Use of intelligent compaction technology

D R Carder, B C J Chaddock (TRL) and L Campton (Halcrow Group Ltd)
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by D R Carder, B C J Chaddock (TRL) and L Campton (Halcrow Group Ltd)

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(Dr T Messafer/Mr R K W Lung)

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<td><strong>Project Manager</strong></td>
<td>D R Carder</td>
</tr>
<tr>
<td><strong>Technical Referee</strong></td>
<td>B C J Chaddock</td>
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Executive summary

Since the late 1960s, fill material used in the construction of earthworks for Highway Agency road schemes has been placed and compacted primarily by a method compaction procedure, which specifies the thickness of layers and the number of roller passes required for different rollers and soil conditions. Since that time, vibratory roller technology has evolved and instrumentation to monitor roller performance has been introduced together with the development of procedures to amend roller characteristics. All of these advances have led to a process known as "intelligent compaction" that, if suitably incorporated in Highway Agency specifications, could improve the quality and efficiency of the construction of earthworks.

This study appraises the current state-of-the-art on intelligent compaction and commences by reviewing the basic principles of compaction, the current HA requirements for compaction of earthworks, and the development of performance specifications for earthworks. The emphasis in the UK is on compacting soils to a specified air void content (traditionally less than 10% air voids for general fill) substantiated by the realisation that moisture content and air voids, rather than stiffness, are key factors for embankments in limiting settlement, consolidation, and collapse compression on wetting.

The history of the initial research on the topic in Sweden and the development of the theory of intelligent compaction are discussed. The basis of all systems is the recording of the dynamic measuring value derived from the accelerometer(s) fitted to the vibrating roller drum, which is variously known as the CMV, \( k_v \), \( \omega \), \( E_{vib} \), or CCV according to the manufacturer and the equations used in the derivation. A review of commercially available equipment showed that different levels of sophistication are available from different manufacturers so that compaction-monitoring can assist the controlling operator or alternatively, provide for more fully automatic control of the vibration characteristics.

Guidelines for continuous compaction control adopted in the specifications and regulations of other countries were investigated. European countries generally specified site calibrations to establish correlations of dynamic measuring value with stiffness measurements from plate loading tests or the degree of compaction (from Proctor tests). A pilot specification proposed by the Minnesota Department of Transportation uses calibrations of dynamic measuring value against light weight deflectometer results.

Further data were sought from Europe and the US (where the FHWA and NHCRP have been particularly active in recent years) on calibrations of dynamic measuring values against in-situ dry density (i.e. air voids). Calibrations of this type proved hard to locate as acceptance criteria in other countries were primarily for the compaction of pavement foundations and therefore more often based on comparing dynamic measuring values with stiffness measurements from static plate loading tests, light falling weight testers, penetrometers, or similar devices.

From the findings of the study, a draft specification has been developed for HA consideration and possible inclusion in the SHW. It is not intended that the specification should replace existing SHW clauses but that, subject to appropriate site trials, it may provide an optional approach to method compaction. The draft specification places the emphasis on correlating dynamic measuring value with in-situ dry density (i.e. effectively air void content) as this is the fundamental soil property affecting earthwork performance and the approach generally adopted by the Highways Agency in the UK. However the potential for calibrations of dynamic measuring value against static plate loading tests, light falling weight testers, penetrometers, or similar devices is recognised provided that the performance testing device itself is calibrated on each particular site against the fundamental parameter of in-situ dry density.

GPS and mapping techniques can be implemented for quality control when using either method compaction or intelligent compaction technology.
Abstract

This study evaluates the current state-of-the-art on intelligent compaction and begins by reviewing the basic principles of compaction, the current HA requirements for compaction of earthworks, and the development of performance specifications for earthworks. The history of the initial research on the topic in Sweden and the development of the theory of intelligent compaction are discussed. A review of commercially available equipment showed that different levels of sophistication are available from different manufacturers so that compaction-monitoring can assist the controlling operator or alternatively, provide for more fully automatic control of the vibration characteristics. Guidelines for continuous compaction control adopted in the specifications and regulations of other countries were investigated together with calibration data obtained from manufacturers and technical publications. The benefits and limitations of intelligent compaction techniques are discussed. Based on the findings of the study a draft specification is proposed for the Highways Agency to consider for possible inclusion in the Specification for Highway Works (SHW).

1 Introduction

Since the late 1960s, fill material used in the construction of earthworks for Highway Agency road schemes has been placed and compacted by a method compaction developed primarily by TRL and reviewed by Parsons (1992). In 1986, an additional option of end-product compaction was introduced. Since formulation of the method specification however, vibratory roller technology has evolved and instrumentation to monitor roller performance has been introduced together with the development of procedures to amend roller characteristics. All this has led to a process known as "intelligent compaction" that, if suitably incorporated in Highway Agency specifications, could improve the quality and efficiency of the construction of earthworks.

Compaction of embankment fill materials and subgrades is critical to the performance of highway pavements. Variability of fill materials and properties, particularly moisture content, construction plant selection issues and difficulty in supervising uncompacted layer thicknesses can all lead to variable compaction. In seeking ways to overcome such problems and in terms of the development of a performance specification for earthworks, a recent study (Arup, 2006) for the Highways Agency highlighted the importance of air void content in relation to long term embankment performance. Satisfactory performance was sought with regards to total settlement, differential settlement (which is related to ride quality), heave, stiffness (which is also related to settlement/heave), and collapse settlement (eg due to inundation of rising groundwater). The recommendation for further research was that “a compaction control approach using modulus plus moisture content (and air voids) has the potential to fit well into performance specifications and could be monitored in real-time using roller-mounted devices, but before it can be considered for adoption in the UK a similar testing programme to that being performed in the current NCHRP project in the USA will be required on UK soils”.

Intelligent soil compaction has the potential to improve infrastructure performance, reduce costs, reduce construction duration, and improve safety. It involves:

- continuous assessment of mechanistic soil properties (e.g., stiffness, modulus) through compaction-roller vibration monitoring;
- continuous modification of roller vibration amplitude and frequency;
- an integrated global positioning system to provide a complete GIS-based record of the quality of earthworks compaction at the site.

Research findings in Europe and in the United States have shown that continuous monitoring, feedback, and automatic adjustment of the vibration of compaction
equipment can significantly improve the quality of the whole compaction process. Standard specifications for the application of compaction monitoring and intelligent compaction systems in the UK are therefore needed.
2 Basic principles of compaction

Compaction is measured quantitatively in terms of the dry density of the compacted soil and the principal factors which influence the dry density are the moisture content, the energy input in the compaction process, the volume (or effectively the thickness of the layer) being compacted, and the soil characteristics (for example, the plasticity if clays are being considered). Other factors which may have an influence on the dry density achieved include the stiffness of the layer immediately underlying the one being compacted and the presence of large lumps in cohesive fills, particularly over-consolidated clays from a deep cutting or borrow pit, which may not break down easily.

2.1 Effect of moisture content

It is readily visualised that the effect of increasing moisture is to lubricate the relative movement of soil particles which gives rise to better compaction. However, in the case of many soils particularly clays, a more applicable representation is that of undrained shear strength reducing with increasing moisture content so making it easier for the compaction process to deform the soil to fill voids by overcoming its shear strength. Clearly, once the compaction process has achieved a near zero air void condition\(^1\), the addition of further water is no longer beneficial and dry density reduces. A typical relationship between dry density and moisture content of a clay soil for constant compactive effort is shown in Figure 2.1.

![Figure 2.1. Typical relation between dry density and moisture content of a clay soil (Parsons, 1992)](image)

\[^1\] Air voids (\%) \( V_a = 100 \times \left( 1 - \frac{\rho_d}{\rho_s + \frac{\rho_w w}{100}} \right) \), where \( \rho_d \) is the dry density, \( \rho_s \) is the particle density, \( \rho_w \) is the density of water (assumed equal to 1), and \( w \) is the moisture content in %. 
In Figure 2.1 the peak in the dry density occurs at what is defined as the “optimum moisture content”. At moisture contents considerably less than the optimum, a reversal is often shown with dry density increasing with decreasing moisture content. This effect is particularly marked in granular soils when vibratory compaction is used.

2.2 Effect of energy input

The energy used in the compaction of soils by vibratory equipment is dependent on a number of factors such as the vibrating force, the contact area and number of passes of the compactor. In turn, the vibrating force is dependent on the mass of the vibratory equipment, such as the drum of a roller, and its acceleration. Also the contact area of the compactor is, for a roller, dependent on its width. The increase in dry density (and hence decrease in air void content) with successive increments of energy, as for example with successive passes of a roller, is explained in terms of shear stress and the shear strength concept by Parsons (1992). In essence, during the first pass, the roller will sink into the fill as compaction occurs until a soil shear strength is mobilised that equals the applied shear stress associated with an initially large contact area. Successive passes of the roller will reduce the contact area of the compaction roller and increase the applied shear stress until such time that little further reduction in air void content is achieved.

An excessive number of passes may result in over-stressing and this is one area where intelligent compaction may be beneficial. For example with non-cohesive soils such as sands (particularly those of a single-sized nature), over-stressing can occur in the near surface material. With cohesive soil, after the minimum air void content is reached, some of the compaction stress may generate excessive pore water pressure immediately below the compactor at which time further compaction is of little benefit and can be harmful in reducing the stability of the soil under its own weight and that of vehicles. With other materials, such as chalk, overstressing leads to breakdown of the larger particles, giving rise to wet plastic fines and a severe weakening of the freshly placed fill. Better control of compaction equipment and its energy input has been developed over the last two decades and automatic control of centrifugal force, frequency and amplitude means that the progression of compaction can be continuously monitored and problems of over-stressing minimised.

2.3 Effect of layer thickness

The nature of the compaction process means that, provided over-stressing at the surface does not occur, the dry density is at a maximum immediately below the roller and then decreases throughout each compacted layer as the depth increases. This means that, for a particular compactive effort, the effect of increasing the thickness of the compacted layer is to reduce the average dry density and to increase the average air void content within each layer.

The inter-relation between depth in the compacted layer, dry density and moisture content is illustrated in Figure 2.2. These results were obtained with 32 passes of an 8 tonne smooth-wheeled (non-vibratory) roller on heavy clay. For any particular moisture content, the measurements show that dry density (and air void content) decreases as the depth in the 300mm thick compacted layer varies in stages from 0-50mm to 200-300mm.
2.4  Effect of soil characteristics

The compaction of soils at or near the optimum moisture content is important in maximising the resulting dry density (and minimising the air void content) thus producing more desirable physical properties for use for civil engineering purposes.

Figure 2.3 illustrates the range of behaviour in laboratory tests using the 2.5kg rammer compaction test (BS1377: Part 4, 1990) for various types of soil and a crushed limestone aggregate. As the soil becomes less plastic and more granular the relation between dry density and moisture content generally moves upwards and to the left, with increased values of maximum dry density.

The exception to this trend is the uniformly graded sand, and also other uniformly graded soils, where packing of the single sized particles means that large voids cannot be avoided. In these cases the increase in dry density with moisture content is relatively small and an optimum moisture content is hard to establish because of the free-draining nature of the soil.
Figure 2.3. Relations between dry density, moisture and air void contents for various soils
3 Current HA requirements for compaction of earthworks

The method compaction requirements in the Specification for Highway Works were based on a significant programme of research on the compaction of soils undertaken at TRL and summarised by Parsons (1992). This research was initiated in 1946 and continued for more than four decades. The principle of the method specification was that the contractor should have as free a choice of compaction plant as possible. Having selected the type of plant, then the maximum depth of layer and the minimum number of passes required were given in the specification for the particular soil type encountered. The compactive effort used was designed to achieve, in well-graded soils, an average state of compaction of 10% air voids at the lower end of the likely natural moisture content of each soil type. Thus for soils dry of the design condition an air content higher than 10% will be produced, whilst with increasing moisture content beyond the optimum moisture content/maximum dry density condition, dry density will decrease at an approximately constant air content. Overstressing and shear failure of the soil may occur when the minimum air void condition is reached if excess pore water pressures are generated beneath the compactor and this leads to remoulding of the surface and rutting beneath the wheels or rolls of the compactor. The principles of the method specification are illustrated in Figure 3.1.

![Figure 3.1. Principle of the method specification for the compaction of well-graded soils (Parsons, 1992)]
The method specification was first published in the 1969 edition of the Specification for Road and Bridge Works and forms the basis, with many detailed refinements and additions, of the latest Series 600 Earthworks in the Specification for Highway Works (MCHW1, 2006) available on the Highways Agency’s website. Tables 6/1 to 6/4 of Series 600 tabulate the classification and compaction requirements of acceptable earthworks material, the grading requirements, and the plant and methods to be used for the method compaction.

It must be noted that the Specification for Highway Works states that within 600mm of a pavement structure, extra compactive effort is required, such that an air void content of 5% or less will be produced.

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2 www.standardsforhighways.co.uk/dmrb/index.htm
4 Development of performance specifications for earthworks

In recent years there has been an increasing emphasis on the development of a performance specification for earthworks, following various initiatives in developing a performance specification in the engineering of the pavement and its foundation. For this reason the Highways Agency recently commissioned a study to investigate the link between air void content of placed fill and long term embankment performance.

The findings are reported by Arup (2006) and satisfactory performance was sought with regards to total settlement, differential settlement (which is related to ride quality), heave, stiffness and compressibility (which are also related to settlement/heave), and collapse settlement (e.g. due to inundation by rising groundwater). The study investigated the engineering properties in terms of compressibility, consolidation and creep of fill types ranging from clay, sand, rock to chalk. Case history studies were reviewed which illustrated the role of compliance testing of earthworks during construction.

There proved to be a paucity of data linking the properties of the fill materials to the long term embankment performance, although there was evidence for many of the fills that low air voids were generally related to satisfactory performance. It is not however satisfactory to specify air voids content as the sole end-performance criteria as this parameter can be minimised by simply increasing the moisture content and/or using lower shear strength material; neither of which will improve embankment performance. One of the conclusions of the report was therefore that air void content needs to be specified in conjunction with either a maximum moisture content, a minimum undrained strength, or minimum relative compaction (or moisture condition value) for the soil type encountered.

The report also concluded that, whereas stiffness is a good parameter for bound and unbound pavement layers, due to the requirements of load spreading in these structural layers, the stiffness is not the prime criteria for earthworks, as both moisture content and air voids need to be controlled to limit settlements. It is usually also necessary to control the air voids in the compacted fill to minimise self-weight consolidation and/or, on wetting, collapse compression.

Due to the fact that the air void content of the fill cannot be measured directly, the usual method is to determine the in-situ dry density so that together, with knowledge of the moisture content and particle density (i.e. specific gravity), the air void content can be determined. Various methods of determining in-situ density are described in Part 9 of BS1377 (1990); the most commonly used being the sand replacement test and the use of a nuclear density gauge. The former is labour intensive and does not give instantaneous values, whilst the latter requires a government licence and special safety precautions. A compaction control approach using vibration modulus plus moisture content (and air voids) has the potential to fit well into performance specifications and could be monitored in real-time using rollers equipped with compaction monitoring and intelligent compaction systems.
5 Development of compaction monitoring technology

5.1 Historical development

Early devices were known as the “compaction meter” or “compactometer” and followed a research project in the early 70’s carried out by Dr Heinz Thurner of the Swedish Highway Administration. In this project a test roller was equipped with triaxial accelerometers with a towed mini-roller to register vibrations passing between the two rollers. Geophones were installed in the ground to monitor the vibrations. This early work led to the adoption of a single drum accelerometer and formed the basis for so-called compaction meters that have been used primarily in Europe for about 30 years.

Initial work by manufacturers in the 70’s was carried out by Geodynamik in Sweden, Bomag in Germany, and Ammann in Switzerland. Early papers by Forssblad (1980) and Thurner and Sandström (1980) presented at the International Conference on Compaction in Paris gave the research findings from field tests using the equipment.

In the 1990s vibrating roller technology developed rapidly. Bomag introduced the VarioControl roller with two counter-rotating exciter masses, which are concentrically shafted on the axis of the drum to produce a directed vibration. The direction of the excitation can be adjusted by rotating the complete exciter unit in order to optimise the compaction effort for the respective soil type. Ammann introduced rollers with servo-hydraulic two-piece eccentric mass and frequency control. Other manufacturers followed with similar technologies and their various products are discussed in more detail in Section 6.

Since the 1990’s, instrumentation systems, algorithms to estimate soil properties and documentation systems have advanced considerably. Bomag developed the Terrameter® system using the omega value in the late 1980s, which was followed by Amman developing the soil stiffness parameter (k_s). Bomag in 2000 introduced the use of modulus $E_{vib}$ and correlated it to plate loading test values.

5.2 Current state of the art

Current intelligent compaction systems combine the instrumentation technology with a documentation and feedback system that processes the data in real time for the roller operator and uses the measured data to control the equipment performance continuously. Measurements of drum acceleration are made by the instrumented roller and are used to control the drum vibration, amplitude, frequency and working speed of the equipment. These measurements are coupled with on-board global positioning systems (GPS) and graphical mapping via an on-board computer.

For the vibrating rollers, high amplitude and low frequency are used to compact soft soils and to reach deeper zones. Low amplitude and high frequency are used for stiff soils and shallow depths.

5.3 Theory of compaction monitoring

Intelligent compaction applies to vibratory rollers that can adjust the energy output. The drum of a vibrating roller is excited by a rotating eccentric mass which is shafted on the drum axis. The rotating mass sets the drum in a circular translatory motion, i.e. the direction of the resulting force is corresponding with the position of the eccentric mass. Compaction is achieved mainly by transmitted compression waves in combination with the effective static drum load. The vibration of the roller drum changes in accordance with the soil response. The more compact the soil, the more rebound it gives on impact.
The downward force amplitude ($F$) of the roller is proportional to the first harmonic of the vertical acceleration of the drum. A cylinder deformation modulus ($E_c$) is defined as the ratio of the force and the corresponding displacement ($s$) as:

$$E_c = c_1 \cdot \frac{F}{s} = c_2 \cdot \omega^2 \cdot \frac{A_1}{A_0}$$

where $\omega$ = fundamental angular frequency of the vibration,
$A_0$ = acceleration amplitude of the fundamental component of the vibration,
$A_1$ = acceleration amplitude of the first harmonic component of the vibration (i.e. twice the eccentric excitation frequency),
$c_1$, $c_2$ = constants.

This is the basis used by Thurner and Sandström (2000) and others for defining the compaction meter value, CMV, as $300 \cdot (A_1 / A_0)$ where the constant has been selected to give a full scale reading. CMV is determined by analysis of the drum acceleration measured over two cycles of vibration. This approach of measuring CMV was first introduced by Geodynamik and is used by others, e.g. Dynapac and Caterpillar (see Section 6). More recently, Sakai introduced a continuous compaction value (CCV) that additionally includes the first sub-harmonic and higher order harmonics in its calculation. The theory of this is discussed more fully by Nohse and Kitano (2002).

The relationship between contact force and drum displacement has been analysed by Krober et al (2001) based on elastic half-space theory to derive an $E_{ vib}$ value which is extensively employed by Bomag in their systems. The basis of this approach was first employed by Bomag in the Terrameter® system, where a measure of the energy transmitted to the soil (omega value) was calculated from theory and the measured drum acceleration time history. The force transmitted to the soil is established from the static weight of the roller, drum inertia and eccentric force over two consecutive cycles of vibration.

A number of authors (for example Mooney and Adam, 2007; Briaud, 2003) present the equations for determination of vibration modulus. The force ($F_s$) transmitted to the soil by the roller is defined as:

$$\text{Force} = -m_d \ddot{y}_d + m_u r_u \omega^2 \cos(\omega t) + (m_f + m_d)g \quad \text{Eq. 5.1}$$

where $m_d$ = drum mass;
$\ddot{y}_d$ = vertical acceleration of the drum;
$m_u$ = eccentric mass;
$r_u$ = radial distance at which $m_u$ is attached;
$\omega$ = fundamental angular frequency of vibration;
$t$ = elapsed time;
$m_f$ = frame mass;
$m_d$ = drum mass;
$g$ = acceleration due to gravity.

This force is balanced by that developed in the soil which can be modelled as a spring and dashpot system by:

$$\text{Force} = k_s y_d + d_s \dot{y}_d \quad \text{Eq. 5.2}$$

where $k_s$ = soil stiffness;
$y_d$ = vertical displacement of the drum;
$\dot{y}_d$ = vertical velocity of drum;
$d_s$ = soil damping coefficient (usually assumed to be 0.2).
When the two equations 5.1 and 5.2 are equated, the only unknown is the soil stiffness which can then be determined.

Soil stiffness in this instance is dependent on the loaded area and is not a true soil modulus. Lundberg (1939) gave a theoretical solution for a rigid cylinder statically loading a homogeneous elastic half-space and this can be used to determine the ‘true’ modulus $E$ (or $E_{\text{vib}}$). His equations are:

$$y_d = \frac{2 (1-\nu^2) \cdot F_s \cdot (1.8864 + \ln L/b)}{\pi E L}$$

where $b$ is the contact width given by:

$$b = \sqrt{\frac{16R (1-\nu^2) F_s \cdot \pi E L}{\pi E L}}$$

In these equations $\nu$ is the Poisson’s ratio, $L$ and $R$ are the drum length and radius respectively.

### 5.3.1 Double jump and rocking mode

Double jump and rocking mode may occur when using a vibratory roller to compact relatively stiff ground. During double jump the whole drum is in the air, whilst rocking mode is when only one side of the drum is in the air at a time. Neither mode is desirable as the machine becomes less controllable and the compacted layer is often re-loosened. Roller control is normally re-gained by reducing the vibration amplitude.

Measurements from compaction monitoring systems are not meaningful when this occurs as the CMV reduces to about half its normal value. Geodynamik have developed a warning indicator for this, called the resonance meter value (RMV).
6 Review of commercially available equipment

6.1 Bomag

Bomag’s intelligent compaction systems are fitted to single drum rollers with VarioControl. The VarioControl system utilises a directed exciter, which automatically adjusts the compaction energy generated by the vibration system of the roller, according to a pre-defined vibration modulus target and the effectiveness of the compaction already achieved. All VarioControl systems are equipped with the Bomag measuring system Terrameter plus (BTM plus) or Terrameter prof (BTM prof) which act to control the level of vibration. Other Bomag rollers, not equipped with VarioControl, can be fitted with the Terrameter systems or the Bomag $E_{vib}$ meter (BEM) which monitors and displays the vibration modulus for manual control by the operator.

As discussed in Section 5.3 the vibration modulus is determined from the measured drum acceleration and the theoretical relationship between the soil contact force and the deflection of the roller drum. The $E_{vib}$ value is considered by Bomag to be directly related to the deformation moduli $E_{v2}$, determined from the second load cycle, in the German standard DIN 18134 plate bearing test.

The Terrameter (both BTM plus and BTM prof) comprises two accelerometers, a processor to determine the $E_{vib}$ values, as well as an operation panel to control and monitor the compaction process displaying $E_{vib}$, frequency, speed and a line diagram of the rolled track. The BTM prof is equipped with a printer to document the measurements in the form of line or bar charts. The Terrameter indicates when further compaction is not possible, identifies and records soft spots and non-uniform areas.

For large scale construction projects, the BCM 05 compaction management system can be used together with a GPS to sense and document the roller position with an accuracy of up to 5cm (depending on the specification of the GPS selected). This permits the number of roller passes to be displayed to the operator at various zoom factors and compared with the $E_{vib}$ values at the same locations. The roller does not need to adhere to a lane pattern as the system is based on a cell pattern with a maximum size of 50cm x 50cm. The data can be downloaded and documented for future usage.

Further details of the VarioControl system and the compaction data management and documentation system are reported by Kloubert (2006).

6.2 Dynapac

The Dynapac intelligent compaction system measures and reports the compaction meter value (CMV). The CMV has been used in Europe since the 1970s, and is an accepted indicator of the progress in compacting the soil (Section 5.3).

The Dynapac compaction analyzer (DCA) documents the results from the compaction meter and can be used for quality assurance and as indication for acceptance inspection. The DCA provides full operator support during the compaction process, supplies compaction control data, documentation and analysis. It has also full flexibility regarding accuracy and position monitoring options when a GPS system is incorporated as in model DCA-S. It guides the operator as to when effective compaction is finished and on where further roller passes are needed to achieve a target CMV. The system needs to be calibrated to a known spot control method using a static load plate test or density measurements.

The Dynapac compaction optimizer (DCO) is capable of automatically adjusting the drum’s amplitude “from zero up to a maximum, depending on the state of compaction or the stiffness of the material under compaction”. The DCO system can be operated in
automatic mode with maximum force values selected, but it also allows for manual operation.

### 6.3 Geodynamik

The Geodynamik’s CompactoBar™ provides an instantaneous compaction meter value (CMV). A more sophisticated compaction meter, the Compactometer™, was the first ever roller integrated device which can be fitted to all types of vibrating roller. The current ALFA-022R version has electronics for the detection of double jump or rocking mode. This is measured continuously and presented as a resonance meter value (RMV) which is registered alongside of the CMV values.

Typical CMVs for different soils in the compacted state are given by Geodynamik and these are reproduced in Table 6.1.

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<th>Soil type</th>
<th>CMV</th>
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<tr>
<td>Rock fill</td>
<td>60 - 100</td>
</tr>
<tr>
<td>Gravel</td>
<td>20 - 50</td>
</tr>
<tr>
<td>Sand</td>
<td>20 - 50</td>
</tr>
<tr>
<td>Clay and silt</td>
<td>5 - 30</td>
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Geodynamik’s compaction documentation system (CDS-012) provides an advanced tool for charting so that the roller operator can watch indicators for travel speed and vibration frequency on a ‘working screen’, and also follow the position of the roller. During the compaction process, the CDS system continuously displays the current CMV values for every square metre. After the 4th roller pass, the mean CMV values for passes 1-3 and the last pass are displayed for comparison. The CDS system can also calculate the so called ‘compaction gradient’, which provides the operator with guidance on whether further compaction is required and the anticipated number of extra passes.

A GPS system can be connected to upgrade to CDS-012-P which displays on the screen a rectangular surface showing 10 adjacent roller strips with a length that can be chosen between 60m and 600m. The accuracy of available GPS units varies, however a locational accuracy to better than 50cm is achievable by current systems. CdsView displays graphical representations to assess the compaction results and to monitor the compaction process.

### 6.4 Ammann

Ammann Compaction Expert (ACE) defines its intelligent compaction system as “an electronic measuring and control system that automatically adjusts the amplitude and frequency of a vibratory roller to suit material characteristics”. Areas with lower load-bearing capacity are compacted with high effective amplitude, and hard areas with low effective amplitude. The frequency is adjusted to the resonance of the ground. The ACE system can be installed on either drum; the vibration of the other drum is automatically switched on and off according to the setting for the ACE drum unit.

The ACE system determines “dynamic ground-bearing capacity” by equating the drum’s action to a plate-loading test, in which a circular pad is pressed into the soil with a known force and the resulting displacement of the soil is measured. Ammann define this measurement, which is bearing capacity related, as the “k5” value, which is normally
measured in MN/m. ACE enables continuous monitoring of the compaction process with displays of $k_e$, amplitude, frequency and speed being available to the operator.

The standard ACE system is normally used with the Ammann documentation system (ADS). ACEplus upgrades the system with GPS capability to monitor the roller's position and provide a record that is accurate to within a few centimetres, so that in addition to the parameters described above the number of passes can be recorded.

The Ammann system is available from Case in the US.

6.5 Caterpillar

Caterpillar’s intelligent compaction system is a continuously variable amplitude system, which automatically adjusts the drum’s amplitude from zero to a maximum, a maximum that stays comfortably away from the double jump. Along with variable amplitude however, the Cat IC system employs three frequency settings, one of which the system will automatically select depending on the amplitude range in which the drum is operating.

Caterpillar designs its rollers for contractors and agencies that use one roller for all phases of compaction ie. breakdown, intermediate, and finish. Caterpillar’s "Versa Vibe" system takes a basic approach to controls: the drum can be mechanically set for either of two amplitude settings, and a toggle switch in the operator’s station offers a choice of two vibration frequencies. The operator can set the automatic speed control system to match impact spacing requirements for each application.

Accugrade Compaction is the latest intelligent compaction system by Caterpillar. It is an accelerometer based system which uses Geodynamik’s CMV (also called Caterpillar Compaction Value - CCV). It measures soil stiffness and has vibration controls. It also has GPS mapping and GIS based documentation capabilities.

AccuGrade Compaction GPS Mapping and Measurement System for compactors are available in the machine model CS563E, CS573E, CS583E, CS663E and CS683E. AccuGrade Attachment Ready options (ARO), GPS and AccuGrade Office Software are the components of the AccuGrade system that simplify compaction, increase productivity, reduce operating costs and document compaction results.

6.6 Sakai

The compaction control value (CCV) is the parameter measured by Sakai’s ExactCompact system on vibratory rollers. ExactCompact is standard on Sakai’s SW850 and SW900 double-drum rollers, and can be retrofitted for use on any other vibratory roller, regardless of the type or the manufacturer.

The operator determines optimum settings on a test strip and then programs these into the roller. Exact Compact is then used by the operator to maintain the right working speed to achieve the target or the desired compaction. When the roller is powered up, the previously stored impact settings appear on the system’s display; a simple pushbutton control enables the operator to reset the desired target figure to anywhere between 8 and 20 impacts per foot. The operator adjusts the ground speed until a green lamp in the centre of the display is illuminated, confirming the correct operating speed to meet the desired impact spacing. If the machine speed becomes too fast, a red light illuminates; too slow and a yellow lamp lights up.

Sakai have incorporated the CCV measurements into a compaction information system (CIS) which can be integrated with a GPS system for monitoring the locations compacted and the number of roller passes.
6.7 Summary
A summary of the information from manufacturers on compaction monitoring and intelligent compaction systems is given in Table 6.2. Currently Ammann, Bomag and Dynapac supply intelligent compaction equipment where the vibration characteristics of the roller are automatically adjusted, without operator intervention, according to the progress with compaction. The on-board display systems from other manufacturers provide considerable data which enable the operator to rapidly optimise the compaction process.

Further developments are being progressed by most manufacturers so it is advisable to consult them when the need for compaction plant of this type arises.
<table>
<thead>
<tr>
<th>Vendor</th>
<th>Ammann (Case)</th>
<th>Bomag</th>
<th>Caterpillar</th>
<th>Dynapac</th>
<th>Sakai</th>
<th>Geodynamik</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>ACE or ACEplus (when GPS supported)</td>
<td>Terrameter plus (BTM plus) or Terrameter prof (BTM prof)</td>
<td>AccuGrade attachment ready option (ARO) provides integrated measurement and documentation for the compaction measurement system</td>
<td>Compaction meter with Dynapac compaction analyser (DCA). Use of the Dynapac compaction optimizer (DCO) enables intelligent compaction</td>
<td>ExactCompact (an impact space indicator and speed meter)</td>
<td>CDS-012 system can be mounted on any vibrating roller</td>
</tr>
<tr>
<td>Feedback</td>
<td>Compaction energy is automatically reduced as $k_B$ increases by control of amplitude and frequency of vibration.</td>
<td>BTM systems fitted to VarioControl rollers enable intelligent compaction by automatically controlling the amplitude of vibration and hence the compaction energy.</td>
<td>An in-cab 3D display of location, speed, drum amplitude, vibration frequency and number of passes to assist operator control.</td>
<td>DCO provides intelligent compaction by automatically adjusting the amplitude of drum vibration. Alternatively, manual control using DCA only.</td>
<td>Operator determines optimum settings on a test strip and programs these settings into ExactCompact.</td>
<td>On screen feedback for operator control</td>
</tr>
<tr>
<td>Monitored parameter</td>
<td>Bearing capacity ($k_B$)</td>
<td>Vibration modulus ($E_{vib}$)</td>
<td>Monitoring uses the Geodynamik measuring system to determine CMV (known as CAT compaction value)</td>
<td>Compaction meter value (CMV)</td>
<td>Compaction control value (CCV)</td>
<td>Compactometer ALFA-022R measuring CMV and RMV (optional)</td>
</tr>
<tr>
<td>GPS capability</td>
<td>ACEplus</td>
<td>BCM 05 software can be used with various GPS</td>
<td>AccuGrade GPS</td>
<td>DCA-S</td>
<td>Available</td>
<td>CDS-012-P</td>
</tr>
<tr>
<td>Documentation system</td>
<td>ACEplus upgrades the ACE system and is used with the documentation system (ADS) to provide a GPS-supported system. The &quot;mapping&quot; shows the number of passes, $k_B$, etc.</td>
<td>BCM 05 system provides extensive data management and various options for documentation and evaluation. Mapping shows the number of passes and $E_{vib}$.</td>
<td>AccuGrade office converts and analyses data, manages and communicates with PCs.</td>
<td>Dynapac's compaction analyser (DCA) is used to record compaction documentation. CompBase software is used to select most suitable equipment.</td>
<td>A compaction information system (CIS) is used to record data obtained from the CCV and GPS systems.</td>
<td>Software CdsView, CdsCom and CdsMap for data processing and evaluation. Compaction gradient calculated after 4 passes.</td>
</tr>
</tbody>
</table>

RMV – Resonance meter value (warning of double jump or rocking mode)

**Table 6.2. Summary of some commercially available compaction-monitoring and intelligent compaction systems**
7 Review of experience in Europe

7.1 TRL studies

In 1991 TRL undertook an assessment of compaction monitoring devices for earthworks and the research findings were published by Snowdon (1992). As part of this study the performance of Bomag Terrameter and Dynapac compaction meters mounted on vibratory rollers were tested at full-scale and compared with in-situ density measurements (and hence air voids content) as well as other soil strength measuring devices. Four soil types (namely a heavy clay, a sandy clay, a well-graded sand and a gravel sand clay) were each available in a test bay 17m long, 5.5m wide and about 1m deep for the investigations.

The Bomag Terrameter was attached to a BW213D self-propelled vibratory roller, with 3000kg mass per metre width of roll. A similar study was carried out using the Dynapac CCS-RA compaction monitoring system attached to a Dynapac CA251PD self-propelled vibratory tamping roller, with 3099kg mass per metre width of roll.

7.1.1 Bomag Terrameter

In operation, the accelerometer monitored the rebound acceleration of the vibrating roller resulting from the changing condition of the soil as it was compacted. Omega values were stored in the processor for comparison with successive passes and when an increase of less than 10% was recorded for two consecutive passes in the same direction, an indicator light showed the operator that further passes would not be economic.

An initial analysis of all the results showed that the range of omega values recorded varied greatly. Individual values obtained on the cohesive fills only reached about 35 whilst those on the granular fills ranged between 65 and 740, depending upon the state of compaction and moisture content.

A typical set of results on a 200mm thick layer of gravel-sand-clay is given in Table 7.1. Findings for a 200mm thick layer of well-graded sand were similar. Snowdon (1992) considered that the actual value of omega proved unsuitable as an indicator of the state of compaction as it depended upon both dry density and moisture content. However for these granular soils the rate of increase in omega value of less than 10% did indicate when the roller had reached its limit of useful compaction. There was a good correlation between the latter and the SHW requirement of less than 10% air voids through an acceptable moisture content range, the exceptions being on the dry side of the moisture contents required by the Specification for Highway Works (Series 600, MCHW 1).

With the cohesive soils (i.e. sandy clay and heavy clay) the omega value decreased rapidly after the second or third roller passes (whereas for granular soils, omega would be increasing). Thus, if using the less than 10% increase in omega criteria for control, this would indicate that an acceptable state of compaction had been reached. Comparing this to the actual air void content at this time showed that an acceptable state of compaction had not been achieved, except for clays at the highest moisture contents.

Requirements for compaction of the four soils, as per Table 6/4 of the SHW (MCHW 1), together with their respective numbers of passes required as indicated using the less than 10% omega criteria are shown in Table 7.2. For the granular soils, an acceptable state of compaction (i.e. less than 10% air voids) was achieved when controlling using the less than 10% omega criteria. When controlling compaction in this way with the cohesive soils, acceptable compaction was indicated by the compaction monitoring device when this was not the case and 10% air voids had not been achieved.

---

3 As defined in Section 5.3.
### Table 7.1. Variation of Bomag omega value with dry density and air voids (gravel-sand-clay)

<table>
<thead>
<tr>
<th>Moisture content per cent (MCV)</th>
<th>Number of passes</th>
<th>Omega value</th>
<th>Change in omega value per cent</th>
<th>Dry density Mg/m³</th>
<th>Air voids per cent</th>
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</thead>
<tbody>
<tr>
<td>5.9 (&gt;17)</td>
<td>1</td>
<td>210</td>
<td>-</td>
<td>1.840</td>
<td>19.4</td>
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<tr>
<td></td>
<td>2</td>
<td>510</td>
<td>143</td>
<td>1.940</td>
<td>15.1</td>
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<td></td>
<td>3</td>
<td>640</td>
<td>26</td>
<td>1.996</td>
<td>12.6</td>
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<tr>
<td></td>
<td>4</td>
<td>710</td>
<td>11</td>
<td>2.040</td>
<td>10.7</td>
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<td>5</td>
<td>735</td>
<td>4</td>
<td>2.065</td>
<td>9.6</td>
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<tr>
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<td>6</td>
<td>670</td>
<td>-9</td>
<td>2.081</td>
<td>8.9</td>
</tr>
<tr>
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<td>7</td>
<td>640</td>
<td>-4</td>
<td>2.090</td>
<td>8.5</td>
</tr>
<tr>
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<td>8</td>
<td>630</td>
<td>-2</td>
<td>2.096</td>
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<td>2.120</td>
<td>5.1</td>
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<tr>
<td>9.4 (10.2)</td>
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<td>-</td>
<td>1.920</td>
<td>9.2</td>
</tr>
<tr>
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<td>2</td>
<td>460</td>
<td>92</td>
<td>2.030</td>
<td>4.0</td>
</tr>
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<td>-7</td>
<td>2.059</td>
<td>2.7</td>
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<td>400</td>
<td>-7</td>
<td>2.065</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>5</td>
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<td>-5</td>
<td>2.065</td>
<td>2.4</td>
</tr>
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<td>6</td>
<td>375</td>
<td>-1</td>
<td>2.065</td>
<td>2.4</td>
</tr>
<tr>
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<td>7</td>
<td>365</td>
<td>-3</td>
<td>2.065</td>
<td>2.4</td>
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<tr>
<td></td>
<td>8</td>
<td>360</td>
<td>-1</td>
<td>2.065</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>350</td>
<td>-3</td>
<td>2.065</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>340</td>
<td>-3</td>
<td>2.065</td>
<td>2.4</td>
</tr>
<tr>
<td>10.4 (7.5)</td>
<td>1</td>
<td>190</td>
<td>-</td>
<td>1.970</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>240</td>
<td>26</td>
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<td>2.0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>210</td>
<td>-13</td>
<td>2.031</td>
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<tr>
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<td>4</td>
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<td>2.031</td>
<td>1.9</td>
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<td>210</td>
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<td>2.031</td>
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<td>9</td>
<td>210</td>
<td>0</td>
<td>2.031</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>210</td>
<td>0</td>
<td>2.031</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Table 7.2. Compliance with the Specification for Highway Works (MCHW 1)

<table>
<thead>
<tr>
<th>Soil type (SHW Class)</th>
<th>Optimum moisture content, %</th>
<th>Moisture content, % (MCV)</th>
<th>Compacted layer thickness (mm)</th>
<th>Number of passes specified by SHW</th>
<th>Number of passes based on &lt;10% air voids (omega %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well-graded sand (Class 1A)</td>
<td>7.4</td>
<td>7.1 (15.8)</td>
<td>200</td>
<td>4</td>
<td>4 (8.8)</td>
</tr>
<tr>
<td>Gravel-sand-clay (Class 1A)</td>
<td>6.5</td>
<td>6.9 (17.0)</td>
<td>200</td>
<td>4</td>
<td>4 (8.3)</td>
</tr>
<tr>
<td>Heavy clay (Class 2A)</td>
<td>21</td>
<td>25.8 (12.2)</td>
<td>200</td>
<td>4</td>
<td>3 (12.7)</td>
</tr>
<tr>
<td>Sandy clay (Class 2A)</td>
<td>14</td>
<td>15.0 (13.1)</td>
<td>200</td>
<td>4</td>
<td>4 (12.8)</td>
</tr>
</tbody>
</table>

7.1.2 Dynapac CCS-RA

As with the Bomag system, an accelerometer mounted on the vibrating drum of the roller continuously sensed the reaction between the roll and the ground. The signals were passed to an on-board processing unit and relayed to an analogue meter graduated from 0 to 150 in arbitrary units. The reading was known as the compaction meter value (CMV) and further information on this is given in Section 5.3.

CMV readings obtained on the four soil types are shown in Figure 7.1 plotted against the in-situ measurements of dry density. Results that correspond to a satisfactory state of compaction, i.e. an air void content of 10% or less, are highlighted as solid rather than open symbols.

For the well-graded sand and the gravel-sand-clay the CMVs increased as compaction progressed, although a different range of values was obtained for each selected moisture content. For example, with the well-graded sand, compaction to 10% air voids was obtained at a CMV of 21 for a moisture content of 7.4%; a CMV of about 11 was required at a moisture content of about 11%. Results obtained on a 200mm layer of gravel-sand-clay are shown in Table 7.3. In this case, CMVs of about 30 and 19 were required at moisture contents of 6.7% and 7.3% respectively for adequate compaction. Therefore, with these well-graded granular soils, it was only possible to determine a unique CMV corresponding to a specified state of compaction when the soil was in a homogeneous condition. Such a condition does not often exist in bulk earthworks which limits the applications of the compaction-monitoring device.

The results in Figure 7.1 for the cohesive soils showed that CMVs were very low, between 3 and 6 on a scale of 0 to 150, and did not appear to be significantly influenced by soil type, state of compaction or moisture content. With both soils, the same CMV was recorded on the second pass as on the sixteenth, although the measured dry density had increased as compaction progressed. On this basis the device appeared unsuitable for the control of compaction of general earthworks fill, when using this particular vibratory tamping roller, in the state of development existing when the tests were performed in 1991.
Figure 7.1. Relations between Dynapac CMV and dry density for both cohesive and well-graded granular soils
Table 7.3. Variation of Dynapac CMV value with dry density and air voids (gravel-sand-clay)

<table>
<thead>
<tr>
<th>Moisture content per cent (MCV)</th>
<th>Number of passes</th>
<th>CMV</th>
<th>Dry density Mg/m³</th>
<th>Air voids per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.7 (&gt;17)</td>
<td>1</td>
<td>21</td>
<td>1.805</td>
<td>19.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
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<td></td>
<td>14</td>
<td>50</td>
<td>2.055</td>
<td>8.4</td>
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<td>15</td>
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<td>2.060</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>50</td>
<td>2.070</td>
<td>7.9</td>
</tr>
</tbody>
</table>

| 7.3 (15.9)                      | 1                | 17  |                   |                   |
|                                 | 2                | 21  | 1.920             | 13.3              |
|                                 | 3                | 17  | 1.960             | 11.4              |
|                                 | 4                | 19  | 1.980             | 10.5              |
|                                 | 5                | 20  | 1.990             | 9.4               |
|                                 | 6                | 20  | 2.020             | 8.7               |
|                                 | 7                | 20  | 2.025             | 8.5               |
|                                 | 8                | 23  | 2.035             | 8.1               |
|                                 | 9                | 23  | 2.040             | 7.8               |
|                                 | 10               | 32  | 2.045             | 7.6               |
|                                 | 11               | 21  | 2.050             | 7.4               |
|                                 | 12               | 25  | 2.055             | 7.2               |
|                                 | 13               | 32  | 2.060             | 6.9               |
|                                 | 14               | 33  | 2.065             | 6.7               |
|                                 | 15               | 25  | 2.068             | 6.6               |
|                                 | 16               | 33  | 2.070             | 6.5               |

7.1.3 General conclusion

Neither of the compaction-monitoring devices tested by TRL (Snowdon, 1992) were proven to be an effective technique for controlling the compaction of cohesive soils to achieve an air void content of 10% or less as required by the Specification for Highway Works (MCHW 1). The Bomag Terrameter, when changes in omega value were considered, showed some potential for controlling the compaction of well-graded granular soil through an acceptable moisture content range, the exceptions being on the dry side of the moisture contents required by the SHW. The Dynapac CCS-RA compaction monitoring system mounted on a vibratory tamping roller showed an increase in CMV value with increasing compaction of the granular fill, although the actual CMV value appeared very dependent upon the moisture content.

It is important to note that these tests, although comprehensive, were carried out by TRL at an early stage of the development of compaction-monitoring devices and intelligent compaction theory. Any improvements instigated since then by the manufacturers, may well have improved the performance, and thus field validation tests...
for each specific soil condition encountered on a particular construction site, are clearly advisable to confirm performance.

7.2 Other European

Following the development of compaction monitoring by the Swedish Highway Administration in the early 1970’s, much fundamental research in developing the theory of continuous compaction control was carried out in Sweden, Germany and Austria over the following decades. This led to the implementation of specifications and standards in these particular countries. Synopses of the historical development of intelligent compaction technology and its theory have already been given in Sections 5.1 and 5.3 respectively.

The purpose of this section is not to review the research and development of the technique, although the contributions from Europe are fundamental, but to examine correlations between dynamic measuring values and the fundamental soil parameters of dry density and air void content which have been obtained during full scale calibration or acceptance trials.

Although the assistance of the manufacturers was enlisted for this process, few data directly on this particular correlation were available in the public domain. The reason for this is primarily because earthworks specifications in Europe place more reliance on comparisons with results from plate loading tests rather than from measurements of in-situ dry density. Furthermore these findings often form part of the acceptance process at particular construction schemes and are generally not reported in publicly available technical publications.

An example of information presented by manufacturers is given in Figure 7.2. This shows the changes in the dynamic measuring values ($E_{vib}$) and the $E_{v2}$ values derived from plate loading tests plotted against the number of passes for two different rollers compacting a 400mm gravel layer.

![Figure 7.2. Variation of $E_{vib}$ and $E_{v2}$ with number of passes for a gravel layer](by courtesy of Bomag Fayat Group)
Bomag also present a job report for the compaction and testing of the unbound layer on the south runway to Leipzig/Halle airport (Kloubert et al., 2007). The approach adopted followed the German guidelines described in Section 10.1.1 with $E_{vib}$ being correlated to the bearing capacity ($E_{v2}$) and the degree of compaction $D_{pr}$ (with the fill density defined as a percentage of the Proctor density). In the calibrations of the crushed stone base it was found that maximum compaction was usually achieved after three passes with the fourth pass implemented as a measuring pass. For this material an $E_{v2}$ of 150MN/m$^2$ was found to be equivalent to an $E_{vib}$ of 107-110MN/m$^2$. A separate calibration was found necessary for the anti-frost material where an $E_{v2}$ of 120MN/m$^2$ was found to be equivalent to an $E_{vib}$ of 80-103MN/m$^2$. An evenly compacted unbound layer capable of taking the maximum load was produced during runway construction.

Information on calibrations undertaken in Dynapac’s test hall in Karlskrona, Sweden was supplied by Nordfelt (2009). Compaction of the earthworks was undertaken by a Dynapac CA302D roller and correlations obtained between the CMV and the $E_{v2}$ values derived from plate loading tests. Typical results for gravel with maximum particle size of 45mm compacted in 500mm layers at 3.7% moisture content and for clay of intermediate plasticity (plastic limit 16.5%; liquid limit 38.5%) compacted in 300mm layers at 10.5% moisture content are shown in Figures 7.3 and 7.4 respectively.

![Figure 7.3. Variation of $E_{v2}$ against CMV for gravel](by courtesy of Nordfelt)

![Figure 7.4. Variation of $E_{v2}$ against CMV for clay](by courtesy of Nordfelt)
With both soil types, good correlations were obtained between CMV and $E_{v2}$ and the increase in both values with the increasing number of passes of the roller is clearly evident. The results for clay in Figure 7.4 show only a small range in CMV, going from a mean value of 7 after two passes to only 11 after three passes: this indicates the sensitivity of the relationship.

At the same site measurements of air void content at various stages in the compaction of a 500mm layer of gravel (near its optimum moisture content) were also undertaken and the findings are shown in Figure 7.5. The trend of decreasing air voids with additional roller passes is apparent, particularly if the initial data for only two passes of the roller are excluded.

![Figure 7.5. Variation of air void content against CMV for gravel](by courtesy of Nordfelt)

With the clay fill, the small increase in CMV during the compaction process made correlations between air void content and CMV difficult to achieve at moisture contents within a few percent of the optimum. Calibrations of roller dynamic measuring values with plate loading tests (Figure 7.4) may be more successful as both are essentially measurements of stiffness from the surface downwards whereas measurements of in-situ density (i.e. air voids) are taken within the compacted layer.
8 Review of experience in the USA

The extent and depth of research and development on intelligent compaction technology carried out in Europe, stimulated considerable interest in the USA and has led to the implementation of a significant number of research programmes and trials on various highway construction projects. In addition to looking at earthwork construction, much work has also been undertaken on the compaction of asphalt. The latter is however outside the scope of this project.

8.1 US National Co-operative Highways Research Program

A project titled ‘Intelligent Soil Compaction Systems’ run by the US National Co-operative Highways Research Programme (NCHRP, 2008), under the auspices of the Transportation Research Board, aims to determine the reliability of intelligent compaction systems and to develop recommended construction specifications for the application of intelligent compaction systems in soils and aggregate base materials. The research is led by Mike Mooney of the Colorado School of Mines, who has considerable experience of intelligent compaction technology gained over many years and his publications related to intelligent compaction are listed on his website. The final report on the project is not yet publicly available. The findings of this report are expected to be particularly relevant as co-ordination with various state DOTs has taken place to identify construction projects that provide a variety of soil types. At these sites in-situ tests of stiffness and strength using plate loading, dynamic cone penetrometer, light weight deflectometer, etc will take place together with the measurement of the fundamental parameters of in-situ density by sand replacement and nuclear gauge testing as well as moisture content.

8.2 Federal Highway Administration

A comprehensive study (TPF5-128) entitled “Accelerated implementation of intelligent compaction technology for embankment subgrade soils, aggregate base and asphalt pavement materials” was initiated under the Transportation Pooled Fund (TPF) Solicitation 954 by the Federal Highway Administration (FHWA). With the involvement of thirteen states, the objectives are to develop an expertise on intelligent compaction within the associated Departments of Transportation as well as to identify future research requirements. Based on data obtained from field demonstrations to be carried out in 2008 through to 2010 in Georgia, Indiana, Iowa, Kansas, Maryland, Minnesota, Mississippi, North Dakota, New York, Pennsylvania, Texas, Virginia and Wisconsin, the study aims to accelerate the development of intelligent compaction quality control and assessment specifications for subgrade soils, aggregate base and hot mix asphalt pavement materials. Three intelligent compaction field demonstrations have already been carried out in Minnesota focusing on hot mix asphalt and, in Texas and Kansas, focusing predominantly on cohesive soil. The findings from the Texas study are dealt with in Section 8.3.3. Further information on FHWA research on intelligent compaction is available at www.intelligentcompaction.com.

8.3 State Departments of Transportation

In addition to the national studies, some State Departments of Transportation have conducted their own research in some cases part funded by the FHWA or NCHRP.

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4 http://control.mines.edu/mooney/
8.3.1 Minnesota

The Minnesota Department of Transportation has participated in a series of national studies which are summarised by Camargo et al (2006). The more major projects are as follows:

- **Continuous compaction control MnROAD demonstration.** This demonstration was undertaken at MnRoad, an outdoor pavement test facility, in 2004 and the final report was prepared by Petersen (2005). Four soil types, essentially granular, ranging from sand to crushed granite were investigated. $E_{\text{vib}}$ values from the roller were related to measurements using a range of techniques including plate loading tests and dynamic cone penetrometer. The final report does not include any correlations with density measurements although these were a part of the study. It was concluded that continuous compaction control is an effective quality control mechanism for soil compaction, although moisture content was found to affect both the compaction process and the measurement of soil modulus. The demonstration was conducted under conditions near the limits of normal construction practice and recommendations for further studies suggested that performance would have been better with more uniform soils and moisture contents.

- **Intelligent compaction and in-situ testing at Mn/DOT TH53.** A demonstration project took place during 2005 on the TH53 in Duluth, Minnesota. The findings are reported by Petersen and Peterson (2006). The study employed a Caterpillar vibratory soil compactor equipped with both intelligent compaction and GPS technology to compact granular fill. The dynamic measuring values (CMVs) were compared with in-situ tests carried out using a lightweight deflectometer (LWD), dynamic cone penetrometer (DCP) and GeoGauge. Relatively good correlations were obtained between CMV and DCP, when deep DCP values were compared. Good correlations between LWD and GeoGauge measurements were obtained. Sand replacement density tests and determination of moisture contents were carried out at a few selected locations, but no detailed analysis of variation of CMV with in-situ densities appears to have taken place.

- **Field validation of intelligent compaction monitoring technology for unbound materials.** White et al (2007) reported the findings from three field studies which investigated the relationships between roller-integrated compaction measurements from several types of intelligent compaction technology and the engineering properties of cohesive and granular soils.

A further study entitled US 14, investigated compaction meter value (CMV) and machine drive power (MDP) measurements from a Caterpillar vibratory smooth drum roller. Mapping trials were performed in conjunction with in-situ testing of the granular fill at selected locations. It was found that areas of weak or poorly-compacted soil were effectively identified because of the 100% surface coverage of the measurements.

The Ammann ACE system, which calculates soil stiffness $k_b$, was tested in the second study on US14. It was found that the equipment was not very sensitive to small changes in soil stiffness; it performed better on less-uniform material with a wide range of stiffness. This was demonstrated by extensive comparison of machine measurements and a range of in-situ test measurements. It was also found that the relationship between the in-situ test results and $k_b$ for subgrade is relatively weak when the conditions do not vary significantly.

A third study, again employed the Caterpillar roller measuring CCV (i.e. CMV) and involved implementing an intelligent compaction specification on Minnesota TH64. In this study, reported by White et al (2008), intelligent compaction technology (including GPS) was successfully implemented as the principal quality control tool on an earthworks grading project. The soil was classified as poorly graded sand to
well-graded sand with silt, moisture content control was implemented with the contractor adding water or performing blending of materials to keep the moisture content within 65% to 100% of standard Proctor optimum. To develop relationships between the CMV value and other in-situ test measurements, the roller was operated over several proof areas previously test rolled and accepted. Figure 8.1 shows typical findings.

![Figure 8.1. Relationship between CMV and in-situ measurement data](White et al, 2008, reproduced with permission of the Transportation Research Board)

CMV and in-situ test results were correlated by using average values for the different proof sections. Dry unit weight and dynamic cone penetrometer (DCP) index were predicted from CMV with $R^2$ values of 0.52 and 0.79 respectively. Scatter was observed with stiffnesses measured using the lightweight deflectometer (LWD), which was attributed to different measurement influence depths.

- **Intelligent compaction implementation: research assessment.** This study (Labuz et al, 2008) was undertaken to provide a qualitative assessment of Minnesota DOTs intelligent compaction specification (see Section 10.1.5). Four construction sites were visited and both granular and nongranular soils were investigated. Recommendations were that the measured roller dynamic measuring value is useful as an index parameter for comparison purposes but, as it is not a mechanical property of the soil, the equipment should be considered effective at determining local weak spots and therefore can be used to ensure uniformity, rather than as a measure of foundation stiffness. There is also an issue with the variation between sites as different target dynamic measuring values need to be established for every change in soil type or condition using calibration areas. In this project the calibrations were performed using light weight deflectometers. It was also considered that although intelligent compaction offers 100% surface...
coverage, the quantity of data is very time-consuming to process and made decision-making in the field very difficult.

- Field study at Minnesota US14. Thompson et al (2008) presented a paper on “variable feedback control intelligent compaction to evaluate subgrade and granular pavement layers” at the TRB annual meeting. At the site, an Ammann vibratory smooth drum roller was used to determine the dynamic measuring value ($k_s$) and to compare it with other in-situ compaction measurements. Typical results are shown in Figure 8.2 for a test strip comprising the sandy lean clay subgrade material. Linear relationships, with correlation $R^2$ values from 0.3 to 0.8, were found for $k_s$ and plate loading tests ($E_{v1}$), Clegg impact value (CIV), lightweight deflectometer (LWD), and dynamic cone penetrometer (DCP). The best correlation was seen with $E_{v1}$, followed by that with dry unit weight, and it is also worth noting that $k_s$ correlates well with moisture content demonstrating that moisture content control is required if using a target $k_s$ value.

![Figure 8.2. Relationships between $k_s$ and in-situ compaction measurements for the subgrade](Thompson et al, 2008, reproduced with the author’s permission)

### 8.3.2 Kansas

A study (Rahman et al, 2007) of intelligent compaction control of highway embankment soil was carried out using the Bomag Variocontrol roller to compact sandy soil as subgrade on three test sections at two different construction schemes (US56 and I70). In addition to calibrating the roller dynamic measuring value, termed the Bomag Variocontrol (BVC) value, against stiffness values from Geogage, falling weight deflectometer, and dynamic cone penetrometer; in-situ densities were also measured and the degree of compaction determined based on standard Proctor tests. Variation of BVC stiffness and the degree of compaction are shown in Figures 8.3 and 8.4 for test
sections at the US56 and I70 respectively. The results in both figures showed that lower BVC stiffness was obtained for both very high and very low percent compaction, although the I70 test section showed higher degrees of compaction.

Generally it was concluded that intelligent compaction is able to identify ‘soft’ spots with lower stiffness. Roller stiffness is however sensitive to the in-situ moisture content and higher moisture content will result in lower roller stiffness. This research placed emphasis on the need for target BVC stiffness values to be developed for specific soil types. When the target value is in operation, the roller automatically controls to achieve this target. If target values are low, the resulting density will be too low whereas as high target values will result in overcompaction.

![Figure 8.3. Relationship between BVC stiffness and percent compaction (US56)](Rahman et al, 2007, reproduced with the author’s permission)

![Figure 8.4. Relationship between BVC stiffness and percent compaction (I70)](Rahman et al, 2007, reproduced with the author’s permission)

At these particular sites, any correlation between BVC stiffness and the stiffness values obtained from in-situ measurements using geogage, falling weight deflectometers, lightweight falling weight deflectometers and strength values by dynamic cone penetrometer tests were difficult to obtain.
8.3.3 Texas

A field demonstration trial (FM156, Fort Worth, Texas) was undertaken as part of the FHWA TPF project and reported by Chang et al. (2008). The Case (Ammann) single-drum padfoot and smooth drum vibratory rollers and the Dynapac single smooth drum vibratory roller were used to compact three different types of pavement materials, namely fine-grain clay subgrade, stabilised subgrade, and granular base. The main objectives were to introduce intelligent compaction technology to Texas contractors, demonstrate how the compaction process produces a more uniform density/modulus of the soil and stabilised material, and assist in the development of specifications for intelligent compaction quality control.

For the clay subgrade, both padfoot and smooth drum roller-integrated $k_s$ values correlated ($R^2 > 0.6$) with stiffnesses measured by falling weight deflectometer and plate load tests ($E_{v1}$). Correlations with lightweight deflectometer, California bearing ratio, and dry density were not as good and this was attributed to the shallow depth of influence of their measurements.

With the lime stabilised clay subgrade, better correlations (with $R^2 > 0.5$) of $k_s$ were achieved with $E_{FWD}$, $E_{v1}$, $E_{v2}$ and $E_{LWD}$ than with dry density. The $k_s$ values were however sensitive to the moisture content of the compacted layer.

Measurements of CMV were in the range of 20 to 70 on the granular base but did not show a considerable increase in compaction with increasing passes. This was accounted for as some areas were observed as being wetter and softer during the compaction process.

The above project follows earlier work on controlling the quality of flexible pavement construction using instrumented rollers for compaction control carried out in Texas.

8.3.4 Florida

One of the options used to investigate whether layer thickness could be increased from 150mm to 300mm when compacting limerock as base course for pavements was that of intelligent compaction. The study was reported by McVay and Koo (2005) and concluded that the surface stiffness measured by the roller, $E_{vib}$, decreased with pass number and was quite variable over the section. This variability was attributed to crushing of the surface particles.

8.3.5 Wisconsin

In 2007 Wisconsin DOT set up their own highway research programme entitled “Evaluation of IC technology for densification of roadway subgrades and structural layers”, to provide guidance on whether intelligent compaction is a valid approach, identify its advantages and limitations, determine its suitability in differing material types and provide recommendation to the DOT. Preliminary work on a literature review has been completed and experimental work on a test site is scheduled for summer 2009.

8.3.6 Iowa

Iowa DOT is currently engaged in a FHWA study entitled “TPF-5(183) Improving the foundation layers for concrete pavements”. All aspects of the foundation layers will be investigated and in-situ testing will incorporate existing and emerging technologies (e.g. intelligent compaction).

Significant research on the field evaluation of compaction monitoring technology was undertaken by Iowa State University with funding from Iowa DOT. The final report (White et al., 2006) describes an extensive field programme carried out to investigate (i) experimental testing and statistical analyses to evaluate machine drive power in terms of
the engineering properties of the compacted soil (e.g. density, strength, stiffness) and (ii) recommendations for implementing the compaction monitoring technology. The compaction monitoring technology was based on the Caterpillar system which calculates two index parameters, the compaction meter value (CMV) and the machine drive power (MDP), although the emphasis in this study was placed on correlations of soil properties with the latter. During trials on the compaction of sand at one of the three sites used in the study, CMV measurements were found to be weakly correlated with machine power.

A similar project reported by White and Thompson (2008) also used a Caterpillar system measuring CMV and MDP to compact a different granular subbase in each of five test strips. Typical data are shown in Figure 8.5 with CMVs being compared with various spot measurements of in-situ stiffness, strength and also dry density. The authors went on to examine statistical analysis methods.

![Figure 8.5. Relationship between CMV and in-situ test results](image)

(White and Thompson, 2008, by courtesy of ASCE)

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6 Machine drive power relates to the soil properties controlling drum sinkage and the energy necessary to overcome the resistance to motion.
8.3.7 Other States

Demonstration projects have been undertaken in other States, such as Virginia, Georgia, and Maryland. These projects however, relate mainly to intelligent compaction of asphalt and are therefore not considered in this study.
9 Benefits and limitations of intelligent compaction and compaction monitoring

9.1 Benefits
On the basis of this study, the following benefits in utilising intelligent compaction technology have been identified:-

1. Provided that trials on each site provide a good correlation between the dynamic measuring value (i.e. CMV, CCV, k_b or Evib) and the required properties of the compacted soil, there is potential for both reducing the compaction energy and possibly also the number of roller passes without detrimental effect.

2. Over-stressing caused by an excessive number of passes or excessive vibration will be minimised by the use of intelligent compaction. For example with non-cohesive soils such as sands (particularly those of a single-sized nature), over-stressing can occur in the near surface material. With cohesive soil, after the minimum air void content is reached, some of the compaction stress may generate excessive pore water pressure immediately below the compactor causing softening. Better control of compaction will also eliminate crushing of some materials, e.g. larger chalk particles may breakdown if over-stressed so weakening the compacted layer.

3. Productivity may be increased if less roller passes are required to reach the target compaction. This has an associated cost benefit particularly for larger earthwork schemes. Furthermore, provided that the targeted dynamic measuring value is reached and documented, the number of independent spot tests of soil properties such as density and stiffness may be significantly reduced. Tests of this nature, which are often undertaken when using conventional rollers, are time consuming and costly.

4. Improvements in quality control when using intelligent compaction or compaction monitoring systems may be achieved, particularly when using GPS coupled systems, as evaluation of the entire compacted surface is undertaken. Soft spots in the compacted material (which may be related to a soft area in the substratum beneath the compacted layer) can be readily identified and either subjected to further compaction or replacement to provide a layer of more uniform stiffness. Spot tests using conventional stiffness testing techniques may fail to identify soft areas.

5. Incorporation of GPS into the equipment is considered invaluable, as even when compacting earthworks to a method specification, the documentation system will provide proof of the number of roller passes and mapping of the areas that have been compacted. This will have important contractual implications if subsequent earthwork performance problems arise.

6. Tests carried out by some roller manufacturers indicate that effective compaction to greater depths can be achieved by intelligent compaction systems.

9.2 Limitations
The following limitations have been identified:-

1. Intelligent compaction or compaction monitoring systems may be more effective in controlling the degree of compaction in certain soil types. Current indications are that compaction of granular soils will be more effectively controlled than will
the compaction of clayey soils. The latter will need particularly careful evaluation at the trial or calibration stage.

2. Vibrating rollers with intelligent compaction or compaction monitoring systems are more costly to purchase (and presumably hire) than conventional compaction plant. There are also potential maintenance costs in ensuring the electronic equipment continues to operate satisfactorily.

3. Operator controls and displays vary considerably according to the machine manufacturer and adequate operator training is therefore essential. Training needs extend to the downloading of the machine data using the documentation system (if present) and the preparation of interpretative graphics for the client.

4. Site trials and or the set up of calibration areas are likely to be required at each construction site in order to determine the respective dynamic measuring values applicable to each soil type encountered. This would not be cost effective for small projects.

5. The quantity of data produced by the on board measuring system is likely to be large and investment in an efficient data management system is required.
10 Development of draft specification for intelligent compaction of earthworks

10.1 Approach used in specifications/standards of other countries

10.1.1 German specifications and regulations

The German guidelines (Research Society for Road and Traffic, 1993) for continuous compaction control reported a direct relation between static deformation modulus or degree of compaction\(^7\) and the dynamic measuring value for coarse particle granular soils. For predominantly granular soils with a fine particle component (i.e. silt or clay) of \(\leq 15\%\) a similar calibration is also possible as long as the moisture content remains below the optimum. At higher moisture contents, suitable correlations with the dynamic measuring value cannot be achieved. For fine grained soils a good reproducibility of the measurements and an adequate correlation between dynamic measuring value and deformation modulus can be obtained but only at moisture contents considerably below the optimum. The guidelines recognised that the achievable dynamic measuring value was dependent on the stiffness of the foundation or substrate to the compacted layer.

In 1994 the Research Society for Road and Traffic incorporated a specification for “surface covering dynamic compaction control methods” into their additional technical contractual conditions and guidelines for earthworks in road construction (ZTVE StB). This was applicable to vibratory rollers, which produce mainly vertical vibrations and are capable of measuring dynamic deformation properties. Rollers which produce mainly horizontal oscillations were not considered. All data (including measuring value, travel speed, vibration frequency, jump operation, adjusted amplitude and travel distance) were required to be recorded in a contractually agreed form. A field calibration of the “testing” roller had to be performed to detect the correlation of the roller dynamic measuring value and the static modulus of deformation \(E_{v2}\) (second load cycle from plate loading tests) or the degree of compaction \(D_{pr}\) respectively. If the correlation coefficient \((r)\) is \(< 0.7\) its quality is unacceptable and the calibration has to be repeated. Each calibration included trials within three separate areas about 20m long with different degrees of compaction namely light compaction (with one roller pass), medium compaction (with three passes), and high compaction (with as many passes as required until no further measurement changes were recorded).

These guidelines are currently being reviewed and a revised draft is expected in 2009. This draft also presents equations relating static deformation modulus determined from the second loading cycle \((E_{v2})\) of plate load tests to the dynamic deformation modulus \((E_{vd})\) measured with a light drop weight tester, for formation materials. Guidance on the relations between degree of compaction and both \(E_{v2}\) and \(E_{vd}\) are also given for granular soils.

10.1.2 Austrian contract requirements

Technical contract stipulations (RVS 8S.02.6) have been produced for “continuous compactor integrated compaction-proof of compaction” of earthworks by the Federal Ministry of Economic Affairs in Vienna\(^8\).

\(^7\) Degree of compaction \((D_{pr})\) is the in-situ density expressed as a percentage of the Proctor density.

\(^8\) http://egweb.mines.edu/IntelligentCompaction/specifications.html
The calibration area would normally be a 100m length and the entire width of the road, with this test area being subdivided into an integral number of roller tracks. For each particular track, a measuring compaction pass in the forward direction at a constant speed of between 2 and 6 km/h is followed by a static reverse pass on the same track. This procedure is repeated until there is no noticeable increase in the dynamic measuring values (derived from transducers measuring drum acceleration). Immediately after the test passes, a total of nine measurements of the soil modulus are required using a static load plate test, preferably with a 300mm diameter plate. These measurements should be conducted at locations exhibiting low, medium and high dynamic measuring values, where no double jump operation occurred. Correlations between the roller dynamic measuring value and the soil modulus (Ev1) determined from the first loading cycle during plate loading tests can then be achieved\(^9\). Other correlations, for example with results from dynamic load plate (i.e. light falling weight devices), are also viewed as having potential.

In these calibrations a correlation coefficient ≥0.7 is required from a linear regression analysis. The minimum and mean values should be 95% and 105% (or 100% during jump mode) of the determined Ev1 respectively. Measured dynamic values can only be lower than the determined minimum value for ≤10% of the roller path. The measured minimum value has to be ≥80% of the determined minimum dynamic value.

Advice on how to incorporate acceptance criteria within the technical contract is also reported in the same document by the committee.

### 10.1.3 Swedish specification

Significant early work on the development of continuous compaction control was undertaken in Sweden and the technique is included in various standards. Road 94 (Vägverket, 1994) provides a general technical specification for roads and specifies that when a compaction meter is mounted on a roller, the bearing capacity (from static plate loading tests) or degree of compaction (determined from standard proctor compaction tests) of unbound pavement layers should be monitored. Acceptance requirements for different thickness sub-base layers and the roadbase are given based primarily on bearing capacity and the bearing capacity ratio Ev2/Ev1 (i.e. the ratio of the second and first load cycle values which gives an indirect indication of the degree of compaction).

Compaction of unbound roadbases and sub-bases is required to be carried out with a roller moving at a constant speed of between 2.5 and 4.0km/h. The roller must make at least 4 passes if a compaction meter fitted with a documentation system is used. Further passes are required if the bearing capacity is still increasing.

The compaction control has to be performed in accordance with VVMB 603: Surface-coverage compaction control\(^10\) with the selection of points for testing in accordance with VVMB 908: Statistical acceptance inspection\(^11\).

### 10.1.4 TC3 recommendations

Technical Committee TC3 (Geotechnics of Pavements in Transportation Infrastructure) of the International Society for Soil Mechanics and Geotechnical Engineering has provided

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\(^9\) The correlation of the dynamic measuring value with either the deformation modulus Ev2 (second loading cycle) or the ratio Ev2/Ev1 (which gives an indirect indication of the degree of compaction) from the static load plate test was found to be unsuitable.


recommendations for technical contractual provisions. Of particular importance in these recommendations is the calibration of the equipment during a site trial. The Austrian approach has been currently adopted by TC3 and details are therefore as described in Section 10.1.2. Further information on the TC3 (and hence Austrian) approach is reported by Adam (2007).

### 10.1.5 Pilot specifications in the US

In 2007, the Minnesota Department of Transportation drafted a pilot specification for the intelligent compaction of predominantly granular materials based on field calibrations against measurements taken primarily using a light weight deflectometer (LWD). For this purpose a control strip at least 100m long and 10m wide with a maximum depth of 1.2m was required. A modulus test using the LWD was required after each compaction pass at a minimum of three separate test locations spaced at least 25m apart. When additional roller passes caused no significant modulus increase the next layer was placed. The LWD test value shall be determined for each nominal 30mm increment of embankment thickness.

Further control strips are of course required to accommodate changes in the soil type. At the time of compaction, both for the control strip(s) and during production compaction, the moisture content of the embankment materials being compacted has to be controlled to not less than 65% and not more than 95% of the optimum moisture content determined by the standard Proctor method.

Parameters measured by the intelligent compaction roller are recorded continuously throughout the compaction of the control strip or any other proof layers to ensure that a correlation with the LWD test value is obtained. In this way adequate soil modulus should be achieved during the main construction.

Qualitative assessments of the pilot specification have been carried out on a number of construction sites; this information is presented by Labuz *et al* (2008) and White *et al* (2008) and is reviewed in Section 8.

### 10.2 Recommended draft specification for the UK

The latest Series 600 Earthworks in the Specification for Highway Works (MCHW1), together with the relevant Notes for Guidance (MCHW2), are available on the Highways Agency’s website12. Tables 6/1 to /4 of Series 600 tabulate the classification and compaction requirements of acceptable earthworks material, the grading requirements, and the plant and methods used for the method compaction. The basis for the specification was described in Section 3. For some selected fills, end product specifications are employed and any effective means of compaction (including that of intelligent compaction systems) can then be used provided that the required criteria are met.

The efficacy of the earthworks compaction procedure may be improved in some soil conditions by using compaction-monitoring and intelligent compaction systems. For this purpose clauses have been drafted for possible inclusion in the SHW, although it is recommended that they are first issued as an Interim Advice Note to allow further development as new data become available. It is not intended that these clauses replace existing clauses in the SHW but that, subject to appropriate site trials, they may provide an optional approach to method compaction. The proposed specification is presented in Appendix A.

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12 [www.standardsforhighways.co.uk/dmrb/index.htm](http://www.standardsforhighways.co.uk/dmrb/index.htm)
As discussed in Section 10.1.1 (German specifications and regulations) the use of compaction-monitoring and intelligent compaction technology is likely to be more effective in predominantly granular soils, rather than cohesive soils. This advice is supported by the findings in the early TRL trials reported in Section 7.1. A satisfactory field calibration correlating the dynamic measuring value (i.e. CMV, CCV, $k_B$ or $E_{vib}$) to the required properties of the compacted soil are essential prior to any site implementation.

The proposed specification in Appendix A place the emphasis on correlating roller dynamic measuring value with in-situ dry density (i.e. effectively air void content) as this is the fundamental soil property affecting earthwork performance (Arup, 2006) and the approach generally adopted by the Highways Agency in the UK. It must be noted that this is a departure from the approaches adopted by other countries where calibrations of roller dynamic measuring value against static plate loading tests, light falling weight testers, penetrometers, or similar devices as well as degree of compaction ($D_{pr}$) are preferred. Although spot testing of stiffness or strength is currently not included in the proposed specification in Appendix A, in the longer term there may be potential for their adoption provided that the performance testing device itself is calibrated on each particular site against the fundamental parameter of in-situ dry density. This two-stage process would need to be carefully implemented to avoid the risk of providing inadequate control of the compaction process in some soil types.

The proposed specification in Appendix A also considers the incorporation of GPS and mapping facility to provide a more complete traceability of the compaction process. The immediate implementation of these techniques (without necessarily needing to implement compaction-monitoring technology) for the quality control of earthworks construction when using the method compaction approach currently specified in the SHW is viable.
11 Summary

Since the late 1960s, fill material used in the construction of earthworks for Highway Agency road schemes has been placed and compacted primarily by a method compaction procedure which specifies the number of roller passes for different rollers and soil conditions. Since that time, vibratory roller technology has evolved and instrumentation to monitor roller performance has been introduced together with the development of procedures to amend roller characteristics. As a precursor to the study on compaction-monitoring and intelligent compaction technology, the basic principles of compaction, the current HA requirements for compaction of earthworks, and the development of performance specifications for earthworks were briefly reviewed.

Following this, compaction-monitoring and the use of intelligent compaction technologies for earthwork construction were investigated in detail; the main findings were as follows.

1. Accelerometers fitted to vibrating rollers can be used to monitor the rebound acceleration resulting from the changing condition of the soil as it is compacted. Different levels of sophistication are available from different roller manufacturers so that compaction-monitoring can assist the controlling operator or alternatively, provide for more fully automatic control of the vibration characteristics. The basis of all systems is the recording of the dynamic measuring value derived from the accelerometer(s) which is variously known as the CMV, \( k_b \), omega, \( E_{\text{vib}} \), or CCV according to the manufacturer and the equations used in the derivation.

2. The emphasis in the UK is on compacting soils to a specified air void content (traditionally less than 10% air voids for general fill) substantiated by the realisation that moisture content and air voids, rather than stiffness, are prime factors for embankments in limiting settlement, consolidation, and collapse compression on wetting. For this reason data were sought from Europe (where most of the original research and development into intelligent compaction technology occurred) and the US on calibrations of roller dynamic measuring values against in-situ dry density (i.e. air voids). Calibrations of this type proved hard to locate as acceptance criteria in other countries were primarily for the compaction of pavement foundations and therefore more often based on comparing dynamic measuring values with stiffness or strength measurements from static plate loading tests, light falling weight testers, penetrometers, or similar devices.

3. Data from Europe included early studies undertaken by TRL and more recent data supplied by Bomag and Dynapac.
   a. The TRL studies showed potential for controlling the compaction of well-graded granular soil through an acceptable moisture content range to less than 10% air voids, the exceptions being on the dry side of the moisture contents required by the SHW. Compaction control of cohesive soils to achieve an air void content of <10% proved problematic because the CMV hardly changed as the number of roller passes increased.
   b. Bomag reported correlations between \( E_{\text{vib}} \) values and the \( E_{\text{v}^2} \) values derived from plate loading tests. An example from one site where a 40mm gravel layer was being compacted confirmed that the correlations were good and that very even compaction was produced.
   c. Data from Dynapac showed good correlations between CMV and \( E_{\text{v}^2} \) when compacting a gravel in 500mm layers and an intermediate plasticity clay in 300mm layers. With the clay however, only a small increase in CMV was measured from a mean of 7 after two passes to only 11 after three passes which indicated the sensitivity of the relationship. At the same site the trend of decreasing air voids in the gravel with additional roller passes was...
apparent, whereas with the clay fill the small increase in CMV meant that correlations with air void content were difficult to achieve.

4. In the USA there is considerable interest in intelligent compaction technology and a significant number of research programmes and trials on various construction schemes have been implemented.

   a. The US National Co-operative Highways Research Programme, under the auspices of the Transportation Research Board, aims to determine the reliability of intelligent compaction systems and to develop recommended construction specifications for the application of intelligent compaction systems in soils and aggregate base materials. The findings include data from a range of construction projects carried out in various State Departments of Transportation. At these sites in-situ tests of stiffness and strength using plate loading, dynamic cone penetrometer, light weight deflectometer, etc will take place together with the measurement of the fundamental parameters of in-situ density by sand replacement and nuclear gauge testing as well as moisture content. The final report on the project is not publicly available at this time.

   b. A comprehensive study (TPF5-128) on the “accelerated implementation of intelligent compaction technology for embankment subgrade soils, aggregate base and asphalt pavement materials” was initiated by the Federal Highway Administration. Based on data obtained from field demonstrations to be carried out in 2008 through to 2010 in thirteen States, the objectives are to develop an expertise on intelligent compaction in these States as well as to identify future research requirements.

   c. Many State Departments of Transportation have conducted their own research in some cases part funded by the NCHRP and/or the FHWA. Of these States, the Minnesota DOT have been particularly active in carrying out demonstrations in a pavement test facility, field validations at a number of construction schemes, and developing and assessing specification for using intelligent compaction techniques.

   Much of the early data relates to pavement foundation construction, although recently the construction of more general earthworks involving a wider range of soil types has been investigated. The main conclusions from the various trials are presented in the report.

5. Guidelines for continuous compaction control adopted in the specifications and regulations of other countries were investigated. German specifications used calibrations to establish correlations of roller dynamic measuring value with $E_{s2}$ (from the second loading cycle of plate tests) or the degree of compaction (from Proctor tests). Austrian requirements, also adopted by Technical Committee TC3 of the International Society for Soil Mechanics and Geotechnical Engineering, preferred correlations with $E_{v1}$. The Swedish specification also requires correlations with bearing capacity or degree of compaction from Proctor tests. The bearing capacity ratio $E_{s2}/E_{v1}$ also forms part of their acceptance requirements. A pilot specification proposed by the Minnesota Department of Transportation prefers calibrations of dynamic measuring value against light weight deflectometer results. It is worth noting that the German guidelines state that the use of compaction-monitoring is likely to be more effective in predominantly granular soils, rather than cohesive soils.

6. Based on the findings of the study draft clauses are proposed for HA consideration and possible inclusion in the SHW. It is not intended that these clauses for compaction-monitoring and intelligent compaction techniques replace existing clauses but that, subject to appropriate site trials, they may provide an
optional approach to method compaction. The draft clauses place the emphasis on correlating dynamic measuring value with in-situ dry density (i.e. effectively air void content) as this is the fundamental soil property affecting earthwork performance and the approach generally adopted by the Highways Agency in the UK. The potential for calibrations of roller dynamic measuring value against static plate loading tests, light falling weight testers, penetrometers, or similar devices is however recognised, provided that the performance testing device itself is calibrated on each particular site against the fundamental parameter of in-situ dry density.

7. GPS and mapping techniques can be implemented for quality control when using method compaction without needing to necessarily implement intelligent compaction technology. This approach may be desirable in providing a record, alongside with the normal record of the material properties for acceptability specified in Table 6/1, that a location has been compacted by the requisite number of roller passes specified in the SHW. If a subsequent earthworks performance problem should then arise, this evidence will be important in evaluating the most cost effective remedial measure and in resolving any contractual issues.

8. The benefits and limitations of applying intelligent compaction technology are discussed. The potential for both reducing the compaction energy and possibly also the number of roller passes to reach the target compaction means that productivity may be increased which will have an associated cost benefit particularly for larger earthwork schemes. Over-stressing of single-sized sands, generation of excessive pore pressures in clay, and crushing of some materials (such as chalk) caused by an excessive number of passes or excessive vibration energy will be minimised by the use of intelligent compaction. Better quality control, particularly when using GPS coupled systems, as the entire area is subjected to surface evaluation, means that soft spots in the compacted material or the substrate to the compacted layer can be readily identified and subjected to further compaction or replacement. Current indications are that compaction of granular soils will be more effectively controlled than will the compaction of clayey soils. Vibrating rollers equipped with intelligent compaction technology are also more costly to purchase (and presumably hire) than conventional compaction plant and there are potential maintenance costs with the electronic equipment. Operator training in the use of the controls, displays, and documentation system is also essential.
12 Recommendations for further work

Prior to implementation of compaction-monitoring and intelligent compaction techniques in the Series 600 Earthworks in the Specification for Highway Works, further validation of their effectiveness in different soil types is strongly recommended. The following stages are recommended for this process.

1. A significant calibration trial of one (or more) intelligent compaction systems in controlled conditions within test bays containing a range of soil types is required. For this purpose each soil type will need to be tested at a range of moisture contents following the approach recommended in the specification developed in this report. Records of roller dynamic measuring value should be compared with fundamental measurements of in-situ dry density and hence air void content. It is important that correlations between the dynamic measuring value and the soil modulus determined from plate loading tests following approaches used in Europe and elsewhere should also be investigated during the trial.

2. The specification developed in this report should be subject to assessments on construction sites as the opportunity arises. The first assessment should take place at a site where well graded granular material (Class 1A in the SHW) is being compacted for earthwork construction. Even if intelligent compaction techniques are not being employed in the main works, an appropriately instrumented roller and trained operator, can be brought in specifically for the purpose of carrying out the calibration trial. If successful correlations are obtained which ensure effective compaction, further sites in different fill classes should be sought to extend the applications for compaction-monitoring and intelligent compaction technology in the UK.

3. A site should be identified where good compaction of an embankment and its side slopes are particularly critical. The Contractor should then be encouraged, perhaps by financial incentive, to implement a GPS and mapping facility to provide a more complete traceability of the number of roller passes and compaction process at each location. At the selected site, the procedure can be implemented either for quality control when using method compaction or used in conjunction with intelligent compaction technology.
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References


- Specification for Highway Works (MCHW 1)
- Notes for Guidance on the Specification for Highway Works (MCHW 2)


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Appendix A  Proposed specification
General

1. The latest Series 600 Earthworks in the Specification for Highway Works (MCHW1) and the associated Notes for Guidance (MCHW2) are available on the Highways Agency’s website. Tables 6/1 to 6/4 of Series 600 tabulate the classification and compaction requirements of acceptable earthworks material, including the grading requirements and moisture content (or moisture condition value), and the plant and methods used when method compaction is employed. For some selected fills, end product specifications are employed and any effective means of compaction (including that of intelligent compaction systems) can then be used provided that the required criteria are met.

2. If using compaction-monitoring or an intelligent compaction system to replace method compaction, the need to fulfil the material property requirements for acceptability in Tables 6/1 to 6/3 remains unchanged. The depth of the compacted layer specified in Table 6/4 (for the appropriate compaction method specified in Table 6/1) is also as prescribed although the number of passes may be modified by the compaction-monitoring or intelligent compaction subject to the findings from a suitable trial.

3. Provided that trials on each site provide a good correlation between the dynamic measuring value (e.g. CMV, CCV, $k_b$ or $E_{vib}$) and the required properties of the compacted soil, there is potential for either reducing the compaction energy (by control of the amplitude or frequency of vibration) or the number of roller passes without detrimental effect.

4. Compaction-monitoring or intelligent compaction systems are likely to be more effective in the compaction of granular fill, as opposed to cohesive fill.

5. The use of compaction-monitoring or intelligent compaction systems is likely to be particularly effective in identifying soft spots in the material being compacted as the entire area is subjected to surface evaluation. These soft spots can then be subjected to further compaction or replacement.

6. It must be noted that the effectiveness of this proposed approach should be validated on site to the satisfaction of the Overseeing Organisation. The trial procedure should be modified where appropriate to closely simulate the site conditions and processes encountered.

Field calibration

7. A separate trial is required for each soil type (and its different moisture contents if significant variation is encountered) to be compacted on the site using this technique. The trial requirements are as follows:

   a. For each trial, a flat test strip of minimum length 100m which is able to accommodate a minimum of three roller widths (with an overlap of not more than 10% of the drum width) should be identified for calibration purposes.

   b. The foundation material below the test strip should be compacted using intelligent compaction to ensure that it is of uniform stiffness with no soft spots. If considerable variation in foundation stiffness occurs over the site, the trial should take place in an area which is of low relative stiffness.

   c. To form a suitable base at least three layers of fill should be compacted using the layer thickness derived for the class of fill being tested as specified in Tables 6/1 and 6/4 of the SHW. Either method compaction using the number of passes of the roller (with full vibration operating) specified in the SHW or intelligent compaction until there is no significant increase in the mean dynamic measuring value with further passes, can be used for these three layers.
d. Following compaction of the lower three base layers, the following procedure should be adopted for the fourth and main test layer utilising compaction-monitoring or intelligent compaction techniques:

i. The roller dynamic measuring value should be continuously recorded during each compaction pass of the roller (at a selected fixed speed which should be between 2 and 6km/h) until there is no significant increase in the mean dynamic measuring value with further passes when the test is then terminated. In-situ dry densities should also be measured at a minimum of three separate test locations spaced at least 25m apart after each compaction pass (or after alternate passes if the anticipated number of passes is greater than four).

ii. The mean dynamic measuring values should be plotted against mean dry densities and examined for trend to establish a reliable target dynamic measuring value relating to the mean in-situ dry density compatible with less than 10% air voids for general fills or the requirements of the SHW for selected fills or stabilised materials. (Although the use of mean values is suggested, individual densities and roller dynamic measuring values in the immediate vicinity of the individual density test locations can be used as an alternative).

iii. The target dynamic measuring value is likely to be dependent on the soil moisture content and calibrations over a range of moisture contents are therefore advisable. If variation in target dynamic measuring values is significant over the range of moisture contents encountered a different approach may be adopted. In this case, changes in the mean dynamic measuring value from that determined from the previous roller pass may be plotted against individual densities. Examination of the trend may permit a reliable target change in dynamic measuring value to be established which better reflects the state of compaction when moisture content variation occurs as is often normal.

Acceptance criteria

8. In these calibrations a best fit line or curve (with a correlation coefficient of better than 0.7) is required to relate the mean dynamic measuring values to dry densities. If desired, data from the first roller pass, which is often anomalous, may be ignored provided that the calibration includes data from at least three other roller passes. A target dynamic measuring value should be derived such that the in-situ dry density is not lower than its required value over more than 10% of the roller path; this can be assessed from the continuous measurements of dynamic measuring values during relevant roller passes in the calibration trial.

9. When carrying out the interpretation of calibration data, a change in dynamic measuring value of less than 10% between successive layers may prove to be an acceptable criterion for compaction control.

Documentation

10. When using compaction-monitoring or intelligent compaction all available data (e.g. dynamic measuring value, travel speed, vibration frequency, jump operation, adjusted amplitude and travel distance) should be recorded in a contractually agreed form.
GPS and mapping

11. It is advantageous, but not mandatory, to incorporate GPS and mapping facility to provide a more complete traceability of the compaction process. The requirements are:

a. The roller shall be fitted with a GPS system capable of being used continuously to record co-ordinates with a resolution better than $1/5^{th}$ of the width of roll.

b. The visual display for the operator should indicate either by colour or number, the total number of roller passes (with vibration operating) to which each point on the roller path has been subjected within an approved sequence of compaction. The GPS system should be equipped with a suitable documentation system permitting this data to be downloaded to form a permanent record for the compacted areas.

12. The data obtained can be used both with intelligent compaction systems and, independently, for quality control when using method compaction.

a. When used with *intelligent compaction* systems, location mapping provides an invaluable record of the number of passes and dynamic measuring value (e.g. CMV, CCV, $k_b$ or $E_{vib}$) that each point receives during the compaction process.

b. GPS and mapping techniques can be implemented for quality control when using *method compaction* without needing to implement intelligent compaction technology. This approach may be desirable in providing a record, alongside with the normal record of the material properties for acceptability specified in Table 6/1, that a location has been compacted by the requisite number of roller passes specified in the SHW. If a subsequent earthworks performance problem should then arise this evidence will be important in evaluating the most cost effective remedial measure and in resolving any contractual issues.
Use of intelligent compaction technology

This study evaluates the current state-of-the-art on intelligent compaction and begins by reviewing the basic principles of compaction, the current HA requirements for compaction of earthworks, and the development of performance specifications for earthworks. The history of the initial research on the topic in Sweden and the development of the theory of intelligent compaction are discussed. A review of commercially available equipment showed that different levels of sophistication are available from different manufacturers so that compaction-monitoring can assist the controlling operator or alternatively, provide for more fully automatic control of the vibration characteristics. Guidelines for continuous compaction control adopted in the specifications and regulations of other countries were investigated together with calibration data obtained from manufacturers and technical publications. The benefits and limitations of intelligent compaction techniques are discussed. Based on the findings of the study a draft specification is proposed for the Highways Agency to consider for possible inclusion in the Specification for Highway Works (SHW).

Other titles from this subject area

PPR082   A study of water movement in road pavements  J M Reid, G I Crabb, J Temporal and M Clark. 2006
PPR140   Ventilation during road tunnel emergencies. R C Hall. 2006
PPR302   Performance of an interseasonal heat transfer facility for collection, storage and re-use of solar heat from the road surface. D R Carder, K J Barker, M G Hewitt, D Ritter and A Kiff. 2008