1. **Introduction**

For embankment, highway, railway and airfield construction traditionally rockfill, soil and bituminous materials are compacted with static or vibratory rollers. Compaction of a certain area is carried out by a rolling pattern following parallel stages and covering each strip with a fixed number of passes. Most rollers are vibratory rollers which offer a choice of different amplitudes and frequencies. According to the type of material to be compacted and the lift thickness the operator chooses an amplitude, a frequency and a certain roller speed. All the parameters are than kept constant. Practical experience show that a constant number of passes, constant vibratory amplitude, frequency and roller speed not necessarily lead to a homogeneous compaction result on a layer due to variation in material properties and stiffness of the underlying layer, in case of soil compaction the variation of moisture content and in case of asphalt compaction the difficulty in maintaining uniform mix temperature.

Often the compacted area leaves a certain part insufficiently compacted and another part over-compacted.

Common quality control and quality assurance procedure rely mainly on end result spot tests such as core testing, nuclear gauge testing replacement methods, falling weight deflectometers plate load testing or dynamic core penetration testing typically access much less than 1% of the constructed volume and therefore deteriorate the problem of improper compaction which may result in differential settlement and deformation of embankments and pavements and then cause a lot of repair and maintenance costs.
In recent years BOMAG has introduced intelligent rollers such as VARIOCONTROL single drum rollers for soil and rockfill applications and Asphalt Manager tandem rollers for asphalt applications. These rollers allow a new compaction process which aims at meeting the public and political requirements for fast, better and more cost effective infrastructure facilities. Intelligent compaction consists of continuous compaction control using rollers with adjustable compaction energy in order to achieve optimum and uniform compaction, continuous compaction measurement and monitoring of the roller generated material modulus as the roller proceeds over the layer and an integrated global positioning system to provide a complete recording of the job site.

2. Intelligent VARIOCONTROL and Asphalt Manager rollers

The VARIOCONTROL and the Asphalt Manager roller are equipped with a directed vibrator exciter system which consists of counter rotating eccentric masses. The system is generating directed vibrations which can be varied automatically from vertical to horizontal and therefore continuously can modify the compaction energy with the control system based on the material stiffness.
The principle of the intelligent roller is based on the analysis of the interaction between vibrating drum and the stiffness of the material being compacted.

Two accelerometers, which are mounted on the vibrating mass of the roller drum, continuously record the drum acceleration.

The soil contact force, the energy delivered to the compacted material and the displacements are calculated in a process unit taking into consideration the roller parameters such as masses, amplitude, frequency and centrifugal force (Fig.4). By plotting the force settlement curve of the roller drum for one drum oscillation the slope of the curve on the loading portion can be calculated as the dynamic stiffness of the soil or the asphalt (Fig 3).

Further calculations allow the determination of the dynamic modulus of the material being compacted. All data are transmitted to an integrated control system which manages the intelligent rollers automatically according to two criterions:

1. If the roller drum is entering an undesirable bouncing mode the compaction amplitude is immediately reduced.
2. If the specified maximum force / modulus is reached, the amplitude is changed, so that the applied modulus / force does not exceed the maximum modulus / force.

The defined control criteria allow an optimised compaction process and consequently, a higher uniform compaction.

During the compaction the dynamic modulus of the material being compacted is continuously measured, recorded and displayed. The theory of the roller measured modulus which is called vibration modulus $E_{VIB}$ (MN/m²) is based on the ideas of the plate bearing test according to German Standard DIN 18134. With the plate test a circular load plate is gradually loaded and unloaded and the deformation modulus $E$ (MN/m²) itself is gained from the force displacement cycles. The soil is considered as linear, elastic and isotopic.

The vibration modulus $E_{VIB}$ is numerically evaluated on the basis of the slope of the force-displacement – characteristic curve (indicator diagram, Fig. 3) during the compression (loading) phase of the curve. The compression curve will be flat when the stiffness of the soil is low. The slope of the curve will increase as the material stiffens.
Fig. 4 Principle of compaction quality measure $E_{VIB}$ (MN/m$^2$)

Fig. 4 provides an illustration of several load curves representing roller passes 1, 3 and 6 on granular soil. The slope of the loading position of the curve increases as the material stiffens as a result of the increased compactive effort being applied to the soil. The calculated $E_{VIB}$ value also increases, accordingly.

The measured vibration modulus has been found to correlate well with compaction-related properties like bearing capacity and density for granular materials, mixed soils and under certain conditions hot mix materials.

Because of the major impact the intelligent rollers have on compaction quality and the benefits of intelligent compaction to the contractors and clients (maximum productivity of the compaction process, improved density of embankment and pavement materials, measurement and documentation of materials stiffness values and identification of non-compactable areas) VARIOCONTROL and Asphalt Manager rollers have gained high reputation in many European and Asian countries.
Because of the benefits of improving infrastructure performance, quality control and quality assurance, several European countries (Germany, Austria, Switzerland, Sweden, Finland) have introduced continuous compaction control (CCC) specifications. In Germany, where CCC specs already were developed in the early 90th, earthworks and pavement contracts of many airfield-, high speed rail -and highway projects are based on CCC specs.

3. BCM 05 compaction data management and documentation system

For large scale contracts and where continuous compaction control is required or specified, the BOMAG BCM 05 system is used as a supplement to the roller integrated compaction measurement system. The system is designed to accurately record and store continuous compaction data ($E_{\text{VIB}}$, type of roller, frequency, amplitude, operating speed) and the corresponding roller location. The BCM 05 system offers convenient measurement data management and extensive documentation and evaluation possibilities.

BCM 05 includes a robust, shock and vibration resistant tablet-PC with touch screen, a data based compaction management software package BCM 05 mobile and BCM 05 office and USB memory stick to transfer compaction data from BCM 05 – tablet-PC to the office PC’s of project personnel.

The data recording process can be carried out with two different modes: with the “manual” mode the assignment of compaction data to the roller location is done by manual selection of a strip from a displayed rolling pattern and by the distance measuring signals of the roller sensor. With the “automatic” mode the assignment of compaction data to the roller location is done by means of an automatic position detection system such as DGPS with an accuracy of two to five cm.

The BCM 05 offers the ability to provide compaction data in a variety of ways to the roller operator and project personnel. The operator receives clear information during the compaction process showing

- Changes to the results
- Non-compactable or poorly compacted areas
- Results compared to specified range
- Differences in uniformity with tests at specified intervals

Furthermore the compaction data can be transferred to a stationary PC/ Laptop by means of USB memory sticks for analysis and evaluation by project personnel using BCM 05 office software.
The outputs can be displayed in various graphical formats.

![Various compaction measuring protocol formats](image)

**Fig. 8** Various compaction measuring protocol formats

The BCM 05 system allows the connection with a differential global positioning system (DGPS) to monitor roller location in real time. The tracking of the roller is achieved with a mobile GPS receiver on the roller and a stationary reference receiver or a GPS reference service. Depending on the chosen GPS system the roller location can be measured to an accuracy of two to ten cm. The US GPS guarantees high compaction quality, clear continuous compaction documentation and backs up the compaction data without the risk of faulty operation and manipulation.

![Total compaction quality control by IC and GPS equipment](image)

**Fig. 9** Total compaction quality control by IC and GPS equipment

4. **VARIOCONTROL and Asphalt Manager applications**

VARIOCONTROL and Asphalt Manager rollers are used routinely in a number of European and Asian countries in highway, railway, airport and embankment constructions.

For the construction of a North German embankment area BOMAG BW 213 DH-4 VARIOCONTROL rollers with BCM 05 documentation system was used for the compaction of the silty sand. According to German earthworks specifications ZTVE-StB 97 a deformation modulus (EV2 / plate test) of at least 45 MN/m² was required. Calibration measurements which
were performed on test field with the job site area specified a minimum $E_{VIB}$ value of 45 MN/m² as well. Figure 10 shows the North German embankment area and the plan view documentation (strip by strip) with Evib data. 6% of the recorded 3000 m² area indicate Evib values (red colour) lower than the target value (45 MN/m²).

**Fig. 10** IC compaction on foundation area and compaction data documentation with BCM 05

There is an increasing number of intelligent soil compactors in Europe using GPS to measure the roller location in order to provide accurate compaction quality documentations and to support the operator. The use of real time position of the roller along the job site allows the operator to keep control over the quality of his work by perfectly following his compaction plan. The VARIOCONTROL concept including a differential GPS positioning system and the data management and documentation system BCM05 assist the operator and the project personnel by providing a real time map of the work achieved.

Figure 11 and 12 show an intelligent VARIOCONTROL soil compactor, BOMAG BW 213DH-4 BVC and compaction quality and positioning data on a current project in Eastern Germany. The roller is equipped with BCM05 and DGPS. The local highway agency has specified intelligent compaction using GPS in order to improve quality and uniformity of compaction. The actual work is recorded in terms of Evib, number of passes at every point and on each layer of the project. At the end a global quality control plan will be performed.

**Fig. 11** VARIOCONTROL roller with GPS equipment and BCM 05 documentation and data management system on Eastern German job site
Since asphalt stiffness is temperature related, the surface temperature is sensed by an infrared measuring unit underneath the cab of the Asphalt Manager roller and displayed on an analogue gauge. Site experience shows that temperature sensitivity of the $E_{\text{VIB}}$ value is between 100 and 150°C and is therefore within reasonable limits. The effect of increasing compaction is very distinct and provides an assessment of the compaction progress. Given a uniformly stable base beneath the asphalt layer and taking the asphalt temperature into account, compaction measurements using an isotope probe show a direct correlation between the $E_{\text{VIB}}$ vibration modulus and Marshall density (Fig. 13).

In 2004 an intelligent asphalt compaction research project was implemented in a highway reconstruction project (highway 30, Osnabrück) by the German Federal Highway Research Institute (BAST) in order to study the relationship between asphalt density and the vibration modulus $E_{\text{VIB}}$, which rely on the dynamic responses of the roller. Typical correlation of asphalt base is shown in figure 13. Another research goal referred to the sophisticated documentation system using GPS.

The monitoring system of the BW 174 Asphalt Manager roller was fitted with a differential global positioning system (DGPS) to monitor roller location to an accuracy of five cm in real time. The results were promising as can be seen in figure 13 and 14.
5. Benefits of intelligent soil and asphalt technology

The intelligent compaction technology offers high compaction performance, better depth effect and the excellent adaptability. The combination of amplitude control with directed vibration and the $E_{\text{VIB}}$ measurement system of the VARIOCONTROL and Asphalt Manager rollers enable a particular advantage with the IC technology. Up to five $E_{\text{VIB}}$ values (45, 80, 100, 120, 150 MN/M²) can be pre-selected at the VARIOCONTROL soil compactors as target values. So the system enhances the uniformity of compaction, which is of increasing importance in modern road, rail track and airfield construction as well as in the construction of foundation areas.

Intelligent compaction technology enables the operator to increase productivity and improve compaction quality. It eliminates the need for the driver to make critical rolling decisions and enables less experienced drivers to achieve consistent compaction results.

Improved compaction without aggregate crushing on thin layers by using horizontal vibration, are further benefits of both VARIOCONTROL and Asphalt Manager rollers. Horizontal vibration allows thin layers to be compacted on soft subbases without loosening and without subsequent compaction of the sublayer.

Intelligent compaction rollers are prepared to be equipped with documentation systems that allow continuous recordation through an accurate positioning system of roller location and corresponding compaction related output such as roller generated modulus measurements and number of roller passes.

A key advantage of VARIOCONTROL / Asphalt Manager rollers becomes apparent when used in urban areas and on bridges where unwanted vibration occurs. Measurements show that environmental vibration can be reduced by pre-selecting the horizontal level. The transmitted vibration speed can be held below the limits specified under German DIN 4150-3.
6. Summary

Intelligent compaction systems such as VARIOCONTROL or Asphalt Manager rollers with adjustable amplitudes and integrated compaction measurement system are following the changing demands of construction projects in modern earth work, highway and railway construction which are characterised by higher productivity, greater significance of costs and higher quality demands.

VARIOCONTROL and Asphalt Manager rollers automatically adapt the compaction energy to the actual operating conditions and at the same time provide a surface covering documentation of the dynamic stiffness in terms of the $E_{vib}$ value in MN/m$^2$ which has been found to correlate well with compaction – related properties like soil bearing capacity and percent of target density for soil materials and under certain conditions for hot mix materials.

Sophisticated data management and documentation systems and the use of a differential positioning system (DGPS) offer the ability to provide compaction data in a variety of ways to the roller operator and the project personnel. The data collected can be utilised in a large scale - project quality control.

References:


