

Roller-Integrated Compaction Monitoring Technology: Field Evaluation, Spatial Visualization, and Specifications

David J. White, Pavana K. Vennapusa, and Gieselman, Heath Dept. of Civil Construction and Environmental Engineering, Iowa State University, Ames, Iowa, U.S.A.

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ABSTRACT: Roller-integrated compaction monitoring technologies provide virtually 100-percent coverage of compacted areas with real-time display of the compaction measurement values. Although a few countries have developed quality control (QC) and quality assurance (QA) specifications, broader implementation of these technologies into earthwork construction operations still requires a thorough understanding of relationships between roller measurement values and traditional in-situ spot test compaction measurements. The objectives of this paper are to (a) present field measurements from the vibratory-based Compaction Meter Value (CMV) and the vibratory or static rolling resistance based Machine Drive Power (MDP) monitoring technologies, (b) provide example correlations and spatial comparisons developed between roller measurement values and in-situ spot test measurements, and (c) summarize selected international specifications to highlight some of the key specification parameters and provide some practical points for successful implementation of the technologies.

1 Introduction

Roller-integrated compaction monitoring technologies (e.g. intelligent compaction or continuous compaction control) for vibratory rollers was initiated some 30 years ago in Europe for compacting mostly granular soils (e.g., Forssblad, 1980; and Thurner and Sandström, 1980) and has since been a subject of international discussion. There are different manufactures of vibratory-based technologies that make use of accelerometers mounted to the roller drum to effectively create a record of machine-ground interaction. The analysis approaches have been explained in detail by others (e.g., Adam and Brandl, 1997; and Sandström and Pettersson, 2004). Recently, a new machine measurement technology has been developed for use in granular or cohesive soils and is based on the principal of rolling resistance due to drum sinkage. The approach has the advantage of working in both vibratory and static modes. Regardless of the technology, by making the compaction machine a measuring device and insuring compaction requirements are met the first time, the compaction process can be better controlled to improve quality, reduce rework, maximize productivity, and minimize costs (White et al. 2006). Recent advancements with global positioning systems (GPS) present a significant benefit of real time spatial viewing of the roller measurement values. Some of these technologies have recently been implemented on fullscale earthwork construction projects in the United States (White et al., 2008), and its use is anticipated to increase in the upcoming years. In the U.S., effective implementation of this technology is following a path for which on-site calibrations and development of relationships between roller measurement values and traditional insitu spot test compaction measurements (e.g. plate load test modulus, density, etc.) are required. This builds confidence in the technology and provides insight as to the key parameters affecting the machine measurement values. This paper describes two technologies - Compaction Meter Value (CMV) and Machine Drive Power (MDP) - and presents comparisons between the machine measurement values and various in-situ spot test measurements. A summary of empirical correlations are discussed. Some of the field measurements were evaluated using spatial modelling (variogram) and visualization techniques for a staged field test. Variogram analysis provides a unique opportunity to quantify and characterize the non-uniformity and spatial continuity of the measurements. The results should be of interest to both the earthwork industry and the pavement design community because of the ability to spatially document and quantify ground conditions. At the end of the paper, a brief summary of existing roller-integrated compaction monitoring specifications are presented for comparison, and some practical points for successful implementation of the technology are discussed.

2 Compaction Monitoring Technologies

The machines evaluated in this study were manufactured by *Caterpillar* and use a compaction measurement device supplied by *Geodynamik* that outputs the compaction meter value (CMV), resonant meter value (RMV), drum vibratory frequency (*f*) in Hz, and drum vibration amplitude (*a*) in mm. The CMV technology uses accelerometers installed on the drum of a vibratory roller to measure drum accelerations in response to soil behavior during compaction operations. The ratio between the amplitude of the first harmonic and the amplitude

of the fundamental frequency is found to provide a good indication of the soil compaction level (see Thurner and Sandström, 1980). An increase in CMV indicates increasing compaction level. CMV is calculated as:

$$CMV = C \cdot \frac{A_1}{A_0}$$
(1)

where C = constant (300), A_1 = acceleration of the first harmonic component of the vibration, and A_0 = acceleration of the fundamental component of the vibration (Sandström and Pettersson, 2004). CMV is a dimensionless parameter that depends on roller dimensions (e.g. drum diameter, weight) and roller operation parameters (e.g. frequency, amplitude, speed). Reportedly, CMV at a given point indicates an average value over an area whose width equals the width of the drum and length equal to the distance the roller travels in 0.5 seconds (Geodynamik ALFA-030). RMV is not discussed here (see White et al., 2008 for details), but provides an indication of drum double jump.

Recent field studies by White et al. (2006) and (2007a) verified that roller-integrated machine drive power (MDP) may reliably indicate soil compaction for granular and cohesive soils. This is a relatively new concept and has not yet been incorporated into production machines. The use of MDP as a measure of soil compaction is a concept originated from study of vehicle-terrain interaction (Bekker, 1969). The basic premise of determining soil compaction from changes in equipment response is that the efficiency of mechanical motion pertains not only to the mechanical system but also to the physical properties of the material being compacted. MDP is calculated as:

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

where P_g = gross power needed to move the machine (kJ/s), W = roller weight (kN), a = machine acceleration (m/s²), g = acceleration of gravity (m/s²), α = slope angle (roller pitch from a sensor), V = roller velocity (m/s), and m (kJ/m) and b (kJ/s) = machine internal loss coefficients specific to a particular machine (White et al., 2005). The second and third terms of Eq. (2) account for the machine power associated with sloping grade and internal machine loss, respectively. MDP is a relative value referencing the material properties of the calibration surface, which is generally a hard compacted surface (MDP = 0 kJ/s). Positive MDP values therefore indicate material that is less compact than the calibration surface, while negative MDP values would indicate material that is more compacted than the calibration surface (i.e. less roller drum sinkage).



Figure 1. Compaction monitoring technology with display system (upper left), GPS measurement using handheld rover to link machine measurements with in-situ test locations for correlation analysis (upper right), and mobile geotechnical laboratory for rapid field testing and wireless data transfer (bottom).

Effective use of the compaction monitoring technology is aided in large part by the integration of a GPS system and an on-board compaction monitor which displays the roller location, machine measurement values (CMV/MDP), vibration amplitude and frequency, and roller speed. The technology enables a roller operator to make judgments regarding the condition of the compacted fill material in real-time. The Caterpillar rollers used in these studies had on-board display systems with integrated data acquisition systems and displayed real-time position and measurement values. The system uses real-time kinematics (RTK) GPS with accuracies of about ± 10 mm in the horizontal plane and ± 20 mm in the vertical plane. On the roller, the GPS system is positioned over the center of the roller drum (Figure 1).

While these technologies offer significant advantages in earthwork construction practice, it also produces large data files that create analysis, visualization, transfer and archival challenges. ArcGIS modules can be utilized to perform traditional statistical analysis (comparisons to in-situ compaction test measurements), complex geostatistical analysis (evaluating proof areas for uniformity), data visualization, and data archiving (see White et al., 2007b and White et al., 2008). The data files that are generated from these rollers should ideally be transferred in real-time for data analysis and final decision making. This is quite possible with the recent advancements in wireless technology. The lowa State University mobile geotechnical laboratory (Figure 1) for example can receive the machine signal in real-time and display the data prior to being sent through a satellite dish to a remote office location for additional analysis and archiving.

3 Field Evaluation of CMV/MDP

Results from extensive field testing and correlation analysis between CMV/MDP measurement values and in-situ spot test compaction measurements were documented recently by White et al. (2006), White et al. (2007a), White and Thompson (2008), and Thompson and White (2008). Experimental testing for these field studies involved construction of two dimensional test strips of about 30 m x 3 m, each comprising a different material type. The test strips with granular and cohesive soils were compacted using a CS-533 vibratory smooth drum roller and a CP-533 vibratory padfoot roller, respectively.

In-situ compaction testing devices included: (a) nuclear moisture density gauge to determine moisture and dry unit weight, (b) Keros and Zorn light weight deflectometers (LWD) to determine elastic modulus (E_{LWD}) (c) Clegg impact testers to determine CIV using 20-kg and 4.5-kg drop hammers, (d) dynamic cone penetrometer to determine penetration index (DCP Index), and (e) Static plate load test to determine elastic modulus (E_{PLT}). These test measurements (except static plate load test) were taken at ten locations while static plate load tests were performed at only one test location across the test strips. Test measurements were typically made after 1, 2, 4, 8, and 12 roller passes. The spot test measurement location information was obtained using GPS rover receiving a correction signal from a base station to pair the data with CMV/MDP measurement values.

3.1 Correlations between CMV/MDP and soil properties

Simple linear and multiple linear regression relationships to predict in-situ spot test compaction measurements (e.g. γ_d , DPI, E_{LWD}, E_{PLT}, CIV) using roller measurement values (CMV/MDP) for various soil types are discussed in detail in Thompson and White (2008), White and Thompson (2008), White et al. (2006) and (2007). A summary of these relationships for three granular and cohesive soil types is provided in Table 1. Unified Soil Classification System (USCS) group symbols for these soils are provided in Table 1. Note that the relationships (except for static plate load tests) presented in Table 1 are based on an average of ten in-situ compaction and CMV/MDP measurement values following a roller pass. Relationships to E_{PLT} are based on one test point following a roller pass.

For granular soils, logarithmic relationships were observed between in-situ soil compaction measurements and MDP, while linear relationships were observed for CMV. For the cohesive soils, regression relationships were improved in many cases for predicting soil compaction parameters (γ_d , DCP Index, etc.) from MDP when soil moisture content and MDP-moisture interaction parameters were included in the prediction models (Thompson and White, 2008). The R² values observed for the correlations generally exceeded 0.90, while R² values of less than 0.90 are mostly observed in estimating soil modulus. This is attributed to the complexity involved in estimating soil modulus and the relative variability associated with this measurement (White and Thompson, 2008).

4 Spatial Analysis of In-Situ and Roller Compaction Measurement Values

Roller-integrated compaction monitoring technology offers a unique advantage of quantifying and characterizing "non-uniformity" of compaction measurement values. This topic presumably should be of considerable interest to pavement engineers. White et al. (2007b) demonstrated the use of variogram analysis in combination with conventional statistical analysis to effectively address the issue of non-uniformity in quality assurance during earthwork construction. A variogram is a plot of the average squared differences between data values as a function of separation or lag distance, and is a common tool used in geostatistical studies to describe spatial variation. Three important features of a variogram include: sill, range, and nugget. *Sill* is defined as the plateau that the variogram reaches, *Range* is defined as the distance at which the variogram reaches the sill, and *Nugget* is defined as the vertical height of the discontinuity at the origin which mostly represents sampling error or short scale variations (Srivastava, 1996). From a variogram model, a low "sill" and longer "range of influence" can represent best conditions for uniformity, while the opposite represents an increasingly non-uniform condition.

To evaluate the application of spatial analysis, a test section was created for comparison analysis of CMV/MDP to DCP Index values. The comparisons are shown using theoretical and experimental variogram models, and Kriged surface maps generated for in-situ compaction measurements using the theoretical (exponential) variogram model. The theoretical variograms were fit to the experimental variograms by checking for its "goodness" using the modified Cressie goodness of fit approach suggested by Clark and Harper (2002) as well as the cross-validation process. A lower Cressie "goodness" factor indicates a better fit. The study area was comprised of a compacted subgrade material (Edwards glacial till material, USCS classification: CL), and a scarified portion (to a depth of 200 mm) in a "Z" shape. The scarified portion was prepared intentionally to represent a common condition in earthwork construction resulting from utility trench construction where the backfill may not be as compact as the neighboring unexcavated materials. After subgrade preparation, the area was mapped using a CS-533 smooth drum machine in seven lanes using a vibration amplitude = 2.1 mm and frequency = 29 Hz. DCP tests were performed at 144 locations in the upper 200 mm (shown in gray circles on Figure 2) following roller mapping passes. The DCP test locations were strategically spaced such that the boundaries of compacted and uncompacted areas were captured during Kriging interpolation.

CMV and MDP spatial data along with experimental and theoretical variogram models are shown in Figure 2. Log transformation was required to obtain a clear structure in the experimental variogram of the CMV data. Kriged surface map and variogram model generated for the DCP index values are also presented in Figure 2. The univariate statistics (mean (μ), standard deviation (σ), and coefficient of variation (COV)) of the measurement values are also provided on the Figure for reference. The compacted and uncompacted areas were generally well captured by the CMV/MDP and DCP index measurements; however, they were more clearly delineated by the DCP Index measurements.

Univariate statistics show that the COV of the MDP (89%) and DCP index (86%) measurements are comparable and are also significantly higher compared to that of CMV (39%). Similarly, the exponential variogram models of MDP and DCP index exhibit significantly lower *range* values than CMV. This suggests that the MDP and DCP index measurements have less spatial continuity and higher variability compared to CMV measurements. This high variability is likely due to differences in the measurement influence depths of these measurements. The CMV measurement influence depth is believed to be up to 1.5 m according to ISSMGE specifications, while the MDP measurement is more influenced by properties of the compaction layer and other unquantified measurement errors (Thompson and White, 2008).



Figure 2. Spatial comparison of dynamic cone penetration (DCP) index and roller-integrated CMV and MDP measurements on compacted and scarified Edwards glacial till subgrade soil.

Soil Name/ Property	<i>Granular soils</i> Relationships	Soil Name/ Property	Cohesive soils Relationships		
CA6-C (USCS	Classification: SM)	Edwards Till (USCS Classification: CL)			
γ _d (kN/m ³)	γ_d = -4.2 Log(MDP) + 22.7, R ² = 0.96 γ_d = 0.1 CMV + 17.2, R ² = 0.96	γ _d (kN/m³)	γ_d = 15.3 – 0.2 MDP + 0.1 w R ² = 0.60		
DCP Index (mm/blow)	DCPI = 99.6 Log(MDP) – 61.2, R ² = 0.96 DCPI = -2.9 CMV + 70.2, R ² = 0.98	DCP Index (mm/blow)	DCPI = 31.4 + 5.8 MDP - 0.7 MDP ² + 0.2 w + 0.7 w ² - 0.1 MDP*w, R ² = 0.81		
CIV _{4.5-kg}	CIV = -25.9 Log(MDP) + 38.0, R ² = 0.98 CIV = 0.8 CMV + 3.1, R ² = 0.96	CIV _{4.5-kg}	CIV = 10.8 - 0.5 MDP $R^2 = 0.84$		
E _{PLT} (MPa)	E_{PLT} = -12.2 Log(MDP) + 20.0, R ² = 0.86 E_{PLT} = 0.4 CMV + 3.7, R ² = 0.77	E _{PLT} (MPa)	$E_{PLT} = 7.1 - 0.3 \text{ MDP}$ $R^2 = 0.44$		
E _{LWD} (MPa)*	E_{LWD} = -27.1 Log(MDP) + 54.6, R ² = 0.96 E_{LWD} = 0.9 CMV + 21.6, R ² = 0.90	E _{LWD} (MPa)*	E_{LWD} = 41.4 – 2.3 MDP R ² = 0.78		
RAP (USCS CI	assification: GM)	Kickapoo Silt (USCS Classification: ML)			
γ _d (kN/m ³)	γ_d = -1.7 Log(MDP) + 20.8, R ² = 0.90 γ_d = 0.2 CMV + 15.7, R ² = 0.83	γ _d (kN/m³)	$\gamma_d = 13.0 - 0.2 \text{ MDP} + 0.2 \text{ w}$ $R^2 = 0.93$		
DCP Index (mm/blow)	DCPI = 27.4 Log(MDP) – 35.7, R ² = 0.96 DCPI = -2.7 CMV + 45.9, R ² = 0.94	DCP Index (mm/blow))	DCPI = -88.8 + 5.4 MDP + 6.2w R ² = 0.93		
CIV _{4.5-kg}	CIV = -13.6 Log(MDP) + 46.7, R ² = 0.94 CIV = 1.4 CMV + 6.0, R ² = 0.96	CIV _{4.5-kg}	CIV = 14.4 - 0.2 MDP - 0.3 w + 0.03 MDP*w R ² = 0.98		
E _{PLT} (MPa)	$E_{PLT} = -1.2 \text{ Log}(\text{MDP}) + 5.6, \text{ R}^2 = 0.56$ $E_{PLT} = 0.1 \text{ CMV} + 2.2, \text{ R}^2 = 0.50$	E _{PLT} (MPa)	E_{PLT} = 11.3 - 0.9 MDP + 0.03 MDP ² + 0.1 w ² + 0.3 w, R ² = 0.77		
E _{LWD} (MPa)*	E_{LWD} = -39.7 Log(MDP) + 126.7, R ² = 0.94 E_{LWD} = 4.2 CMV + 7.4, R ² = 0.94	E _{LWD} (MPa)*	E _{LWD} = 43.77 - 1.55 MDP R ² = 0.63		
CA5-C (USCS	Classification: GP)	Kickapoo Clay (USCS Classification: CL)			
γ _d (kN/m ³)	γ_d = -2.6 Log(MDP) + 20.2, R ² = 0.96 γ_d = 0.1 CMV + 12.0, R ² = 0.96	γ _d (kN/m ³)	γ_d = 10.6 – 0.2 MDP + 0.3 w R ² = 0.78		
DCP Index (mm/blow)	DCPI = 29.1 Log(MDP) – 28.1, R ² = 0.96 DCPI = -1.3 CMV + 60.6, R ² = 0.92	DCP Index (mm/blow)	DCPI = -88.5 + 3.9 MDP + 8.8 w R ² = 0.93		
CIV _{4.5-kg}	CIV = -3.1 Log(MDP) + 19.8, R ² = 0.61 CIV = 0.1 CMV + 10.5, R ² = 0.59	CIV _{4.5-kg}	CIV = 7.3 - 0.3 MDP $R^2 = 0.64$		
E _{PLT} (MPa)	E_{PLT} = -31.0 Log(MDP) + 90.4, R ² = 0.96 E_{PLT} = 1.5 CMV - 4.3, R ² = 0.96	E _{PLT} (MPa)	$E_{PLT} = 5.8 - 0.3 \text{ MDP}$ $R^2 = 0.48$		
E _{LWD} (MPa)*	(MPa)* E _{LWD} = -44.3 Log(MDP) + 144.2, R ² = 0.96 E _{LWD} = 2.1 CMV + 9.5, R ² = 0.96		E _{LWD} = 48.5 – 1.9 MDP R ² = 0.46		

 Table 1. Relationships between average in-situ compaction and roller-integrated compaction measurements for granular and cohesive soils (White and Thompson, 2008, Thompson and White, 2008, White et al., 2006, White et al., 2007a).

* E_{LWD} determined using Keros light weight deflectometer

5 Implementation of Compaction Monitoring Technology

A few countries and governmental agencies have developed specifications to facilitate implementation of rollerintegrated compaction monitoring technologies into earthwork construction practices. A summary of key elements of selected specifications is provided in Table 2. The specifications typically require performing either static or dynamic (e.g. LWD) plate load tests on calibration strips to determine average target values (typically based on 3 to 5 measurements) and use the same for quality assurance later in production areas. The German specification suggests performing at least three static plate load tests in locations of low, medium, and high degree of compaction during calibration process. Further, it is specified that linear regression relationships between roller measurement values and plate load test results should achieve a regression coefficient, $R \ge 0.7$. Although it is not clear yet what the right number of test measurements is to develop a field calibration, the experience of the authors shows increasing the number of measurements to 10-15 points substantially increases the statistical significance of the predictions. Figure 3 presents an example plot using test results from a CA6-C granular material test strip to demonstrate this issue. The open circles in the figure indicate in-situ compaction test measurements paired with spatially nearest CMV values. As in-situ tests were performed at ten locations following 1, 2, 4, 8, and 12 roller passes, these scatter plots are typically comprised of roughly 60 data points. Possible sources of scatter include: (1) inherent soil variation, (2) location measurement error (relating to GPS measurements), (3) machine measurement error, and (4) test device/measurement error.

Specifica- tion	Equipment	Field Size	Location Specs	Documentation	Compaction Specs	Speed	Freq.
Mn/DOT (USA)	Smooth drum or padfoot vibratory roller (25,000 lbs.)	100 m x 10 m (mini- mum at base). Max 1.2 m thick.	One calibration/ control strip per type or source of grading material	Compaction, stiffness, moisture, QC activities, and corrective actions (weekly report)	90% of the roller compaction measurements and average of LWD modulus measurements (based on 3 tests) must be at 90% of the target values established in the calibration strip.	Same durin calibration production compaction	ng and n
ISSMGE	Roller chosen by experience	100 m by the width of the site	Homogenous, even surface. Track overlap ≤ 10% drum width.	Rolling pattern, sequence of compaction and measuring passes; amplitude, speed, dynamic measuring values, frequency, jump operation, and corresponding locations	Correlation coefficient ≥ 0.7 . Minimum value $\ge 95\%$ of E_{v1} , and mean should be $\ge 105\%$ (or $\ge 100\%$ during jump mode). Dynamic measuring values should be lower than the specified minimum for $\le 10\%$ of the track. Measured minimum should be $\ge 80\%$ of the specified minimum. Standard deviation (of the mean) must be $\le 20\%$ in one pass.	Constant 2–6 km/h (± 0.2 km/h)	Constant (± 2 Hz)
Earthworks (Austria)	Vibrating roller compactors with rubber wheels and smooth drums suggested	100 m long by the width of the site	No inhomogeneities close to surface (materials or water content). Track overlap ≤ 10% drum width.	Compaction run plan, sequence of compaction and measurement runs, velocity, amplitude, frequency, speed, dynamic measuring values, jump operation, and corresponding locations	Correlation coefficient ≥ 0.7 . Minimum value $\ge 95\%$ of E_{v1} , and median should be $\ge 105\%$ (or $\ge 100\%$ during jump mode). Dynamic measuring values should be lower than the specified minimum for $\le 10\%$ of the track. Measured minimum should be $\ge 80\%$ of the set minimum. Measured maximum in a run cannot exceed the set maximum (150% of the determined minimum).Standard deviation (of the median) must be $\le 20\%$ in one pass.	Constant 2–6 km/h (± 0.2 km/h)	Constant (± 2 Hz)
Research Society for Road and Traffic (Germany)	Self-propelled rollers with rubber tire drive are preferred; towed vibratory rollers with towing vehicle are suitable.	Each calibration area must cover at least 3 partial fields ~20 m. long	Level and free of puddles. Similar soil type, water content, layer thickness, and bearing capacity of support layers. Track overlap ≤ 10% machine width.	Dynamic measuring value; frequency; speed; jump operation; amplitude; distance; time of measurement; roller type; soil type; water content; layer thickness; date, time, file name, or registration number; weather conditions; position of test tracks and rolling direction; absolute height or application position; local conditions and embankments in marginal areas; machine parameters; and perceived deviations	The correlation coefficient resulting from a regression analysis must be \geq 0.7. Individual area units (the width of the roller drum) must have a dynamic measuring value within 10% of adjacent area to be suitable for calibration.	Constant	
Vägverket (Sweden)	Vibratory or oscillating single-drum roller. Min. linear load 15– 30 kN.	Thickness of largest layer 0.2– 0.6 m.	Layer shall be homogenous and non-frozen. Protective layers < 0.5 m may be compacted with sub-base.	_	Bearing capacity or degree of compaction requirements may be met. Mean of compaction values for two inspection points \geq 89% for sub-base under road base and for protective layers over 0.5 m thick; mean should be \geq 90% for road bases. Required mean for two bearing capacity ratios varies depending on layer type.	Constant 2.5–4.0 km/h	_

Table 2. Summary of existing roller-integrated compaction monitoring technology earthwork specifications.

If an average of in-situ and roller compaction measurement values is taken for each roller pass, the scatter is significantly reduced. These test results demonstrate that a single test point does not provide statistically an adequate level of confidence in the regression relationships. In case of comparing roller and in-situ compaction measurements, soil property variation and measurement influence area/depth must also be considered. Recall that the CMV measurement represents an average across an area whose width equals the width of the drum and length equals the distance that the roller travels in 0.5 seconds and the measurement influence depth is up to 1.5 m. These issues of spatial variation in the soil and measurement error are particularly important when calibration testing and acceptance requirements are specified. Statistical averaging of roller and in-situ test measurements across a test strip for a given roller pass can help mitigate problems associated with these errors and improve confidence in predictions. Further, regression relationships can be improved significantly if multiple regression analysis is performed by incorporating statistically significant parameters into the prediction models, e.g. moisture content (Thompson and White, 2008).



Figure 3. Relationships between average in-situ compaction measurements and CMV – CA6C granular material

Roller-integrated compaction monitoring technologies provide spatial data which can be effectively used in evaluating the compacted areas for non-uniformity. Geostatistical analysis techniques can be utilized in characterizing spatial continuity of engineering parameters over the compacted area. The application of geostatistics into quality assurance can help identify localized poorly compacted areas or highly non-uniform conditions which are often a root cause of pavement problems (White et al., 2007b).

Considering the issues of statistical averaging during calibration and the importance of documenting nonuniformity, some additional features that can be incorporated into a specification include: (a) rigorous verification testing during calibration by determining the number of tests based on desired statistical reliability; (b) selection of in-situ test measurement spacing using variogram models generated for the roller data; (c) developing target values based on simple and multiple regression analysis, i.e. incorporating statistically significant parameters (e.g. moisture content) into prediction models to determine soil compaction properties; and (d) evaluating production areas for uniformity with aid of geostatistical variogram analysis – by establishing target *sill* values (which is a measure of uniformity) from calibration areas and checking the production areas to achieve these target values. White et al. (2007b) provided a conceptual framework for quality assurance using these key features.

6 Summary

The following statements summarize the key elements addressed in this paper:

- Roller-integrated compaction monitoring technology with GPS integrated location measurements and real-time viewing of compaction data on the on-board monitor allows the operator identify areas of poor compaction and make necessary adjustments in rolling operations.
- Review of regression relationships published in the literature indicates that the roller-integrated CMV and MDP are correlated well with in-situ compaction measurements (e.g γ_d, E_{LWD}, DCP Index, CIV). Incorporating moisture content into prediction models, if statistically significant, can improve the predictions of soil properties. A summary of relationships between CMV/MDP and in-situ compaction measurements for three granular and three cohesive soils are provided in this paper.
- Geostatistical analysis techniques can be utilized in characterizing spatial continuity of engineering properties over a compacted area using the 100-percent coverage data from the rollers. Spatial comparison results showed that compacted and uncompacted areas were well captured by the CMV/MDP and DCP index measurements.
- Statistical averaging of roller and in-situ compaction measurements may be helpful when developing correlations to mitigate problems associated with measurement and location errors and to improve confidence in predictions.
- Considering the issues of statistical averaging during calibration and the importance of minimizing nonuniformity, rigorous verification testing during calibration and application of geostatistics for process control may help in effective implementation of this technology.

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