Intelligent Asphalt Compaction.
1. Introduction
Efficient compaction equipment plays a key role in the processing of rolled asphalt. In addition to the operating weight of a roller, vibration with its characteristic variables of frequency and amplitude are also crucial to optimum compaction performance. Vibration enables asphalt mixes to be compacted with fewer passes. This is particularly apparent with those asphalts which have increased in stiffness over the last few decades and which subsequently require higher compaction output. Throughout Europe, more than 70% of asphalt applications are compacted using vibratory rollers.

The correct operation and handling of vibratory rollers assumes some knowledge of compaction equipment and the compactibility of the asphalt mix, as well as experience in working with compaction per se. Vibratory rollers are often not operated in a targeted way; vibration is continued for too long or on a mix that has already cooled down. Too many passes with vibration and excessive amplitudes can lead to aggregate crushing or loosening of the base layer. Supporting the roller driver with specific optimised, dynamic compaction and increasing the compaction output of equipment were the goals for BOMAG from the end of the 1990s in designing self-regulating rollers for soil and asphalt compaction. This intelligent compaction equipment calculates the compaction energy required and adjusts this automatically by regulation of the amplitude. At the same time, the system determines the EVIB stiffness module of the material being compacted, which gives an indication of compaction progress. More than 2000 of these units have been marketed across the world. This article reports on experiences with and subsequent developments to the asphalt roller.

2. Conventional vibratory rollers
Conventional asphalt vibratory rollers are equipped with circular exciters. The vibration reduces the internal friction in the mix, so that the simultaneous effect of basic weight and dynamic load increases layer density. Besides static linear load, other factors such as the vibrating mass of the compaction equipment, frequency and amplitude are also influential in determining the compaction effect. For optimum compaction of different layer thicknesses, tandem vibratory rollers with operating weights upwards of around 6 t are in most cases equipped with two amplitudes and two frequencies. Low amplitude with high frequency is recommended for surface layers and asphalt binders, as well as easily compacted mixes. Depending on the equipment model, values lie between 0.2 and 0.4 mm or 50-60 Hz. For base layers or mixes that are difficult to compact, the recommended solution is a combination of high amplitude (0.5-0.9 mm) and low frequency (40-45 Hz).
For the vibration technology to be used correctly, the roller driver requires some experience and must ensure that the correct parameters are chosen to avoid unwanted loosening and disruption to the structure, and he must also be able to switch off vibration promptly.

Figure 1 shows contact forces of the roller drum on the asphalt for fixed, adjustable amplitudes. The roller works with static load at the beginning of compaction, i.e. the roller drum is always in contact with the mix. The contact force \( F_K \) is never zero (Figure 1 top diagram). Contact force grows with increasing compaction due to the consistent vibration amplitude (Figure 1 bottom diagram). This results in the roller drum lifting, and even creates periodic drum bounce where the alternating low and very high impact forces can damage the asphalt surface. Drivers of vibratory rollers with fixed amplitudes only have the option of turning off vibration at the appropriate time based on experience and instinct.

3. Intelligent vibratory rollers

Since the end of the 1990s, ASPHALT MANAGER rollers developed by BOMAG have provided the industry with compaction equipment that determines and automatically adjusts the compaction energy required. This is intelligent compaction which provides compaction energy where required.
by adjusting the amplitude and reduces the energy where it is superfluous or even harmful. There is no need for the roller driver to intervene. The rollers have a directed vibrator system which can continuously adjust vibration direction and therefore the decisive, effective amplitude for compaction. The control is based on the analysis of the interaction between drum (= roller drum) and the stiffness of the material being compacted.

By utilising acceleration signals, the effective compaction amplitude is automatically optimised which prevents adverse drum bounce. Aggregate crushing, structural disruption to the asphalt, unevenness and loosening are all avoided.

The bounce behaviour of the drum and a power level control act as control criteria for the first generation of intelligent asphalt compactors. The drum is kept predominantly in contact with the asphalt. Three power levels, symbolised by three hammers, can be selected to limit the contact force between drum and asphalt even at the beginning of compaction. If the preselected power level is exceeded, the system throttles back the amplitude and therefore the contact force between drum and asphalt layer. This means that the depth effect of the system can be influenced and, for example, adjustments made on more yielding road structures or on layer subbases with non-uniform stability.

The acceleration signals are also used in ASPHALT MANAGER rollers to determine the dynamic stiffness module $E_{V1}$ (MN/m²) of the layer being worked. As numerous measurements show, this module (also called vibration module) for compaction temperatures $>100$ °C can also be referred to in order to assess compaction progress and is used as a correlation to the volumetric density of the mix assuming uniform stiffness in the subbase. ASPHALT MANAGER rollers are equipped with infrared sensors which inform the roller driver about compaction temperatures by measuring the asphalt surface temperature and displaying it on a control screen.

The stiffness module is calculated for each eccentric rotation from the compression phase of the force-
travel diagram, which is derived from the equilibrium of forces and the vibration path of the drum (see Fig. 3). The contact force and compression deformation exercised on the asphalt layer by the drum are calculated at the same time according to a method developed by BOMAG. Since the machine’s geometry and masses are already included in the calculation method, the dimension-related dynamically calculated vibration module can be viewed as an absolute characteristic independent of the machine.

In addition to automatic mode which governs the self-regulating function, the ASPHALT MANAGER rollers also offer the option of preselecting a required direction of vibration with a choice of six settings between vertical and horizontal. The roller driver makes adjustments on the control screen (BOP, BOMAG Operation Panel). Horizontally directed vibration greatly reduces the vibration loads on structures in contrast to conventional vibratory rollers. This Asphalt Manager presetting is ideally used on bridges and in inner-city areas near buildings.

With three articulated and six pivot steered ASPHALT MANAGER rollers, there are a total of 12 different models available in weight classes from 7 to 13 t.

The applicational advantages of the ASPHALT MANAGER rollers are universal use of the equipment with high compaction output, no risk of aggregate destruction, progressive adjustability, even compaction, better surface finish, low-vibration surface compaction and the option of using EVIB measurements for surface covering control.

Wide experience has been gained over the last 10 years. Systematic trials and feedback from wide-ranging construction projects have led to further developments in control criteria and improvements in the algorithm for the automatic stiffness-related amplitude control. This is based on data records from EVIB density correlations and the associated compaction temperatures arranged by mix type, layer thickness and other placement conditions. Nominal stiffnesses and EVIB target values can initially be

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Fig. 3: Determining the $E_{VIB}$ stiffness module.

Fig. 4: Intelligent compaction with a BW 203 AD-AM ASPHALT MANAGER on chip mastic asphalt. The (BOP) control screen displays the $E_{VIB}$ value, amplitude, speed and surface temperature.
deduced from this; these are then included as control criteria and enable optimised control with improved amplitude adjustment when compared to the first generation. There have also been further improvements to the validity of the EVIB value and its reproducibility. Figure 5 shows the increase of EVIB and density, as well as the correlation for a CMA cover layer mix on two different sites.

4. Target value control
Further developments in the control system had the following aims: On one hand, inexperienced users should be able to rely on an efficient, non-destructive compaction process by simply selecting the layer thickness to be compacted, without further need for adjustments and settings when used in automatic mode. The nominal stiffnesses saved and allocated to layer thicknesses help in this process. On the other hand, users are also given the opportunity of setting individual target values for any mix type based on their own EVIB density correlations.

Bomag creates “active amplitude management” adjusted to the increasing density of the asphalt layer using the new target value control in ASPHALT MANAGER. The greatest possible compaction output with maximum amplitude is made available in the initial passes and at optimum compaction temperature. The asphalt exhibits increasing resistance to the drum as compaction progresses; the contact force and stiffness module EVIB increase with density. During ongoing compaction, the movement of the drum and the increase in stiffness is monitored; the amplitude is throttled back if there is a risk of drum bounce, or of the maximum contact force being exceeded or of reaching a nominal stiffness (Fig. 6).

The interplay of control parameters in automatic mode is shown in a simplified form in Fig. 6. The roller driver selects the desired layer thickness on the control screen. This is all he needs to do to activate all the benefits of this intelligent compaction system. The input values for the target value control create the individual power level and EVIB target value for the selected layer. The control continually receives current data, such as amplitude, contact force, compression and actual stiffness, from the vibrating drum. The optimum nominal amplitude is calculated and progressively adjusted just-in-time based on these reference variables. With no further action by the driver, compaction energy is optimised and automatically adjusted to the compaction status. The number of passes is reduced because full power is provided during the hot initial phase and the amplitude is greatly

Fig. 5: EVIB, density, asphalt temperature and correlation with increasing passes.
If a nuclear gauge is available, the asphalt stiffness module $EVIB$ can be individually correlated to the density for the existing asphalt layer by rolling over the measuring point.

By using this particular $EVIB$ target module, the target value control of the ASPHALT MANAGER is capable for the first time of individual, layer-related compaction to a specific nominal density. This is an important step in avoiding over-compaction and in meeting permeability specifications.

The target value control not only provides benefits, such as

- Optimum use of compaction energy
- Automatic adjustment of the effective depth and measuring depth
- Prevention of drum bounce, aggregate crushing and uneven layers
- Correlation to asphalt density within a compactible temperature range
- Controlled compaction to a target value,

but is also an essential precondition for surface covering quality assurance on asphalt.

*Fig. 6: Operating and control concept of the new ASPHALT MANAGER generation.*

Reduced only towards the end of compaction or when the material is too cold. The effective amplitude is limited from the start for thinner layers. The measuring depth and the layer being installed are also limited by adjusting the effective depth. This minimises disruption to the subsurface. The driver can track the current status or compaction progress on the control screen using $EVIB$, temperature and effective amplitude.
5. Measuring results on asphalt

**A61 motorway with 15 cm base layer**

In the course of renovating the Koblenz carriageway on the A 61 near Erftstadt, a 7.5 t pivot steered BW 154 AP-AM ASPHALT MANAGER roller with target value control was used in automatic mode on the bottom 15 cm thick layer of the asphalt base layer (AC 32 TS, B50/70). Trial compaction gave a target value of 250 MN/m². Subsequent measurements showed a continuous increase in volumetric density and in the EVIB value. The surface temperatures, which were measured directly by infrared sensors on the roller, were between 160 °C and 140 °C.

Additional measurements using an inserted thermometer gave a temperature difference between asphalt core and asphalt surface of approx. 15 °C. Density increased from 82% behind the paver to 97% after 6 passes with the BW 154 AP-AM (3x forwards and 3x backwards); the EVIB value rose from 140 MN/m² (1st pass) to 230 MN/m² (6th pass) (Fig. 9).

Analysing the change in amplitude shows that the first two passes were compacted at maximum amplitude (0.9 mm) and that compaction was continuously throttled back from the third pass to 0.5 mm (Fig. 9). A further reduction in amplitude was unnecessary in relation to the density of the laid material (15 cm). The amplitude is regulated automatically with no input from the roller driver.

**A48 motorway CMA, cover layer 3 cm**

During renovations to the Trier carriageway on the A 48, trials were carried out on the Polch Mayen section with a 10 t ASPHALT MANAGER roller, type BW 174 AP-AM, on a 3 cm chip mastic asphalt layer. The compaction requirement was 98%. Sample compaction on the CMA 8 S PmB 25 / 55-55 gave a target value setting of 300 MN/m².
The stable CMA layer, which was only 3 cm thick, required rapid automatic reduction of the vibration amplitude. A relatively high amplitude (0.5 mm) was still used for compaction in the first pass, but during the second and third passes the amplitude was throttled to 0.2 and finally to 0.1 mm. Although the asphalt temperature had in the meantime dropped from 160 °C to 110 °C, the system still measured a growth in stiffness due to increasing compaction. After three vibration passes, an $E_{\text{VIB}}$ value of approx. 300 MN/m² was achieved with a density of 98%, as measured with a Troxler probe.

For work on the A48, the ASPHALT MANAGER roller was equipped with the BCM 05 documentation system (BOMAG Compaction Management) and a DGPS system (BOMAG Starfire iTC) to monitor the $E_{\text{VIB}}$ values, compaction temperatures and machine parameters over a larger area and to compare them with the previously determined target value. The systems can be relatively easily and quickly attached to ASPHALT MANAGER machines. All decisive variables for compaction are recorded and shown in different colours to the roller driver individually or in combination on the BCM 05 display.

The position accuracy of the BOMAG Starfire iTC GPS system is between 20 and 30 cm. USB memory sticks are used to transfer data to the construction site office. This is where data is evaluated and managed with the BCM 05 Office program module.
The measured EVIB values and operating parameters of the ASPHALT MANAGER roller are documented in Fig. 13 for a section 370 m long and a placing width of 7.10 m, and in Fig. 14 for a smaller section. 88% of the EVIB values for the measured area of 2625 m² achieved a target value of at least 300 MN/m². The average value is 312 MN/m². 90% of the surface temperatures were above 120 °C. The temperature distribution for the smaller section is shown in Fig. 15. When combined with the EVIB/density correlation which was made, this gives surface covering evidence of compaction and also ensures that the entire area has been evenly compacted with virtually the same temperature conditions.

The two representative examples show that preselection of nominal stiffness and subsequent target value control can very precisely monitor and continuously adjust the amplitude. The stiffness measurement is related more closely than before to the layer being compacted. Re-producibility and validity in terms of compaction quality are improved.

The new target value control will be part of the latest ASPHALT MANAGER generation for series BW154AP-4 AM, BW174AP-4 AM from spring 2010.

6. Outlook
Further developments to intelligent compaction technology by implementing target value control based on stiffness calculations will optimise vibratory roller compaction and improve quality.

Target value control makes it possible to coordinate compaction control to the compactibility of the mix and to produce better correlations between the EVIB vibration module and asphalt density for compaction temperature ranges from 160-100 °C. The data base, which has already been developed
Another step towards practical implementation of comprehensive surface covering documentation of compaction and surface covering compaction control for asphalt applications through the networking of all machines involved in the placing and compacting process. Fig. 16 shows BOMAG’s concept of BCM net data management. Information about the compaction status, number of compaction passes and the compaction temperature are exchanged between rollers and finishers.

The cooling behaviour of the mix is determined, and a working window is communicated to the whole workforce which helps to improve the overall construction process by making operations more consistent. The first practical deployment is planned for the summer of 2010.

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