

Quality Assurance and Self Control in Road Construction Advanced Measurement Technology

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Maintenance and repair costs are increasingly influencing the life cycle costs of road constructions and in addition slowing down the economic growth. Higher quality – i.e. homogeneity and stability of the road – can be reached by means of an improved self-control. Necessary aids are roller integrated compaction meters, documentation systems and accurate positioning systems, assisting the machine operators in both soil and asphalt compaction.

Quality assurance

The total cost of a construction consists of costs for planning, construction, maintenance, repair, reconstruction and a certain rest value. Especially on roads and other infrastructure objects, maintenance and repair works delay traffic flow and transports, causing increasing losses and slowing down the economic growth. This trend can only be broken by longer lifetime of the construction. Longer lifetime means improved homogeneity and durability of the construction. Both can be achieved by continuous self-control during construction.

The average lifetime of a road is about 12 years. At the same time the contractor's warranty period in Europe is 4 to 5 years. It is apparent that the warranty period within a not to distant future will be prolonged. If the contractor wants to offer a longer life time of his construction, he has to implement a reliable quality assurance system from the very start of the construction work, a system that covers each m^2 and assists the machine operators to optimise their work, avoiding unnecessary compaction passes. In addition, a system for continuous quality assurance will provide both contractor and customer with instant job documentation at the site. It is obvious, that such systems require not only highly sophisticated measurement and data acquisition technology, but also detailed knowledge of the compaction process carried out on non-linear soil and viscoelastic hot mix material.

Self control

Increasing quantities in earth moving and asphalt paving demand reconsideration of conventional self control concepts. Traditional spot test methods interrupt or stop the construction work, result presentation may take hours or even days – spot test methods do not any longer meet the requirements of large construction sites. The present ratio between compacted volumes and checked volumes is another matter of concern: a few litres of soil sample or one asphalt core is used to check thousands of m^3 , giving a ratio of about 1 : 1.000.000 which would be totally unacceptable in any other technical field.

Improved self control also is needed for the new tender and contract models, i.e. "Public-Private-Partnership, PPP", "Build-Own-Operate-Transfer, BOOT" and functional contracts. For these models it is in the interest of the contractor to achieve homogeneity and durability of the construction in the most efficient and reliable way. This is possible only if compaction of both unbound and asphalt materials is controlled and optimised by means of continuous

construction methods. Instant on site documentation of the result of continuous methods is expected to be approved by the owner as official result documentation, which will contribute to a more efficient construction work and a considerable reduction of test costs.

According to some specialists, continuous control methods are based on relative methods only, while traditional spot test methods result in "absolute" values. The critics seem to forget, that results from traditional methods only can be defined as "absolute" if they strictly correspond to their specifications in terms of instrumentation, performance and evaluation. It is well known, that results from different spot test methods cannot be compared with each other without calibration under comparable conditions.

In the following an attempt is made to describe and to compare examples of measurement technologies for different methods - conventional spot tests, continuous methods and future, "intelligent" self-adjusting machines.

Conventional measurement techniques in road construction

Most conventional test methods in road construction are spot test methods, used systematically or statistically. In soil compaction there is static plate load testing, water balloon and sand replacement volumeters, as well as radiometric sonds and falling weight deflectometers. In asphalt compaction mainly drilled cores, radiometric sonds and PQI-equipments are used.

All these methods are standardised and their results may be expressed in absolute terms and compared with each other, as long as their performance meets the standard. It should be noticed, that the depth range of the individual methods is different both in soil and in asphalt compaction. The depth range of an E_{v2} -value of the static plate load test is assumed to be approximately 1.5 x plate diameter, but results obtained with 30 cm and 60 cm diameter may not be directly compared with each other. The E_{v2} always is an average value, dependant of heterogeneous conditions, i.e. concentration of fine or coarse material under the plate or of weaker layers underneath the top layer. Consequently E_{v2} -values of measurements at short distances may differ significantly.

Density values from measurements with replacement methods (water balloon, sand, Bentonite) are valid only for the volume taken and consequently operator dependant, i.e. the density value will differ if the measurement has been carried out at the top of a layer (low value due to re loosened zone under a vibratory roller), in the middle (often highest value) or at the bottom of a layer (lower value).

Radiometric sonds used to check soil and asphalt compaction, have different depth range depending on equipment and source, where deeper zones have a decreasing influence on the average value obtained. In addition water content or bitumen content as well as chemical differences will affect the average density value.

Measurement technology in continuous soil compaction

Methods according to "Continuous Compaction Control, CCC" are part of national specification in Austria [9], Germany [10] and Sweden [11] and have been so for years. These methods are based on roller integrated compaction meters that continuously measure the acceleration of the roller drum and calculate a compaction meter value from the acceleration signal [2], [7].

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. Corresponding compaction meter values represent the condition of the compacted area (Figure 1). This condition is presented to the roller operator instantly and continuously, enabling him to evaluate where compaction work is finished, where additional passes are required and what sections cannot be sufficiently compacted with the present roller.

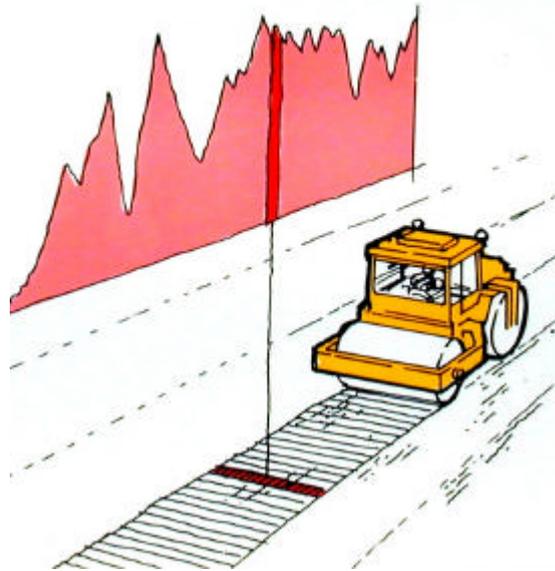


Figure 1. Compactometer value in "Continuous Compaction Control, CCC"

So far, the compaction meter values CMV (Compactometer), Omega (Terrameter) and OMV (Oscillometer) are dimensionless, relative values requiring constant roller parameters (drum diameter, linear load, frequency, amplitude, speed etc.). On request the values can be calibrated against static or dynamic plate load tests [1], [2], [4].

It is not necessary to calibrate CCC for compaction self control. The general overview over the entire compacted area - even when based on dimensionless values only - supplies the roller operator with sufficient information to carry out useful compaction, avoiding over and under compaction.

When the roller operator has decided that the compaction work has been accomplished, he can print out a CCC-protocol at the site. The protocol is his quality assurance documentation which also can be used to locate spot tests for calibration.

Under special conditions - for example when compacting fine-grained material - it might be difficult or impossible for the roller operator to decide if low CMV-values are caused by insufficient compaction or by high pore water pressure. In such cases a specialist in soil mechanics should be consulted for a site investigation in order to evaluate the local conditions and to recommend proper measures to improve the compacted layer by means of stabilisation of the ground or, if necessary, by material exchange.

Test roller - standard roller - cylinder modulus

Calibration of each roller or compaction meter on a site is time consuming and costly. Therefore test rollers have been used in different countries. In Austria such test rollers have been specially calibrated on different soil materials, in Germany the calibration was made for specific conditions on certain construction sites. On sites with test rollers, the contractor first carries out compaction with rollers he has available and afterwards the compaction result is checked and documented with a test roller.

When the contractors continuous self-control is accepted as test method by the owner, it will be advantageous to use rollers or measurement techniques which are standardised comparable the present standardisation of conventional methods.

To standardise a roller and the CCC-method - comparable to a standardised plate load test - the following items have to be considered:

- The roller drum is a cylinder with length, radius, linear load etc., which vary from roller to roller.
- Static load and suspension varies between rollers.
- Loading and unloading varies between rollers, i.e. drums compact with different frequencies and amplitudes.
- Roller speed, vibration frequency and vibration amplitude can be changed during compaction, either stepwise or continuously.

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 [1], [2]. 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.

When a cylinder is loading a flat soil surface a failure zone will always be created. The width of the contact zone will be approximately proportional to the square root of the vertical depth of the indentation $B \approx \sqrt{2rp}$ (see Figure 2). [5].

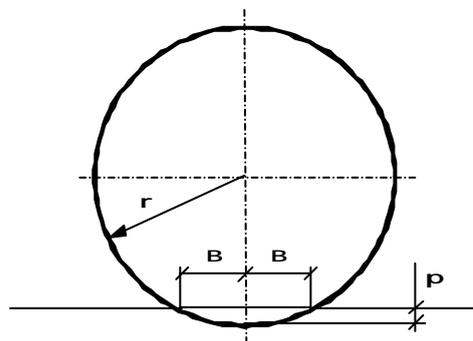


Figure 2 . Cylinder on cohesionless soil.

In analogy with bearing capacity calculations for a rectangular strip foundation on cohesionless soil the failure load is assumed to be proportional to B^2 .

The end result is that there is a linear relationship between force and displacement for the plastic part of the vertical displacement. This has been confirmed by laboratory experiments [3].

The elastic displacement of the soil from the loading by the cylinder depends on the thicknesses and moduli of the layers below the contact zone. An example of a computer simulation of the behaviour of a typical vibratory drum on cohesionless soil is shown in Figure 3. [5]. The plastic effect is characterized by the depth of the indentation of the soil surface (p) generated by the static load alone.

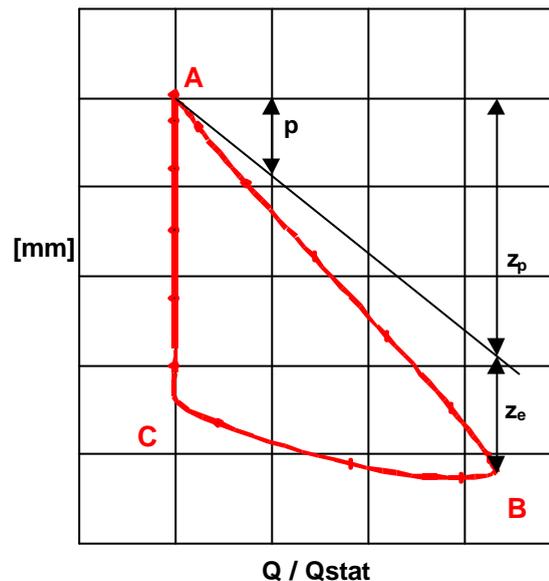


Figure 3. Vertical load and displacement under a cylinder on cohesionless soil.

The diagram shows the relation between vertical load and displacement during one cycle of the vibration. The time is marked along the curve each 1/16 of the cycle.

The loading phase A-B comprises both plastic and elastic deformation. At the maximum load the plastic part is z_p and the elastic part is z_e . During the reload phase B-C only part of the elastic energy is returned to the drum, the rest being lost as radiation and viscous losses. None of the plastic deformation is recovered. Some of it generates compaction, but a large part is consumed as useless re loosening of the soil in the failure zone.

This example clearly demonstrates the difficulty in assessing the soil stiffness by simply using the loading phase A-B. A separation of plastic and elastic part of the displacements can and should be done. This gives an elastic modulus E (or G) and the additional parameter p that characterizes the soil regarding plastic properties. The elastic modulus can be expressed as a "cylinder deformation modulus, E_c ".

E_c can be given the dimension MPa and can be compared - with for practical applications sufficient accuracy – to standardized E_{v1} , E_{v2} or E_{vd} . But only if the following conditions are valid:

1. Parameters of the standard roller may not be changed.
2. Calculation methods have to include plastic deformations.
3. The depth range of the roller has to be taken into account.

Ad1: If one of the roller parameters is changed, E_c will no longer meet the defined standard. This is especially valid for self-adjusting rollers, so called “Intelligent compaction machines, ICM”, because these rollers adjust their speed, frequency and amplitude automatically to the ground conditions under the roller drums.

There are theoretical connections, allowing calculation of E_c in absolute dimensions under different presumptions. The instrument manufacturer has to prove that a value, presented on the screen on the roller or documented in a CCC-protocol in fact is parameter independent. Although this parameter independence can be certified theoretically, it should be documented by measurements on and under the roller as well as after an accomplished compaction.

Ad 2: In soil compaction first of all plastic deformations are required and it is well known, that underneath a vibrating drum there always is, also during the last pass, a distinct plastically deformed zone. This fact has to be considered in the calculation of E_c . Consequently calculation methods based on ideal elastic assumptions cannot be used [5].

Ad 3: Obviously the depth range of the roller has to be taken into account also when using E_c on heterogeneous or multi-layered material. In advance unknown anomalies in the underground will always lead to a certain scattering of the results of measurements and of compaction. These scatterings are, comparable to the conditions in conventional methods, caused by influences from the underground, the instrument, the evaluation method and, last but not least, by the human factor. The undisputable advantage of all continuous methods lies in the instant access to measurement results as well as in its overview, which cannot be gained by any systematic or statistic spot test method.

Measurement technology in continuous methods for asphalt paving

Homogeneity and durability, as well as efficiency in asphalt paving demand continuous methods for optimum self-control of the paving and the compaction process. But in asphalt paving the conditions for measurement techniques are more complex than in soil compaction.

In soil compaction, in principle, insufficiently compacted areas can be recompacted at any time, while hot mix is very much temperature dependant. In addition, asphalt paving is carried out not in rectangular areas but continuously, requesting a mobile positioning system. Consequently, both temperature measurement and exact positioning of the paver and all rollers are essential parts of the “Continuous Asphalt Compaction, CAC” (Figure 4).



Figure 4. Continuous Asphalt Compaction on BAB A20.

CAC is a method for continuous control of the compaction work for hot mix with the goal to achieve homogeneous compaction work. The result of the compaction work can be documented by printouts showing both a graphic overview and statistic values [6], [8].

CAC is based on an electronic system (“Asphalt Compaction Documentation System, ACD”), offering the operators of a paving crew (one paver and up to 6 rollers) to work within a preset temperature band and to carry out “useful” compaction work, avoiding over-compaction and under-compaction. All members of the paving crew can simultaneously, updated each second, read the following information:

- Hot mix temperature behind the screed of the paver and in front of each roller.
- Graphic presentation of the compaction work achieved by paver and all the rollers together.
- Position of paver and rollers by means of a positioning system with the accuracy of a few cm.

The value of the ACD-system, the “Asphalt Compaction Value, ACV”, is – analogous to the CMV in soil compaction – a dimensionless relative value. For the calculation of the ACV-value the compacted area is divided in cells with the size of about 1 m² and for each cell an ACV is calculated from:

- The degree of precompaction behind the sceed of the paver.
- The accumulated value from all previous drum passes in that cell.
- The ACV-increment of the last drum pass.

In the calculation of the incremental value the hot mix temperature, the number of drum passes as well as all relevant machine parameters are implemented.

CAC is aiming at control and documentation of the compaction work only and does not result in any “absolute” modulus of stiffness. “Control” stands for the assistance to the operator to carry out useful compaction work, avoiding under and over compaction, and “documentation” includes both CAC-protocols and data storage for later evaluation.

Documentation of compaction work has to cover the entire compaction process of each cell, starting with the condition behind the paver’s screed and ending with the last roller pass. Documentation of the accomplished compaction work is the contractors result report. But it is at least equally essential to document each single roller pass. First of all, the accumulated compaction work has to be shown on the system screen in order to assist the operator to avoid compaction at wrong temperature or compaction with too high amplitude and to carry out useful compaction work. Storing all relevant data for later evaluation offers the opportunity to study consequences of improper compaction work and to improve the compaction process.

Last but not least, CAC-systems have to be designed for all types of rollers, including static rollers.

Deformation modulus – modulus of stiffness – integral modulus

To measure some kind of modulus from the roller is complex. Not only because of the viscoelastic and temperature depending conditions in the compacted layer and the elastoplastic conditions underneath the compacted layer, but also because of the considerable differences in deformation modulus E_v and modulus of stiffness E_s in the compacted layer and in deeper layers.

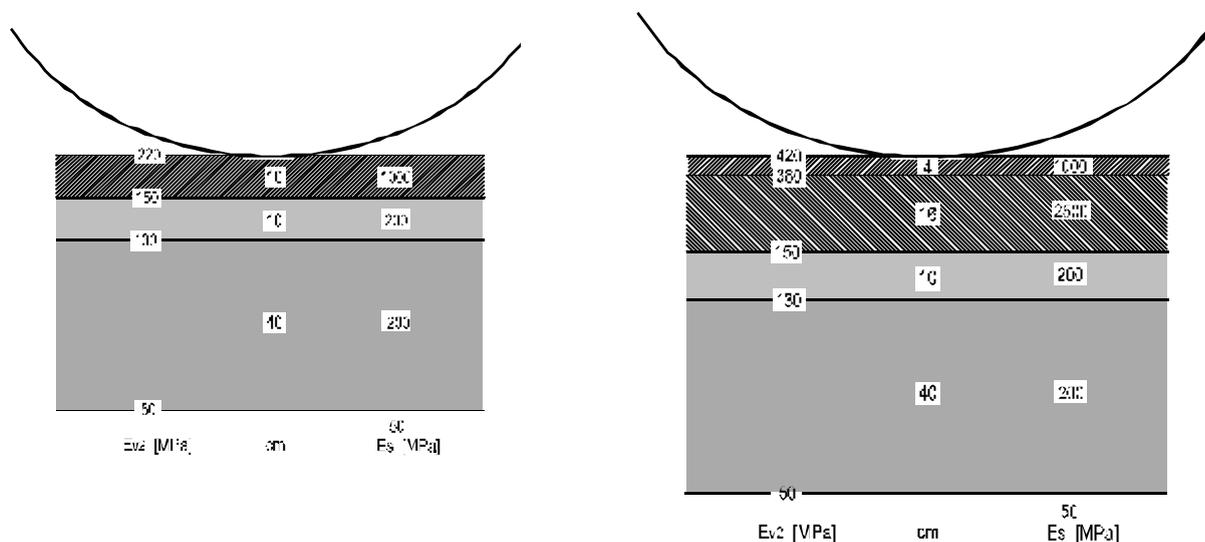


Figure 5. Deformation moduli and moduli of stiffness in and under a compacted hot mix layer.

Figure 5a illustrates compaction of a 10 cm asphalt layer on top of an unbound road embankment, consisting of 10 cm road base and 40 cm sub base. The sketch is intended to visualise the situation at the end of the compaction of the asphalt layer. E_{v2} values are indicated on the left hand side and E_s values to the right. Comparing the layer thicknesses with the drum dimension at similar scale, one can estimate the depth range of the drum.

In this case, the stiffness of the asphalt layer is the most important parameter. Looking at one single cell, during the first pass of the first drum all compaction energy will be needed to compact the hot, weak asphalt layer and not much or no compaction energy at all will

reach down to the unbound road base. With increasing numbers of drum passes the stiffness of the asphalt layer will increase and at the same time the influence of deeper layer will increase. At the end of the compaction, in principle, the asphalt layer can be assumed being a rather thin membrane and most of the compaction energy will be transferred to deeper and weaker layers.

Figure 5b illustrates the compaction of a 4 cm top layer on the surface of a 16 cm old asphalt layer, again laying on 10 + 40 cm of unbound material. In this case the old, stiff asphalt layer will influence compaction work from the beginning. Due to the considerable differences in the moduli of stiffness, also in this case the unbound layers sooner or later will influence compaction of the thin top layer.

This example is intended to demonstrate the problems involved in the measurement technique on asphalt:

1. A modulus of stiffness, measured from the roller drum is an integral value, which strongly depends on plastic deformation and will be influenced by deeper layers.
2. Already after the first drum pass the part of the asphalt layer in the integral value will decrease.
3. The stiffness of the viscoelastic asphalt layer very much depends on the hot mix temperature.
4. Both the asphalt layer and deeper layers are heterogeneous, i.e. their stiffness varies.

One should also bear in mind that compaction of an asphalt layer under normal conditions is accomplished after about 10 roller passes. During this period the hot mix temperature decreases about 100°C and the modulus of stiffness increases from about 20 MPa to about 2.000 MPa. Therefore, the demand on measurement technology, data acquisition and data evaluation has to be high in order to control and to document compaction of an asphalt layer in a way that is understandable and useful for the practical engineer for his daily work in the field.

At present, measurement technology, i.e. roller integrated sensors and algorithms involving plastic deformations, non-linear and multi layer conditions, are not capable to fulfil this demand satisfactorily. Consequently, CAC-systems so far do not integrate stiffness or similar physical parameters in the ACV-value and instruction how to control useful compaction work is based mainly on the hot mix temperature in front of the roller.

“Intelligent” compaction machines

The first prototype of an “Intelligent Compaction Machine, ICM” already was on display at the BAUMA 1992. In the meantime additional prototypes have been built and tested, some with excellent results. But obviously there still is no market for such advanced equipment. One may expect as logic consequence of CCC and CAC, that different types of self adjusting machines will be in production in a not to distant future. Measurement technology will need some improvement and will have to be converted in systems suitable for the engineer in the field. Probably also new laboratory and in-situ test methods have to be developed, better suited to represent both the compaction process and the performance conditions in and under an asphalt layer.

If methods are used that do not fulfil the requirements of CCC and CAC, their compaction result should be questioned. Compaction measurement should be seen in close relation to quality assurance and advanced measurement technology should be the fundament for all machine control.

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