurements vary significantly between successive tests. Relatively good correlations were obtained between LWD and GeoGauge. The GPS technology used for the demonstration is not adequate to distinguish between lifts.

Title: Intelligent Soil Compaction: Technology, Results, and Roadmap
Author(s): Charles R. Nelson, David Lee Petersen, John Siekmeier, Ryan L. Peterson
Date: 2006
Doc ID/URL: Report No. 06-2914, TRB Annual Meeting 2006 CD-ROM.
http://www.mdt.mt.gov/research/docs/trb_cd/Files/06-2914.pdf. See slideshow,
http://www.mrr.dot.state.mn.us/research/ictgi/trb_Presentation_2006_version4.pdf.
Description: 14 pp.
Contents: Intelligent Compaction, also called Continuous Compaction Control, is a new technique in the United States construction market that uses an instrumented compactor to control soil or asphalt compaction in real time. This paper focuses on compaction of unbound materials. This technology provides one of the first opportunities to apply process control to civil construction. Intelligent Compaction (IC) is based on measuring the mechanical characteristics of the compacted soil, commonly soil stiffness but other properties are also used. Initiatives in both the U.S. and Europe, started more than 10 years ago, have demonstrated the technical viability of measuring in situ

soil stiffness. The measured soil stiffness is used to estimate or compute in situ soil modulus, based on assumptions about soil behavior and the interaction between the compaction machine and the soils. Intelligent Compaction offers immense potential benefits in embankment, buried structure, dam and pavement construction. These benefits, including improved quality, reduced compaction cost, reduced life-cycle cost and the integration of design with construction and maintenance, arise from surface-covering documentation and process control of the compaction operation.

Title: Compaction monitoring using intelligent soil compactors
Author(s): R. Anderegg, Dominik A. Von Felten, Kuno Kaufmann
Date: 2006
Doc ID/URL: *GeoCongress 2006: Geotechnical Engineering in the Information Technology Age*, February 26-March 1, 2006, Altanta, Georgia: 41.
Description: 1 p.
Contents: The nonlinear vibrations of dynamic soil compactors are taken as the basis for feedback control systems for intelligent compaction. According to the achieved compaction, the parameters of the soil compactor are continuously changed. The vibratory roller measures the stiffness of the subgrade. In conjunction with GPS-data, this measurement can be used as a QA/QC tool. The stiffness data are directly correlated to plate bearing test. In practice, the intelligent compaction ensures that the compaction job is completed in a minimum number of passes, the result is monitored and the compaction energy is automatically adjusted while measuring the soil stiffness. Copyright ASCE 2006.

Title: Power-based compaction monitoring using vibratory padfoot roller
Author(s): David J. White, Max Morris, Mark Thompson
Date: 2006
Doc ID/URL: *GeoCongress 2006: Geotechnical Engineering in the Information Technology Age*, February 26-March 1, 2006, Altanta, Georgia: 44.
Description: 1 p.
Contents: Controlled test sections were constructed using a prototype CP-533 vibratory padfoot roller to evaluate relationships between machine drive power and measures of soil compaction. Machine power determined from internal sensors and number of roller passes was logged nearly continuously during construction of the test sections using an onboard computer and GPS mapping system. In this paper, machine power results are compared to spot measurements of nuclear density gauge moisture/density and dynamic cone penetration (DCP) index measurements. A framework for statistically analyzing power-based compaction monitoring data is presented with broader implications for other intelligent compaction and continuous compaction control systems that generate near continuous spatial data. Copyright ASCE 2006.

Title: Vibratory plate loading of compacted and instrumented field soil beds
Author(s): Michael A. Mooney, Cyril O Bouton
Date: May 2005
Doc ID/URL: *Geotechnical Testing Journal*, Vol. 28 (3), May 2005: 221-230.
Description: 10 pp.
Contents: The paper reports on full scale vibratory plate loading tests that were performed to investigate nonlinear plate and soil acceleration response when subjected to various plate loading frequencies and amplitudes. The focus of this paper is on characterizing the vibration response upon compacted soil, a reference state for intelligent compaction.

Title: Continuous compaction control: MnROAD demonstration
Author(s): D. Lee Petersen
Date: 2005
Doc ID/URL: Final report, MN-RC-2005-07, St. Paul, Minn.: Minnesota Department of Transportation, Office of Research Services, 2005. http://www.lrrb.gen.mn.us/PDF/200507.pdf
Description: 132 pp.
Contents: In September 2004, engineers conducted a Continuous Compaction Control (CCC) demonstration at MnROAD, an outdoor pavement test facility. Continuous Compaction Control (CCC), also called Intelligent Compaction (IC), is a new technique in the United States construction market that uses an instrumented compactor to measure soil or asphalt compaction in real time and adjusts compactive effort accordingly to control the level of compaction. This demonstration used the BOMAG Compactor and focused on Young's soil modulus as the soil parameter of interest. CCC may potentially provide substantial benefits, including improved quality due to more uniform compaction, reduced compaction costs because effort is applied only where necessary, reduced life-cycle

cost due to longer pavement life, and a stronger relationship between design and construction. State departments of transportation have expressed interest in exploring this method as a way of meeting quality-assurance requirements within a tight budget environment. In general, this study found CCC to be an effective quality-control mechanism for soil compaction. However, further questions arose as a result of the study and certain variables affected the results and measurements, including moisture content and the use of different measurement tools. Further research is needed to determine the level of uniformity in using CCC and the extent of reliability in achieving target values when using this method.

Title: Field Evaluation of Compaction Monitoring Technology, Phase I
Author(s): David J. White, Edward J. Jaselskis, Vernon R. Schaefer, E. Thomas Cackler, Isaac Drew, Lifeng Li
Date: September 2004
Doc ID/URL: Iowa DOT Project TR-495, Final Report. http://www.ctre.iastate.edu/reports/tr495.pdf
Description: 93 pp.
Contents: This Phase I report describes a preliminary evaluation of a new compaction monitoring system developed by Caterpillar, Inc. (CAT), for use as a quality control and quality assurance (QC/QA) tool during earthwork construction operations. The CAT compaction monitoring system consists of an instrumented roller with sensors to monitor machine power output in response to changes in soil-machine interaction and is fitted with a global positioning system (GPS) to monitor roller location in real time. Three pilot tests were conducted using CAT's compaction monitoring technology. Two of the sites were located in Peoria, Illinois, at the Caterpillar facilities. The third project was an actual earthwork grading project in West Des Moines, Iowa. Typical construction operations for all tests included the following steps: (1) aerate/till existing soil; (2) moisture condition soil with water truck (if too dry); (3) remix; (4) blade to level surface; and (5) compact soil using the CAT CP-533E roller instrumented with the compaction monitoring sensors and display screen. Test strips varied in loose lift thickness, water content, and length. The results of the study show that it is possible to evaluate soil compaction with relatively good accuracy using machine energy as an indicator, with the advantage of 100% coverage with results in real time. Additional field trials are necessary, however, to expand the range of correlations to other soil types, different roller configurations, roller speeds, lift thicknesses, and water contents. Further, with increased use of this technology, new QC/QA guidelines will need to be developed with a framework in statistical analysis. Results from Phase I revealed that the CAT compaction monitoring method has a high level of promise for use as a QC/QA tool but that additional testing is necessary in order to prove its validity under a wide range of field conditions. The Phase II work plan involves establishing a Technical Advisor Committee, developing a better understanding of the algorithms used, performing further testing in a controlled environment, testing on project sites in the Midwest, and developing QC/QA procedures.

Title: Intelligent compaction with vibratory rollers: feedback control systems in automatic compaction and compaction control
Author(s): Roland Anderegg, Kuno Kaufmann
Date: 2004
Doc ID/URL: *Transportation Research Record 1868*, 2004: 124-134.
Description: 11 pp.
Contents: Dynamic compactors with parameters that adjust automatically to the condition of the subgrade form the basis for intelligent compaction. Dynamic soil compactors create nonlinear vibrations, and the typical characteristics of these vibrations are taken as the basis for the feedback control system for intelligent compaction. With the model of the machine and the soil as the starting point, the periodic loss of contact between the drum and the subgrade is postulated to be the main nonlinear effect. This nonlinearity leads to near periodic and subharmonic vibration phenomena, and it can bring about unstable drum dynamics. The machine behavior can be investigated with the help of the chaos theory. Feedback control systems for rollers are based on the results from the theory of nonlinear oscillations, and they allow optimal compaction performance thanks to continuous adjustment to the compaction status. Starting with large amplitudes and low frequencies, the automatic control system ensures a good depth effect. As the compaction increases, the frequencies rise and the amplitudes are automatically reduced; those actions lead to optimal surface layer compaction at the end of the process. The soil stiffness measurement, which is performed in parallel with the automatic control, is directly correlated with the plate-bearing test to enable continuous compaction control. In conjunction with a documentation system, intelligent compaction makes it possible to prove the homogeneity and the achieved compaction degree. In the field, intelligent compaction ensures that compaction jobs are completed in a minimum number of passes and allows monitoring of results as work progresses. In addition to optimal compaction with no risk of overcompaction, laboratory costs are reduced and process reliability is maximized.

Title: Intelligent Compaction: Overview and Research Needs
Author(s): Jean-Louis Briaud, Jeongbok Seo
Date: December 2003
Doc ID/URL: Texas A&M University, 2003.
http://www.webs1.uidaho.edu/bayomy/trb/afh60/IntCompaction_Briaud_September2004_.pdf
Description: 69 pp.
Contents: There are a number of research needs which have to be addressed before intelligent compaction can reach its full potential in the USA. a) Demonstrate that intelligent compaction leads to better compaction than conventional compaction. Costs differences between the two techniques should be documented. b) Understand the interdependence between the modulus and the water content, as well as the shape of the modulus versus water content curve. c) Develop a simple laboratory test to obtain ahead of time the target modulus from a modulus versus water content curve; this target modulus must be verified in the field using the same test. d) Study the depth of compaction that can be achieved by various rollers for various soils. e) Study existing specifications and draft standard specifications for the USA. An approach is proposed which satisfies the ideas developed above. It consists of running the usual Proctor test in the laboratory but adding the Briaud Compaction Device test (BCD lasts 2 seconds) on top of the soil in the mold to get the modulus. This gives the target values. In the field, the instrumented roller performs intelligent compaction and is checked at chosen intervals with the BCD. The advantage of the BCD is that the same test can be run in the lab and in the field in very little time.

Title: Innovative Technology for Accelerated Construction of Bridge and Embankment Foundations in Europe
Author(s): Chris Dumas, et al
Date: September 2003
Doc ID/URL: FHWA-PL-03-014. http://international.fhwa.dot.gov/bridgeemb/BridgeEmbankment.pdf
Description: 46 pp.
Contents: In June 2002 the scan team met in Europe with technical and industry leaders representing Belgium, Germany, Italy, the Netherlands, Sweden, and the United Kingdom to identify and evaluate innovative European technologies in accelerated construction of bridge and embankment foundations. The scan team also explored opportunities for cooperative research and development and implementation of accelerated construction technology. The scan team identified and evaluated 30 technologies and 15 processes with the potential for accelerating construction in the areas of bridge foundation systems, equipment, and ground improvement methods; embankment deep foundation systems, equipment, and ground improvement methods; embankment mat foundation systems and equipment; embankment construction equipment and methods; innovative earth-retention systems; and processes and implementation methods. The report provides tabular summaries of these technologies along with a relative ranking in terms of anticipated improvements in construction time, cost, and quality. The overall goal of the scan trip is to implement technologies of best practice in the United States. With this objective clearly in mind, team members developed an implementation ranking. The technologies that were selected for immediate implementation action are: Column-supported embankments; Continuous flight auger and cased secant pile bridge foundations; Automated computer installation control and installation documentation; Self-compacting concrete.

Title: Health monitoring during vibratory compaction of soil
Author(s): Michael A. Mooney, Essam F. Tawfik, Godfrey B. Chan, Jie L. Pan
Date: 2002
Doc ID/URL: *Proceedings of SPIE, The International Society for Optical Engineering, Smart Structures and Materials 2002: Smart Systems for Bridges, Structures, and Highways*, March 18-20, San Diego, Calif., Vol. 4696, 2002: 112-123.
Description: 12 pp.
Contents: Vibratory compaction is a proven and commonly adopted densification technique applicable for a wide variety of soil types and compositions. There is a clear need to develop performance-based intelligent vibratory soil compaction techniques wherein the state of the soil is determined during compaction (i.e., health monitoring, continuous quality control). The application of vibration-based structural health monitoring strategies utilized in damage detection applications to the problem of soil compaction appears promising. A vibratory compactor (plate or drum) operating on a soil mass constitutes a coupled dynamic system. As the soil densities and its mechanical properties change, the dynamic response of the compactor will change. This paper examines the changes in dynamic response of a vibratory plate during compaction. The analysis of vibration data taken from sensors on the plate and embedded within the soil reveals clear changes in both amplitude and frequency components that provide insight into the evolving nonlinear response of the system.

CITATIONS – FLEXIBLE PAVEMENTS

Title: Factors Affecting Compaction of Asphalt Pavements
Author(s): Transportation Research Board
Date: September 2006
Doc ID/URL: *Transportation Research E-Circular E-C105*, September 2006.
http://onlinepubs.trb.org/onlinepubs/circulars/ec105.pdf
Description: 190 pp.
Contents: An all-day workshop at the 84th Annual Meeting of the Transportation Research Board (TRB) addressed asphalt practitioners' concerns related to specifying and achieving density during hot-mix asphalt (HMA) pavement construction. The workshop was divided into four mini-sessions with the following themes: Optimizing HMA Construction Temperatures; Recent Advances in Compaction Equipment, Including "Intelligent Compaction"; Longitudinal Joint Density; and Incentives-Disincentives for Construction Quality. The papers in this document are invited papers for this workshop.

Title: Automating asphalt compaction
Author(s): Dan Brown
Date: June 2006
Doc ID/URL: *Public Works*, Vol. 137 (7): 62-63.
http://www.pwmag.com/industry-news.asp?sectionID=770&articleID=314714
Description: 2 pp.
Contents: This article describes the state of automated asphalt compaction in terms of the improving technology in that field. As more complicated specific densities are necessary as asphalt technology improves, rollers are faced with a dilemma between increasing vibrator impact and the requisite speed with which this compaction must be made. The use of intelligent compaction systems is also discussed, which essentially monitor the stiffness of the hot mix asphalt (HMA) being laid and using that information in the compaction process. Drum physics are important to this process as well, as increasing demands on compaction specificity require more precision in the tools used. The author also writes of the soon-to-be-merged intelligent compaction technologies with global positioning systems (GPS), which has already begun to take shape in Europe.

Title: Asphalt construction: a window to the future
Author(s): Dan Brown
Date: 2006
Doc ID/URL: *Asphalt*, Vol. 21 (1): 22-26.
http://www.asphaltmagazine.com/singlenews.asp?item_ID=999&comm=0&list_code_int=MAG01-INT
Description: 5 pp.
Contents: More performance-based specifications and design-build projects will allow for greater freedom in hot mix design and construction methods. Contractors will complete large milling and resurfacing projects in record times. There will be more knowledge-based systems for delivering mix to projects, and pavers will become more automated and operator friendly. Global Positioning Systems and intelligent compaction systems will enable asphalt compactors to measure density on the go, and then send the information to an analysis center which will return information telling the roller where more compaction is needed. Warm mix asphalt will extend the paving season on both ends. The use of material transfer vehicles to remix and move asphalt from trucks to the paver will increase and, as a result, smoothness and quality control will improve. This article discusses these and other changes expected to occur in the future of asphalt construction. Specific topics covered include construction innovations, tracking and communications, intelligent paving, more uniform mix, and intelligent compaction.

Title: Computer methods in intelligent compaction
Author(s): R. Edward Minchin, Jr., David C. Swanson, H. Randolph Thomas
Date: 2005
Doc ID/URL: *Proceedings of the 2005 ASCE International Conference on Computing in Civil Engineering*, 2005: 1145-1155.
Description: 11 pp.
Contents: The term "intelligent compaction" is now heard often enough to make one believe that the method used for documenting the quality of hot-mix asphalt pavement has evolved to a more modern state than is actually the case. In fact, the current process for determining the density of an asphalt mat uses 1960's technology. The nuclear density gauge was a major break through in the mid-1960's and quickly became the state-of-the-art for measuring asphalt density. It revolutionized the asphalt paving industry because it allowed the owner of the project to check the

density of the asphalt mat much more quickly than methods used up to that time. That ability, coupled with improved asphalt production methods led to tremendous increases in constructor productivity. Now, however, the owner rarely checks the density of the asphalt mat during the paving and compaction process. The responsibility for quality control (QC) of the paving and compaction process has largely been given to the contractor. This shift in responsibility comes at a time when the construction industry as a whole is faced with the worst labor shortage in history, limiting the number of qualified QC technicians and equipment operators. Recently, researchers introduced a patented system that, when mounted on a vibratory asphalt compactor, can render an asphalt density reading (in pounds per cubic foot) every one-second in real-time. Details of the system and its successes and limitations have been documented in the literature. This paper briefly describes the system and details the essential contributions made by computer hardware and software to a successful onboard asphalt density measuring system.

Title: New mixes alter compaction technology
Author(s): Tom Kuennen
Date: September 2004
Doc ID/URL: *Better Roads*, Vol. 74 (9), September 2004: 32-46. http://obr.gcnpublishing.com/articles/sept04a.htm
Description: 13 pp.
Contents: New asphalt mix designs complicate rolling. Fortunately, a new generation of compactors is evolving which can provide ultra high vibration, and vary amplitude (force) with vibration (frequency) according to the type of asphalt and aggregate being placed, thus avoiding dangerous over-compaction. Key to the success of these equipment lie on the ability of the operator to balance the demands of new mixes and equipment technologies against the vicissitudes of weather, variations in plant mix, and out-of-spec mixes caused by nothing more than traffic jams, and still make the pavement come out perfect.

Title: Making a difference
Author(s): A. Peterson
Date: 2002
Doc ID/URL: *World Highways/ Routes du Monde*, Vol. 11 (8): 34-35, 38, 41-42.
Description: 5 pp.
Contents: Proper compaction is essential in ensuring a durable road surface. This article describes the major types of compaction rollers available, and the benefits and drawbacks of each. Vibratory asphalt compaction rollers are the most widely used. Although vibratory rollers work well for the normal thickness of a traditional asphalt wearing course, they are less suitable for compacting thinner stone mastic asphalt wearing courses. The combination of low frequency and high amplitude needed to achieve the desired density and depth of compaction for thicker layers has a tendency to over-compact thinner layers and crush their larger aggregates. An oscillating roller, which provides a horizontal alternating sheer force to achieve faster compaction, has been developed for bridge decks and other surfaces where the power of a vibratory roller can be harmful. Static rollers are also available. One promising new development is an "intelligent" roller that can monitor and adjust the amplitude according to the soil type and desired degree of compaction.

RESEARCH IN PROGRESS

Title: Intelligent Soil Compaction Systems
Principal Investigator(s): Michael Mooney, Colorado School of Mines, 303-273-3650 or mooney@mines.edu.
Start Date: 8/30/2006
RIP URL: http://rip.trb.org/browse/dproject.asp?n=11206
Sponsor Organization: NCHRP
Contents: Compaction of embankment, subgrade, and base materials is a significant portion of state highway construction budgets and is critical to the performance of highway pavements. Heterogeneity of earth materials, variability in equipment and operators, and difficulty in maintaining uniform lift thickness and prescribed moisture content combine to make desired earthwork compaction difficult to achieve. Current quality-control and quality-assurance testing devices – such as the nuclear gauge, the dynamic cone penetrometer, the stiffness gauge, and the lightweight falling weight deflectometer – are typically used to assess less than one percent of the actual compacted area. In addition each of these testing devices measures values unique to the device. Intelligent soil compaction has the potential to improve infrastructure performance, reduce costs, reduce construction duration, and improve safety. Intelligent soil compaction involves: (a) continuous assessment of mechanistic soil properties (e.g., stiffness, modulus) through compaction-roller vibration monitoring; (b) continuous modification of roller vibration amplitude and frequency, and (c) an integrated global positioning system to provide a complete GIS-based record of the earthwork site. Research findings in Europe and in the United States have shown that soil stiffness and modulus can be assessed through vibration of the compaction roller drum and that continuous monitoring, feedback, and

automatic adjustment of the compaction equipment can significantly improve the quality of the compaction process. Standard specifications for the application of intelligent compaction systems in the United States are needed. Such specifications should build on existing specifications and experience gained in Germany, Switzerland, Finland, Sweden, Japan, and other countries. The objectives of this research are to determine the reliability of intelligent compaction systems and to develop recommended construction specifications for the application of intelligent compaction systems in soils and aggregate base materials.

Title: Preliminary Field Investigation of Intelligent Compaction of HMA
Principal Investigator(s): G.W. Maupin, Virginia Transportation Research Council, 434-293-1948 or bill.maupin@vdot.virginia.gov.
Start Date: 6/1/2006
RIP URL: http://rip.trb.org/browse/dproject.asp?n=11893
Sponsor Organization: Virginia Transportation Research Council
Contents: A new roadway construction concept called intelligent compaction, IC, uses rollers that have the ability to change compaction effort as the roller drum senses the stiffness of the layer. If the stiffness measurements recorded by the roller correlate to density as expected, there is potential that the roller might be used as an acceptance tool in the future. This project is designed as a preliminary study to a national pooled fund study and will determine the correlation of density to stiffness and influence of temperature on the ability to achieve adequate stiffness/density.

Title: Field Validation of Intelligent Compaction Monitoring Technology for Unbound Materials and HMA
Principal Investigator(s): David White, Iowa State University, CTRE, 515-294-1463 or djwhite@iastate.edu.
Start Date: 10/15/2005
RIP URL: http://rip.trb.org/browse/dproject.asp?n=11386
Sponsor Organization: Minnesota Department of Transportation
Contents: New intelligent compaction technology will be evaluated at several test sites in Minnesota with the objective of increasing earthwork and asphalt pavement quality through more efficient compaction operations and innovative quality control /quality assurance (QC/QA) equipment.

Title: Demonstration of Intelligent Compaction Control for Embankment Construction in Kansas
Principal Investigator(s): Mustaque Hossain, Kansas State University, 785-532-1576 or mustak@ksu.edu.
Start Date: 7/1/2005
RIP URL: http://rip.trb.org/browse/dproject.asp?n=11029
Sponsor Organization: Kansas Department of Transportation
Contents: The objective of this research is to demonstrate the Intelligent Compaction Control (ICC) technology for performance-based specification for in-situ embankment compaction quality control.