NACOE
NATIONAL ASSET CENTRE OF EXCELLENCE

LITERATURE REVIEW

P105: Implementing Intelligent Compaction Technology for use in Queensland for Earth Fill, Granular and Stabilised Materials (Year 1 – 2018/19)

ARRB Project No.:	014125
Author/s:	A/Prof. Behzad Fatahi, A/Prof. Hadi Khabbaz and Yang Dong
Prepared for:	Queensland Department of Transport and Main Roads

27/1/2019

Version 2

Submitted to ARRB under Contract Number PRO19/61

AN INITIATIVE BY:
arrb
Queensland Government

SUMMARY

This report presents a literature review of the use of intelligent compaction (IC). The aim of the review was to gain the experiences and understanding of recent advances in the use of IC technology for earth fill, granular and stabilised materials.

A brief summary on the background and history of IC is presented, followed by an introduction of IC instrumentation systems. The benefits and disadvantages of IC are then discussed. The main advantages of IC technology are the improvement in compaction quality and uniformity, as well as the reduction in construction and maintenance costs, including the liability costs associated with repairs and maintenance after construction

The report also presents details of current IC equipment, including both original IC rollers and the retrofit kit that can be incorporated onto conventional rollers. The adopted measurement values (MVs) used by different roller vendors are presented, with the emphasis on the theory behind these measurement values to correlate measurements to the soil stiffness/modulus.

A summary of existing specifications adopted in Europe and the USA is also presented, which may serve as references for the development of Australian specifications on the use of IC. A series of findings derived from previous case studies on the correlations between roller measurement values and spot tests on different soil types and underlying materials is also provided. Based on the findings obtained from the case studies and the existing specifications, the general IC in situ calibration procedure is summarised, which may be adopted as a guideline to carry out an IC trial in Queensland.

Finally, preliminary recommendations are made on how IC can be incorporated into current Department of Transport and Main Roads Technical Specifications, including MRTS04, MRTS05 and MRTS07B.

CONTENTS

TABLES

FIGURES

GLOSSARY

LIST OF SYMBOLS

A: Amplitude of the drum

$A_{2\Omega}$: Acceleration of the first harmonic component of the vibration

A_{Ω}: Acceleration of the fundamental component of the vibration

B: Contact width of the drum

E_{vib}: Vibration modulus

E_{V1}: Modulus derived from the first loading loop in the static plate load test

E_{LWD}: General modulus from LWD device

E_{V2}: Modulus derived from the second loading loop in the static plate load test

E_{LWD-Z2}: Modulus from Zorn LWD device with 200 mm diameter, plate

F_K: Contact forces

f: Frequency of the drum

k_{susp}: Roller suspension stiffness

k_s: Roller integrated stiffness

P_g: Gross power needed to facilitate the movement of the roller

R^2_{adj}: Adjusted regression coefficient

R: Radius of the drum’s cross-section

Z_d: Drum vertical displacement

ϑ: Poisson’s ratio

Ω_0: Excitation frequency

LIST OF ACRONYMS

AFC: Automatic feedback control

BV: Bouncing value

CMV: Compaction meter value

CCV: Compaction control value

CCC: Continuous compaction control

CBR: California Bearing Ratio

DCO: Dynapac’s compaction optimiser

DCP: Dynamic Cone Penetrometer

FWD: Falling Weight Deflectometer

IC-TV: Intelligent compaction target value

IC: Intelligent compaction

ICMV: Intelligent compaction measurement value

LWD-TV: Lightweight Deflectometer target value

LWD: Lightweight Deflectometer

MV: Measurement value

MnDOT:	Minnesota Department of Transportation
MDP:	Machine Drive Power
MT-TV:	Measurement value target value
NG:	Nuclear Gauge
NCHRP:	National Cooperative Highway Research Program
OEM:	Original equipment manufacturer
PLT:	Plate loading test
RTK:	Real-time kinematic
RMV:	Resonant meter value

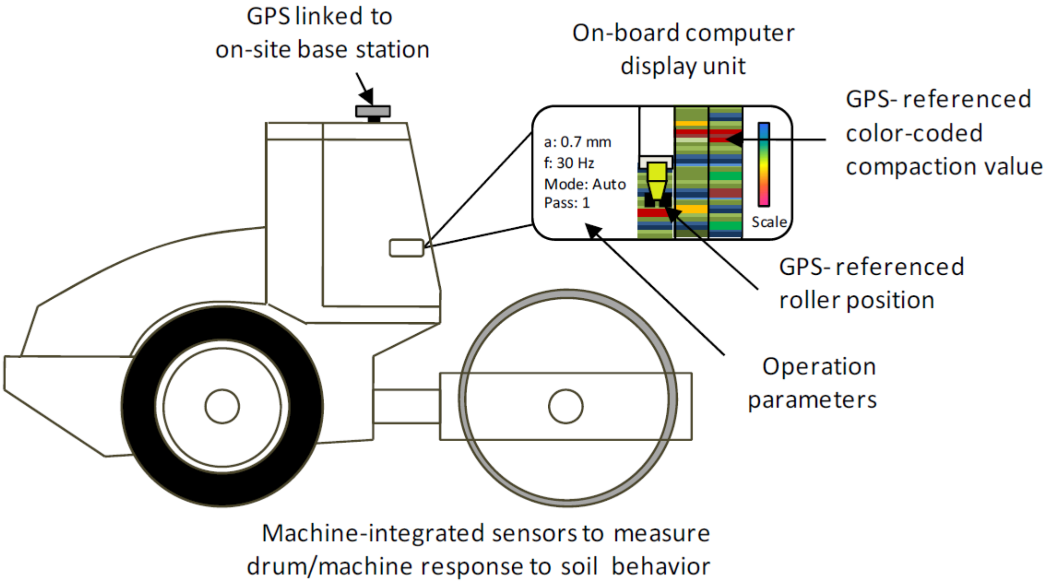
1 BACKGROUND AND HISTORY OF INTELLIGENT COMPACTION (IC)

The use of conventional compaction methods and quality control procedures can result in under-compacted or over-compacted materials, which may result in excessive differential settlement and poor performance. Uniform compaction may not be easily achieved because the operator does not receive live feedback of the material's response or compaction level. To confirm adequate compaction has been achieved, in situ spot tests are generally carried out post-compaction using Light Weight Deflectometers (LWD), Dynamic Cone Penetrometers (DCP), nuclear moisture-density gauges (NG), sand replacement measurements, Falling Weight Deflectometers (FWD), or static plate loading tests (PLT). However, in situ spot tests are limited and take place at random locations. As a result, those tests do not necessarily represent the entire pavement area (Kumar et al. 2016).

According to Mooney et al. (2010) and Gallivan, Chang & Horan (2011), the devices currently used for quality control and quality assurance testing (i.e. spot testing) are typically used to assess less than 1% of the actual compacted area. Correia et al. (2014) pointed out that limited in situ testing carried out during the QC and QA stage may be insufficient for quality control of road construction. This issue can potentially be addressed using intelligent compaction (IC) technology that can provide a more comprehensive assessment of the level of compaction achieved during construction.

An IC system typically includes a single drum roller, an accelerometer mounted on the drum, an integrated roller measurement system, and a global positioning system (GPS) receiver/base station. **Error! Reference source not found.** shows a typical IC system; the instrumentation is described in more detail in the next section.

Figure 1.1 Overview of ICMV compaction monitoring system (Chang et al. 2011)



The number of roller passes, the drum acceleration, velocity and amplitude can be recorded continuously with the measurement system. The collected information can then be interpreted as Intelligent Compaction Measurement Values (ICMVs) to assess the level of compaction achieved. Based on the modulus reported by the measurement system, optimisation of the compaction process can be achieved by the roller operator through ensuring that the ICMVs achieved are equal to or greater than a predetermined threshold value. This process is recognised as continuous compaction control (CCC). In addition, there is an automatic feedback control (AFC) system that uses the information collected by the measurement system to adapt the equipment performance continuously and automatically to optimise the compaction effort and meet the required conditions. This system automatically adjusts the compaction parameters for the roller, such as the drum vibration amplitude, frequency and the roller operating speed (impact distance) in order to optimise compaction.

It should be noted that there was not a unified definition of intelligent compaction in the literature reviewed. Mooney et al. (2010) defined intelligent soil compaction systems as systems that can continuously assess the mechanical soil properties by monitoring roller vibration, real time adjustment of roller settings, including a GPS to provide a complete geographic information-based compaction record of the site. Correia & Parente (2014) stated that IC is a real-time automatic adjustment and continuous compaction control technology for geomaterials or asphalt. However, in other literature, roller-integrated systems that can provide continuous compaction control (CCC) are considered to be IC systems (e.g. Hossain et al. 2006; Mooney & Adam 2007; White et al. 2009; Cai et al. 2017). The latter definition is adopted in this report.

According to Correia et al. (2014), the concept of IC first appeared in Europe around 1980 and it has been more than 40 years since the first roller integrated continuous compaction control (CCC) system was patented (Forssblad 1980; Thurner et al. 1980).

The first research carried out on roller-integrated measurements can be traced back to 1974 when the Swedish Highway Administration examined a Dynapac vibratory roller fitted with an accelerometer. The tests showed that the ratio between the amplitude of the first harmonic and the excitation frequency could be correlated to the state of compaction and the stiffness of the soil, as measured by the static plate load test (PLT) (Forssblad 1980; Thurner & Sandström 1980).

In 1975, the Geodynamik Company was established. The compaction meter value (CMV) to assess the level of compaction was developed and introduced in 1978. Dynapac began offering the CMV-based Compactometer commercially in 1980. A number of roller manufacturers (e.g. Ammann and Caterpillar) subsequently began offering the Geodynamik CMV Compactometer measurement system.

In the late 1990s, Bomag developed a vibratory modulus, E_{vib} – which is calculated using the single-degree-of-freedom lumped parameter model and Lundeberg’s theoretical solution – to measure the dynamic stiffness of soils (Mooney & Adam 2007).

In 1999, Ammann introduced the roller integrated stiffness, k_s – which considered a lumped parameter two-degree-of-freedom spring-mass-dashpot system – to access the level of soil compaction (Mooney et al. 2010; Savan, Ng & Ksaibati 2015). The introduction of these two parameters (i.e. E_{vib} and k_s) can be regarded as an evolution towards the measurement of more mechanistic, performance-related soil properties.

In 2003, Caterpillar introduced the Machine Drive Power (MDP) system to access the state of compaction of granular and cohesive soils. The MDP system is based on the principal of rolling resistance; the approach works in both vibratory and static modes. These roller measurement values are still used by roller manufacturers. Information about these measurement values and their associated theories are presented in detail in Section **Error! Reference source not found.**.

In 2004, Sakai developed the compaction control value (CCV) based on CMV using the harmonic content from the drum vibration to evaluate the state of compaction.

2 INTELLIGENT COMPACTION (IC) SYSTEMS

The rollers used to carry out IC on soils and pavement materials are the same as those adopted for conventional compaction. The difference is that an instrumentation system is integrated into the roller for data measurement, recording, processing and display. There are typically five instrumentation systems: an accelerometer, an integrated GPS, an on-board computer processing system, a visual display monitor and an automatic feedback control system. These systems are now briefly discussed.

2.1 ACCELEROMETER

Accelerometers are mounted on the roller frame near the vibratory drum to continuously measure the acceleration, the movement or vibrations of the drum, as well as the roller drum's amplitude and frequency during compaction. These measurements are then correlated to the modulus of the underlying materials to assess the level of compaction. **Error! Reference source not found.** shows a typical accelerometer attached to the roller frame.

Figure 2.1 Accelerometer sensor mounted on the roller frame (Nieves 2014)

2.2 INTEGRATED GPS

An integrated GPS is utilised full-time to geographically record the measurements across the compacted area. The position data are collected by a real-time kinematic (RTK) differential GPS with an accuracy of 10-20 mm. The position data are then converted to Cartesian X and Y coordinates, where X is the direction of driving. **Error! Reference source not found.** shows the RTK GPS receiver and antenna on a Sakai IC roller.

Figure 2.2 Real-time kinematic GPS receiver and antenna on a Sakai roller (White & Vennapusa 2010)

2.3 ON-BOARD COMPUTER PROCESSING SYSTEM

The downward displacement of the drum, the roller amplitude, frequency and the velocity are determined by the speed sensor and accelerometer. The collected information is transferred to an on-board computer processing system and the measurements are correlated with the modulus of the underlying material via the algorithm analysis developed by different roller vendors. The on-board computer processing system is also responsible for merging the correlated compaction measurement values (CMV) to the GPS.

2.4 VISUAL DISPLAY MONITOR

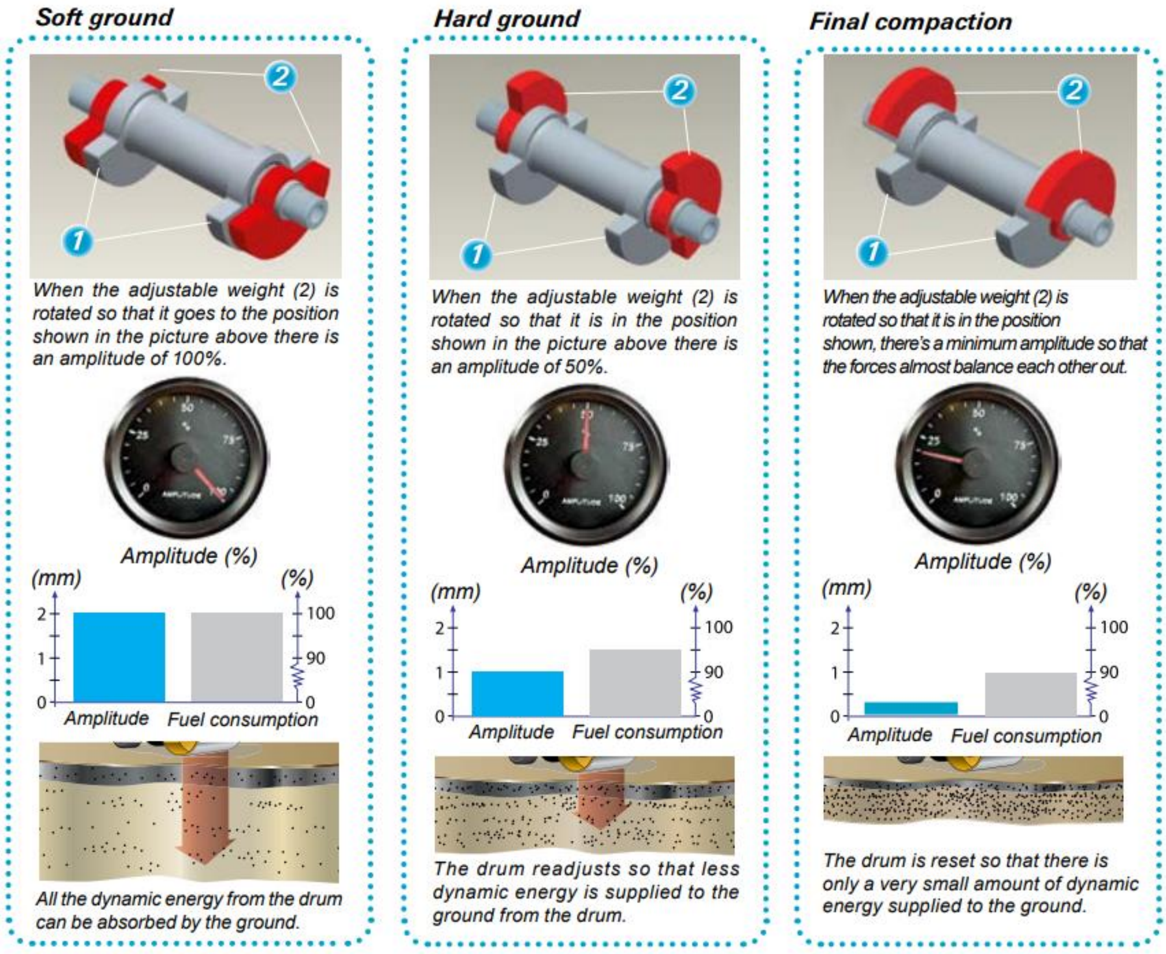
The visual display monitor in the cab of the roller provides the operator with a real-time colour-coded display of the state of compaction, as well as the material stiffness, the number of roller passes, the frequency, speed, and amplitude of the roller and the drum. The Caterpillar documentation system is shown in **Error! Reference source not found.**.

Figure 2.3 Caterpillar documentation system illustrating completed passes (left) and CMV (right) (Mooney et al. 2010)

2.5 AUTOMATIC FEEDBACK CONTROL (AFC) SYSTEM

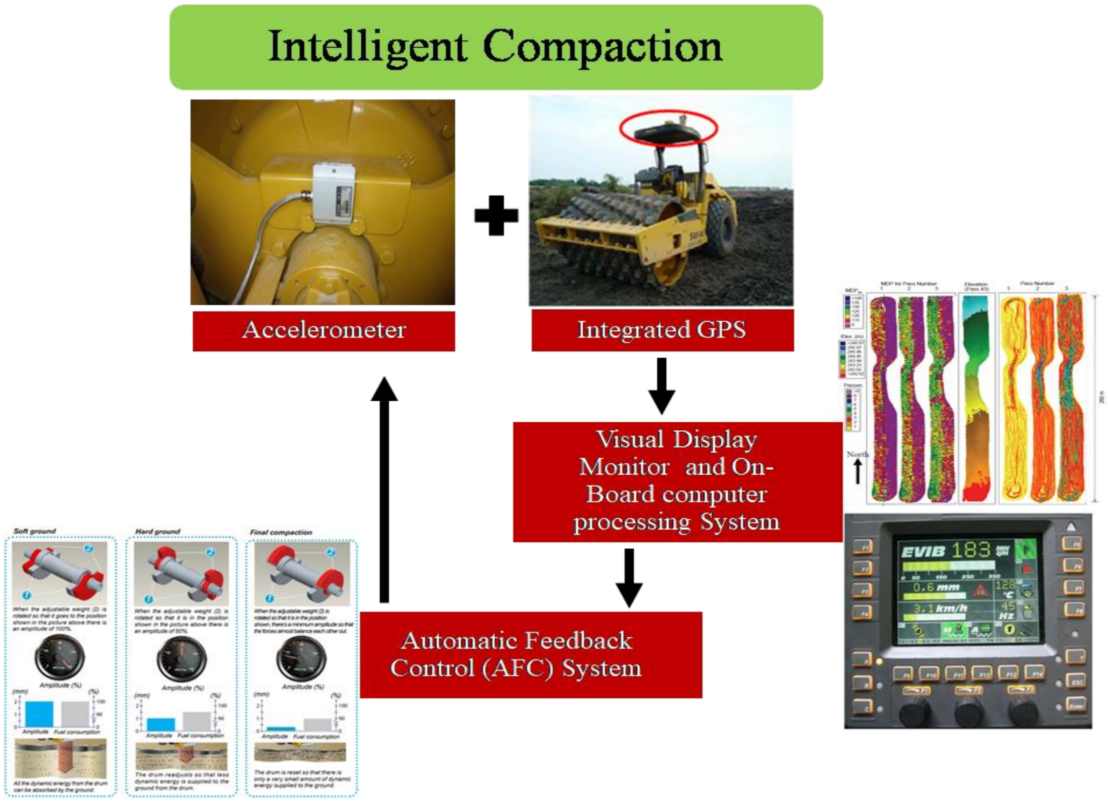
Automatic feedback control (AFC) systems can control the amplitude of the vertical excitation force automatically during the compaction process to prevent unstable "jump" of the drum. More advanced AFC systems can also automatically improve the degree and uniformity of compaction through an increase/decrease in the drum amplitude by comparing the roller measurement values with a predetermined target value. **Error! Reference source not found.** illustrates the operating principles of the Dynapac AFC system.

Figure 2.4 Overview of Dynapac's compaction optimiser (DCO) (Åkesson et al. 2008)



A logic diagram showing a typical intelligent compaction system is shown in **Error! Reference source not found.**.

Figure 2.5 Logic diagram illustrating the relationships between intelligent compaction components



3 BENEFITS AND DISADVANTAGES OF USING INTELLIGENT COMPACTION (IC) TECHNOLOGIES

The use of IC technologies for roadway construction has the potential to provide the following benefits over conventional compaction equipment:

1. Improved quality and uniformity of compaction.
2. It allows the roller operators to visualise the compaction process continuously, which assists with ensuring a consistent rolling pattern. IC technology can also improve the roller patterns by limiting the number of passes needed to compact a soil; this is important because compacting soil with the predetermined optimum number of passes maximises the density and stiffness, whereas insufficient or excessive passes significantly reduces the quality of compaction. Live feedback for the operator during compaction often improves compaction uniformity. Using IC technology, the pass count mapping helps the operator achieve the target density more efficiently, while eliminating excessive overlap and incomplete and missing passes, especially during night-time operations.
3. Reduced testing costs and construction costs associated with rework.
4. The ability to identify soft spots during construction to allow timely removal and replacement.
5. With the capability of determining weak spots during the pre-mapping, the compactive effort is applied only where necessary, which in turn reduces the roller's fuel consumption and equipment wear and tear. Moreover, the enhanced uniformity of compaction will inevitably reduce excessive differential settlement and therefore lower the maintenance cost and optimise the labour deployment.
6. With the roller integrated CCC, the data recording during the compaction process provides 100% coverage, which is essential to the pavement management process since long-term performance may be correlated with the properties produced during construction. Similarly, evaluating the mechanical properties of subgrade and pavement materials during compaction relates directly to the mechanical properties used in the structural design of the pavement.

Further details on the benefits of IC can be found in Correia (2008), Chang et al. (2011), Gallivan et al. (2011) and Horan et al. (2012).

However, there are several considerations associated with IC technology that contractors and highway agencies should take into account before implementation:

- Equipment cost – Equipped with advanced instrumentation, the cost of a new IC roller is approximately 3-5% higher compared with a conventional roller. Despite the fact that a retrofit kit is available to upgrade existing conventional rollers to IC rollers, the cost ranges from $40,000 to $75,000 depending on the manufacturer and the desired features of applied technology.
- Roller operator skills – Roller operators must be trained to use IC rollers, but since the training is not overly complicated or time consuming, it is generally offered by the vendors when the equipment is purchased, leased, or rented.

4 CURRENT INTELLIGENT COMPACTION EQUIPMENT AND MEASUREMENT VALUES

The primary manufacturers of IC soil rollers include Bomag, Ammann, Dynapac, Sakai and Caterpillar, of which Ammann, Bomag and Dynapac provide the automatic feedback control (AFC) that automatically adjusts the amplitude and frequency of the roller to improve compaction and uniformity. **Error! Reference source not found.** shows the IC r ollers available from different vendors. As well as the original equipment manufacturer (OEM) IC rollers, retrofit IC systems are available for upgrading conventional rollers to IC capability. In this section, the existing IC rollers commercially available for continuous compaction control, and their respective measurement values and associated theories, will be presented. This is followed by a brief introduction to a retrofit kit.

Figure 4.1 Pictures of different rollers used for intelligent compaction (a) Sakai (b) Ammann (c) Dynapac (d) Sakai (e) Caterpillar smooth-drum rollers (adapted from Chang et al. (2011))

4.1 ORIGINAL EQUIPMENT MANUFACTURER (OEM) IC ROLLER

4.1.1 BOMAG

The Bomag IC roller utilises a vario-control system which contains two acceleration transducers, a processor/control unit, a distance measurement device and a GPS unit. The system adopts a constant frequency compaction (f = 28 Hz), and two accelerometers with measurement axes arranged at ±45º from vertical to measure the vertical acceleration of the drum.

The Bomag vario-control system calculates a "vibration modulus", E_{vib}, using lumped parameter vibration theory and cylinder on elastic half-space theory; the principle behind E_{vib} is presented in Krober et al. (2001). The vibratory modulus (E_{vib}) value is calculated using the one-degree-of-freedom lumped parameter model and Lundeberg's theoretical solution (Lundberg 1939) for a rigid cylinder on an elastic half-space, based on the compression paths of contact forces (F_K) and drum displacement (Z_d) curves. A typical compact path and the Bomag operation panel are shown in **Error! Reference source not found.** and **Error! Reference source not found.**, respectively.

Figure 4.2 Contact-force drum displacement behaviour (Briaud & Seo 2003)

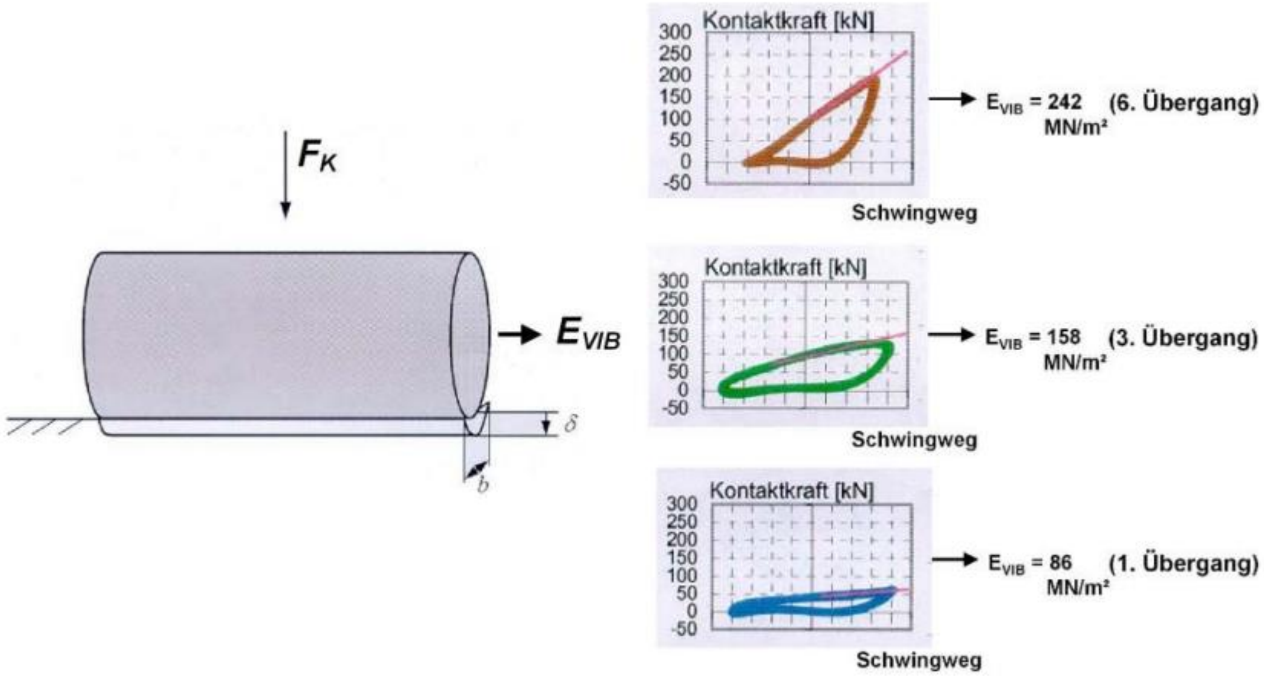


Figure 4.3 Bomag IC on board display (Chang et al. 2011)

The determination of the contact force and the drum displacement are confidential information of Bomag and only the formulations used to derive E_{vib} (MN/m^2) are presented here, as shown in Equations (1) and (2).

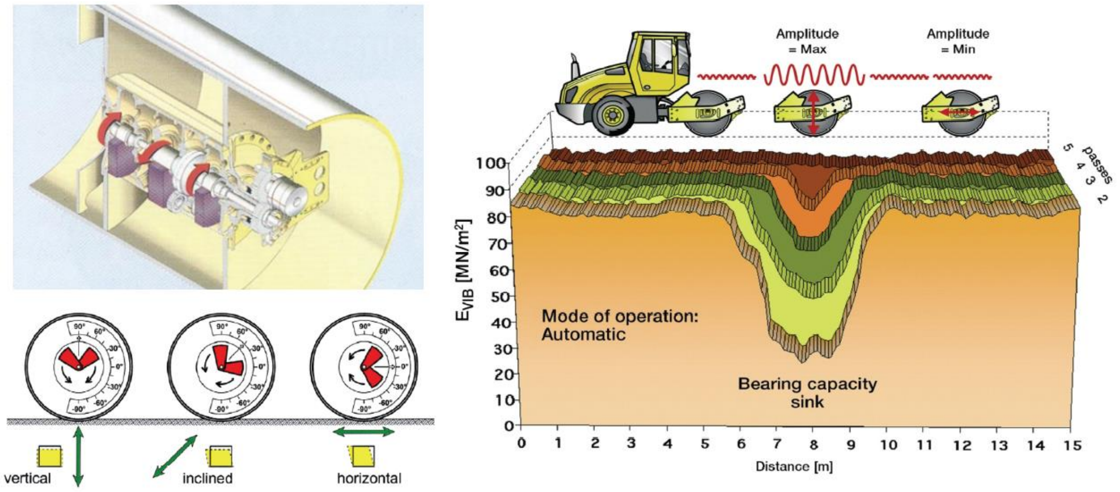
$$Z_d = \frac{1-\vartheta^2}{E_{vib}} \cdot \frac{2F_K}{\pi L} \cdot \left(1.8864 + ln\frac{L}{B}\right) \tag{1}$$

$$B = \sqrt{\frac{16}{\pi} \cdot \frac{R(1-\vartheta^2)}{E_{vib}} \cdot \frac{F_K}{L}} \tag{2}$$

where ϑ is the material Poisson's ratio, L is the length of the drum (m), B is the contact width of the drum (m), and R is the radius of the drum's cross-section (m).

Note that the Bomag also has an AFC system that enables an automatic adaption of amplitude during compaction. The Bomag roller eccentric mass assembly and a schematic diagram of the AFC system are shown in **Error! Reference source not found.**.

Figure 4.4 Principle of variable-amplitude system (White & Vennapusa 2010)

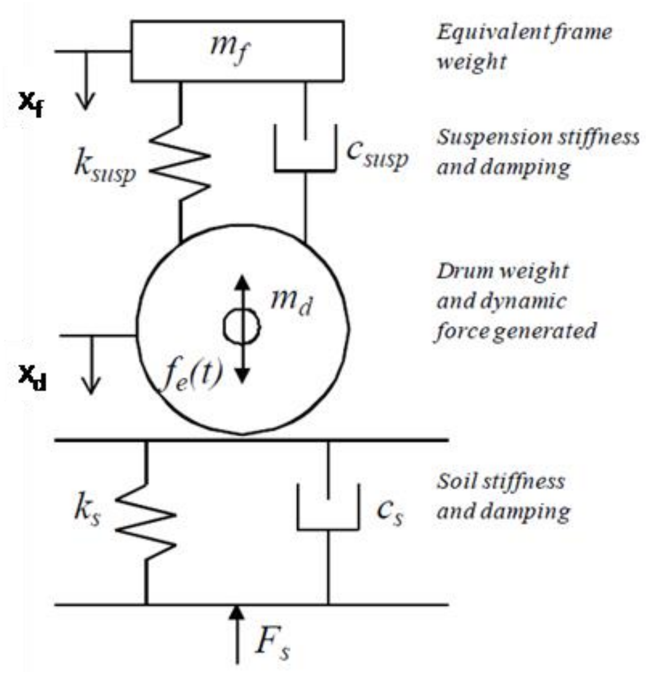


In **Error! Reference source not found.**, the maximum vertical excitation (i.e. maximum drum displacement amplitude) is reached when the horizontal excitation is zero, and conversely, when the horizontal excitation reaches its maximum, vertical excitation has the minimum value (i.e. minimum amplitude and contact force).

4.1.2 AMMANN

The Ammann IC and the AFC system, also known as the ACE plus system, contains a measurement component and a feedback control system. This system adopts a roller-integrated stiffness (k_s), that was introduced during late 1990s, which considers a lumped parameter two-degree-of-freedom spring-mass-dashpot system. A schematic of the spring-mass-dashpot system is shown in **Error! Reference source not found.**.

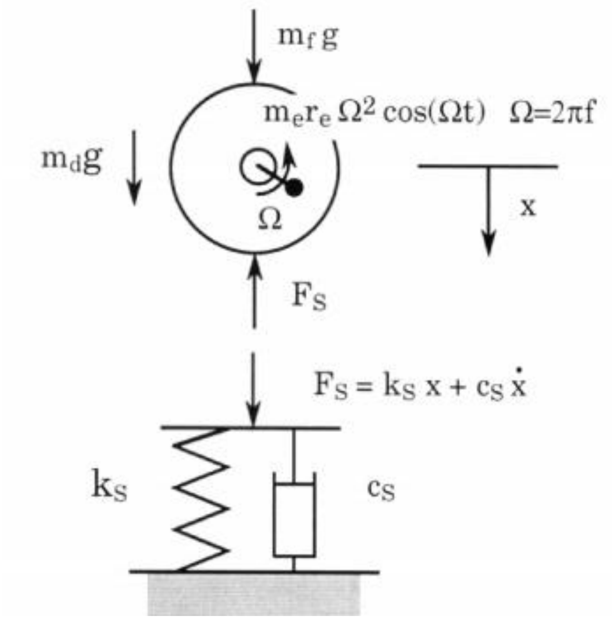
Figure 4.5 Lumped parameter two-degree-of-freedom spring dashpot model representing vibratory compactor and soil behaviour (Yoo & Selig 1980)



where m_d and m_f are the mass of the drum and frame (kg), X_d and X_f are the displacement of the drum and frame (m), k_{susp} is the suspension stiffness (MN/m), c_{susp} and c_s are the dashpots/damping components (MNs/m) of the roller and the soil, and F_s is the drum-soil contact force (KN).

These detailed formulations can be found in Anderegg & Kaufmann (2004) and only the essential information is presented here. During roller compaction, the resulting free-body diagram can be depicted as shown in **Error! Reference source not found.**.

Figure 4.6 Simplified model for intelligent compaction (Anderegg & Kaufmann 2004)



where $m_e r_e$ is the eccentric moment of the unbalanced mass, Ω is the circular vibration frequency, t and f are the time and frequency of the excitation, X is the displacement of the drum, and $\dot{X}$ represents the differentiation with respect to time.

In the Ammann IC system, the vertical drum displacement is determined via spectral decomposition and integrating peak drum accelerations, according to Anderegg & Kaufmann (2004). The roller-integrated stiffness, k_s,is solved when the velocity of the drum is zero, i.e. at its furthest most position during compaction. The stiffness (k_s) can be determined using the following equation:

$$k_s = 4\pi^2 f^2 \left[\frac{m_d + m_e r_e \cos \emptyset}{x}\right] \quad (3)$$

where Ø represents the phase lag between the eccentric force and drum displacement.

As with the Bomag IC system, the Ammann ACE plus system can perform AFC by controlling the drum and soil contact force F_s. According to Anderegg, Von Felten & Kaufmann (2006), there are three AFC operation settings available using the ACE plus system:

1. Low performance setting: maximum applied force = 14 kN with vibration amplitude varying from 0.4 to 1.5 mm.
2. Medium performance setting: maximum applied force = 20 kN with vibration amplitude varying from 1.0 to 2.0 mm.
3. High performance setting: maximum applied force > 25 kN with vibration amplitude varying from 2.0 to 3.0 mm.

At a selected force, the roller adjusts the eccentric mass to maintain its maximum force on the soil to be compacted. The ACE plus system can also use a user-specified k_s value as the control parameter. In the so-called plate modulus measurement mode, a limit value for k_s is selected. When the predetermined value is reached, the eccentric mass moment will be reduced to optimise compaction with the least desirable number of passes.

4.1.3 DYNAPAC

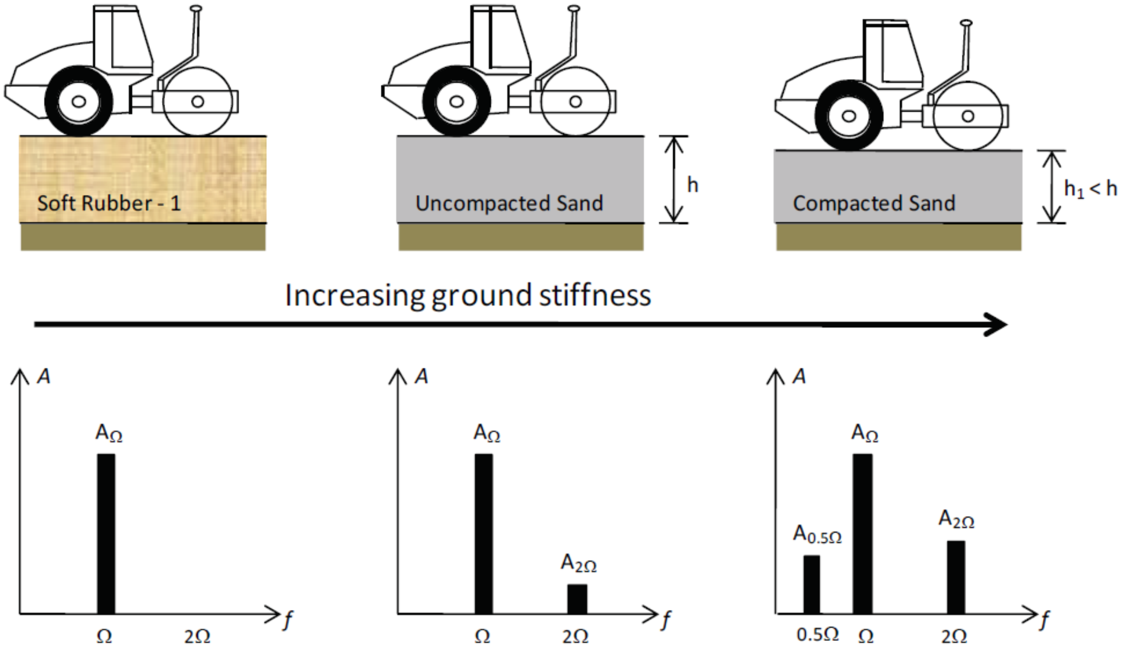
CMV, used by Dynapac in assessing the level of soil compaction, is a dimensionless indicator developed by Geodynamik in the 1970s and introduced commercially in 1980. The Dynapac technology utilises accelerometers to measure drum accelerations in response to soil behaviour during compaction (White et al. 2009). According to the Dynapac soil IC system, the ratio between the amplitude of the first harmonic frequency and the amplitude of the fundamental frequency can reflect the level of soil compaction, where an increase in CMV value corresponds to an increase in the level of compaction level. Hence, the equation for calculating the CMV is:

$$CMV = C \cdot \frac{A_{2\Omega}}{A_{\Omega}} \tag{4}$$

where C is a constant (typically 300); $A_{2\Omega}$ is the acceleration of the first harmonic component of the vibration, and A_{Ω} is the acceleration of the fundamental component of the vibration.

The concept of developing different harmonic components of drum vibration with increasing ground stiffness is shown in **Error! Reference source not found.**. It can be explicitly observed that, as the ground stiffness increases, the f undamental component of the vibration (i.e. A_{Ω}) accelerates, and therefore the CMV increases monotonously.

Figure 4.7 Illustration of changes in drum harmonics with increasing ground stiffness (Thurner & Sandström 1980)



Furthermore, the Geodyncmik system uses a resonant meter value (RMV) along with the CMV to indicate drum behaviour, including continuous contact, partial uplift, double jump, rocking and chaotic motion. In the Dynapac IC system, the RMV value is reported as a bouncing value (BV). According to Sandström & Pettersson (2004), the RMV (i.e. BV) is defined as the ratio between the sub-harmonic acceleration amplitude $A_{0.5\Omega}$ caused by rolling jumping and A_{Ω}, as shown in the following equation:

$$RMV = BV = C \cdot \frac{A_{0.5\Omega}}{A_{\Omega}} \tag{5}$$

The Dynapac IC system utilises the Dynapac Compaction Optimiser (DCO) to provide the AFC for the eccentric excitation force to prevent jumping by monitoring the RMV (i.e. BV). The amplitude of the roller is reduced when a threshold RMV is reached.

During operation, the DCO compares the measured RMV and the threshold RMV. The roller is operated at its maximum amplitude when the measured RMV is less than the threshold value; otherwise the amplitude is reduced. It is noteworthy to mention that Dynapac does not use feedback control based on the CMV.

4.1.4 SAKAI

The Sakai IC system employs the compaction control value (CCV) to evaluate the level of compaction. The CCV index, which is dimensionless, is similar to the CMV adopted in the Dynapac IC system, but there are more excitation frequencies adopted as benchmarks. Hence, it can be regarded as an extension of the CMV index.

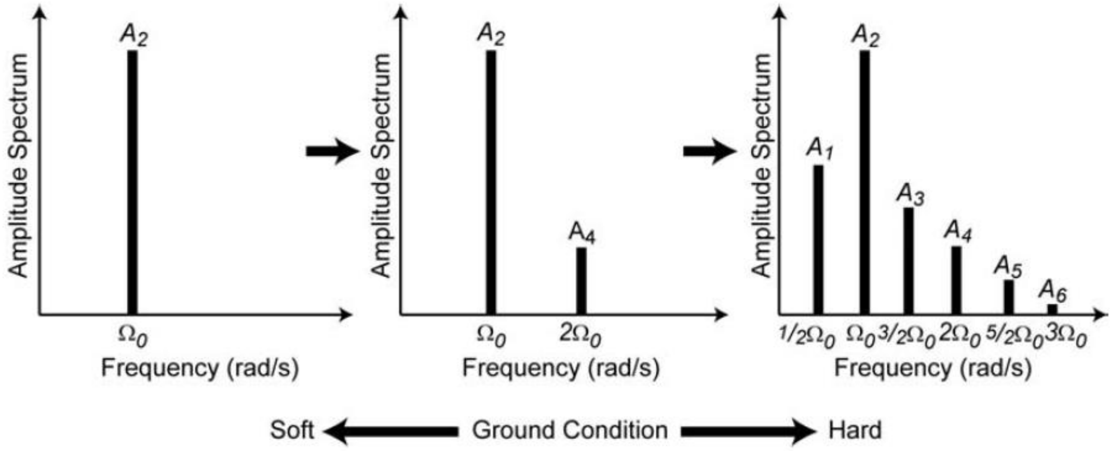
The Sakai IC system comprises one accelerometer monitoring vertical drum vibration. The value represents the stiffness of the compacted soil underneath. The concept associated with the CCV is such that the roller drum can begin a jumping motion that results in increased vibration accelerations with respect to an increase in ground stiffness. The Sakai IC system adopts analog bandpass filters to capture acceleration at the excitation frequencies, Ω_0, 0.5 Ω_0, 1.5 Ω_0, 2 Ω_0, 2.5 Ω_0 and 3 Ω_0, as shown in **Error! Reference source not found.**. Those amplitudes at each of these frequencies are used to compute the CCV using Equation (6):

$$CCV = \left[\frac{A_1+A_3+A_4+A_5+A_6}{A_1+A_2}\right] \times 100 \qquad (6)$$

where A_1 to A_6 represents the amplitude corresponding to the excitation frequencies Ω_0 to $3\Omega_0$, respectively.

The current Sakai IC system does not incorporate any AFC systems.

Figure 4.8 Drum acceleration frequency domain components used in Sakai CCV (Scherocman, Rakowski & Uchiyama 2007)

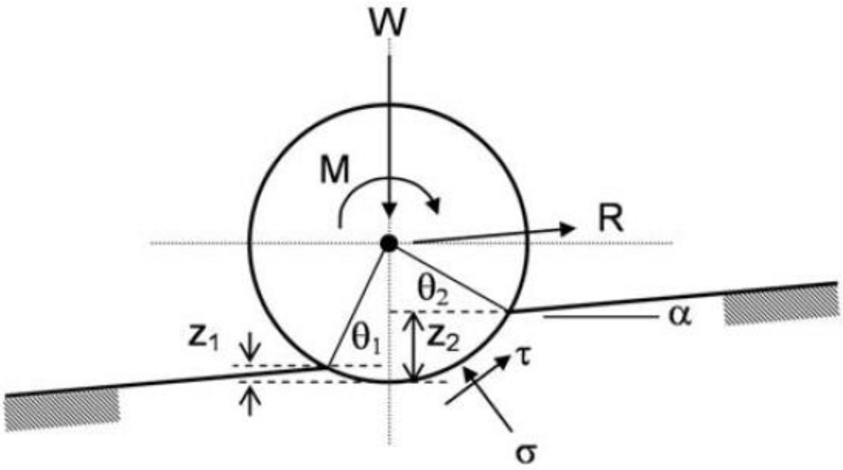


4.1.5 CATERPILLAR

The Caterpillar IC system consists of an accelerometer attached to the drum, a slope sensor and a real-time kinematic GPS receiver where the slope sensor measures the longitudinal direction of tilt of the drum to ±45º. Unlike any other roller manufacturers, the Caterpillar IC system utilises two different measurement values: the compaction meter value (CMV) and the machine drive power (MDP). The former measurement value (i.e. CMV) has the same characteristics as the Geodynamic/Dynapac CMV reported in Section **Error! Reference source not found.**.

The development of the MDP index as a measure of soil compaction level commenced with a study of vehicle-terrain interaction (Bekker 1969). The theory of MDP is based on rolling resistance to derive the stresses acting on the drum during compaction. This fundamentally measures the amount of power required for the compactor to propel itself over the soil (i.e. the energy overcoming the resistance to motion), by providing an indication of its load bearing strength. The simplified two-dimensional free body diagram of stresses acting on a drum is illustrated in **Error! Reference source not found.**.

Figure 4.9 Simplified two-dimensional free body diagram of stresses acting on a rigid compaction drum (Mooney et al. 2010)



The equation used to calculate the MDP is given in Equation (7):

$$MDP = P_g - WV\left(\sin\theta + \frac{a}{g}\right) - (mV + b) \tag{7}$$

where P_g is the gross power needed to facilitate the movement of the roller, W is the weight of the roller, V is the velocity of the roller, θ is the slope angle, a and g are the machine and gravity accelerations, respectively, and m and b are the machine internal loss coefficients of a particular roller type.

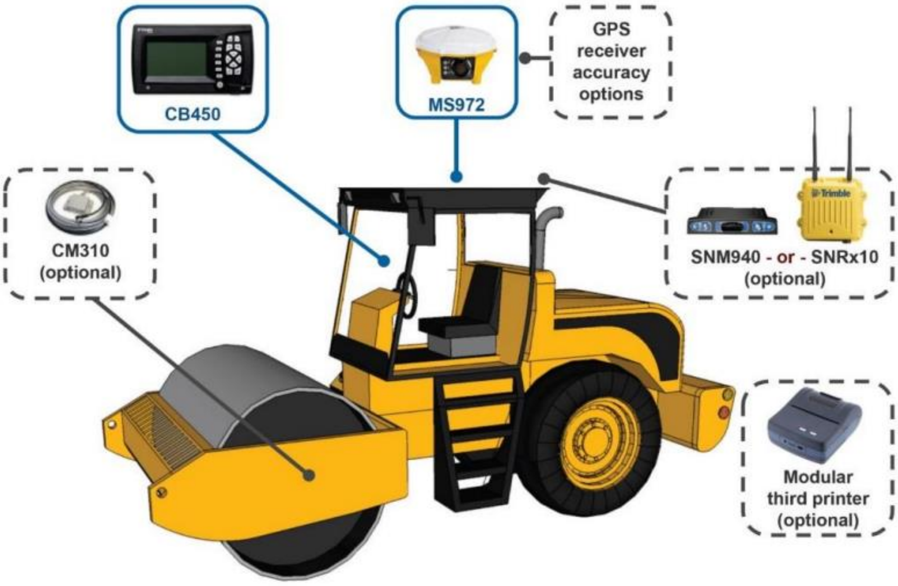
To use the equation means calibrating the coefficients θ, m and b. Details of this calibration procedure can be found in Thompson & White (2008). MDP is a relative value that refers to the material properties of the calibration strip. A positive MDP reading indicates that the level of compaction is less than the calibration strip, whereas the soil is considered to be more compacted if a negative MDP is obtained.

4.2 INTELLIGENT COMPACTION (IC) RETROFIT KIT

Besides the OEM IC roller, a retrofit kit is a more affordable compaction control system. In 2008, Trimble introduced an IC retrofit kit than can be incorporated into most regular vibratory rollers for controlling compaction. Besides the Trimble, Topcon recently launched an IC retrofit kit. Both retrofit kits include a GPS antenna and receiver, a vibration sensor (i.e. accelerometer), connecting cables, and an in-cab display monitoring the compaction process (Nazarian et al. 2015). **Error! Reference source not found.** shows the components of the retrofit kit installed on a regular roller. T he features of the IC retrofit kit are almost the same as the OEM IC roller, including the mapping function (i.e. pass count and compaction measurement value), the real time information display (i.e. speed, location, amplitude and frequency of the roller), and the live reports (i.e. compaction performance, CMV data and position data).

However, there are limitations associated with the IC retrofit kit, including that the measurement values are different from many other roller manufacturers. The current Trimble retrofit kit is based on the compaction meter value (CMV), which is the same roller measurement value used by Dynapac. Furthermore, the accelerometer must be installed by a certified technician and properly verified to ensure that the sensor is mounted vertically, securely, and in a position that can capture the actual vibration of the drum.

Figure 4.10 Components of the retrofit kit installed on an existing single drum smooth roller (Nazarian et al. 2015)



5 EXISTING SPECIFICATIONS ADOPTED IN EUROPE AND THE USA

In this section, a selection of existing specifications that incorporate roller-integrated measurement systems for continuous compaction control are presented. IC specifications were first introduced in Austria in 1990, and Germany subsequently developed its own specification in 1994, followed by Sweden, also in 1994. Based on the Austrian specification, the International Society for Soil Mechanics and Foundation Engineering (ISSMGE) developed the *Recommended Guidelines and Construction Specification* in 2005 (Adam 2007). In the USA, the Minnesota Department of Transportation (DOT) also implemented pilot specifications in 2006. The principal components of the various specifications are now described; more detailed specifications can be found in Mooney et al. (2010), Chang et al. (2011) and Chang, Xu, Rutledge & Garber (2014).

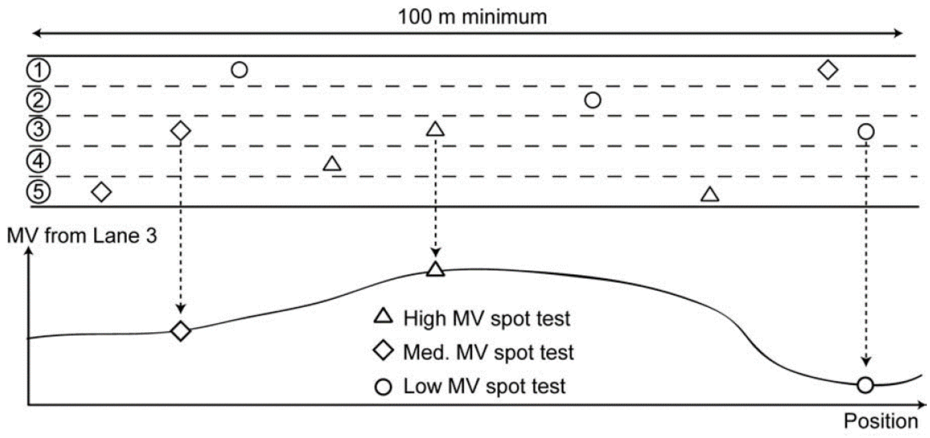
5.1 AUSTRIAN/ISSMGE SPECIFICATIONS

The Austrian/ISSMGE specifications (SSMGE 2005) allow two different approaches for roller-integrated CCC. The first approach involves acceptance testing using a regression-based correlation developed during on-site calibration, whereas the second approach requires continuous compaction until the mean roller MV increases by no more than 5% compared to the previous pass. The second approach is recommended for small sites where calibration (i.e. first approach) cannot be achieved. Acceptance is then based on static plate load testing (PLT) or dynamic plate load testing using the lightweight deflectometer (LWD) modulus at the weakest area.

5.1.1 APPROACH 1 – REGRESSION CORRELATION BASED ON CALIBRATION

The more recent Austrian/ISSMGE roller integrated CCC method involves the development of a relationship between roller measurement value (MV) and the initial PLT modulus, E_i (i.e. E_{V1} or E_{LWD}). It is noteworthy to mention that E_{V1} represents the modulus derived from the first loading loop in the static plate load test. Calibration is required over the entire width of the calibration strip and for a length of at least 100 m for each material (subgrade, subbase, and base). Roller-integrated measurements must be carried out with constant roller parameters (frequency, amplitude, and forward velocity) throughout calibration. Roller MV data is captured during each run, and subsequent PLT or LWD testing is performed at values of low, medium and high roller MV, as depicted in **Error! Reference source not found.**.

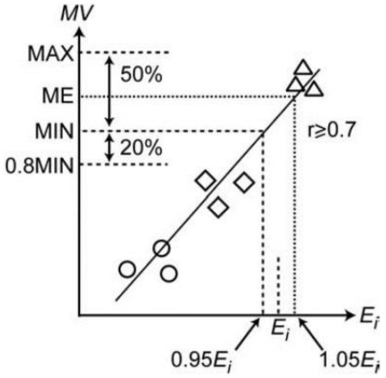
Figure 5.1 Illustration of calibration approach for Austrian/ISSMGE specifications (Mooney et al. 2010)



A minimum of nine locations are needed for PTL testing. If LWD testing is used, then the average of four E_{LWD} values at a minimum of nine locations must be reported, which results in a total of 36 LWD tests.

Using the determined roller measurement values (MVs) and the E_i (i.e. E_{V1} or E_{LWD}) derived from the aforementioned tests, a linear regression analysis is then carried out, as illustrated in **Error! Reference source not found.**.

Figure 5.2 Roller MV vs. E_{V1} /E_{LWD} regression and key parameters in Austrian/ISSMGE (Mooney et al. 2010)



As required by the Austrian/ISSMGE specification, the correlation coefficient (r) must be ≥ 0.7. However, additional PLT or LWD tests may be performed to achieve $r \geq 0.7$. With the determined regression equation and a specified E_i (i.e. E_{V1} or E_{LWD}) (see **Error! Reference source not found.** for Austrian values), the minimum roller MV (MIN) and the mean roller MV (ME) can be determined.

Table 5.1: E_{V1} and E_{LWD}values required in Austria specification (Mooney et al. 2010; Indraratna, Chu & Rujikiatkamjorn 2015)

Level	**E_{V1} (MN/M²)**
1 m below subgrade	15 (cohesive); 20 (cohesionless)
Top of subgrade	25 (cohesive); 35 (cohesionless)
Top of subbase	60 (rounded); 72 (angular)
Top of base	75 (rounded); 90 (angular)
Level	**E_{LWD} (MN/m²)**
1 m below subgrade	18 (cohesive); 24 (cohesionless)
Top of subgrade	30 (cohesive); 38 (cohesionless)
Top of subbase	58 (rounded); 68 (angular)
Top of base	70 (rounded); 82 (angular)

As illustrated in **Error! Reference source not found.**, the minimum (MIN) MV value corresponds to 0.95E_i (i.e. E_{V1} or E_{LWD}), and the mean roller measurement value (ME) corresponds to 1.05 E_i (i.e. E_{V1} or E_{LWD}). The maximum (MAX) MV value is defined as 1.5 times the minimum MV value. The Austrian/ ISSMGE acceptance criteria are summarised as follows:

- the mean roller MV must be ≥ ME
- 100% of roller MVs must be ≥ 0.8 MIN
- 90% of roller MVs must be ≥ MIN.

5.1.2 APPROACH 2 – CONTINUOUS COMPACTION BASED ON MV INCREASE PERCENTAGE

If the regression method based on on-site calibration (i.e. Approach 1) cannot be attained on small construction sites, then compaction must be continued until the increase in mean roller MV is less than 5% compared to the previous pass, as recommended by Austrian/ISSMGE specifications. PLT or LWD testing is subsequently performed at the weakest areas according to the roller measurements values determined. Acceptance can only be awarded if the determined PLT or LWD values (i.e. E_{V1} or E_{LWD}) is equal to or greater than the values required by the Austria/ISSMGE specification, as tabulated in **Error! Reference source not found.**.

5.2 GERMAN SPECIFICATIONS

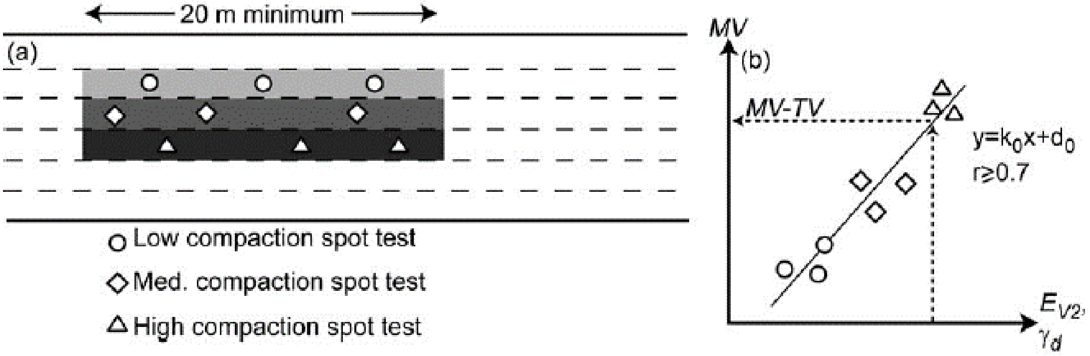
The German specifications for earthwork quality assurance (QA) using roller integrated CCC were introduced in 1994. Similar to the Austrian/ISSMGE specifications, there are two approaches available for specifying roller integrated CCC in Germany. The first method involves a regression-based correlation developed during on-site calibration of roller MVs to PLT modulus (E_i), or unit weight (γ_d)/density, while the second method uses CCC to identify weak areas for spot testing via PLT or density methods (Mooney et al. 2010).

5.2.1 APPROACH 1 – REGRESSION CORRELATION BASED ON CALIBRATION

According to the German specifications, calibration must be carried out by adopting three test strips with different degrees of compaction, and each test strip must be at least 20 m long (see **Error! Reference source not found.**).

During the roller operation, roller MVs are collected on a low degree of compaction test strip (e.g. after one compaction pass), a medium degree of compaction test strip (e.g. three to five compaction passes), and a high degree of compaction test strip (multiple passes until no further compaction observed).

Figure 5.3 Illustration of calibration approach for German specifications (Mooney et al. 2010)



After compaction, three to five static PLTs or density tests are carried out on each test strip, and a regression analysis is subsequently performed adopting the roller MVs and spot-test data (i.e. static PLTs or density tests), as depicted in **Error! Reference source not found.**. It must be highlighted that the German specification, unlike the Austrian/ISSMGE specification, adopts the modulus from the second loading loop in the static plate load test (E_{V2}), as shown in **Error! Reference source not found.**. Referring to **Error! Reference source not found.**, the correlation coefficient (r) must be greater than 0.7. However, additional spot tests may be performed to achieve $r \geq 0.7$. With the determined regression equation and a minimum value of E_{V2} and unit weight/density, the determination of a measurement value target value (MV-TV) can be determined. According to the German specification, the minimum E_{V2} value for clay or silty soils is 45 MPa, and the granular materials require a minimum E_{V2} of 80 to 100 MPa. During acceptance testing, it is required that over 90% of roller MVs in an evaluation area must exceed the MV-TV value.

In addition, the German specification requires that the frequency and the amplitude of the roller during calibration or acceptance testing must be constant, and the project site must be homogeneous in terms of soil type and underlying stratigraphy. Furthermore, the German specifications allow the use of AFC intelligent compaction rollers during compaction. However, the AFC mode must be disabled during calibration and acceptance testing stages.

5.2.2 APPROACH 2 – CONTINUOUS COMPACTION BASED ON SPOT TESTING VALUES

The second approach requires the identification of the weak areas from the roller-generated maps based on the roller MVs. Once the weakest spots are identified, the spot testing via PLT or density method is subsequently conducted. According the German specification, a minimum number of four (4) spot tests are required for each 5000 m^2 area. The soil must be reworked or continuously compacted until the spot test results (e.g. E_{V2}) are equal to or greater than the predetermined target values.

5.3 SWEDISH SPECIFICATIONS

The development of the specifications for the use of roller integrated CCC in Sweden was firstly introduced in 1994. Quality assurance (QA) in Sweden is usually performed for the basecourse and subbase course layers. Typically, Swedish construction includes a 300-700 mm thick base layer and a 300-400 mm subbase layer. Owing to these considerable thicknesses of base and subbase layers, the Swedish specifications require no QA for the subgrade. In addition, the maximum percentage of particles finer than 0.06 mm permitted in base and subbase layers is 7%.

Similar to the German specification, the Swedish specifications also permit the use of roller-integrated CCC to identify weak spots for subsequent PLTs. Once the weak spots are determined using roller-integrated CCC, a minimum of two PLTs must be carried out on these weak spots indicated by the roller MV data map. However, the number of PLTs can be further reduced to one per weak spot if the previous control areas show small variations. The criteria for acceptance during the QA process are summarised in **Error! Reference source not found.**. Referring to **Error! Reference source not found.**, the soil must be reworked or continuously compacted so that the PLT modulus (E_{V2}) is equal to or greater than the threshold values, and the ratio between two PLT modulus (E_{V2}/E_{V1}) must also satisfy the specified requirements. It must be highlighted that these threshold values vary with the depth below the surface of the basecourse (Mooney et al. 2010).

Table 5.2: Unbound material acceptance criterion when CCC is used (Sweden specification) (Mooney et al. 2010)

Depth below basecourse surface (mm)	Asphalt pavement		Concrete pavement	
	E_{V2min} (MPa)	E_{V2}/E_{V1}	E_{V2min} (MPa)	E_{V2}/E_{V1}
0-250	125	≤ 1+ 0.0136 E_{V2}	105	≤ 1+ 0.0162 E_{V2}
251-500	32	≤ 1+ 0.078 E_{V2}	45	≤ 1+ 0.056 E_{V2}
501-550	32	NA	45	NA
551-650	20	NA	30	NA
651-750	15	NA	20	NA

NA = not applicable.

5.4 MINNESOTA DEPARTMENT OF TRANSPORTATION PILOT SPECIFICATION

In 2007, the Minnesota Department of Transportation (MnDOT) developed pilot specifications for the QC and QA of granular and non-granular embankment soil using roller integrated CCC and/or LWD (Mooney et al. 2010; Chang et al. 2011; Chang et al. 2014).

The MnDOT specification requires the construction of control strips to determine the intelligent compaction target value (IC-TV) for each type and/or source of soil. The IC-TV will be the optimum compaction value determined by the engineer when additional compaction passes do not result in a significant increase in stiffness. According to THE MnDOT pilot specification, each control strip must be at least 100 m long and 10 m wide, and the lift thickness must be equal to the thickness planned while constructing the control strips. Besides the determination of the target IC-TV, the LWD target value (LWD-TV) is also required. Referring to the MnDOT specification, a minimum of three LWD tests are needed on each proof layer of control strip constructed, and the minimum spacing between these LWD tests is 25 m unless modified by the engineer. To determine the moisture sensitivity correction for IC-TV and LWD-TV, the control strip must be constructed and maintained at or near each extreme of 65% and 95% of optimum moisture content (OMP), as determined by the standard Proctor test method. Moisture testing is required at a minimum of 1 per 3000 m^3 of earthworks placed. The resulting data is utilised to produce a moisture correction trend line showing a linear relationship of the IC-TV and LWD-TV with different moisture contents.

During quality assurance (QA), the engineer observes the final compaction recording pass of the roller on each proof layer. For acceptance of each proof layer, all segments of proof layers must be compacted so that at least 90% of the IC measurements are at least 90% of the IC-TV prior to placing the next lift. According to the MnDOT specifications, the minimum accepted MVs are 80% of the moisture corrected IC-TV. For those areas less than 80% of the IC-TV, re-compaction must be carried out until all areas meet the acceptance criteria prior to placing the next lift. If a significant portion of the layer is more than 20% in excess of the moisture corrected IC-TV, the engineer shall re-evaluate the determined IC-TV from the control strips or construct additional control strips to re-determine the IC-TV based on the afore mentioned process.

In addition, during QA, a minimum number of one LWD test and one moisture test per proof layer per 300 m are required for the entire embankment being constructed. Each LWD test measurement taken must be at least 90% but not more than 120% of the moisture-corrected LWD-TV obtained on the applicable control strip Re-compaction must be carried out (dry or add moisture to the soil as needed) until all areas meet the acceptance criteria prior to placing the next lift. The engineer may perform additional LWD tests and moisture content tests in areas that visually appear to be noncompliant or as determined by the engineer.

A brief summary of the of IC specification adopted in Europe and the USA can be found in **Error! Reference source not found.**.

Table 5.3: Summary of intelligent compaction (IC) specifications adopted in Europe and the USA (modified from Chang et al. 2011)

Country/state	Equipment	Field calibration site characteristics	Site characteristics	Documentation	Compaction specification	SPEED of roller	Frequency of roller
Austrian/ISSMGE	Rollers chosen by experience. Vibrating roller compactors with rubber wheels and smooth-drums are suggested.	100 m long by the width of the site.	Homogenous (soil and water content) close to the surface, even surface. Track overlap ≤ 10% of the drum width.	Rolling pattern. Compaction passes; amplitude; speed of the roller; dynamic measuring values; velocity and corresponding location of the roller.	Correlation coefficient ≥ 0.7. Mean roller MV ≥ ME 100% roller MVs ≥ 0.8 MIN. 90% of roller MVs ≥ MIN.	Constant 2-6 km/h (±0.2 km/h).	Constant (±2 Hz).
Germany	Self-propelled rollers with rubber tire drive are preferred. Vibrating roller compactors with rubber wheels and smooth-drums are suitable.	Three test strips with different degrees of compaction, and each test strip must be at least 20 m long.	Flat surface, similar soil type, water content, layer thickness. Track overlap ≤ 10% of the drum width.	Registration number; weather conditions; position of the test track; water content and soil type. Rolling pattern. Compaction passes; amplitude and speed of the roller; dynamic measuring values; velocity and corresponding location of the roller.	Correlation coefficient ≥ 0.7. Over 90% of roller MVs in an evaluation area must exceed the predetermined MV-TV value based on the spot tests.	Constant.	Constant.
Sweden	Vibrating roller compactors with rubber wheels and smooth-drums are suitable.	Thickness of thickest layer.	Maximum percentage of particles finer than 0.06 mm permitted in based and subbase layers is 7%.	n/a	Soil must be reworked or continuously compacted so that the PLT modulus (E_{V2}) is equal to or greater than the threshold values, and the ratio between two PLT modulus (E_{V2}/E_{V1}) must satisfy the requirement.	Constant 2.5-4.0 km/h.	n/a

Country/state	Equipment	Field calibration site characteristics	Site characteristics	Documentation	Compaction specification	SPEED of roller	Frequency of roller
USA (Minnesota)	Smooth-drum or padfoot vibratory roller for granular and cohesive soil compaction.	100 m long by 10 m wide; the lift thickness must be equal to planned thickness during the construction of the control strips.	One calibration/control strip per type or source of material.	Moisture corrections. Quality control activities; compaction and measuring passes.	90% of the stiffness measurement must be at least 90% of the corrected compaction target value.	Constant during calibration and production compaction.	n/a

6 CORRELATION/RELATIONSHIP BETWEEN ROLLER MV'S AND SPOT TESTS

6.1 LINEAR REGRESSION ANALYSIS

In this section the correlation/relationship between roller measurement values and spot tests will be presented based on the research findings from the field studies presented in Mooney et al. (2010) under NCHRP 21-09 (2010). Other studies carried out on the correlation between roller MVs and spot tests can be found in Chang et al. (2011) and Von Quintus et al. (2010).

The motivation for presenting the study by Mooney et al. (2010) is due to its comprehensiveness since the study involved a field evaluation of five different IC measurement values produced by different IC rollers on 17 different soil types. These 17 different soil types can be generally categorised into three groups based on their soil classification and location within the pavement foundation layers: non-granular subgrade, granular subgrade and granular subbase/base materials. The compaction was carried out adopting both smooth-drum and padfoot drum rollers with different amplitudes, frequencies and speed settings in 60 controlled test beds (TBs).

To make the correlations between the roller MVs and in situ point measurements, spot tests were carried out at several locations and with selected roller passes to ensure that measurements could be obtained over a wide range of conditions. The spot tests were conducted at one or three locations over the drum width. The measurements were averaged over the drum width when three tests were performed to compare with the roller MV, which represented an integrated response over the width of the drum. The spot tests conducted in this field study consisted of density measurements using a nuclear gauge (NG); stiffness or modulus measurements using a LWD, soil stiffness gauge (SSG), static PLT, Falling Weight Deflectometer (FWD), Clegg Hammer (CH) and a Dynamic Cone Penetrometer (DCP).

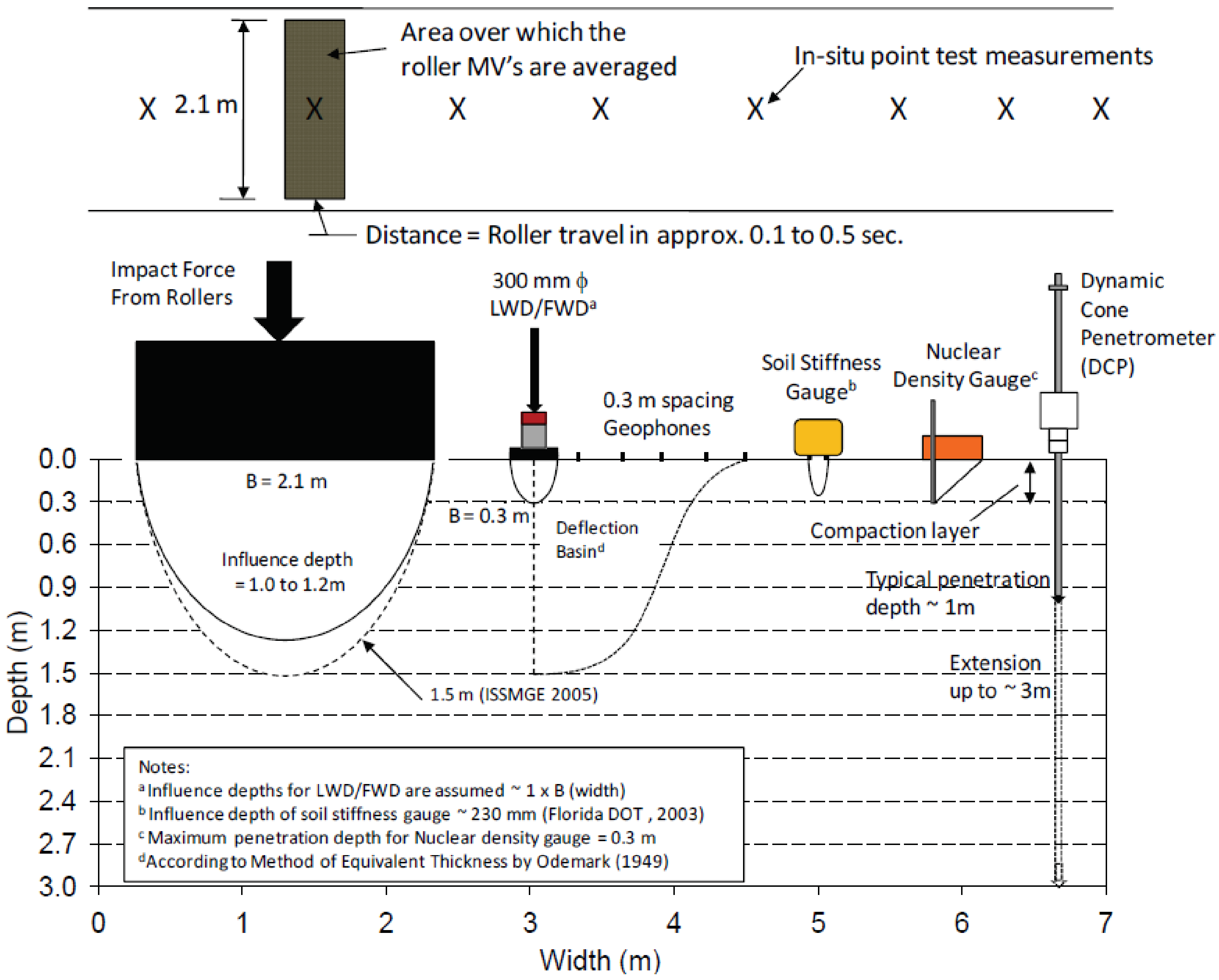
The summary of factors that commonly affect the correlation between ICMV and in situ test measurements identified from the field study are given in **Error! Reference source not found.**.

Table 6.1: Summary of factors affecting correlations between MV's and in situ point measurements (Mooney et al. 2010)

No.	Factors affecting correlations between roller MV's and in situ spot tests
1	Heterogeneity in underlying-layer support conditions
2	High moisture content variation
3	Narrow range of measurements
4	Machine operation setting variation (e.g. amplitude, frequency, speed) and roller "jumping"
5	Non-uniform drum/soil contact conditions
6	Uncertainty in spatial pairing of point measurements and roller MVs
7	Limited number of measurements
8	Insufficient information to interpret the results
9	Intrinsic measurement errors associated with roller MVs and in situ point-test measurements

It can be observed that heterogeneity in the underlying layer support conditions is the principal factor that affects the correlations between roller MVs and the in situ measurement. According to Mooney et al. (2010), this is largely attributed to differences in measurement depths between the roller and point measurements, as shown in **Error! Reference source not found.**, where the impact depth of roller can reach 1 to 1.2 m, while the impact depth for in situ measurements shows a significant variation. Hence, an appropriate method to overcome this issue is to make comparisons between roller MVs with point measurements having similar influence depths.

Figure 6.1 Illustration of differences in measurement depths for different measurements (Mooney et al. 2010)



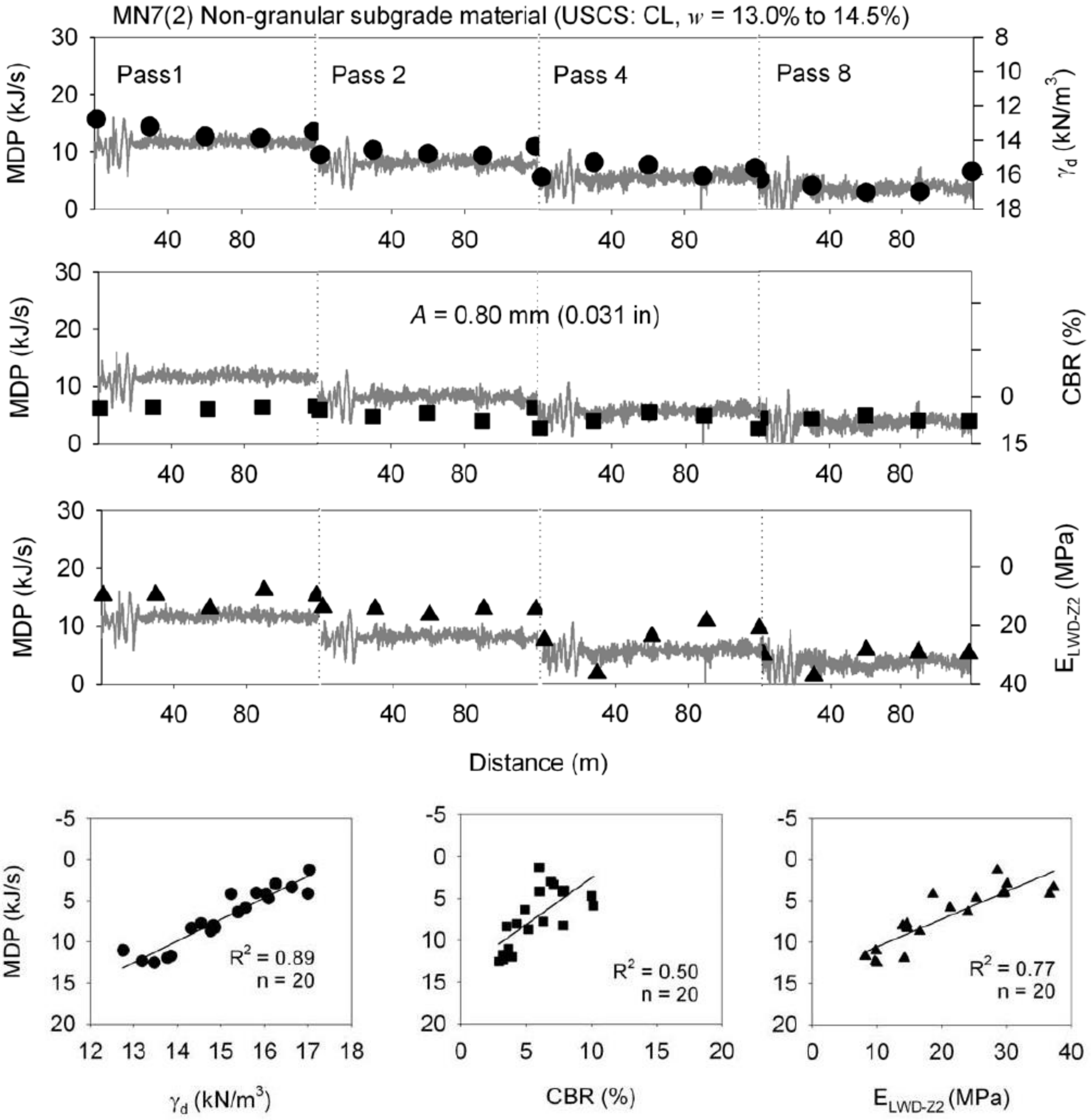
6.1.1 CATERPILLAR VIBRATORY PADFOOT ON A NON-GRANULAR SUBGRADE LAYER

The compaction of a non-granular subgrade layer (120 m long by 25 m width) with a moisture content of 13% to 14.5% was conducted by a Caterpillar vibratory padfoot roller with constant operation settings using a nominal amplitude A= 0.80 mm, frequency f= 33 Hz, and operational speed V= 4 km/h.

The underlying soil below the compacted layer, according to the DCP test, was relatively homogeneous. The in situ measurements adopted for comparison purposes included dry density (γ_d), California Bearing Ratio (CBR) and Modulus from a Zorn LWD device with a 200 mm diameter plate (E_{LWD-Z2}). These in situ measurements were obtained at roller passes 0, 1, 2, 4, 8 and at five test locations along the centreline of the roller path. The roller MV was based on the MDP value, and the comparisons made between the roller MVs and in situ measurements are shown in **Error! Reference source not found.**.

The correlation between the roller MVs and in situ measurements were developed based on a linear regression analysis for all three spot tests conducted, with the correlation coefficient R^2 ranging between 0.77 and 0.89 for the density and stiffness measurements (refer **Error! Reference source not found.**), confirming relatively good correlation. However, the correlation between moisture condition (MC) and CBR was poorer with an R^2 of 0.5. Hence, it can be concluded that good correlations are possible between MDP and in situ point measurements for a relatively homogeneous layer and underlying support conditions.

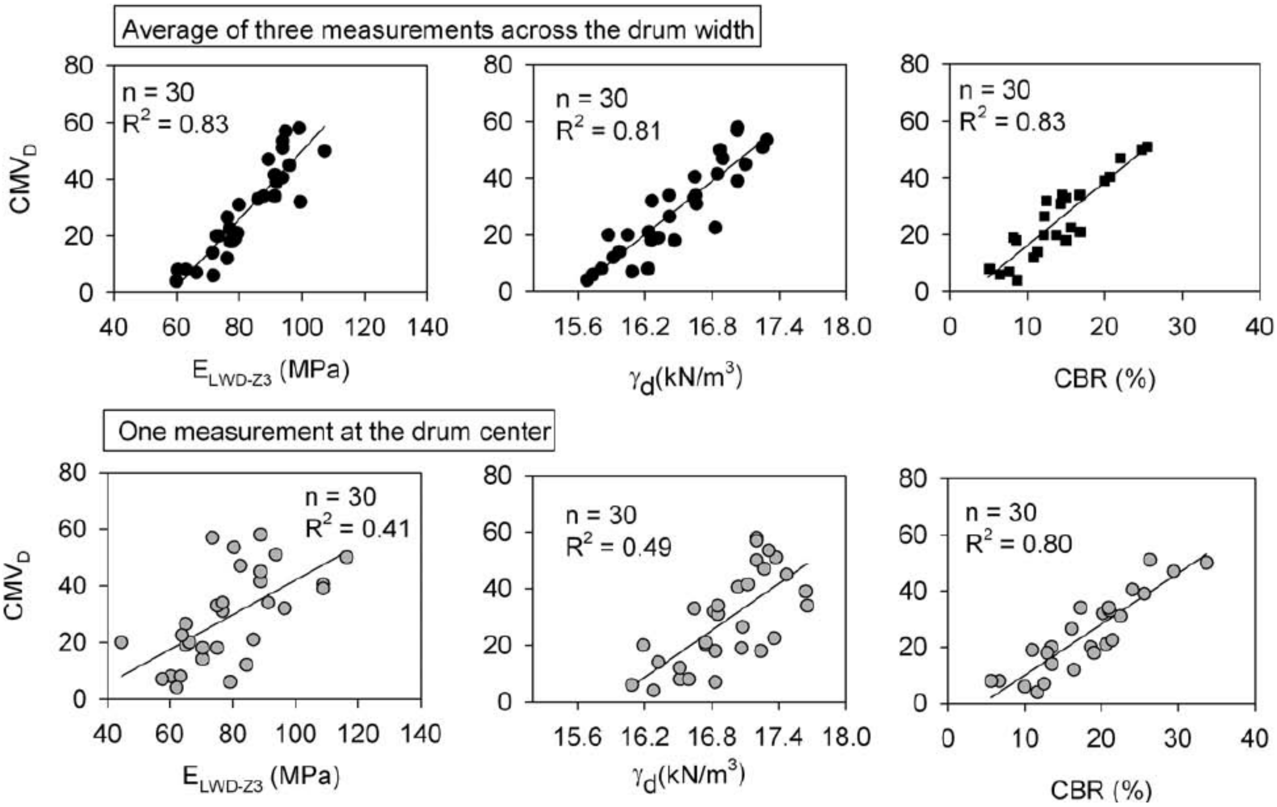
Figure 6.2 Comparison between roller MV and in situ point measurements (top), and single linear regression relationships between spatially nearest roller MV and in situ point measurements (bottom) (Mooney et al. 2010)



6.1.2 DYNAPAC VIBRATORY SMOOTH-DRUM ROLLER ON A GRANULAR BASE MATERIAL

A Dynapac vibratory smooth-drum roller was used to compact 150 mm thick loose granular base materials with relatively consistent moisture content ranging from 8.8 to 9.2% over a relatively stiff stabilised subgrade. A total of 13 roller passes were carried out with constant roller operation settings including A= 0.90 mm, f= 30 Hz, and V= 4-4.5 km/h. In situ point measurements (i.e. γ_d, E_{LWD-Z3} and CBR) were obtained at five locations along the test bed after roller passes number 1, 2, 3, 4, 8, and 12, and the tests were conducted at three positions across the width of the drum. The relationship between the CMV and the point measurements is illustrated in **Error! Reference source not found.**.

Figure 6.3 CMV and in situ point measurement compaction curves (top), and single linear regression relationships between MV's and in situ point measurements (bottom) (Mooney et al. 2010)

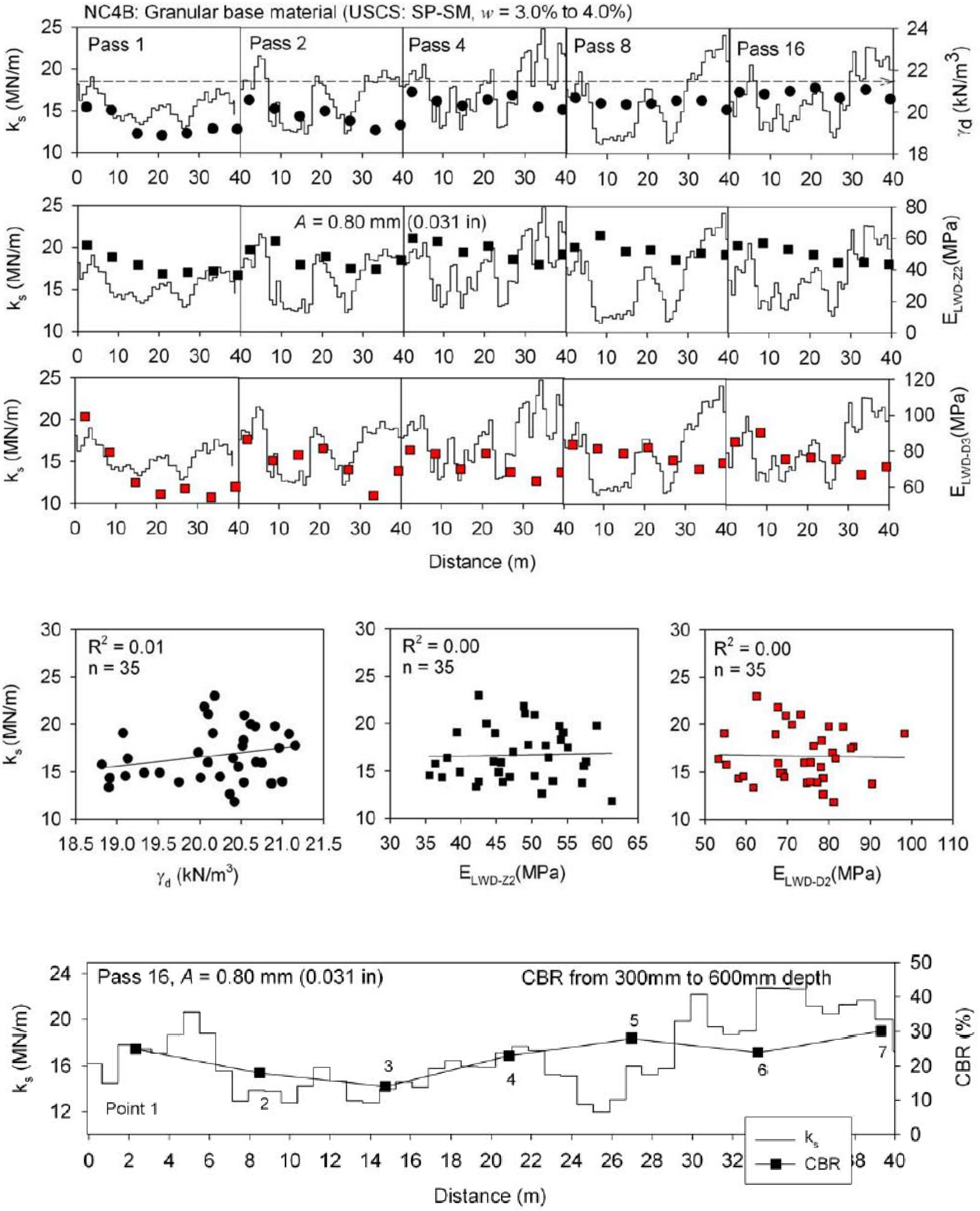


Linear regression relationships developed based on the averaged in situ point measurements across the drum width (i.e. top of **Error! Reference source not found.**) and roller CMV show an exceptionally good correlation, whereas the relationships based on single in situ point measurements at the drum centre were less ideal.

6.1.3 AMMANN VIBRATORY SMOOTH-DRUM ROLLER ON GRANULAR BASE MATERIAL

An Ammann vibratory smooth-drum roller was used to compact a granular base material with a depth of about 100 mm. The moisture content of the material was considered to be constant (i.e. 3-4%), and compaction was carried out with 16 roller passes at constant settings, where A= 0.80 mm, f= 30 Hz, and V= 4 km/h. The material dry density and the modulus from LWD tests were taken to obtain in situ point measurements. These measurements were taken after 1, 2, 4, 8 and 16 roller passes at seven test locations. At each location, three point measurements were taken to obtain an averaged value. The comparison between the roller MV (k_s) and the in situ point measurements is depicted in **Error! Reference source not found.**. Referring to **Error! Reference source not found.**, the roller MV does not show a good match with the in situ point tests. The linear regression relationships between roller MVs and point measurements also confirmed poor correlations.

Figure 6.4 Comparison MV and in situ point measurements (top), and simple linear regression relationships (Mooney et al. 2010) (middle), comparison MV and CBR derived from DCP tests (bottom)

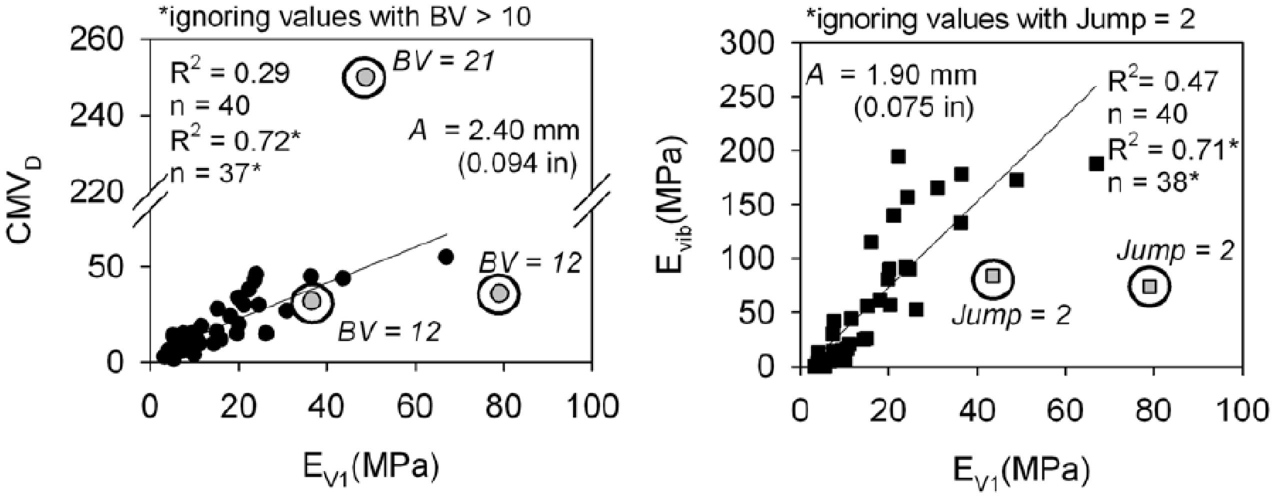


DCP tests were also carried out due to the poor correlations with the in situ point measurements (possibly as a result of their relatively shallow depth of influence compared to the roller). Even though the CBR derived from the DCP tests showed a non-uniform profile of the subsurface layer below 300 mm, the average CBR value correlated well with the roller MVs. These results confirmed that the roller MVs could be affected by the uniformity of the underlying layers. Moreover, in situ tests with a deep influence depth could potentially be used (e.g. DCP) to interpret the vibratory roller MVs due to its relatively deep impact depth.

6.1.4 DYNAPAC AND BOMAG VIBRATORY SMOOTH-DRUM ROLLER ON A GRANULAR BASE MATERIAL

A nominal 150 mm thick layer of granular base material was compacted by both Dynapac and Bomag vibratory smooth-drum rollers at consistently high amplitude settings to evaluate the influence of drum 'jumping'. The Dynapac roller adopted constant settings, with A= 2.4 mm, f= 30 Hz, and V= 4 km/h, while the Bomag used A= 1.9 mm, f= 28 Hz, and V= 4 km/h. It is worth mentioning that the Dynapac IC roller reports a CMV while the Bomag reports the vibration modulus/stiffness (E_{vib}). The in situ point tests conducted were static PLTs, and modulus from the first loading loop in the static plate load test was adopted for the regression analysis, as seen in **Error! Reference source not found.**. Referring to **Error! Reference source not found.**, the roller MVs (i.e. CMV and E_{vib}) and the measurements obtained from spot tests showed a good correlation when the bouncing values (BV) and jump values were less than 10 and 2 respectively. In other words, the jump mode (particularly when the machine is operating at high amplitude settings) should not be considered when analysing the relationship between roller MVs and in situ point measurements.

Figure 6.5 Influence of roller "jumping" on regression relationships between PLT test and CMV (left), and PLT test and E_{vib} (Mooney et al. 2010)



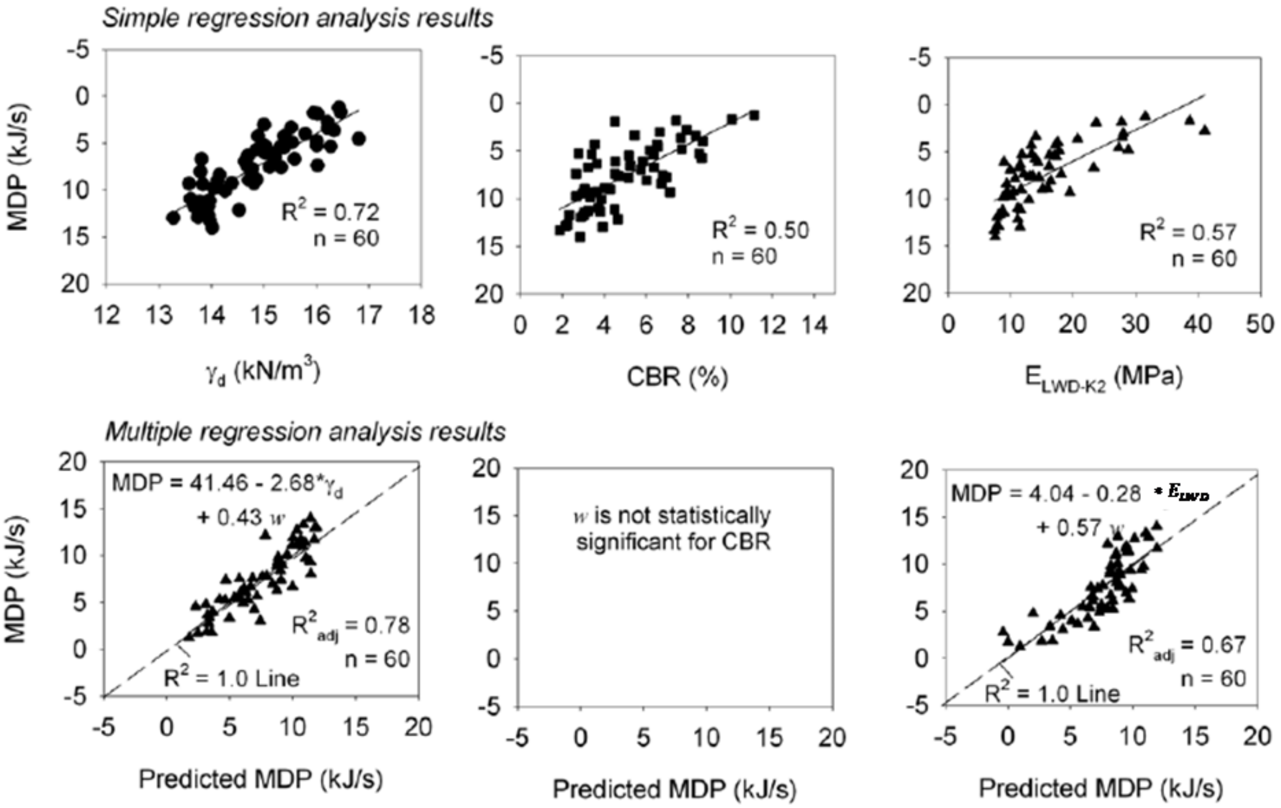
These correlations are based on simple linear regression analyses. However, there are various factors (i.e. variables) that can affect the regression relationships, such as the lift thickness of the compacted soil layer, the moisture content, the underlying material properties, and the machine operation settings. Therefore, a statistical multiple regression analysis should be used to evaluate the influence of these variables. A multiple regression analysis is carried out by incorporating variables of interest as independent variables into a general multiple linear regression model. The equation for this model can be presented as:

$$\mathrm{MV} = b_0 + \alpha b_1 + w b_2 + A b_3 + \beta b_4 + \gamma b_5 + w^2 b_6 + f b_7 + v b_8 \qquad (8)$$

where b_0 is the intercept, b_1 to b_8 are the regression coefficients, α is the in situ point measurements (i.e. γ_d, E_{LWD}, etc.), w is the soil moisture content, A is the amplitude, β is the measurements obtained from spot tests, γ is the lift thickness, f is the roller vibration frequency, and v is the velocity.

According to Mooney et al. (2010) and Chang et al. (2011), the p- and t-values were used to represent the statistical significance of each variable, with the p-value indicating the significance of a parameter, and the t-value representing its relative importance (i.e. the higher the absolute value, the greater the significance). A description of this method can be found in Mooney et al. (2010). By using the multiple regression analysis, field tests on granular base, subbase and subgrade materials were carried out using the Bomag and Ammann rollers to evaluate the influence of roller operating frequency (f) and amplitude (A). The results confirmed that both A and f are statistically significant parameters, and the dependency of frequency and amplitude on the roller MVs varied with types of soil and the field conditions. Moreover, the influence of the moisture content on correlations between in situ point measurements (i.e. w, γ_d, E_{LWD} and CBR) and the MDP was investigated, and regression coefficients obtained were 0.72, 0.50 and 0.57 for γ_d, CBR and E_{LWD}respectively. However, the multiple regression analysis indicated that the moisture content is statistically significant in predicating MDP from γ_d and E_{LWD} but not significant for CBR measurements, as illustrated in **Error! Reference source not found.**.

Figure 6.6 Simple regression relationships between roller MV's and in situ point measurements (top) and multiple regression relationships, including moisture content for predicting roller MV's (bottom) (Mooney et al. 2010)



Referring to **Error! Reference source not found.**, by considering the moisture content as an independent variable, the c orrelations were improved (R^2_{adj}= 0.78 and 0.67, R^2_{adj} being the adjusted regression coefficient) for predicting MDP from γ_d and E_{LWD}, respectively.

The case studies presented in this section confirmed that a simple linear regression analysis could be used to correlate the in situ point measurement results with the roller MVs if the tests beds are relatively homogeneous and have relatively stiff underlying materials. The techniques to improve these correlations include averaging point measurements across the width of the drum and operating the roller during calibration and production compaction with constant settings (i.e. constant A, f and v). Furthermore, adopting multiple regression analysis by incorporating variables of interest as independent variables into a multiple regression model can, to some extent, improve the correlation between the roller MVs and the spot tests results.

In addition to the field studies reported in Mooney et al. (2010), the correlation studies carried out by other researchers are tabulated in **Error! Reference source not found.**.

Table 6.2: Summary of field correlation studies (modified from Chang et al. (2011))

Reference	Roller type(S) and MV(S)	Soil type(s)	In situ point measurements for benchmarking	Key findings and outcomes
Floss, Gruber & Obermayer (1983)	Dynapac dual smooth-drum roller, CMV.	Sandy- to silty-gravel.	Water balloon method, sand cone, PLT and DCP.	Results confirmed a strong correlation between roller MV, density and DCP. CMV are dependent of roller speed, vibration frequency and amplitude, soil types and moisture content.
Nohse & Kitano (2002)	Sakai smooth-drum roller, CMV.	Clayey-gravel.	Radio-isotope measuring the density.	Results showed that the dry density and CMV increases with an increase in roller passes. Simple linear regression analysis with R^2 > 0.9 observed for correlations between CMV and dry density.
Kröber et al. (2001)	Bomag smooth-drum roll, E_{vib}.	Silty-gravel.	PLT.	Simple linear regression analysis based on calibration showed a strong correlation with R^2 > 0.9 between E_{vib} and E_{v1} and E_{v2}. Note: E_{v1} and E_{v2} are the moduli from the first and second loading loop in the static PLT, respectively.
Preisig, Caprez & Ammann (2003)	Ammann dual smooth-drum roller, k_s.	Sandy gravel materials.	PLT.	Simple linear regression analysis showed R^2= 0.68 and 0.56 for correlations between k_s and E_{v1}, k_s and E_{v2}, respectively. However, if only data points with E_{v1}/E_{v2}< 3.5 were adopted in the regression analysis, R^2 improved to 0.80.
Hossain et al. (2006)	Bomag smooth-drum roller, E_{vib}.	Well-graded silty sand.	NG and DCP.	Results obtained confirmed that E_{vib} is sensitive to soil moisture content. Weak correlations were reported between E_{vib} and CBR, E_{vib} and density.
Thompson & White (2008)	Caterpillar padfoot roller, CMV & MDP.	Silt and lean clay.	NG, DCP, Clegg Hammer and LWD.	Averaging the data along the fill length of the test strip can improve the correlations. Multiple regression analysis that considers the effect of moisture content can further improve the correlations.
White & Vennapusa (2009)	Caterpillar smooth-drum roller, CMV & MDP.	Poorly-graded sand with silt to silty sand.	LWD, PLT, and DCP.	Correlations between CMV and point measurements had coefficient R^2 ranging from 0.2 to 0.9. The primary factor leading to the scatter was the difference in measurement depth. Correlations were improved using measurements at a depth of 150 mm below the compacted surface.

7 CALIBRATION

This section presents the procedures required for the calibration and implementation of IC in Minnesota, based on MnDOT's pilot specifications. Examples of procedures that can be used as a reference include Chang et al. (2011), Chang, Xu & Rutledge (2012),Chang et al. (2014), Chang et al. (2018), White et al. (2009), Mooney et al. (2010), Gallivan et al. (2011) and Commuri et al. (2017).

7.1 GPS TESTING

GPS coordinate validation is the first step in any IC fieldwork (Chang et al. 2014). Indeed, the implementation of IC requires a high precision position system (HPPS). IC systems normally use differential correction GPS (or DGPS) to improve accuracies. Differential correction requires a second GPS receiver, a base station, and data collecting at a stationary position at a precisely known point (e.g. a surveyed benchmark). When the physical location of the base station is known, a correction factor can be computed by comparing the known location with the GPS location determined using satellites. The correction factor can be subsequently applied to the GPS data collected by a GPS receiver in the field.

Chang et al. (2011) presented the procedure included in a GPS calibration process. It must be highlighted that the GPS coordinate validation should be carried out daily during production operations.

7.2 CALIBRATION

Once the GPS coordinates have been validated, the calibration section must be set up to determine the number of passes needed to achieve compaction at the optimum moisture content for the materials.

1. Setting up the evaluation and calibration section:

   The evaluation section is where QC acceptance testing is carried out. It is an area of production earthwork that exhibits homogeneity, or consistently distributed heterogeneity, both in the longitudinal and transverse directions. Aa a portion of the evaluation section should be used as the calibration area, the material, the material placement procedures, moisture condition, and lift thickness should be consistent between the calibration and evaluation sections.

   According to the MnDOT pilot specifications, control strips/calibration areas must be constructed. The minimum dimensions needed for a control strip is 100 m long by 10 m wide. However, the size of the control stripe may be modified by the engineer.

2. Determining the optimum moisture content:

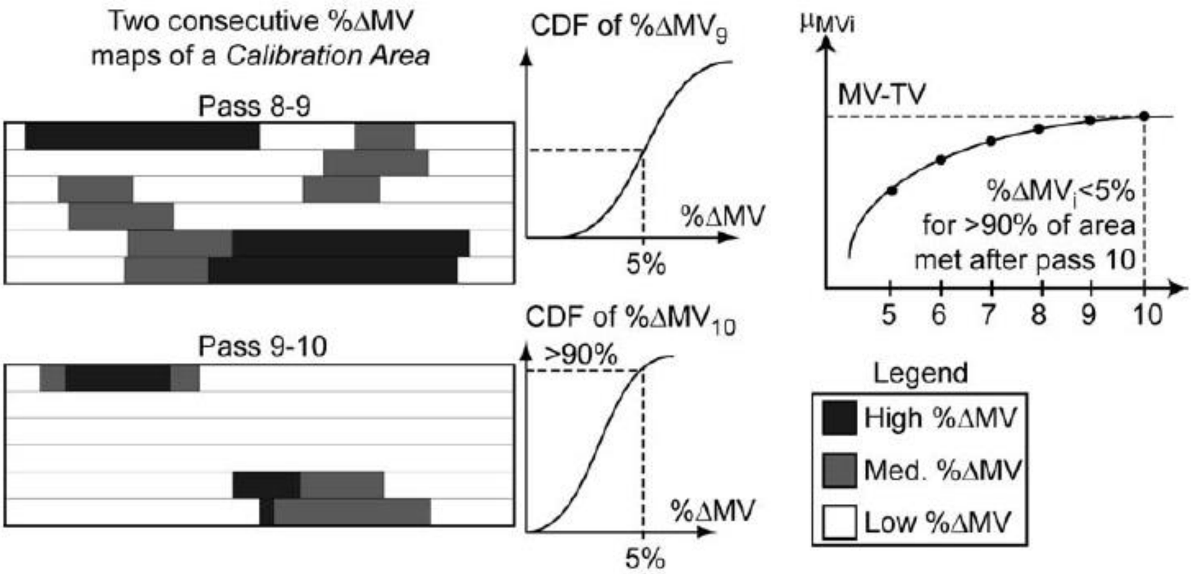
   The standard proctor test method is used to determine the OMC of the control strip. Once the OMC has been determined, the control strips should be constructed at or near each extreme of 65% and 95% of OMC. A moisture correction trend line showing the linear relationship of the moisture content with roller MV is produced.

3. Determining the IC target measurement value (IC-TV):

   The IC-TV must be determined for the various material types, on every lift where the type of material is changed. During this calibration process, the IC rollers must adopt constant settings, including drum amplitude, frequency, and operating speed.

   The IC-TV is reached when additional passes do not result in a significant increase in the MV (i.e. average change in MV less than 5% between successive passes). The IC-TV is defined as 90% of the MVs are greater than 90% of the IC-TV. The logic diagram showing the determination of the IC-TV is denoted in **Error! Reference source not found.**.

Figure 7.1 Logic diagram to determine the IC-TV adopting compaction curve (Mooney et al. 2010)



4. Determining the target in situ point test measurement values:

   After each roller pass, LWD testing must be conducted to estimate the modulus of the material. A minimum of three LWD tests are required with a minimum spacing of 25 m between tests. The moisture-corrected target LWD test value (LWD-TV) is determined in a similar way as the IC-TV.

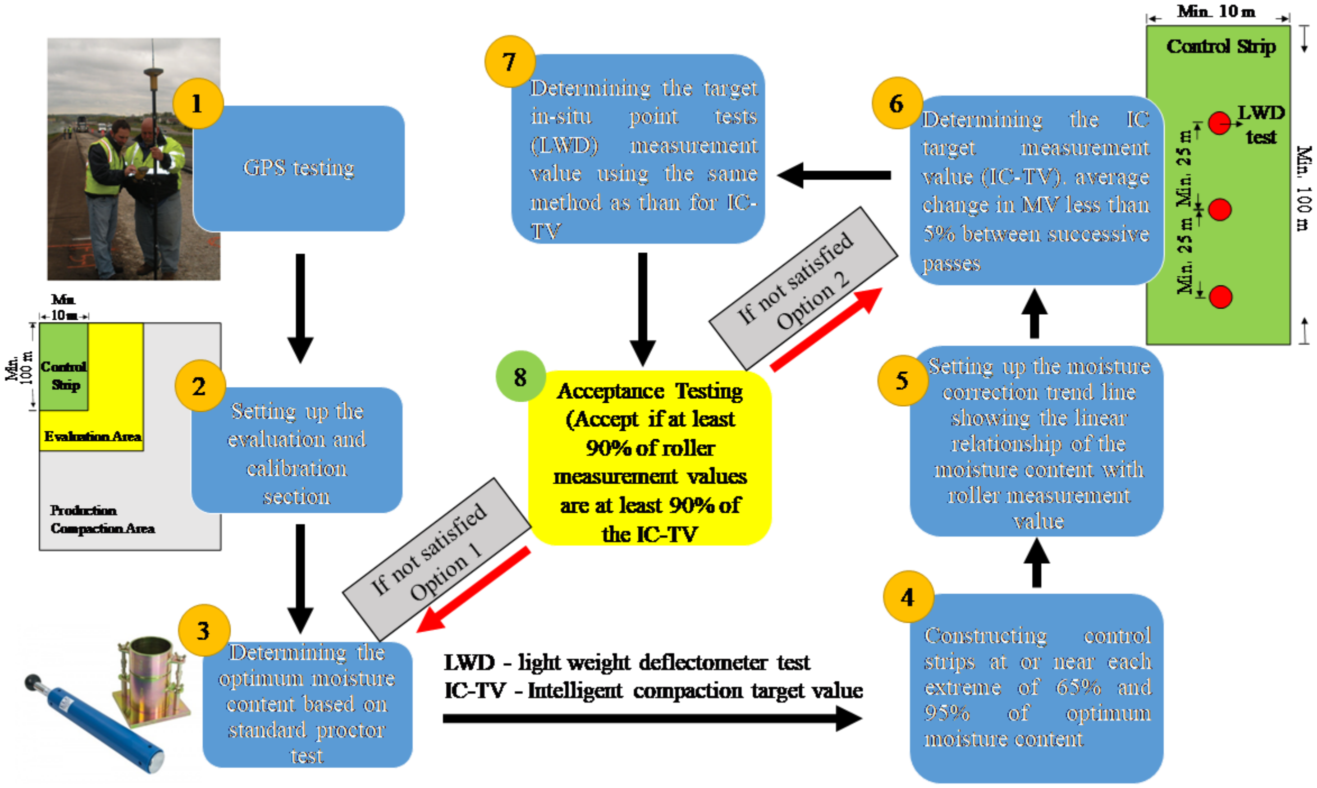
   The determined target values are recommended for quality control (QC) /quality assurance (QA). Separate calibrations are needed if the compaction process is interrupted due to natural events such as rain or equipment breakdown.

7.3 ACCEPTANCE TESTING

Acceptance testing is carried out on the evaluation section. Acceptance is based on the MnDOT pilot specifications, which require that at least 90% of the MVs are at least 90% of the IC-TV determined in the calibration process prior to placing the next lift, and all of the MVs must be at least 80% of the determined IC-TV. The areas must be re-compacted until all areas meet these acceptance criteria. If a significantly large portion of roller MV is greater than 20% in excess of the moisture corrected IC-TV, the engineer must re-evaluate the IC-TV determined from the control strip or carry out further control strips to re-determine the IC-TV based on the aforementioned process.

The summarised IC in situ calibration procedures based on the MnDOT specifications are shown in **Error! Reference source not found.**.

Figure 7.2 A flow chart illustrating the IC in situ calibration procedures based on the MnDOT specifications



8 BRIEF REVIEW OF TMR TECHNICAL SPECIFICATIONS FOR THE POTENTIAL INCORPORATION OF IC

This section presents a brief review of the TMR standard specification (MRTS) for potential incorporation of IC. The discussion herein concentrates on pavement, subgrade and surfacing specifications, particularly MRTS04 for general earthworks, MRTS05 for unbound pavements, and MRTS07B for in situ stabilised pavements using cement or cementitious blends (TMR Specifications 2018).

8.1 MRTS04 – GENERAL EARTHWORKS

1. Clause 2 (Definition of terms): the terms associated with intelligent compaction should be defined, including the IC system components, measurement values, and technical terminologies.
2. Clause 4 (Standard test methods): the method for determining the elastic modulus by adopting LWD, FWD and PLT should be recommended as field spot tests for IC implementation. These in situ point measurements are used in European and US specifications for compaction acceptance testing and quality control.
3. Clause 5.4.3 (Compaction): should be expanded to incorporate intelligent compaction. Details of the trial section should be included, and the acceptance requirements should be established for IC implementation. A a systematic calibration procedure should also be defined.
4. Clause 5.6 (Testing frequency) and the table pertaining to testing frequency in Appendix A: the requirement for the frequency of the in situ point measurements, particularly the in situ tests that determine the modulus/stiffness, may be added and updated to incorporate IC. For example, the MnDOT pilot specifications clearly indicate that at least three LWD tests are needed for each control strip, and the minimum distance between these tests should be 25 m.
5. Clause 6 (Geometrics): the requirements for horizontal and vertical tolerances may be updated. With the assistance of the IC, the compaction is expected to be more uniform. Hence, more rigorous requirements for horizontal and vertical tolerances may be updated accordingly.
6. Clause 12.2.1.3 (Compaction of in situ material below embankments): pre-mapping with IC rollers could be included as a more effective option to identify potential soft spots/defects in otherwise unknown materials and corrective actions performed to improve the quality of compaction.
7. Clause 15 (Compaction): a subsection addressing IC should be included. The current method of compaction and the required compliance tests are based on the density of the compacted materials. However, IC utilises stiffness rather than density. Hence, compliance tests based on modulus/stiffness should be added. In addition, the compliance test based on ICMV should be introduced. For example, the method adopting regression correlation to determine the IC-TV (i.e. German specification), or the method based on the compaction curve (i.e. MnDOT pilot specification) could be considered. Furthermore, the requirements for IC equipment, calibration procedures, and documentation should be added to the current specifications, and the requirements listed in Chang et al. (2011), Mooney et al. (2010), and the reported existing IC-related specifications may be used as valuable references.

8.2 MRTS05 – UNBOUND PAVEMENTS

1. Clause 4 (Standard test methods): the method for obtaining in situ point measurements for material stiffness/modulus should be included for unbound pavements. However, this section can be referred to the MRTS04 – General earthworks updated Clause 4 as recommended in Section 9.1.
2. Clause 5.2.2 (b) vii: a method explaining how the materials will be placed and compacted using IC to meet the minimum requirements should be included.

3. Clause 8 (Construction), particularly 8.1 (trial pavement): As IC may be used for a trial pavement, the procedures and requirements (e.g. coverage of area meeting the optimal number of roller passes) for implementing IC should be indicated.
4. Clause 9 (Compliance testing): the in situ point testing determining the material modulus/stiffness for QC of the IC should be included, with minimum testing frequency and minimum number of tests to be conducted clearly indicated.

8.3 MRTS07B – STABILISED PAVEMENTS

The incorporation of IC for stabilised pavements is similar to that of unbound pavements described in Section 8.2. The potential modifications and amendments could be applied to Clause 4 (Standard test method) and Clause 5.2 (Construction procedures). These modifications and amendments could include:

1. In situ point measurements to determine material stiffness/modulus for stabilised pavement.
2. Detailed procedures and requirements for in situ tests and IC implementation on pavement layers.
3. Minimum frequency for in situ point tests for compliance testing (i.e. IC quality control).

9 SUMMARY

This report has presented a literature review of the use of IC internationally, particularly the experiences gained to date. The literature review found that recent advances in IC technology have contributed to the increased use of IC for earth fills, granular layers and soil stabilisation. Based on this literature review, it can be concluded that the development of the IC technology has the potential to revolutionise the conventional compaction method, since the operator can receive live feedback provided by the integrated IC system to achieve a uniform compaction more efficiently. With the enhanced uniformity of compaction, excessive differential settlement and permeability of the soil can be reduced and the shear strength of the soil can be significantly enhanced. This should result in a significant reduction in construction and maintenance cost.

In addition to the general information associated with IC, information on IC rollers and the retrofit kit available to be incorporated into existing conventional rollers has been provided. Despite the fact that the retrofit kit is a more affordable compaction control system, the installation and calibration must be carried out carefully to ensure that the sensor is mounted vertically, securely, and in a position that can capture the actual vibration of the drum accurately.

Existing IC specifications adopted in Austria/ISSMGE, Germany, Sweden and the Minnesota Department of Transportation (MnDOT) were summarised. Austrian/ISSMGE and German specifications are mainly based on the regression correlation between the roller measurement values with the static plate load test (PLT) modulus. As required by these specifications, the regression coefficient (r^2) must be greater than 0.7 so that the IC target values (IC-TV) can be determined to evaluate the state of compaction. On the other hand, Swedish specifications permit the use of IC to identify weak spots for static plate load tests (PLT), and the soil must be continuously compacted or reworked until the determined PLT modulus is equal to or greater than the threshold value. The MnDOT specifications, unlike other specifications, use the method based on the compaction curve to determine the IC target values (IC-TV), and the measurement values that are obtained must be corrected considering the effects of moisture content. These specifications reported may serve as references for the development of Australian specifications for IC.

The report has also presented the findings of previous case studies on the correlations between roller measurement values and spot tests on different soil types and underlying materials, in which both the linear regression and multiple regression methods were introduced. The findings confirm that a simple linear regression analysis may be suitable to correlate the in situ point measurement results with the roller MVs if the test beds are relatively homogeneous and have relatively stiff underlying materials. It should be noted that the correlations can be improved by adopting constant roller operation settings (i.e. constant amplitude, frequency and speed) and averaging point measurements across the width of the drum. Based on the findings of the case studies and the existing specifications, a summary pf a typical IC in situ calibration procedure is presented which may be adopted as a guideline to carry out an IC trial in Queensland.

The study also included a review of TMR standard specifications (MRTS) for potential incorporation of IC in MRTS specifications for pavements, subgrade and surfacings, particularly the MRTS04 for general earthworks, MRTS05 for unbound pavements, and MRTS07B for in situ stabilised pavements using cement or cementitious blends. Since the compaction compliance tests of TMR specifications are based on the density rather than soil stiffness utilised by IC, specifications based on the soil stiffness/modulus should be formulated. The specification may consider including in situ soil modulus tests such as the LWD, FWD and PLT as adopted in the European and MnDOT specifications. In addition, a detailed calibration procedure should be drafted to facilitate the implementation of IC.

REFERENCES

Adam, D 2007, 'Roller integrated continuous compaction control (CCC) technical contractual provisions & recommendations', *In* A Correia, Y Monoya & F Tatsuoka (eds), *Design and construction of pavements and rail tracks: geotechnical aspects and processed materials*, CRC Press, Boca Raton, FL, USA, pp. 111-38.

Åkesson, F 2008, *Dynapac compaction analyzer and optimizer*, Dynapac, Dallas, TX, USA.

Anderegg, R & Kaufmann, K 2004, 'Intelligent compaction with vibratory rollers: Feedback control systems in automatic compaction and compaction control', *Transportation Research Record*, vol. 1868, pp. 124-34.

Anderegg, R, Von Felten, DA & Kaufmann, K 2006, 'Compaction monitoring using intelligent soil compactors', *GeoCongress, 2006, Atlanta, GA, USA*, American Society of Civil Engineers, Reston, VA, USA, pp. 1-6.

Bekker, MG 1969, *Introduction to terrain-vehicle systems: part I: the terrain: part II: the vehicle*, University of Michigan Press, Ann Arbor, MI, USA.

Briaud, JL & Seo, J 2003, *Intelligent compaction: overview and research needs*, A&M University, College Station, TX, USA.

Cai, H, Kuczek, T, Dunston, PS & Li, S 2017, 'Correlating intelligent compaction data to in situ soil compaction quality measurements', *Journal of Construction Engineering and Management*, vol. 143, no. 8.

Chang, G, Xu, Q & Rutledge, J 2012, *Intelligent compaction: quality assurance for in-place density acceptance-asphalt: IC demonstration in Maine*, FHWA research project DTFH61-07-C-00032, Federal Highway Administration, Washington, DC, USA.

Chang, G, Xu, Q, Rutledge, J & Garber, S 2014, *A study on intelligent compaction and in-place asphalt density*, FHWA research project FHWA-HIF-14-017, Federal Highway Administration, Washington, DC, USA.

Chang, G, Xu, Q, Rutledge, J, Horan, B, Michael, L, White, D & Vennapusa, P 2011, *Accelerated implementation of intelligent compaction technology for embankment subgrade soils, aggregate base, and asphalt pavement materials*, FHWA research project FHWA-IF-12-002, Federal Highway Administration, Washington, DC, USA.

Chang, GK, Mohanraj, K, Merritt, D & Gallivan, VL 2018, *Intelligent compaction and infrared scanning field projects with consulting support*, report cmr 18-003, The Transtec Group, Austin, TX, USA.

Commuri, S, Zaman, MM, Arshadi, A, Imran, S & Barman, M 2017, *Special provisions for intelligent compaction of stabilized soil subgrades*, Southern Plains Transportation Center, University of Oklahoma, Norman, OK, USA.

Correia, AG 2008, 'Innovations in design and construction of granular pavements and railways', in E Ellis, H Yu, G McDowell, A Dawson & N Thom (eds), *Advances in Transportation Geotechnics*, CRC Press, pp. 17-28.

Correia, AG, Cortez, P, Tinoco, J & Marques, R 2013, 'Artificial intelligence applications in transportation geotechnics', *Geotechnical and Geological Engineering*, vol. 31, no. 3, pp. 861-79.

Correia, AG & Parente, M 2014, 'Intelligent compaction technology for geomaterials: a demonstration project', *Transport Research Arena, 5th, 2014, Paris, France,* 10 pp.

Floss, R, Gruber, N & Obermayer, J 1983, 'A dynamical test method for continuous compaction control', *European conference on soil and foundation engineering, 8th, 1983, Helsinki, Finland,* AA Balkema, Rotterdam, Netherlands, pp. 25-30.

Forssblad, L 1980, 'Compaction meter on vibrating rollers for improved compaction control', *Proceedings of the international conference on compaction, 1980, Paris*, vol. 2, pp. 541-6.

Gallivan, VL, Chang, GK & Horan, DR 2011, 'Intelligent compaction for improving roadway construction', in D Chen, J Chang, M Zaman, C Zhao & Z Yao (eds), *Emerging technologies for material, design, rehabilitation, and inspection of roadway pavements*, ASCE, pp. 117-24.

Horan, RD, Chang, GK, Xu, Q & Gallivan, VL 2012, 'Improving quality control of hot-mix asphalt paving with intelligent compaction technology', *Transportation Research Record*, vol. 2268, no. 1, pp. 82-91.

Hossain, M, Mulandi, J, Keach, L, Hunt, M & Romanoschi, S 2006, 'Intelligent compaction control', *Airfield and highway pavements specialty conference, 2006, Atlanta, GA,* American Society of Civil Engineers, Reston, VA, USA, pp. 304-16.

Indraratna, B, Chu, J & Rujikiatkamjorn, C 2015, *Ground improvement case histories: compaction, grouting and geosynthetics*, Butterworth-Heinemann, Oxford, UK.

ISSMGE 2005. “Geotechnics for pavements in transportation infrastructure,” Roller-Integrated Continuous Compaction Control (CCC), Technical Contractual Provisions – Recommendations, *International Society for Soil Mechanics and Geotechnical Engineering*.

Kröber, W, Floss, E & Wallrath, W 2001, 'Dynamic soil stiffness as quality criterion for soil compaction’, in AG Correia & H Brandl (eds), *Geotechnics for Roads, Rail Tracks and Earth Structures*, CRC Press, Boca Raton, FL, USA.

Kumar, SA, Aldouri, R, Nazarian, S & Si, J 2016, 'Accelerated assessment of quality of compacted geomaterials with intelligent compaction technology', *Construction and Building Materials*, vol. 113, 824-34.

Lundberg, G 1939, 'Elastische berührung zweier halbräume', *Forschung auf dem Gebiet des Ingenieurwesens A*, vol. 10, no. 5, 201-11.

Mooney, M & Adam, D 2007, 'Vibratory roller integrated measurement of earthwork compaction: an overview', *International symposium on field measurements in geomechanics, 7th, 2007, Boston, MA, USA*, Reston, VA, USA, pp. 1-12.

Mooney, MA, Rinehart, RV, Facas, NW, White, DJ, Vennapusa, PKR & Musimbi, OM 2010, *Intelligent soil compaction systems*, report 676, Transportation Research Board, Washington, DC, USA.

Nazarian, S, Mazari, M, Chang, G, Aldouri, R & Beltran, J 2015, *Intelligent compaction roller retrofit kit validation*, report FHWA TIDP-130 (096), University of Texas at El Paso, El Paso, TX, USA.

Nieves, A 2014, Intelligent compaction: *summary of intelligent compaction for HMA/WMA paving*, FHWA, Washington, DC, USA.

Nohse, Y & Kitano, M 2002, 'Development of a new type of single drum vibratory roller', *International Conference of the International Society for Terrain-Vehicle Systems, 14th, 2002, Vicksburg, MS, USA,* International Society for Terrain-Vehicle Systems, Hanover, NH, USA.

Preisig, M, Caprez, M & Ammann, P 2003, 'Validation of continuous compaction control (CCC) methods', in J Grabe (ed), *Workshop Soil Compaction*, TU Hamburg, Hamburg, Germany.

Sandström, AJ & Pettersson, CB 2004, 'Intelligent systems for QA/QC in soil compaction', *Annual Transportation Research Board meeting, 83rd, 2004, Washington, DC, USA,* Transportation Research Board, Washington, DC, USA, 17 pp.

Savan, CM, Ng, KW & Ksaibati, K 2015, *Implementation of intelligent compaction technologies for road constructions in Wyoming,* MPC-15-281, Mountain Plains Consortium, Fargo, ND, USA.

Scherocman, JA, Rakowski, S & Uchiyama, K 2007, 'Intelligent compaction, does it exist?', *Proceedings of the annual conference-Canadian Technical Asphalt Association, 52nd, 2007, Niagara Falls, ON, Canada*, Polyscience Publications, Laval, QC, Canada

Thompson, MJ & White, DJ 2008, 'Estimating compaction of cohesive soils from machine drive power', *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 134, no. 12, pp. 1771-7.

Thurner, H & Sandström, A 1980, 'A new device for instant compaction control', *International conference on compaction*, *1980, Paris, France*, Anciens ENPC, Paris, France.

Von Quintus, HL, Rao, C, Bhattacharya, B, Titi, H & English, R 2010, *Evaluation of intelligent compaction technology for densification of roadway subgrades and structural layers*, WHRP #0092-08-07, Wisconsin Highway Research Program, Madison, WI, USA.

White, DJ, Vennapusa, P, Zhang, J, Gieselman, H & Morris, MD 2009, *Implementation of intelligent compaction performance-based specifications in Minnesota*, MN/RC 2009-14, Iowa State University, Ames, IA, USA.

White, DJ & Vennapusa, PKR 2010, *A review of roller-integrated compaction monitoring technologies for earthworks*, Report ER10-04, Iowa State University, Ames, IA, USA.

Yoo, T & Selig, E 1980, 'New concepts for vibratory compaction of soil', International conference on compaction, 1980, Paris, France, Anciens ENPC, Paris, France.Queensland Department of Transport Standards

MRTS04:2018, *General earthworks*.

MRTS05:2018, *Unbound pavements.*

MRTS07B:2018, *In situ stabilised pavements using cement or cementitious blends*.