U.S. Department of Transportation

Federal Highway Administration

Transportation Pooled Fund Program

Intelligent Compaction for Soils and Subbase Materials

TechBrief

The Transportation Pooled Fund (TPF) study, "Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base and Asphalt Pavement Material" is being conducted under TPF-5 (128). It is a three year study beginning September 2007 and ending September 2010.

Visit the IC project website for further details on IC technologies:

IntelligentCompaction.com

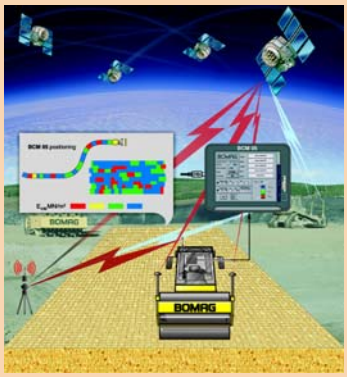
Introduction

Intelligent compaction (IC) is a construction method relatively new to the USA that uses modern vibratory rollers equipped IC components and technologies.

The IC technology and IC-related quality assurance (QA) specifications on earth work has existed in Europe for more than 20 years. Under the on-going FHWA/TPF IC studies, various single drum IC rollers from manufacturers around the world have been demonstrated at full scale projects targeting cohesive/incohesive soils, granular subbase, and stabilized base .

Components of soils and subbase IC include: single-drum IC rollers, roller measurement system, global position system (GPS) radio/receiver/base station, infrared temperature sensors, and integrated reporting system. Therefore, a soils/subbase IC roller can "adapt its behavior in response to varying situations and requirements" - being "intelligent"!

There are many benefits using soils/subbase IC rollers. To name a few: improved quality control (QC) of compaction, better correlate to compaction of deeper layer, monitor levels of compaction for 100% coverage area, and many more...



IC System (courtesy of Bomag)

Top Three Factors for Soils/Subbase Compaction:

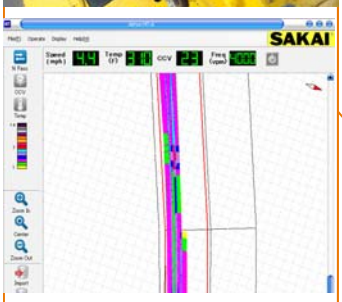
Moisture! Moisture! and... Moisture!

Soils/Subbase IC Rollers in the US

There are at least 5 vendors around the world have been developing single-drum IC rollers. Currently, there are two various types of soils/subbase IC rollers available in the US that meet the above IC roller requirements: Bomag USA, Case/Ammann, Caterpillar, Dynapac, Sakai America, and Volvo. Most of the above single-drum IC roller manufacturers offer smooth drum and padfoot models.

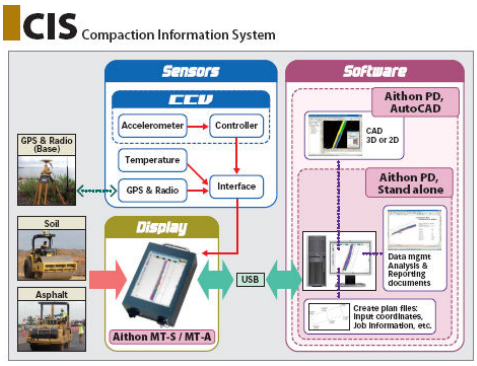
Bomag *Case/ Ammann* *Caterpillar* *Dynapac* *Sakai*

Sakai IC system

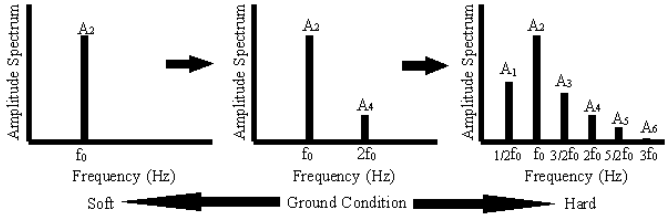


Sakai Soil IC System

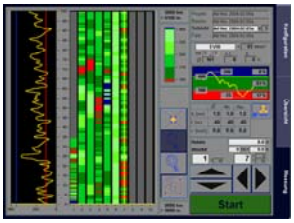
The basis of the Sakai IC system is the IC roller (equipped with CCV measurement system, temperature sensors, and GPS radio/receiver) and a GPS with radio base station. All measurements are consolidated to the CIS display. IC data can then be transferred to PCs via USB ports for further reporting/documentation and integration with CAD systems.



The Sakai Compaction control value (CCV) is a unitless vibratory-based technology which makes use of an accelerometer mounted to the roller drum to create a record of machine-ground interaction. Its value represents the stiffness of the compacted pavement layers underneath. The concept behind the CCV is that as the ground stiffness increases, the roller drum starts to enter into a "jumping" motion which results in vibration accelerations at various frequency components. The current Sakai IC system does not yet consist of auto-feedback.

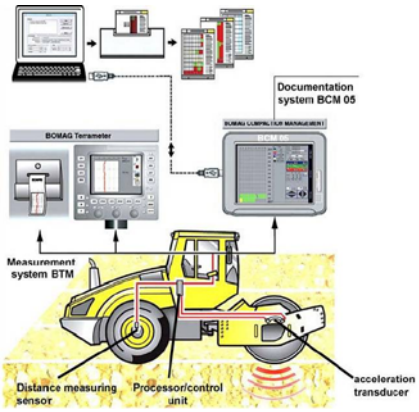


Bomag BCM05 System

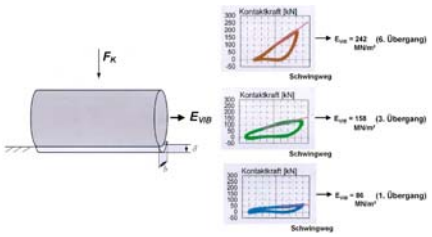


Bomag Soil IC System

The Bomag IC system is called VarioControl IC system. The Bomag IC roller is equipped with two acceleration transducers, processor/control unit, distance measurement, GPS radio/antenna, Bomag Operation Panel (BOP), and onboard BCM 05 documentation system (BCM 05-Tablet-PC, BCM 05 mobile software). This system is capable of measuring compaction values that can be transferred to another computer using USB memory sticks for further analysis and reporting using the BCM05 office software.

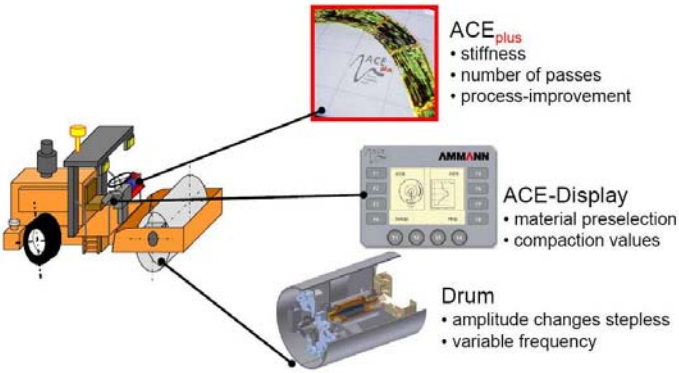


The Bomag IC measurement value is called E_{vib} [MN/m^2] or vibration modulus (more strictly, stiffness). The E_{vib} values are computed based on the compression paths of contact forces vs. drum displacement curves. The E_{vib} values increase with increasing pass number. E_{vib} also responds to changes of material density and asphalt mixture temperature (with dropping compaction temperature, E_{vib} of asphalt mixtures becomes greater). The Bomag E_{vib} values correlate well with load bearing capacities (E_{v1}/E_{v2}) from the plate loading tests. The feedback control in the Bomag IC system is called VarioControl that enables the automatic adaption of the amplitude during the compaction process.

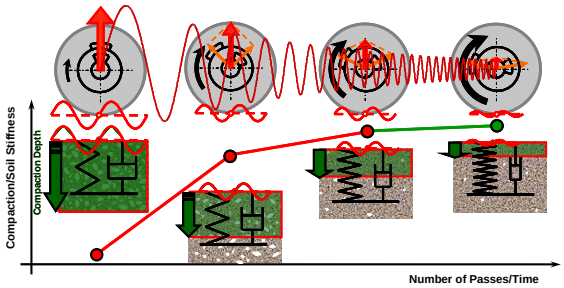


Case/Ammann Soil IC System

The Case/Ammann IC system is called the ACE and feedback drum system. The ACEplus system was formed by combining the former Ammann Compaction Expert (ACE) measurement and control system with continuous compaction control (CCC).

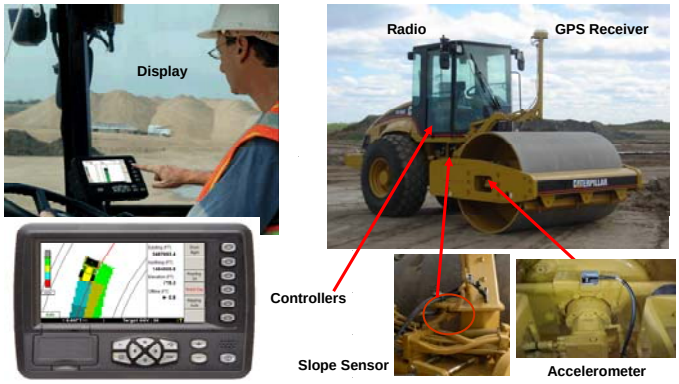


The roller-integrated stiffness (ks) measurement system on the Case/Ammann IC rollers was introduced by Ammann during late 1990's considering a lumped parameter two-degree-of-freedom spring-mass-dashpot system. The spring-mass-dashpot model has been found effective in representing the drum-ground interaction behavior. The drum inertia force and eccentric force time histories are determined from drum acceleration and eccentric position (neglecting frame inertia). The IC soil stiffness, ks, can be determined when there is no loss of contact between drum and soil. It is closely related to the plate loading test results.



ACE is an electronic measuring and controlling system for vibrating rollers. It is an automatic close-loop control automatically adjusts roller vibratory amplitudes and frequencies to suit the characteristic of the compacted ground condition. The Case/Ammann ACE auto feedback system can adjust the roller vibratory frequency and amplitude at each roller pass – depending on the condition of the compacted ground condition – thus, optimize the compaction with least desirable number of passes.

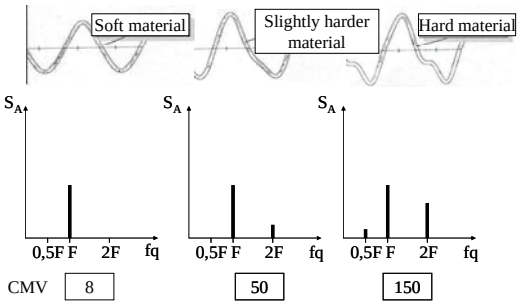
Caterpillar Soil IC System



The Caterpillar IC system include an accelerometer, slope sensor, controllers, communication data radio, Real-time Kinematic (RTK) GPS receiver, an off-board GPS base station, and onboard report system. The slope (angle) sensor measures the left/right tilt of the drum to a range of ±45°. Collectively, the above components are integrated into so-called Caterpillar AccuGrade system to provide accurate IC measurements during compaction.

The Caterpillar IC measurement values for indication of levels of compaction include compaction meter values (CMV), resonance meter values (RMV), and machine drive power (MDP).

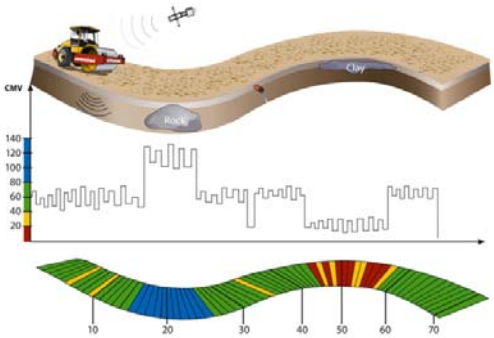
The CMV was developed by Geodynamic in 1970's. CMV is defined as a scaled ratio of the second harmonic vs. the first harmonic of the drum vertical acceleration amplitudes based on a spectral analysis. The scaling is made so that CMV values could cover a range of 150. The CMV is reported as average values within two cycles of vibration or typically 0.5 seconds. The resulting CMV is a dimensionless, relative value requiring constant roller parameters such as drum diameter, linear load, frequency, amplitude, speed, and etc. Since the CMV is an integral with contribution from large depths (3 to 6 ft for Caterpillar IC rollers) with the highest weighting of the layers closest to the surface, caution should be taken when comparing CMV to the top layer compaction level (often measured by other in-situ devices such as nuclear gauges or LWD) only.



Dynapac Soil IC System

The DCA system measures CMV as an indicator of compaction quality. The CMV technology uses accelerometers to measure drum accelerations in response to soil behavior during compaction operations (Figure 17). The ratio between the amplitude of the first harmonic and the amplitude of the fundamental frequency provides an indication of the soil compaction level. An increase in CMV value indicates increasing compaction.

CMV is a dimensionless parameter that depends on roller dimensions (i.e., drum diameter, weight) and roller operation parameters (i.e., frequency, amplitude, and speed). The machine used on this project reported a measurement value approximately every 0.5 m at the drum center along the direction of travel.



The machine also reported a bouncing value (BV) which provides an indication of the drum behavior (e.g., continuous contact, partial uplift, double jump, rocking motion, and chaotic motion) and is calculated using Equation 3. When the machine is operated in AFC mode, reportedly the amplitude is reduced when BV approaches 14 to prevent drum jumping.

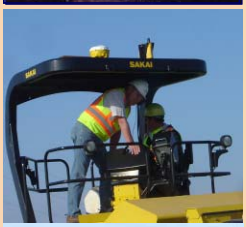
In-situ Point Tests

For IC correlation analysis, in-situ tests are used to directly obtain the response of the compacted materials under various loading situations and drainage/moisture conditions. Recommended in-situ test devices for soils/subbase/stabilized IC are as followings (Dynamic Seismic Pavement Analyzer - DSPA - and Briaud Compaction Device - BCD - are still being evaluated):

- Light Weight Deflectometer (LWD)
- Dynamic Cone Penetrometer (DCP)
- Calibrated Nuclear Moisture-Density Gauge for soils and subbase (NG)
- Falling Weight Deflectometer (FWD)
- Static Plate Loading Test (PLT)

In-situ moisture testing is also recommended if available. Soil samples are often taken from the test sites to perform moisture measurement, Proctor tests, and etc. When a padfoot roller is used for compaction, the compacted materials should be carefully excavated down to the bottom of the pad to create a level surface for in-situ testing.

Global Positioning System (GPS)



The Global Positioning System (GPS) is a location system based on satellite signals and their ground stations. Depending on the quality of the receiver, the environment, the type of measurements made, and how the measurements are processed, the positioning accuracy of GPS can vary from a few meters to below 1 centimeter, permitting a wide range of positioning applications from vehicle navigation to studies of the motion of the Earth's tectonic plates.

GPS is used in the IC system to record the coordinates of rollers at each pass. However, there are several external sources that may introduce errors into a GPS position including: atmospheric conditions, ephemeris errors/clock drift/measurement noise, selective availability, multipath, and etc.

The IC systems normally use differential correction GPS (or DGPS) to improve accuracies. Differential correction requires a second GPS receiver, a base station, collecting data at a stationary position on a precisely known point (e.g., a surveyed benchmark). With the known physical location of the base station, a correction factor can be computed by comparing the known location with the GPS location determined by using the satellites. Then, the correction factor can be applied to the GPS data collected by a GPS receiver in the field.

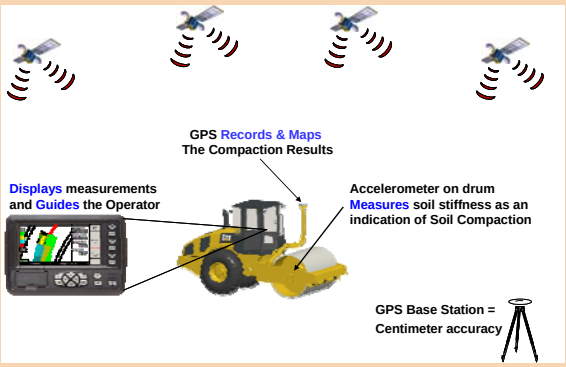
Recommended GPS requirements for IC are as follows:

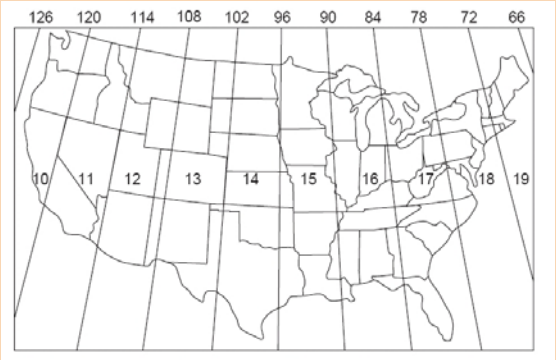
- RTK-GPS (Real Time Kinematic-GPS) system (radio and receiver) on IC rollers.
- System reports and records values in Northing and Easting and vertical position in meters in UTM coordinates for the project site.
- If an offset is necessary between GPS antenna and center of drum, the IC system settings and GPS measurements have to be validated onsite.

Current RTK-GPS system for IC may require a GPS base station, though stand-alone systems are evolving to obtain desirable accuracy.

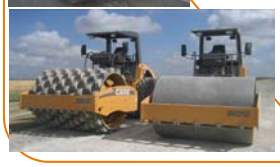
The Universal Transverse Mercator Coordinate (UTM) system provides coordinates, northings and eastings, on a world wide flat grid for easy computation. Therefore, UTM is normally used in the IC data processing. The Universal Transverse Mercator Coordinate system divides the Earth into 60 zones, each being 6 degrees longitude wide, and extending from 80 degrees south latitude to 84 degrees north latitude. The polar regions are excluded. The first zone starts at the International Date Line (longitude 180 degrees) proceeding eastward. Cautions should be taken when the area of interest extends from one zone to another.

Under this IC study, the UTM zones are restricted in the US from zone No. 10 to zone No. 19. It is recommended that all in-situ test locations are measured using portable DGPS systems and reported with the same UTM zone as IC data.





- FM 156, Fort Worth, TX
- Cohesive SG, Stabilized SG, and Aggregate SB

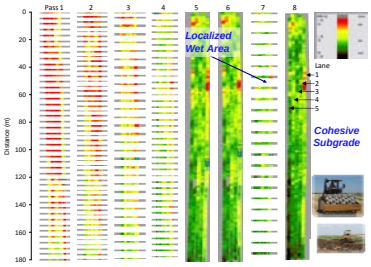


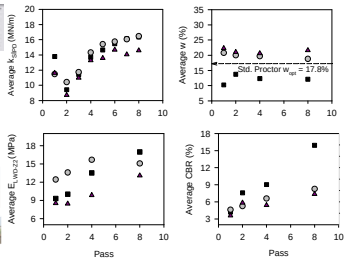
TX IC Demonstration

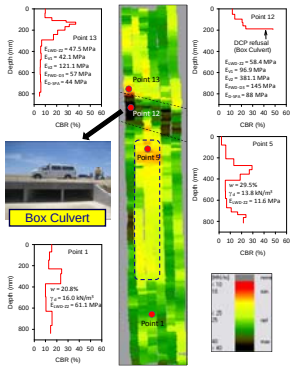
Case/Ammann IC padfoot roller measures soil stiffness ks values for multiple passes. It identifies localized wet area with moisture content of about 27% that could be not compacted.

Compaction curve (i.e. compaction values vs. roller passes) can be effectively established using the Case/Ammann IC padfoot roller. The curve is consistent with back-calculated mechanistic soil properties from in-situ tests such as LWD and DCP.

Soft spots (i.e. hard-to-compacted) and underground structures can easily located by the Case/Ammann IC roller.







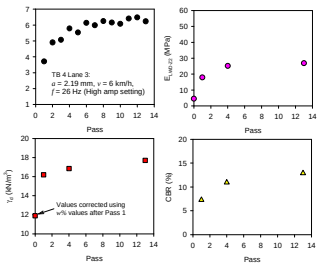
- US 69, Pleasanton, KS
- Cohesive SG, and Aggregate SB

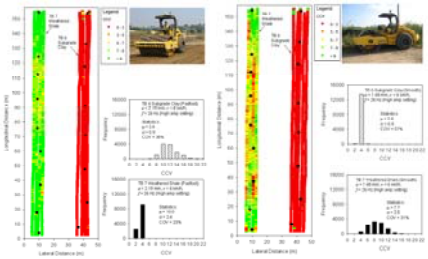
KS IC Demonstration

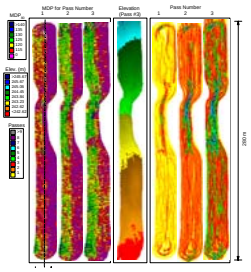
Compaction curve for cohesive soils using the Sakai padfoot IC roller was established the first time according to the past published literature.

Comparison between the Sakai padfoot and smooth drum IC measurements indicates that they results are consistent—which is very encouraging.

Production compaction using the Caterpillar padfoot IC roller successfully track compaction levels of various materials such as fat clay and lean clay subgrade.







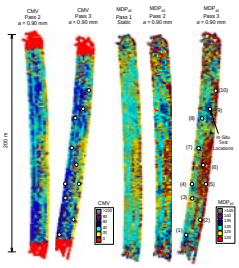
- US 219, Springville, NY
- Non-cohesive SG, and Aggregate SB

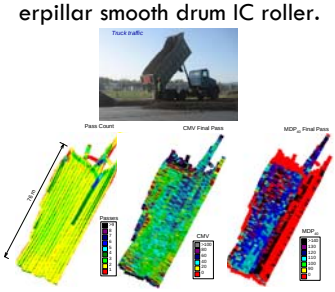
NY IC Demonstration

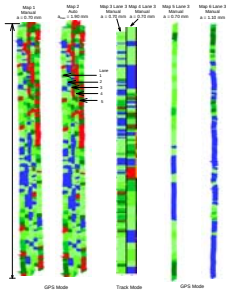
The Caterpillar smooth drum IC measurements of CMV and MDP on granular subgrade are found to be comparable.

Contribution of truck traffic to compaction on aggregate base is identified by the Caterpillar smooth drum IC roller.

Compaction with the Bomag smooth drum IC roller were evaluated using manual/auto modes and track/GPS modes.

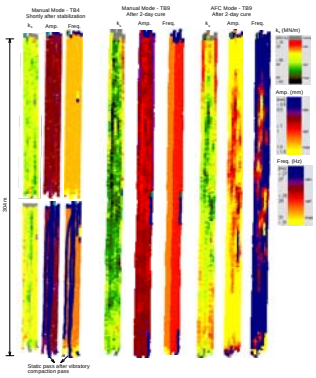




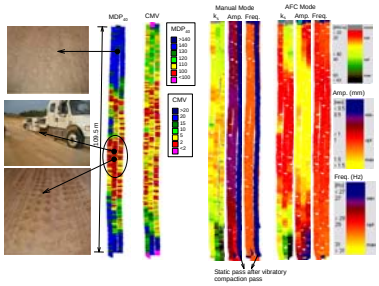


MS IC Demonstration

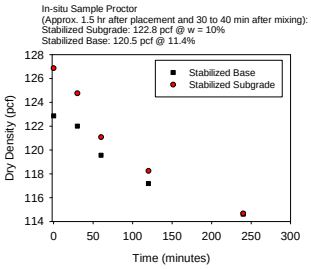
The effects of curing vs. time for stabilized granular subgrade can be monitored with the Case/Ammann smooth drum IC roller.



The unstabilized granular subgrade compactability were evaluated with both the Caterpillar and Case/Ammann smooth drum IC rollers with consistent results.



Effects of time delay for compacting stabilized base materials are being investigated with the prelim results indicates that the delay of compaction may reduce the dry density.



- US 84, Wayne County, MS
- Non-cohesive SG, Aggregate SB, STB

Factors Affecting IC RMVs

There are many factors affecting IC roller-integrated measurements (RMV). It is crucial to future harmonization of IC RMVs and IC-based acceptance specification to understand these effects thoroughly.

- Heterogeneity in underlying layer support conditions
- Moisture content variation
- Range of measurement values
- Machine operations (amplitude, frequency, speed) and roller "jumping"
- Non-uniform drum/soil contact
- Limited number of in-situ measurements for correlation
- Uncertainty in spatial pairing of point measurements and RMVs
- Not enough information to interpret the results
- Measurement errors associated with the RMVs and in-situ point test measurements

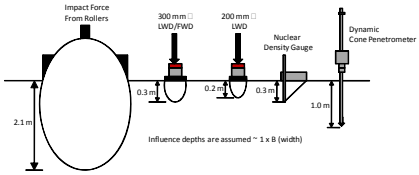
Moisture Effects were modeled via multiple regression techniques.

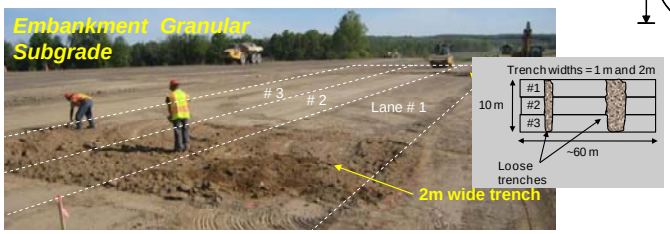
Model
$CCV_{PD} = b_0 + b_1 E_{LWD\text{-}Z2} + b_2 a + b_3 w$
$CCV_{PD}^{\dagger} = b_0 + b_1 E_{FWD\text{-}D4.5} + b_2 a$
$CCV_{PD} = b_0 + b_1 \gamma_d + b_2 a + b_3 w$
$CCV_{PD} = b_0 + b_1 CBR + b_2 a + b_3 w$

Influence Depth of IC RMVs and In-situ Tests

Investigation of the influence depths of IC roller compaction and measurements vs. other in-situ point tests (e.g. LWD, DCP, NG, and BCD) are being investigated.

The relationship among influence or measurement depths of various devices would affect how correlation tests should be conducted and analyzed/interpreted.





Stay tuned for more results from the IC research team.

TPF States get plenty of hands-on the IC technologies at the IC Demo Open Houses.

Recommendations

- 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.
- To correlate in-situ tests with IC data properly, 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.
- Use of IC RMVs can be as part of intelligent QC/QA. Further study on linking IC RMVs to mechanistic QA parameters in top 1~3 m are strongly recommended.
- Standardization is strongly recommended to accelerate the implementation IC for State agencies: a standard IC data storage format, an independent viewing/analysis software tool, and detailed data collection plan

Benefits of Intelligent Compaction

- Improve Density… better performance
- Improve Efficiency… cost savings
- Increase Information… better QC/QA

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Key Words — compaction, intelligent compaction, roller, soils, subgrade, aggregate, embankment, stabilized base, asphalt, HMA, pavement performance, quality control, quality assurance.

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