Continuous Compaction Control for Earthworks Operations on Scottish Road Construction Projects

M G Winter
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Executive Summary

The UK Specification for Highways Works (MCHW 1) currently makes no specific provision for the use of Continuous Compaction Control (CCC) in the construction of earthworks for roads and highways. Such techniques can be used by the constructor but the provisions of the MCHW 1 take primacy leaving little incentive to do so.

The potential benefits of the use of CCC include, for example, real time monitoring of compaction operations and the provision of a permanent record of the process. The use of CCC can confer a number of benefits to the earthworks compaction process. These include:

- Monitoring and recording (quality control) of the coverage of compaction plant including the number of passes applied at a given location as an aid to compaction control using a method specification,
- Identification of soft spots (quality assurance) to allow their remediation during the construction process and the monitoring of the relative increase in compaction as successive passes are applied. This is particularly helpful in ensuring that over-stressing does not occur resulting in low density and high air voids.
- Determination of the stiffness or relative density of a compacted material subject to performance specification.

Intelligent compaction can also allow the variation of the input of the compaction plant (frequency, amplitude) in response to the development of stiffness in the material being compacted.

Not all of these potential applications of CCC are suited to all soil types and, of course, none of them militate against the basic need to ensure that the soil is in an acceptable moisture condition prior to compaction.

Against this background Bomag (Great Britain) Ltd have asked TRL to assist them to independently demonstrate the proven benefits of CCC in Scotland and subsequently in the rest of the UK.

In this report the background science and technology of earthworks compaction is set out in the context of the UK Specification (MCHW 1) and of the potential use of CCC. Historic and currently available CCC specifications are reviewed and examples of the use of CCC are provided from real construction projects.

There seems to be no major technical obstacle to the introduction of CCC to road and highway earthworks in the UK. Indeed, the existence of a draft specification designed to form part of the MCHW 1, and reproduced in updated form herein, and a new EU Technical Specification mean that the route to the introduction of CCC ought to be relatively straightforward. The work presented in this report is intended to help guide this process and to provide an introduction to infrastructure owners and constructors to the potential benefits of CCC while highlighting the limitations of CCC and the potential pitfalls of an uncontrolled introduction.

The next steps are set out in this report and involve consultation with key Overseeing Organisations and contractors to elicit their support and involvement in a trial (or trials) to demonstrate the use of CCC in earthwork construction.
1 Introduction

Bomag (Great Britain) Ltd wish to expand their operations and plant sales in Scotland and subsequently in the rest of the UK. A major selling point for both the plant manufacturer and its end users, potential and otherwise, is the introduction of Continuous Compaction Control (CCC). This allows both the real time monitoring of compaction operations and the provision of a permanent record of the process. The use of CCC is often described as Intelligent Compaction Control (ICT) in systems where the amplitude or frequency of vibration can be changed automatically as a result of the response of the soil.

The focus is primarily on earthworks which maximises the amount of plant used compared to, for example, asphaltic pavement construction. The latter may attract a greater material value compared to earthworks, but compaction plant use is less extensive.

The work presented in this report is intended to help guide this process and to provide an introduction to infrastructure owners and constructors to the potential benefits of CCC, while highlighting its limitations and the potential pitfalls of an uncontrolled introduction.

The work seeks to assist Bomag to make the case for the introduction of CCC to high volume, bulk general fill earthworks for road construction in Scotland. This is primarily aimed at the introduction of the GPS and mapping capabilities to aid in the effective quality control (QC) of earthworks and to thus ensure the correct number of passes is applied, in support of the existing method specification. It is also intended that the stiffness capabilities of CCC should be employed in the identification, and rectification, of soft spots therefore contributing to the quality assurance of earthworks construction (QA). The recent introduction of a European Technical Specification for CCC additionally makes a strong case for its use in the performance monitoring of the compaction of some materials.

This first phase of evaluation work is intended to prepare the way for and inform discussion that should lead to a trial (or trials) of CCC on a Scottish road construction project(s). The use of CCC to monitor the location and number of passes (QC), to highlight the potential use of CCC to identify soft spots and to minimise the likelihood of over-compaction (QA), and to assess the compaction performance of certain fill materials may all form part of a trial.

Some advance work will be required to develop a previously proposed specification (Carder et al. 2009) to link the European Technical Specification (Anon. 2016), published during the currency of this project, to the UK Manual of Contract Documents for Highways Works (MCHW 1 and 2).

In this report a brief background to the use of CCC in the context of the UK Specification (MCHW 1 and 2) is given (Section 2). Section 3 introduces the fundamentals of the compaction of fills and thus illustrates the development of the UK Specification. Section 4 reviews CCC and Section 5 reviews specifications for CCC. Section 6 gives practical examples of the use of CCC and Section 7 summarises this report and makes recommendations.
2 Background

Continuous Compaction Control has been in existence for many years but its uptake in the UK has been relatively slow. There is a perception that this lack of uptake is a result of, at least in part, the lack of a framework for its use in the specifications used. In the UK the Specification for Highway Works (MCHW 1) and associated Notes for Guidance (MCHW 2) that form part of the Manual of Contract Documents for Highway Works (MCHW) are used for road and highway earthworks. Without such a framework there is little to no perceived benefit in using CCC for those who bear the costs of plant and its use (e.g. constructors and plant hire companies).

There are two approaches to evaluating states of compaction. The first is the measurement of dry density and air voids and this forms the basis of both the end product and method compaction specifications in the MCHW; the method being determined by trials to determine the compaction parameters (plant type and mass, material type, layer thickness, and number of plant passes) needed to obtain a given air voids and/or density. The second involves the measurement of some indicator of the strength or stiffness of the compacted soil. Amongst this latter type are strength tests that include the Clegg Impact Hammer (Winter & Selby 1990), the results from which are primarily influenced by the strength of weaker soils and the stiffness of stronger soils; the Dynamic Cone Penetrometer; and Compaction Meters that measure stiffness or some proxy thereof and are, most commonly, mounted on vibrating drum rollers (Snowdon 1992). It is important to note that in all cases, and regardless of the approach to the specification of compaction, that it is essential that effective control of the moisture content is maintained and in the MCHW 1 this is achieved through the measurement of the acceptability of fill for earthworks compaction.

The use of CCC allows the rapid and near continuous measurement of stiffness. However, this is only one of three primary means of using CCC effectively in the construction of earthworks, as follows:

a) GPS and mapping (QC): As a means of monitoring and recording the coverage of compaction plant including the number of passes applied at a given location. This approach uses the built-in GPS facilities of the plant and supports the effective application of QC procedures to the existing method specification.

b) Soft spots (QA): As a means of identifying ‘soft spots’ that require further compaction and of monitoring the relative increase in compaction as successive passes are applied. This is particularly helpful in ensuring that over-stressing does not occur resulting in low density and high air voids (Parsons 1992).

c) Performance: As a means of determining the stiffness or relative density of a compacted material subject to performance specification (Carder et al. 2009).

Both Snowdon (1992) and Carder et al. (2009) report on the use of CCC as a performance tool while acknowledging the other potential uses. It is considered that the use of CCC to measure performance is limited to a relatively small range of materials, Carder et al. (2009) state that it has more potential for success for granular (coarse-grained) soils than for fine-grained spoils. Bomag and specifications (see Section 5) typically place the limit for this approach at soils with <15% of particles by weight <63μm.
In addition, the UK Specification (MCHW 1 and 2) is largely based upon specifying the method of compaction with a few exceptions for end product, all based on density and air voids, and a culture change would be required in order to achieve a successful introduction of an alternative approach.
3 Compaction

Compaction can be defined as ‘the process whereby soil particles are constrained to pack more closely together through a reduction in the air voids, generally by mechanical means’ (Anon. 1952). The distinction is thus made between the superficially similar process of consolidation, which may be defined as the process of constraining the soil particles to pack more closely together through the expulsion of pore water.

The level of compaction is usually measured in terms of the resulting dry density. The increase in dry density experienced by a given soil will depend on the moisture content of the soil and the amount of energy applied during compaction (Winter 1989). The effect of increasing the moisture content is to lubricate the movement of the soil particles relative to one another thus giving rise to increased compaction. However, in the case of many soils, particularly clays, a more applicable representation is that of undrained strength decreasing with increasing moisture content thus making it easier for the compaction process to deform the soil to fill voids. Once the compaction process has achieved a near-zero air voids condition the addition of further water is no longer beneficial and dry density reduces (Carder et al. 2009) as water must replace solids in a given unit volume (Figure 1). The peak, or maximum, dry density corresponds with the optimum moisture content.

![Figure 1. Typical relationship between dry density and moisture content of a clay soil (from Parsons 1992).](image)

The level of compactive effort, or energy, applied during the compaction process has a fundamental effect on the compaction curve (Figure 1). Figure 2 shows idealised dry density-moisture content (compaction) curves, as increasing amounts of compactive effort, or energy, are applied the value of maximum dry density increases while the optimum
moisture content decreases. However, it should be noted that successively doubling the compactive effort will result in reduced increases in the maximum dry density as a limiting value of density is approached. In the case of a single-sized granular material this will be the density corresponding to tetrahedral packing (Barnes 1987). Data presented by Hogentogler (1938) from static pressure compaction tests indicated that, at values below the limiting dry density, the maximum dry density increases as a logarithmic function of the static compaction pressure, while the optimum moisture content decreases as a logarithmic function of the static compaction pressure.

![Idealised dry-density-moisture content relationship. Compaction curves for three levels of compactive effort and lines of constant 0%, 5% and 10% air voids are shown (from Winter 1989).](image-url)
An excessive number of passes may result in over-stressing. With non-cohesive materials this may involve a reduction of the density of the near surface material. With cohesive materials it may result in the generation of excess pore pressures immediately below the compactor at which time further compaction is of no benefit and may result in a reduction of the stability of the soil under its own weight or that of construction plant. With materials such as Chalk, over-stressing leads to the breakdown of larger particles giving rise to wet plastic fines and a significant weakening of the freshly placed fill. Particle breakdown has also been observed in materials such as spent oil shale (Winter 1998).

Ensuring that soils are compacted at or near the optimum moisture content is important to ensure that dry density is maximised and that air voids are minimised, thus ensuring that the compacted fill is less susceptible to water ingress and an associated loss of strength. As soils become less plastic (and more granular) the compaction curve generally moves upward and to the left (Figure 3), with increased values of maximum dry density and decreased values of optimum moisture content. The exceptions to this are uniformly graded materials, as typified by uniformly graded sand in Figure 3, where the packing of notionally single-sized particles implies large voids. In these cases the increase in dry density with increasing moisture content towards the optimum is small and the optimum is difficult to establish due to the free-draining nature of the material.

![Figure 3. Relations between dry density, moisture content and air voids for various soils (from Parsons 1992).](image-url)
The compaction of earth materials is a repetitive process requiring the use of heavy mechanical equipment and is demanding on resources – energy, cost and time (Gomes Correia et al. 2016). The use of CCC can play a role in ensuring that compaction processes contribute to sustainability by minimising the number of passes that must be applied during earthworks construction, including by allowing the use of heavier compaction plant as pointed out by Gomes Correia et al. (2012).

The UK Specification for Highway Works (MCHW 1) and the associated Notes for Guidance on the Specification for Highways Works (MCHW 2) acknowledge that the prevention of high air void contents within compacted fill materials is the priority if long term weakening and settlement is to be avoided. While the best measure of an acceptable state of compaction is generally accepted to be the dry density and air voids, their field measurement is difficult. For this and other reasons compaction specifications are often written in terms of the method to be used to attain a given compaction state as determined by trials (Parsons, 1992).

MCHW 1 and 2 include the UK specification for earthworks compaction, which is primarily based on method specification, in Series 600 and NG600. The method (plant type, plant mass, layer thickness, number of passes) is generally defined such that it will produce an air voids content of 10% or less within a defined moisture content range for a given soil type. Within 600mm of the pavement structure additional compactive effort is required so as to achieve an air voids content of 5% or less. Some selected fills (e.g. fill to structures and pulverised fuel ash) are required to achieve either a relative compaction value (usually relative to a British Standard maximum dry density) and/or a specific maximum percentage of air voids (i.e. the specifications for these materials and/or classes of fill are end product); end product was first introduced to the UK specification in 1986.

The method compaction requirements in MCHW 1 were based on a programme of research of more than four decades duration and are summarised by Parsons (1992). Underlying the specification was the principle that the constructor should have as free a choice of construction plant as possible and that once the type of plant is selected the specification then sets-out the maximum layer depth and the minimum number of passes required for the particular fill type to be used. The compactive effort thus specified 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% would be produced, whilst with increasing moisture content beyond the optimum moisture content/maximum dry density condition, dry density would increase at an approximately constant air voids 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 may lead to remoulding of the surface and rutting beneath the wheels or rollers of the compactor. The principles of the method specification are illustrated in Figure 4.

Notwithstanding this, controls on the moisture acceptability of fills are applied in order that the completed fill does not have excessive air voids or become overstressed (e.g. Matheson & Winter 1997; Winter 2004).
The pitfalls of refocussing the specification from dry density/air voids to a measure of stiffness and/or strength are illustrated in Figure 5. It is clear from Figure 5 that high California Bearing Ratio\(^1\) (CBR) values can be achieved, indicating that the soils have high strength/stiffness, but that the air voids value is high (and the dry density low). Thus, if a specification is purely based upon stiffness or strength then there is a significant risk that the compacted material would have high air voids and be vulnerable to inundation and loss of strength even though the required stiffness values were achieved during compaction.

Work was undertaken by Arup (2006) to investigate the link between the air voids content of placed fill and long term embankment performance. Satisfactory performance was sought with regards to total settlement, differential settlement, heave, stiffness and compressibility, and collapse settlement (i.e. due to water inundation). There proved to be a paucity of data linking the properties of fill materials to long term embankment performance, although there was evidence for many of the fills studied that low air voids were generally related to satisfactory performance.

\(^1\) The CBR, is essentially a small-scale plate bearing test that measures strength, bearing capacity, for weak soils but the resulting value is increasingly influenced by stiffness as soils of greater strength are tested (Winter, 1989).
Figure 5. Compaction and California Bearing Ratio relations for black sandy clay soil (O’Reilly et al. 1968 from Snowdon 1992).

It is not sufficient to specify air voids content as the sole end-performance criteria as this can be minimised simply by increasing the moisture content and/or using lower shear
strength materials; neither of which will improve fill performance. Air voids needs to be specified in conjunction with either a maximum moisture content, a minimum undrained shear strength, or minimum relative compaction or moisture condition value (Winter 2004) for the soil type encountered. Arup (2006) concluded that whereas stiffness is a good parameter for bound and unbound pavement layers, due to the load spreading requirements placed on these 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 the self-weight consolidation and/or collapse compression on wetting. Notwithstanding this, it is also important not to underestimate the importance of effective compaction to low air voids/high density of both bound and unbound pavement layers.
4 Continuous Compaction Control

A number of devices intended for the monitoring of the state of compaction of earthworks were evaluated by Snowdon (1992). These included vibratory roller-mounted compaction meter devices by Bomag (the Terrameter) and by Dynapac as well a non-roller mounted devices such as the Clegg Meter and the Dynamic Cone Penetrometer (DCP). Comparisons were made between the outputs from the monitoring devices and the dry density and air voids of compacted layers of cohesive and granular fill materials. Snowdon (1992) concluded that “... none of the devices designed to measure the strength or bearing capacity of a compacted layer should be considered for monitoring or controlling the compaction of earthworks.” This was, however, caveated with the possible application of the Bomag Terrameter mounted on a vibratory roller for the compaction of granular fills complying with the relevant (contemporaneous) material specification.

Snowdon (1992) went on to note that hard copy from tachographs could provide evidence with which to assess compliance when used in combination with existing method specifications. And that the output from vibratory roller mounted compaction meters, if considered suitable after site trials, may also assist in assessments for compliance with method specifications and QA schemes.

Snowdon’s (1992) conclusions, although at first sight less than encouraging, essentially opened the door for the use of CCC in the spatial assessment of compliance and the detection of soft spots in the UK. Notwithstanding this, the opportunity to do so seems not to have been widely taken up by contractors constructing road earthworks in the intervening 25 years; this seems most likely to be as a result of the lack of incorporation of such opportunities into the UK Specification (MCHW 1 and 2).

4.1.1 Bomag System

Carder et al. (2009) reviewed the development of compaction monitoring technology from its inception in the 1970s in Sweden, Germany and Switzerland to around 2000. Carder et al. (2009) also reviewed equipment that was commercially available at the time, including Bomag systems. At that time the Bomag Variocontrol system was fitted to single drum rollers. The Variocontrol system utilised a directed exciter, which automatically adjusted 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 were fitted with the Terrameter measuring system either Terrameter plus (BTM plus) or Terrameter prof (BTM prof) to control the level of vibration. It was possible to fit Terrameter systems, or the Bomag EVIB meter (BEM) which monitored and displayed the vibration modulus for manual control by the operator, to other Bomag rollers not equipped with the Variocontrol system.

The vibration modulus was determined from the measured acceleration of the drum and the theoretical relationship between the soil contact force and the deflection of the drum. The $E_{\text{VIB}}$ value was correlated with, and directly related to, the deformation modulus $E_{\text{v2}}$, determined from the second load cycle, in the German DIN 18134 plate bearing test (Floss 2010).
The Terrameter (BTM plus and BTM prof) comprised two accelerometers, a processor to derive the E\textsubscript{VIB} values, as well as an operation panel to control and monitor the compaction process and to display E\textsubscript{VIB}, frequency, speed and a line diagram of the rolled track. BTM prof is additionally equipped with a printer to document the measurements in the form of line or bar charts; this is described as QC in Section 2 albeit that the E\textsubscript{VIB} measurements relate to performance control. The Terrameter indicates when further compaction is no longer possible (i.e. when refusal has been reached), and identifies and records soft spot and non-uniform areas; this is described as QA in Section 2.

Carder et al. (2009) noted that GPS could be integrated into the system (using the BCM 05 compaction measurement system) for larger projects, a qualification that perhaps reflects the high cost of such systems at the time. (In the intervening years GPS measurement and control has become both low cost and ubiquitous and GPS is integral to the system regardless of project size.) The BCM 05 system allowed the documentation of roller position with an accuracy of 5cm (depending on the GPS unit). This permitted the number of roller passes to be displayed to the operator and to be compared with the E\textsubscript{VIB} values at the same locations at a range of scales (i.e. the image may be zoomed). The system was based on a cell pattern with a maximum size of 50cm by 50cm and the data could be downloaded and documented for future use. The Variocontrol system and the compaction data management and documentation are described by Kloubert (2006).

4.1.2 *Current Bomag Plant*

Current (2017) Bomag plant designated BVC (Bomag Variocontrol) include the Variocontrol hardware in the drum and a live display. The Bomag Compaction Management (BCM) system can then be added to include GPS and a mounted Tablet, which enables the capture, storage and later use of the data using an updated version of the BCM 05 Office (Version 4.2) software.

Taking the Bomag BW 213 DH-4i BVC single drum roller as an example with a roller width of 2.130m and drum axle load of 9,400kg this would be designated in the UK MCHW 1 Table 6/4 (see also Clause 6.12.10.iii) as either:

- Smooth wheeled roller (or vibratory roller operating without vibration): Ref. No. 2: over 2700kg up to 5400kg mass per metre roll width.
- Vibratory roller: Ref. No. 9: over 4300kg up to 5000kg mass per metre roll width.

Thus operating without vibration the plant would be suitable for compaction using Methods 1, 2 and 4 and, for lower values of layer thickness, for Methods 6 and 7\textsuperscript{2}. When used as a vibratory roller it would be suitable for Methods 1, 2, 5 and 6 and, for lower values of layer thickness, for Method 7\textsuperscript{2}.

\textsuperscript{2} Note that while the mass per metre width notionally renders the plant suitable for Method 3, the MCHW 1 Clause 612.10.xiv requires that for this method “… the roller shall be towed by track-laying tractors. Self-propelled rollers are unsuitable.”
Similarly the larger Bomag BW 226 DH-4i BVC single drum roller has a roller width of 2.130m and drum axle load of 17,590kg this would be designated in the UK MCHW 1 Table 6/4 (see also Clause 612.10.iii) as either:

- Smooth wheeled roller (or vibratory roller operating without vibration): Ref. No. 3: over 5400kg mass per metre roll width.
- Vibratory roller: Ref. No. 10: over 5000kg mass per metre roll width.

Thus operating without vibration the plant would be suitable for compaction using Methods 1, 2 and 4 and, for lower values of layer thickness, for Methods 6 and 7. When used as a vibratory roller it would be suitable for Methods 1, 2, 5, 6 and 7.

It should also be noted that the MCHW 1 makes provision for end product compaction for certain types of fill. The [minimum] requirement is usually defined as a percentage of maximum dry density from a particular standard test and/or a dry density corresponding to a [maximum] percentage air voids at field moisture content. For such fills CCC can be used as an aid to the constructor to determine when the end product requirements have been reached after suitable trials to demonstrate the correspondence between the end product requirement(s) and the output parameters of the plant. This does not, of course, remove the need to ensure that the moisture content or moisture condition of the fill renders it acceptable prior to compaction. Regardless of the use of CCC the specification requirement would remain unchanged including the need to provide documented test results.

4.1.3 Studies of the Bomag Terrometer

Snowdon (1992) reported on a trial of the Bomag Terrameter considering four materials – two granular (coarse-grained, Class 1A) and two cohesive (fine-grained, Class 2A). The system used by Bomag at the time used a transducer bolted to the vibratory roller drum shaft to measure the change in rebound acceleration during compaction. The data from the transducer, called ‘omega’ values, were recorded and stored for comparison. When an increase in the omega value of less than ten per cent was recorded for two consecutive passes in the same direction then an indicator light showed the operator that compaction was effectively complete: i.e. any further passes would produce only limited improvement in the compaction state and would not be economic.

A print out provided a graph of omega value against distance travelled; the maximum, minimum and average omega values; the percentage increase in omega value for two consecutive passes (in the same direction); the frequency of vibration of the roller; and the speed of travel (Figure 6).

This is clearly not the same system as is currently implemented on Bomag plant. The omega value is a change in acceleration while the current output from Bomag machines is a stiffness, or stiffness ratio. It should, however, be noted that the rebound acceleration will increase with increasing stiffness of the compacted layer and so is perhaps not quite so dissimilar as might, at first, be anticipated. It certainly has merit in terms of an initial evaluation of how CCC might relate to the current UK MCHW 1 specification.

Snowdon’s (1992) initial analysis showed great variation in the omega values recorded, with individual values for cohesive (fine-grained) fills reaching values of only around 35 whilst...
those for granular (coarse-grained) fills ranged from between 65 and 740 depending on the state of compaction and moisture content. A typical set of Snowdon’s results for a 200mm thick layer of a Gravel-sand-clay is given in Table 1. It was immediately apparent that the omega value itself was not suitable as an indicator of the state of compaction for general earthworks as it depended upon both the dry density and moisture content. The rate of increase in omega value was therefore used as the basis for comparison with the state of compaction achieved. As a criterion to indicate that compaction was complete, a percentage change of <10% in the omega value between successive passes was selected, as recommended by the manufacturer.

![Figure 6. Example printout from the Terrameter on a 200mm layer of Gravel-Sand-Clay (from Snowdon 1992).](image)

Figures 7 to 9 illustrate the percentage change in omega value, dry density and air voids respectively with increasing numbers of passes using the data in Table 1. It is apparent that, for this granular material (Gravel-sand-clay; MCHW Class 1A), the <10% change in omega value with an increasing number of passes broadly indicates progression to increased dry density and decreased air voids, in the latter case to an acceptably low value of air voids (i.e. <10%).

The rate of change of the omega value thus indicated when the roller had reached its limit of useful compactive effort on a particular soil under test. However, this did not necessarily ensure that an acceptable state of compaction had been reached.

Carder et al. (2009) were able to access Snowdon’s (1992) original data and confirmed that the less than <10% omega value did indeed indicate when the roller had reached its limit of useful compaction. However, with access to the data for all four soils a more detailed picture emerges (Table 2). For granular fills it is clear that there was a good correlation between the <10% change in the omega value and the MCHW 1 requirement of less than 10% air voids through an acceptable moisture content range; the exception to this was when the...
Material was on the dry side of the moisture contents required in the Specification (see moisture content of 5.9% and MCV of >17 in Table 1).

This emphasises the need for control of the moisture acceptability of fills prior to compaction. For cohesive fills it is clear that the less than 10% air voids criterion has not been met (Table 2) – this is particularly clear for the Heavy Clay (Class 2A) material for which the CCC approach suggests fewer than the number of passes required by the MCHW 1.

Table 1. Omega value, dry density and air voids measured on a 200mm layer Gravel-sand-clay, MCHW Class 1A (data from Snowdon, 1992).

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<th>Moisture content per cent (MCV)</th>
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Figure 7. Changes in the omega value for successive passes (per cent) with increasing number of passes for Gravel-sand-clay (MCHW Class 1A), date from Table 1.

Figure 8. Changes in dry density with increasing number of passes for Gravel-sand-clay (MCHW Class 1A), date from Table 1.
Figure 9. Changes in air voids with increasing number of passes for Gravel-sand-clay (MCHW Class 1A), date from Table 1.

Carder et al. (2009) noted that for the cohesive soils (Class 2A) the omega value decreased rapidly after the second or third roller passes, whereas for the granular soils the omega value would be increasing. This meant that, using the <10% change in omega criteria for control, an acceptable state of compaction was indicated while the measured air voids indicated that an acceptable state of compaction had, in fact, not been reached, except for clays at the higher moisture contents\(^3\).

Table 2. Compliance with the Specification for Highway Works (MCHW 1) (data from Carder et al. 2009).

<table>
<thead>
<tr>
<th>Soil type (MCHW Class)</th>
<th>Optimum moisture content (%)</th>
<th>Moisture content (%)</th>
<th>MCV</th>
<th>Compacted layer thickness (mm)</th>
<th>Number of passes specified in MCHW 1</th>
<th>Number of Passes based on &lt;10% change in omega</th>
<th>Air voids (%)</th>
</tr>
</thead>
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<tr>
<td>Well-graded Sand (Class 1A)</td>
<td>7.4</td>
<td>7.1</td>
<td>15.8</td>
<td>200</td>
<td>4</td>
<td>4</td>
<td>8.8</td>
</tr>
<tr>
<td>Gravel-sand-clay (Class 1A)</td>
<td>6.5</td>
<td>6.9</td>
<td>17.0</td>
<td>200</td>
<td>4</td>
<td>4</td>
<td>8.3</td>
</tr>
<tr>
<td>Heavy Clay (Class 2A)</td>
<td>21.0</td>
<td>25.8</td>
<td>12.2</td>
<td>200</td>
<td>4</td>
<td>3</td>
<td>12.7</td>
</tr>
<tr>
<td>Sandy Clay (Class 2A)</td>
<td>14.0</td>
<td>15.0</td>
<td>13.1</td>
<td>200</td>
<td>4</td>
<td>4</td>
<td>12.8</td>
</tr>
</tbody>
</table>

\(^3\) Snowdon’s (1992) detailed, unpublished data set is no longer available but the data for the two cohesive materials in Table 2 were both compacted wet of optimum and have not reached the maximum 10% air voids limit during compaction.
Notwithstanding this two detailed points regarding the results for the cohesive materials must be made:

- For the Heavy Clay (Class 2A) the <10% omega criterion suggests that compaction was complete after three passes of the roller – it is not clear what air voids value would have been reached if an additional pass had been applied although it seems unlikely that the air voids would have reduced from 12.7% to 10% or less.

- For the Sandy Clay (Class 2A) the <10% omega criterion suggests that compaction was complete after four passes of the roller which conforms with the requirements of the MCHW 1. At face value this seems to suggest that this unfavourable result would have occurred even using the conventional method specification.

While the foregoing points are valid it is also the case that with the rapidly decreasing omega values the <10% change in omega criteria becomes rather sensitive and it seems quite possible that a further trial of the Sandy Clay material may well have yielded a suggested number of passes of three or lower.

4.1.4 Benefits and Limitations

The review of CCC by Carder et al. (2009) includes consideration of the Bomag E\textsubscript{VIB} meter (BEM) amongst plant by other manufacturers. The benefits and limitations of CCC that they set out are summarised and interpreted here. Amongst the benefits that they documented are the following:

1. Provided that trials on each site provide a good correlation between the dynamic measuring value (e.g. E\textsubscript{VIB}) and the required properties of the compacted soils are met, there is potential for both reducing the compaction energy and, possibly, also the number of passes without detrimental effect.

2. Over-stressing caused by an excessive number of passes or excessive vibration will be minimised by the use of CCC or intelligent compaction. Granular soils that are broadly single-sized are particularly prone to over-stressing in the near-surface material. With fine-grained soil, after the minimum air voids 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. the particles of some industrial by-products may breakdown if over-stressed so weakening the compacted layer (Winter 1998); the same may be true of larger chalk particles.

3. Productivity may be increased if fewer roller passes are required to reach the target compaction state. This has an associated cost benefit particularly for larger earthworks 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 CCC or intelligent compaction 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 replaced to provide a layer of more uniform stiffness. Spot tests using conventional stiffness 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 evidence of the compaction coverage and the number of roller passes. This will have important contractual implications if subsequent earthworks 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, although it is far from clear how this relates to the mass and type of plant used independently of whether CCC is in play or not.

Correspondingly, limitations of the systems were also identified, as follows:

1. The use of CCC systems may be less effective in controlling the degree of compaction in certain soil types. Current indications are that the 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 and the potential to generate excess pore water pressures remains a relatively poorly-controlled risk.

2. Vibrating rollers with CCC are more costly to purchase (or to 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. (This is no longer considered to be such a major issue due to the availability of relatively cheap data storage systems.)
5 Continuous Compaction Control Specifications

Carder et al. (2009) also report on specifications that were extant in Germany, Austria, Sweden and the USA as well as on the recommendations provided by the International Society of Soil Mechanics and Geotechnical Engineering’s (ISSMGE) Technical Committee on Geotechnics of Pavements (TC3)\(^4\). The latter are based on the Austrian specification, although updates to the TC3 work and recommendations (Gomes Correia et al. 2012) are primarily based upon the later French specification, which details six main sub-functions of intelligent compaction plant:

- \(F1\): behaviour of the material, dealing with the dynamic response between the vibratory roller and the soil.
- \(F2\): end of compaction, indication to the operator after comparison between successive passes.
- \(F3\): positioning, traceability during process, satellite and associated methods; mapping of results.
- \(F4\): operational information, showing the operator parameters used that influence compaction.
- \(F5\): control report, documentation, allowing the presentation of the end-of-compaction characteristics.
- \(F6\): communication, etc., when the equipment is capable of transferring information.

An early German specification (Anon. 1993), reviewed by Carder et al (2009), generally supported the use of CCC for measuring the compaction performance of granular materials and for those with fines contents \(\leq 15\%\) subject to the moisture content remaining below the optimum. The use of CCC was not supported for higher moisture contents or for fine-grained materials and the use of CCC was subject to a site-based trial(s). This specification was updated in 1994 (Anon. 1994) and this seems to be a forerunner of the current 2007 specification (Anon. 2007). Carder et al. (2009) noted that a revised specification was expected to be released in 2009 although it seems likely that this is the current (Anon. 2007) specification. This was not expected by Carder et al. (2009) to radically alter the underlying philosophy of the specification but to introduce evolutionary refinements such as relations between static and dynamic deformation moduli. Anon. (2007) gives detailed procedures for testing and acceptance including statistical approaches to the determination of density or plate bearing (described as Method 1), the direct application of dynamically measured CCC outputs (Method 2), and by using a trial to determine a job-/material-specific method (Method 3).

The Austrian specification (Anon. 2000: RVS 85.02.6) required a site-specific calibration area of 100m length and the width of the road. The calibration takes the form of a comparison of dynamic and static moduli with compaction being effectively continued to refusal (i.e. until

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\(^4\) TC3 Geotechnics and Pavements is now known as TC202 Transportation Geotechnics.
the measured properties become asymptotic to a measured value). Further details are given by Adam (2007) and cover all aspects of the contemporaneous Austrian specification.

The use of CCC features in a number of Swedish standards, following on from some of the earliest work undertaken on the development of the technique. Vägverket (1994) provided a general technical specification for road earthworks. It specified that when a compaction meter was mounted on a roller, the static plate bearing capacity or degree of compaction (from standard Proctor tests) of unbound pavement layers should be monitored. Acceptance was based primarily upon the bearing capacity and the bearing capacity ratio \( (E_{v2}/E_{v1}) \); the ratio of the second to the first load cycle values which gives an indirect indication of the degree of compaction. A constant roller speed was specified (between 2.5km/h and 4.0km/h) and a minimum of four roller passes was required, more if the bearing capacity was still increasing. Additionally, conventional tests to determine acceptance of the work were required.

Carder et al. (2009) reported on a draft pilot specification produced by the Minnesota Department of Transportation. This was based upon site-specific trials and a comparison of machine-derived data with data from a lightweight deflectometer. One of the features of the specification was the control of the optimum moisture content to values between 65% and 95% of optimum. The low end of this range seems somewhat inexplicable and potentially allows very high values of air voids. However it seems that the intention was most likely to be to allow increased density (reduced moisture content) along a line of constant air voids (see Figure 5) with increased compaction effort (i.e. the comparison was with the original higher optimum moisture content and not the subsequent, as compacted, lower optimum that relates to a higher energy state).

Carder et al. (2009) also reported on (largely) trial specifications in other US states including those from Kansas, Texas, Florida, Wisconsin and Iowa as well as work by the US National Co-operative Highways Research Program and the Federal Highway Administration.

Carder et al. (2009) also considered a potential specification to fit within the UK Specification for Highway Works (MCHW 1) and associated Notes for Guidance (MCHW 2). They make the important point that for some selected fills, end product specifications are employed and any effective means of compaction (including CCC) can be used provided that the required end product criteria are met. In essence, this means that, for these categories of fills, there is no impediment to the use of CCC within the UK Specification. However, it is important to note that this does not mean that measurements from the CCC plant would be an acceptable control; control remains as detailed in the specification (usually relative density).

However, it is important to note that the efficacy of the earthworks compaction procedure would be improved in some soil conditions by using compaction-monitoring and CCC systems. To this end Carder et al. (2009) drafted clauses for possible inclusion in the Specification for Highways Works. They recommended that they should be first issued as an
Interim Advice Note (IAN)\(^5\) to allow the clauses to be further developed as new data became available. It was not intended that the new clauses replace existing clauses but that, subject to successful and appropriate site trials, that they should provide an optional approach to method compaction. To the best of the Author’s knowledge the new clauses have not been issued in either the Specification or in an IAN. The Specification clauses developed by Carder et al. (2009) are reproduced in updated form in Appendix A.

In late-2016 a European Technical Specification for CCC was published (Anon. 2016). This was intended to be available for three years after which, if its application has been successful, it will be converted into a European Standard. The Technical Specification allows for applications related to those set-out in Section 2, viz:

- CCC documentation of the compaction method (Section 10 of the Technical Specification).
- CCC weak area analysis and documentation (Section 8 of the Technical Specification).
- CCC with calibration for indirect density and stiffness control (Section 7 of the Technical Specification).

These applications are analogous to the ‘GPS and mapping’, ‘Soft spots’ and ‘Performance’ applications set out in Section 2 of this report. The Technical Specification also proposes a method for documenting that maximum compaction has been achieved (Section 9 of the Specification).

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\(^5\) IANs (TSIANs in Scotland) are used to introduce new materials, processes, techniques guidance or advice to the MCHW and/or the Design Manual for Roads & Bridges (DMRB). This can allow a phased introduction allowing the results and lessons learned from trials to influence the final form of the implementation.
6 Examples of the Use of Continuous Compaction Control

In this section a number of examples of the use of CCC are presented. These demonstrate the three primary means of using CCC effectively in the construction of earthworks, as repeated here:

a) GPS and mapping (QC): As a means of monitoring and recording the coverage of compaction plant including the number of passes applied at a given location. This approach uses the built-in GPS facilities of the plant and supports the effective application of QC procedures to the existing method specification.

b) Soft spots (QA): As a means of identifying ‘soft spots’ that require further compaction and of monitoring the relative increase in compaction as successive passes are applied. This is particularly helpful in ensuring that over-stressing does not occur resulting in low density and high air voids (Parsons 1992).

c) Performance: As a means of determining the stiffness or relative density of a compacted material subject to performance specification (Carder et al. 2009).

The examples presented in this section have been anonymised at the request of those involved in the individual construction projects. The data is variously drawn from active construction sites in Germany that the author and colleagues from Bomag visited in June 2017, and from selected sites in England.

6.1 Documentation of the Compaction Method

As described in Section 3, the UK Specification for Highway Works (MCHW 1 ad MCHW 2) generally operates a method specification for the compaction of earthworks materials. It is only for more specialised materials that end product specifications come into play. The opportunity to use CCC plant to monitor compliance with a method specification therefore represents the path of least resistance to its use in the UK. A plan of the area to be compacted can be produced showing the number of passes applied and therefore highlighting where additional compaction is required to meet the requirements of the specification (e.g. Figure 10).

This information can also be presented to the operator of the compaction plant in real time in order that the process can be adjusted in order to ensure full compliance during the actual compaction operations. Figure 11 shows a screenshot of the information provided to the operator. In this case the roller was located in an area where the third pass was being applied to the material being compacted. Areas subject to fewer and greater number of passes can also be identified in the immediate locale on the screen. The unusual trafficking patterns of the roller are reflective of the fact that the image was captured during a preliminary training exercise.

Clearly CCC can be used to document the compaction method for any soil to which the compaction plant is suited, whether operated as a vibratory roller or as a dead weight machine.
Figure 10. Example of Bomag CCC output to document the compaction method.
Key: >5 passes; 4-5 passes; <4 passes

Figure 11. Sample in-cab screenshot showing the number of roller passes applied to an area being compacted.
6.2 Identification of Soft Spots

Continuous Compaction Control can be readily employed as a means of identifying ‘soft spots’ that require further compaction, and of monitoring the relative increase in compaction as successive passes are applied. In Figure 12 the threshold for the lowest range has been set to a very low value (in this case of stiffness) in order that genuinely ‘soft’ areas are readily identified.

This approach can also be used to determine weak areas of an existing subgrade that may require treatment prior to the construction of an embankment, for example.

In general CCC can be used to identify soft spots or weak areas for any soil type, although if $E_{VIB}$ is used for other than assessing simply which areas are soft/weak then comments regarding the lack of applicability of the resulting values to some soil types prevail (see Section 6.3).

This approach can also be an aid to the prevention of over-stressing thus avoiding a reduction of the stiffness with successive passes as the compaction energy is applied to an already densely compacted soil causing dilation. Such effects can be especially prevalent on sands with low coefficients of uniformity (i.e. those that are of a single-sized nature) (Parsons 1992).

![Figure 12. Example of Bomag CCC output used to identify soft spots.](image)

**Key:**
- $E_{VIB} > 100\text{MN/m}^2$
- $2 \leq E_{VIB} \geq 100\text{MN/m}^2$
- $E_{VIB} < 2\text{MN/m}^2$
6.3 Performance Specification

The primary use of CCC is as a means of determining the stiffness or relative density of a compacted material subject to a performance specification (Carder et al. 2009) and it seems fair to state that it was this objective that first drove the development of such equipment in the late-1970s and early-1980s.

A calibration between the $E_{\text{VIB}}$ stiffness and relative density is a requirement for Method 3 of the German Specification (Anon. 2007) and an example is presented in Figure 13. The calibration is presented in two forms as neither $E_{\text{VIB}}$ nor relative density ($D_{pr}$) is considered to be a truly independent variable.

Figure 13. Example calibration between $E_{\text{VIB}}$ and relative density ($D_{pr}$). (The numbers refer to the number of the test.)

Key: $E_{\text{VIB}} = -963.45 + 10.571 \cdot D_{pr}$; $D_{pr} = 92.37 + 0.082 \cdot E_{\text{VIB}}$

This confirms the necessity of the continued application of acceptability testing in order to ensure that the material is in a suitable condition for compaction (see Section 3). This ensures that high measured stiffness is not achieved in association with relatively low density – this is of course essential at both the trial stage to determine the calibration and the implementation stage when the works compaction is undertaken. Thus the pitfalls associated with refocussing the specification from dry density/air voids to a measure of stiffness and/or strength are effectively avoided. This requirement is implicit in the current German Specification (Anon. 2007) in which limitations on the allowable moisture content are placed for Method 3 (see Section 5).
The practical implementation of CCC from a performance perspective is illustrated in Figures 14 and 15. Figure 14 illustrates a 20m length of three lanes (Lanes 1, 2 and 3) and shows that these have been subject to four, two and one pass(es) respectively.

Figure 14. Compaction in three lanes having been subject, left to right, to four (Lane 1), two (Lane 2) and one (Lane 3) pass(es) respectively. Also shown are successive mean $E_{VIB}$ values for each pass to each lane.

**Key (left):**
- $E_{VIB} > 125$ MN/m$^2$;
- $94 \leq E_{VIB} \geq 125$ MN/m$^2$;
- $E_{VIB} < 94$ MN/m$^2$
Figure 15. Stiffness in Lane 3 after one pass (Left); in Lane 2 after two passes (Centre); and in Lane 1 after four passes (Right).

Key: \( E_{\text{VIB}} \) Measured; \( E_{\text{VIB}} = 94\text{MN/m}^2 \); \( E_{\text{VIB}} = 125\text{MN/m}^2 \)
The material was a crushed rock with particle sizes in the notional range 0 to 63mm with a limit of <15% passing the 63μm sieve in line with both the German Specification (Anon. 2007) and the European Technical Specification (Anon. 2016) and was laid in a 0.40m thick layer. In this case around 7% of fines was present in the fill and the Coefficient of Uniformity, $C_u$, was 28.6, indicating a wide range of particle sizes, and the Coefficient of Curvature, $C_c$, was 5.9, reflecting the relatively small proportion of particles passing 10mm (<25%) in what is otherwise a well-graded slightly sandy Gravel.

The moisture content was specified as ‘close’ to (+1.2%/-0.85%) the optimum of 3.6%. The maximum density (standard Proctor in accordance with the German standard) was 2.088Mg/m$^3$ and it is immediately apparent from Figures 12 and 13 that the $E_{VIB}$ values achieved correspond to a minimum relative density of around 103%. It is also clear that the graphical representation of the development of increased stiffness (and thus density) in Figure 14 is very clear. Ranges for $E_{VIB} < 94$MN/m$^2$, $94 \leq E_{VIB} \leq 125$MN/m$^2$ (representing 100% $D_{pr}$ at 94MN/m$^2$) are included, as well as the ultimate requirement of $E_{VIB} > 125$MN/m$^2$, in order to make this more clear. The presentation of data in Figure 14 gives an effective summary and is particularly suited to in-cab display.

Figure 15 gives a more detailed display of the same data showing the actual $E_{VIB}$ values for each lane. Thresholds for $E_{VIB}$ values of 94 and 125MN/m$^2$ are shown in red and blue respectively and the individual $E_{VIB}$ values are plotted in yellow. All three plots in Figure 15 show higher values of $E_{VIB}$ at the start of the 20m bay; these are most likely due to earlier compaction and/or trafficking of the adjacent area.

Lane 3 which has been subject to a single pass shows a range of $E_{VIB}$ generally between around 20 and 40MN/m$^2$ (Figure 15). The table at the bottom of Figure 14 reports a mean $E_{VIB}$ value of 25MN/m$^2$ for Lane 3 having been subject to one pass.

Lane 2 (subject to two passes) shows $E_{VIB}$ values generally at or just below 125MN/m$^2$ with an average value of 120MN/m$^2$, the average for one pass was 19MN/m$^2$.

Lane 1 (subject to four passes) shows values generally ranging from around 140MN/m$^2$ to just in excess of 150MN/m2, with an average of 147MN/m$^2$; average $E_{VIB}$ values for three, two and one pass were 145, 117 and 34MN/m$^2$ this demonstrates that the fourth pass had little effect on the stiffness of the material and that from a practical point of view three passes provided adequate compaction.

### 6.4 Summary

The data clearly demonstrates that CCC can be of benefit both during the compaction process, providing clear graphical outputs in real time to assist plant operators to achieve the method specification requirements, and subsequently providing a record of the process for both the constructor and the client.

The identification of soft spots (and the associated prevention of over-compaction) provides a very useful means of quality assurance. However, for suitable soils, the application of a performance specification allows for continuous measurement of stiffness and the potential to correlate with density. While this does not remove the requirement to control the acceptability of the soil, either directly through moisture content or indirectly through the
use of the Moisture Condition Value, it does provide an alternative means of compaction control that relates more directly to the in-service performance of the earthwork.
7 Summary and Recommendations

It is clear that the use of CCC in earthworks compaction offers significant benefits. These include the relatively simple quality control, using GPS, to determine the coverage and number of passes of the compaction roller. This can assist the operator in the cab to monitor and correct progress in real-time and also to reduce the constructor’s risk of non-compliance while giving the client an auditable trail to demonstrate whether or not a method specification has been complied with or not.

At a slightly more sophisticated level CCC can be readily used for the identification of soft spots as part of a quality assurance programme, again providing confidence for all parties that a reliable earthwork product has been delivered. This can also be an aid to the prevention of over-stressing, when a reduction in stiffness will be apparent with successive passes.

The opportunity to introduce a performance specification that means that the control of earthworks construction relates more closely to the in-service performance of the earthwork should be an attractive proposition for both the constructor and the client.

None of these approaches removes the need to control the acceptability of the soil, either directly through moisture content or indirectly through the use of the Moisture Condition Value. This is necessary in order to prevent the compaction of fill in a state too dry of optimum, which may still achieve stiffness requirements but will not achieve high density and low air voids potentially leading to excessive settlement as the fill subsequently takes on water.

In this report the principles behind the UK Specification for Highway Works (MCHW 1 Class 600) have been explained and then the potential for CCC to fit within and enhance that specification have been captured and, at least in part, illustrated with examples of its use.

For some selected fills, end product specifications are used in the MCHW 1 and 2 and any effective means of compaction (including CCC) can be used provided that the required end product criteria are met. Thus for these categories of fills, there is no specification-led impediment to the use of CCC within the UK Specification. However, it is important to note that measurements from the CCC plant would not be an acceptable control and currently there is thus little encouragement to use CCC.

The existence of the EU Technical Specification (Anon. 2016) significantly reduces the number and height of the barriers to the use of CCC on trunk road projects in Scotland. While the Specification for Highway Works (MCHW 1) is used for such works the EU Technical Specification carries significant weight and it would be difficult to prevent a competent Contractor from using it as the basis for earthworks compaction, particularly at a low risk location.

However, Carder et al.’s (2009) proposed specification sought to provide a means of implementing CCC within the MCHW 1. The introduction of the EU Technical Specification (Anon. 2016) means that the most straightforward path to implementation, which ought to be to the benefit of all, would be to use the specification proposed by Carder et al. (2009) as the basis for introducing the EU Technical Specification to earthworks for road construction works in Scotland and highway construction works in the UK more widely.
Such adaptations to the MCHW are beyond the scope of the present work but it is considered that such adaptations need not form a major piece of work, provided that the adapted CCC Specification (based on that of Carder et al. 2009) forms a distinct element of the MCHW 1 and ‘calls up’ the EU Technical Specification (Anon. 2016).

It is recommended that the next step in this process should be to contact and arrange meetings with key players in Scotland’s national trunk road and motorway Overseeing Organisation, Transport Scotland. The key people will be from the Major Transport Infrastructure Projects (MTRIPS) Division and meetings will be sought at which a TRL and Bomag presence will be required in order to secure their support for the use of the EU Technical Specification (Anon. 2016) and its integration into the MCHW using the modified specification of Carder et al. (2009).

Through Transport Scotland and Bomag’s contacts with major contractors (e.g. Morrison Construction, Balfour Beatty Construction, RJT Excavations) potential trial sites for the use of CCC on the Scottish trunk road and motorway network will be sought with a view to developing a proposal for a collaborative trial(s) to demonstrate the effectiveness of CCC in controlling earthworks operations undertaken to the MCHW.
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References


- MCHW 1: Specification for Highway Works.


Appendix A  Proposed Specification

This specification is reproduced from Carder et al. (2009) with edits only to reflect changes to the MCHW since publication of that report and changes of intent. For example, the provision of GPS and mapping data is mandatory in this version but was optional in the original.

A.1  General

1. The latest Series 600 Earthworks in the Specification for Highway Works (MCHW 1) and the associated Notes for Guidance (MCHW 2) are available on the Standards for Highways website (http://www.standardsforhighways.co.uk/ha/standards/). 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 Continuous Compaction Control, CCC, and intelligent compaction systems) can then be used provided that the required criteria are met.

2. If using CCC 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, kb 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. CCC 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 CCC 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.

A.2  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 CCC or 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 MCHW 1. Either method compaction using the number of passes of the roller (with full vibration operating) specified in the MCHW 1, or CCC 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 CCC 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 density 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 density 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 MCHW 1 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.

A.3 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 values of 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.

A.4 Documentation

10. When using CCC 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.

A.5 GPS and Mapping

11. A GPS and mapping facility shall be incorporated to provide 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 1/5th of the width of roll.

   b) The visual display for the operator should indicate either by colour and/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 CCC or intelligent compaction systems and, independently, for quality control when using method compaction.

   a) When used with CCC or intelligent compaction systems, location mapping provides an invaluable record of the number of passes and dynamic measuring value (e.g. CMV, CCV, kb or $E_{vb}$) 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 CCC or 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 MCHW 1. 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.
Continuous Compaction Control for Earthworks Operations on Scottish Road Construction Projects

The UK Specification for Highways Works (MCHW 1) currently makes no specific provision for the use of Continuous Compaction Control (CCC) in the construction of earthworks for roads and highways. Such techniques can be used by the constructor but the provisions of the MCHW 1 take primacy leaving little incentive to do so. In this report the potential benefits of the use of CCC are outlined. These benefits include the provision of real time monitoring of compaction operations and of a permanent record of the process, the identification of soft spots, and the determination of the stiffness or relative density of a compacted material subject to performance specification. It is concluded that there is no major technical obstacle to the introduction of CCC to road and highway earthworks in the UK. The potential introduction of CCC is described in the context of the UK Specification for Highway Works.