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Continuous Compaction Control, CCC
Contrôle Continu de Compactage, CCC

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ABSTRACT

Continuous Compaction Control, CCC has been accepted in many countries and even been implemented in some national compaction standards. CCC is recognised as the optimum tool for the roller operator to achieve a homogeneous compaction result in a minimum of time. Located weak spots can be improved by means of directive measures. The paper deals with the background and the principle of the CCC, as well as with compaction standards and the application of CCC on “function contracts”.

RESUME

Le compactomètre et CCC sont acceptés dans le monde entier et font part des standards nationaux de beaucoup des pays. Les projets de R&D considérables ont prouvé que le CCC est la seule méthode capable d’atteindre un résultat de compactage homogène dans un minimum de temps. Ce n’a pas toujours été facile de convaincre les fournisseurs d’abandonner la méthode du compactage traditionelle et les mesures ponctuelles – on ne se refait pas facilment dans la domaine de construction. Mais maintenant l’opérateur du roleau peut participer à la réalistation et la satisfaction d’un résultat de qualité. Dans l‘éssai sont traités l’histoire de CCC aussi bien que les applicvations presentes, standards nationaux et quelques idées du developpement potentiel.

INTRODUCTION

Almost exactly 20 years ago during the Conference on Compaction in Paris, the roller integrated compaction meter for the first time was subject of an international discussion. The instrument was called the Compactometer and several papers [Forssblad, 1980] and [Thurner and Sandström, 1980] dealt with R&D-results as well as with experience from the field.

The Compactometer was the first step from traditional soil compaction to today‘s Continuous Compaction Control, CCC. Modern electronic devices assist the roller operator in his self control, aiming at an efficient compaction work and a homogeneous compaction result. The use of CCC will replace previous detailed specifications with function contracts, offering the contractor the opportunity to apply innovative and creative methods for optimum construction performance.

TRADITIONAL SOIL COMPACTION

Traditionally, soil and rock fill materials are compacted with static or vibrating rollers and since about 15 years also with oscillating rollers. Compaction of a certain area is carried out by parallel strips - edge to edge or with some overlapping - covering each strip with a fixed number of passes. Most rollers are vibrating rollers, their vibration frequency and amplitude is kept constant and the roller operator chooses the rollers speed.

It is obvious that a certain number of passes and constant roller speed (v), vibration frequency (f) and amplitude (a) hardly can achieve a homogeneous compaction result on a layer with varying material properties (M), varying water content (W) and heterogeneous stiffness of the underlying layer (U), see Figure 1. Constant number of passes and constant roller parameters will always leave a certain part of the area insufficiently compacted, another part overcompacted and the rest sufficiently compacted.

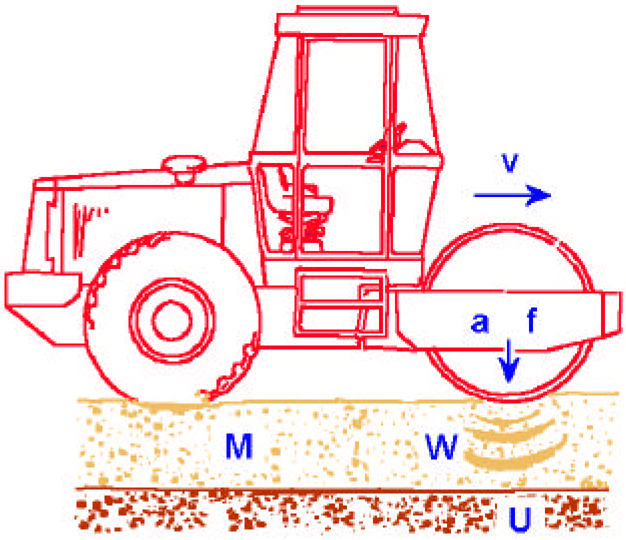


Figure 1. Constant roller parameters and varying ground conditions.

Traditionally the compaction result achieved by means of a heavy vibrating roller is checked by means of some spot test method which normally has a sample volume of about 2 litres. Such small sample volumes can never reliably represent the compaction result of the entire area, nor contribute to an improvement of the homogeneity of the compaction work. According to national compaction standards in different countries one sample is taken on 2.000 m^3 of compacted soil, which means a relation between sample volume and compacted volume of 1 : 1.000.000. Such quality control relation probably is very hard to find elsewhere.

Most spot test methods are time consuming - one has to wait hours or days until the result is presented - and will in addition delay or stop construction work, because the tests have to be carried out without any disturbing vibrations around the test spot.

Neither proof rolling nor the demand to compact until no further deformation behind the compacting drum will ever be able to meet modern requirements on a homogeneous compaction result.

COMPACTION METER

There obviously was a need for new ideas to improve compaction in terms of efficiency and quality. A Swedish R&D-project in the early seventies was intended to find out if and how the compaction result could be measured instantly and continuously. For the purpose a test roller had been equipped with triaxial accelerometers, a miniroller behind the compacting roller was intended to register vibrations passing from the large to the mini roller. Finally triaxial geophones were buried in the ground in order to measure ground vibrations. See Figure 2.

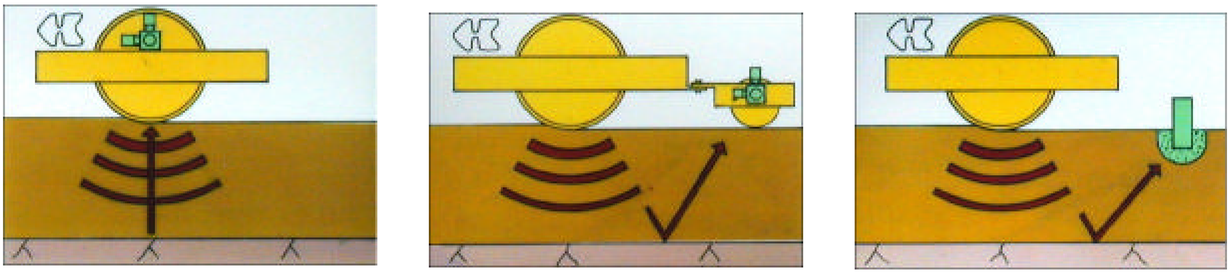


Figure 2. Test recordings of vibrations on the roller, a mini roller and geophones.

Simultaneous recordings from all sensors were analysed and it was found that the accellerometer on the roller gave significant changes in the time history of the sensor signal. The changes could be related to the increase of the stiffness in the layer, documented by spot tests after each roller pass. The evaluation of these tests led to the development of the first roller integrated compaction meter – the Compactometer - using the roller drum as the measuring tool for instant and continuous compaction control.

The drum of a vibrating roller exposes the soil to repeated blows - one per cycle of the vibration. Analogous to a dynamic plate load test the blows from the cylindrical drum can be used as a load test of the soil (Figure 3).

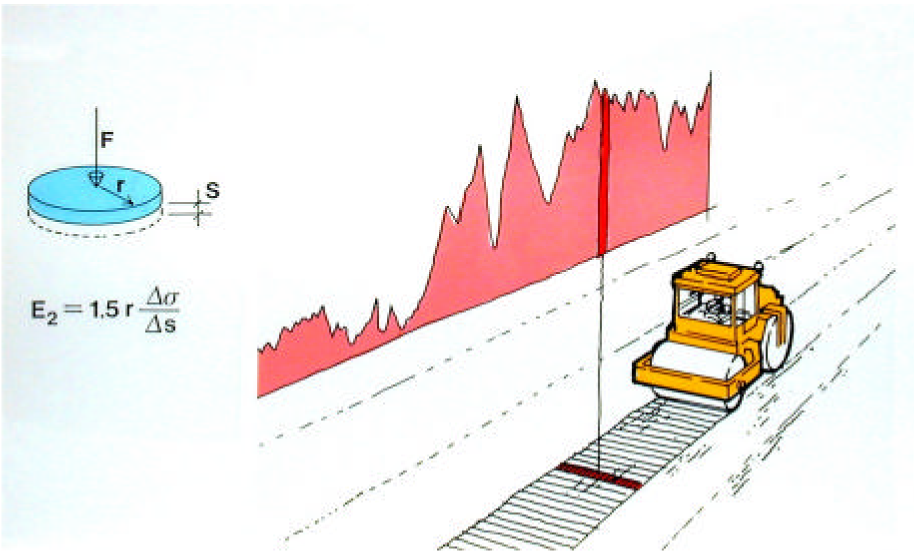


Figure 3. Compactometer – the first compaction meter for vibrating rollers.

It can be shown that the force amplitude ‘F’ of the blows is proportional to the first harmonic of the vertical acceleration. The displacement ‘s’ during the blow can be approximated by the amplitude of the double integral of the fundamental acceleration component [Sandström 1985], [Adam 1996].

Therefore it is relevant to express a “cylinder deformation module” E_c as the ratio of the force and the corresponding displacement as

$$E_c = \text{constant} * F / s = \text{constant} * \mathbf{w}^2 * A_1 / A_0$$

where

$\mathbf{w}$ = 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

This is the basis of defining the “Compaction meter Value” as

$$CMV = 300 * A_1 / A_0$$

The loading area from the cylindrical roller drum is a rectangular strip and the size of this area depends on roller parameters like line load and drum radius as well as of various soil parameters. The excitation frequency and the rolling speed is also influencing the result.

It is obvious that the actual CMV will vary from roller to roller and that the roller parameters – especially the frequency – have to be kept constant and equal to the parameters used during a calibration. However a standardised roller operated at a standardised setting could be equally well used as a means for the assessment of the stiffness of the surface as an FWD-equipment. The great advantages of using the roller as the measuring tool are that a complete coverage of the area is obtained and that the result is received immediately.

Figure 4 shows the components of the Compactometer. An accelerometer is attached to the bearing plate of the roller drum in vertical direction. The acceleration signal is analysed in the processor and the result is presented on a dial or display as the "Compaction Meter Value”, CMV.

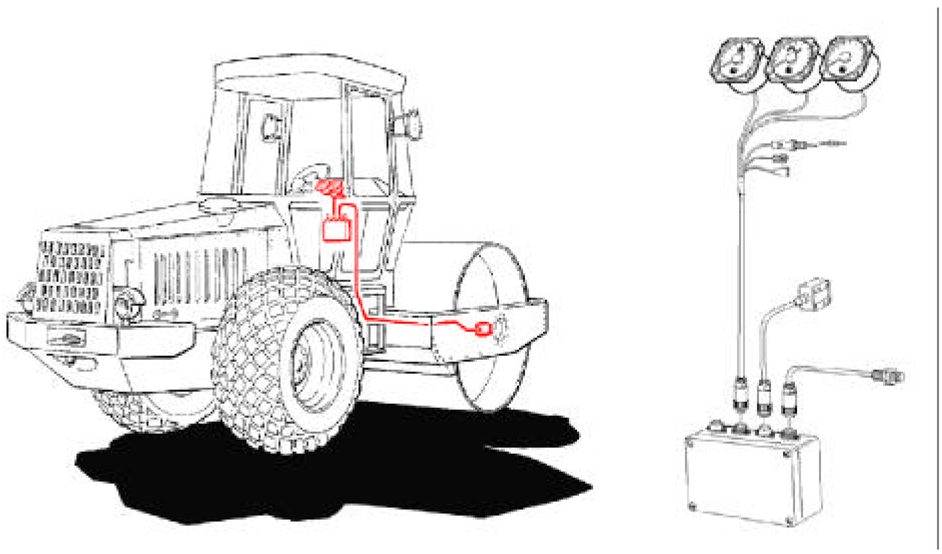


Figure 4. Compactometer components.

The Compactometer has three different dials, indicating the CMV-value, the vibration frequency f and the “Resonance meter value”, RMV. The frequency dial is intended to assist the roller operator to keep the frequency constant during the compaction process. The RMV-dial indicates if and when the roller drum starts to double jump or enters a rocking mode. Both behaviours are affecting any compaction meter value and will in addition contribute to a reloosening of the already compacted surface. The RMV-value is calculated from the acceleration signal and represents the amplitude of half the fundamental vibration frequency.

The first oscillating rollers – almost two decades ago - were designed for soil compaction [Sandström 1993]. Although the oscillating compaction principle now mostly is used for compaction of asphalt pavement, there still are oscillating rollers working on soil in different countries. The introduction of the Vario-principle has made shear force compaction very popular again [Kopf 1999].

The drum of an oscillating roller, see Figure 5, exposes the soil to repeated horizontal shear forces in addition to the vertical load applied. The corresponding compaction meter is the "Oscillometer". For the Oscillometer the accelerometer on the non turning bearing plate has to be installed horizontally in order to measure the horizontal acceleration of the drum axis. Then again, the acceleration signal is analysed in a processor and the result - the "Oscillometer Value", OMV is displayed to the roller operator.

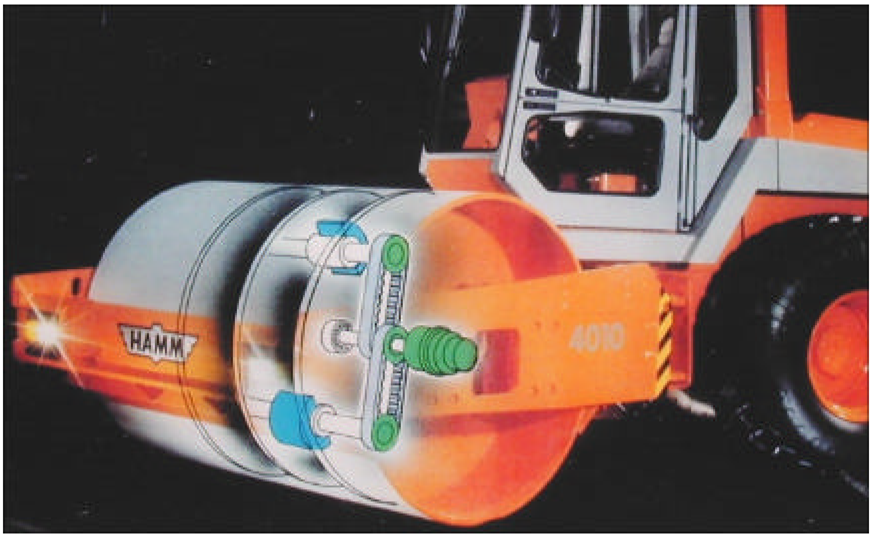


Figure 5. Oscillating roller.

The OMV-value is obtained from the amplitude of the horizontal acceleration of the drum centre. This value reflects the horizontal force transferred from the drum to the soil. The occurrence of slip between the drum and the soil is a complication that is dealt with by the built in signal analysis of the Oscillometer. [IRF Madrid].

The OMV is a value representing the horizontal stiffness of the soil surface when loaded dynamically by a cylinder. As for a vibratory roller the loading area is a rectangular strip, the size of which is a function of roller and soil parameters.

In addition to the Compactometer and the Oscillometer, there are other compaction meters available, e.g. the Terrameter or byproducts from the development of „Intelligent Compaction Machines“. Geodynamik‘s solution for the Hamm IQ also calculates a value characterising the plastic conditions of the layer.

CONTINUOUS COMPACTION CONTROL, CCC

Continuous Compaction Control, CCC, is based on the use of a compaction meter, i.e. either the Compactometer, the Oscillometer or comparable compaction meters [Thurner and Sandström 1991], [Thurner 1993]. The compaction meter value is stored in and displayed on an LCD-display. On the display the roller operator can observe the position of the roller on the compaction area, as well as indicators for roller speed and vibration/oscillation frequency. In addition to the graphic image, the compaction result is also presented as digital values for individual passes and strips. Depending on the means to display the value (see Figure 6), the operator can read the compaction meter value CMV/OMV.

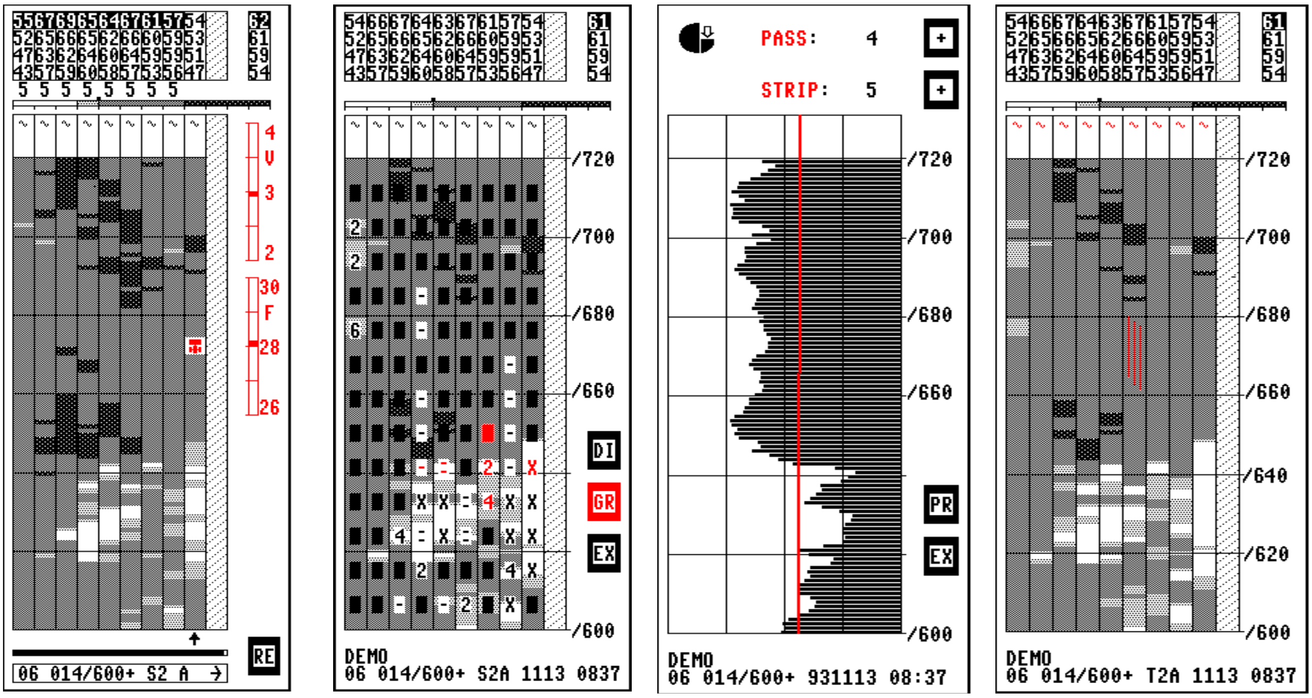
Compactometer dials Compaction Indicator display Documentation system display.

Figure 6. Different means to display the compaction result to the roller operator.

Dials show the CMV-value, the vibration frequency and the RMV-value. Observation of the CMV-dial will indicate to the roller operator what CMV-value he has achieved right under the roller drum. Comparing this CMV-value with a recommended or calibrated CMV-minimum-value, the operator is able to see where he has accomplished his compaction work and where additional passes are needed.

The “Compaction Indicator” replaces the dials with a diode matrix and a mini-display. The diode matrix indicates in a simple and easy readable way in green colour where the compaction result has been reached or exceeded and in red colour where additional passes are needed. On the mini-display the roller operator can read the CMV-value right under the roller drum, the roller speed and the vibration frequency as well as the distance travelled from the start line.

The ultimate tool for CCC is a compaction documentation system. Such a system presents all relevant and necessary information to the roller driver, assisting him in the optimum performance of his compaction job (see Figure 7.)



a) Working screen result b) Gradient c) Strip diagram d) Compaction

Figure 7. Screen information to the roller operator.

On the „working screen“ (Figure 7a) the roller operator can watch indicators for travel speed and vibration frequency as well as follow the position of the roller by means of the roller symbol. The „gradient“ display (7b) divides the graphic overview over the compacted area in cells, each of them indicating if when compaction work has been accomplished (black cell), the number of additional passes required to reach the preset CMV-limit or if the soil material in the particular cell is incompactable (“X” or “-“) or overcompacted (“=”). Strip diagrams (Figure 7c) show the CMV distribution along a selectable strip and for a selectable pass, necessary to locate cells with weak or water saturated material and helpful for the selection of consequent spot tests. The compaction result display (Figure 7d) presents the final mV-distribution to the roller operator both graphically and as average CMV-values for each strip and pass. In addition irregular travel speed, vibration frequency and double jump are documented.

It is important to keep in mind that the CCC-method uses the roller as a measuring tool. quantifying the soil conditions via the dynamic response of the roller. This implies that the result is related mainly to the stiffness of the layer as seen from the surface. To some extent also the damping conditions from plastic deformations and viscous effects are included. Consequently, the result from a CCC-recording cannot - and should not - be expected to correspond to the density or to the compaction degree of the layer - especially in fine grained materials at optimum or above optimum water content, when the relation between density and stiffness is rather weak or even non-existent.

Another important factor when interpreting CCC-results is the depth range of the measurement.

The depth range of the compaction effect is governed by the level of stress and acceleration generated by the roller. These levels must exceed certain threshold values in order to cause a rearrangement of the grains. The compaction depth therefore is influenced by the size of the roller, the force level that it can generate and the vibration frequency.

The depth range of the CCC-method, on the other hand, is not limited by a stress or acceleration threshold but extends to relatively great depth. The value is an integral to a large depth with the highest weighting of the layers closest to the surface.

Generally the CMV-value represents the soil condition to a greater depth than the compaction depth.

NATIONAL CCC STANDARDS

Since the first CCC-protocols obtained in the early eighties in Germany, CCC has been implemented in national standards of Austria (RVS 8S.02.6), Germany (ZTVE StB94) and Sweden (VÄG 94). Also countries like France, Ireland and the Netherlands are planning for an introduction of national CCC standards. So far, details of the national standards differ somewhat, especially concerning calibration routines, but one can expect that the European Market sooner or later will lead to a rather uniform structure of these standards.

The efficient use of the CCC method presupposes a certain level of education and skill of the contractor with regard to the use of the equipment, the handling of the generated documentation and organized utilisation of the accumulated experience. The CCC method should be incorporated in the contractor's system of quality assurance / quality control and may in the future be included in a certification system for contractors.

SELF CONTROL

CCC must not be seen just as a means to document the compaction result. The main purpose of CCC is to guide the performance of the compaction process in order to achieve a homogeneous compaction result in a minimum of time. Homogeneity means a minimum of under- and overcompacted spots and consequently a minimum of maintenance and repair costs – not to forget the costs for traffic stop, congestion and environmental pollution connected with repair jobs on roads under traffic.

„Active design" – i.e. adjustment of the construction work to unexpected site conditions – and self control in the compaction process can be improved considerably with CCC. The roller operator instantly sees where additional passes are required, where compaction is accomplished and where further passes with his roller will not leed to any improvement, but should be avoided in order to prevent reloosening of the compacted layer or even crushing of brittle aggregates. Thus the operator can concentrate on a useful compaction work, saving time, fuel, emissions and costs.

On the CCC-protocol, i.e. the printout of compaction data stored in a documentation system, the contractor can locate incompactable weak spots and direct complementary measures (using a different roller, stabilising the material, exchanging the material etc.) in order to improve the weak spots and to generate homogeneous conditions over the entire compacted area.

One must not forget that the roller is the last machine used on the site, before the asphalt or concrete pavement is put in place. Homogeneous ground conditions are essential to avoid settlement differences under any construction on top of the compacted layer of unbound material. If the contractors is forced to or interested in a good quality result, he certainly will do his best to achieve and to document a homogeneous ground before he leaves the site.

FUNCTIONAL CONTRACTS

Homogeneous compaction results are particularly important when applying "Function Contracts" [Jönsson 1998] on a construction project. Unlike normal contracts, the function contract includes a project planning and maintenance section, resulting in a more co-ordinated construction process which reduces the need for construction administration and thereby lowers the costs. Since the project planning section is part of the commission, construction work can start sooner, which reduces the total construction time considerably.

After the construction period, the contract includes a maintenance period when the contractor is responsible for the road structure and any defects that may occur. In Sweden, where function contracts totalling about USD 360 million have been negotiated, the maintenance period has varied between 3 and 10 years depending on the type of commission.

For obvious reasons, CCC will contribute considerably to reduce Life Cycle Costs, LCC for function contracts. Using CCC from the natural ground surface, throughout the embankment and the unbound road base, the entire compaction process can be optimised in terms of time and costs. In addition, a homogeneous compaction result is the best guarantee for a minimum of maintenance and repair.

It is a well known fact that maintenance and repair work on roads under traffic generate extensive costs through traffic losses, traffic accidents and environmental pollution.

CCC has the potential of generating a homogeneous unbound soil layer of a documented quality and the natural next step is to use a system for Continuous Asphalt Compaction (CAC) for self control and documentation of the subsequent pavement layers [Utterodt 1999].

CONCLUSIONS

Modern requirements of efficient compaction work and homogeneous compaction result cannot be met by constant numbers of passes, constant roller parameters and spot test methods. Today‘s contractors need Continuous Compaction Control, CCC to meet the increasing demands on efficiency and homogeneity, especially in connection with function contracts. CCC as the basis for active design, self control for useful compaction work and directive improvement of incompactable spots doubtless offer a considerable potential to reduce Life Cicle Costs, LCC for future contraction jobs.

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