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TOO HOT TO HANDLE, TOO COLD TO CONTROL - INFLUENCE OF COMPACTION TEMPERATURE ON THE MECHANICAL PROPERTIES OF ASPHALT

Frank Bijleveld[1], Seirgei Miller[3], Arian De Bondt[2], André Dorée[1]
[1]University of twente, department of construction engineering and management, Enschede, The Netherlands
[2]Ooms Avenhorn Groep bv, The Netherlands
[3]Vusela Construction, South Africa

ABSTRACT

Density is one of the most prominent measures for road quality. Often nuclear density measurements are taken during compaction operations. It is expected that the layer will reach the specified properties if the asphalt mixture is compacted within a desired temperature window. But what happens when the compaction process is undertaken outside of this ideal "temperature window of opportunity"?
This paper deals with these questions and proposes a method to determine the optimal temperature and time frames to compact hot-mix asphalt. It demonstrates this procedure for one mixture by determining the influence of compaction temperature on the density and mechanical properties. The research project combined a literature review, laboratory-experiments, and data-collection on a construction project. In the laboratory a Roller Sector Compactor was used to compact 24 slabs at four different temperature windows and the mechanical properties were verified by the ITS-test (indirect tensile strength) and the CC-test (cyclic compression). On the construction project, three lanes were compacted within three different temperature windows. Paver and roller movements were tracked with high resolution GPS-technology and the asphalt temperature was measured with infraredcameras, thermocouples and an infrared laserlinescanner. The results of this study show that while similar densities can be reached for all temperature windows, other mechanical properties such as tensile strength and fracture toughness may suffer. This means in quality control that it is not sufficient to only check and steer on density, but also the compaction temperature and the representative properties should be taken into account.

Keywords: Compaction, density, mechanical properties, crack propagation, indirect tension, quality assurance, performance contracting, high-tech instruments, GPS, infrared

1. INTRODUCTION

Important changes are occurring in the Dutch road construction industry, resulting in changing roles for road agencies and contractors. Road agencies currently seem to concentrate on their core tasks (governing and exploitation) and contractors undertake the design of the project in addition to their primary construction functions. Because of these changing roles important risks shift from road agencies to contractors. Within these roles, contractors are free to choose the type of asphalt construction, the mixes to be used and the paving process, to develop their own products and improve them (Dorée et al, 2008). Also, agencies are shifting towards performance contracting with longer guarantee periods. Within these new roles and contracts, contractors are directly confronted with shortcomings in quality during the guarantee period. Therefore, it is important for contractors to control the quality of the asphalt pavement during construction. In this search for quality control, the paving process is crucial.

However, the current asphalt paving process depends heavily on the skills and experiences of people working on the construction site. According to Miller (2010) the asphalt paving process depends heavily on craftsmanship, work is mainly undertaken without instruments to monitor key process parameters and no research effort is put into the systematic analysis and mapping of the asphalt paving process. This results in long learning cycles and difficulties to intervene in the process. Operations outside the domain of the experience of the asphalt team makes the results of the paving process uncertain (Ter Huerne, 2004). Also, because contractors are free to develop their own asphalt mixtures, operations are often outside the experience-domain of the asphalt team. This can lead to a degree of uncertainty and variability in the quality they deliver. Since not many parameters are mapped during the paving process, it is difficult to learn from previous projects and intervene in the process. Moreover, more off-the shelf technologies are available to monitor and visualize the paving process. These technologies can help to make the paving process explicit and map this process in a structured way.

So, if contractors seek more quality control, it is important to professionalise the paving process. Measuring and mapping the paving process and standardization through methods and procedures are important for improving process quality. To improve control over the paving process, contractors need to measure and monitor their own process, gain more understanding of the important mechanisms during this process and the interdependencies between these mechanisms. To professionalise the paving process the University of Twente and 11 Dutch contractors created a cooperative network, called ASPARi, short for ASphalt PAving, Research and innovation. Within this network, GPS-technology, a laserlinescanner and infraredcameras are used to provide insight in the paving process. This data can be transferred to graphs and animations (Miller and Hartmann, 2010) and the results are used to give feedback to asphalt teams. The intention is to reduce variability in working methods and results, improve process quality and reduce the risks (Dorée and Ter Huerne, 2005; Miller and Dorée, 2009).

Under the auspices of the ASPARi network, a study was conducted at Ooms Nederland Holding bv specifically researching the question: What are the effects on the mechanical properties of the pavement, if we compact the asphalt mixture at different temperatures? If these effects are known, it may be possible to more precisely determine at which temperatures rollers need to compact the asphalt mixture at the construction site, in order to reach a certain level of quality. This is called the compaction window. In this paper, we subsequently describe: The research approach, the results of the empirical research, consequences for the asphalt industry and possibilities to further professionalise the paving process.

2. RESEARCH APPROACH

Asphalt technologists agree that the density of an asphalt mixture is one of the most prominent measures for road quality (Ter Huerne, 2004; Decker, 2006; Miller, 2010, etc.). Reaching a certain desired density optimizes the desired mixture characteristics, like stiffness, fatigue characteristics, resistance against deformation and moisture (Decker, 2006). Poor density can lead to settlements in a later stage with a shorter life span of the pavement as a result, because rutting will occur in the wheel paths. So, good compaction is very important. The compaction process as currently practiced is mainly based on experience (De Man, 2007; Miller, 2010). In contrast, if the asphalt team works outside their experience-domain, the result is uncertainty with a fair degree of variability (Ter Huerne, 2004; Miller, 2010). Currently, this occurs more frequently: There is less time available to construct the road, many new asphalt mixtures are introduced, often work is planned outside the ideal paving season and as a result, work undertaken in less than ideal weather conditions and circumstances. So, reaching the desired quality during the compaction process is under threat, which often makes the result more and more uncertain. Therefore, it is important to work towards a more method-based process, which will make it possible to reach the desired quality, despite working under less than ideal circumstances. These methods and procedures can then be a starting point to become a ‘learning organization’.

Within the compaction process it is generally known, that compaction temperature is important for the final quality of the pavement. This research is based on the work of Timm et al (2001), that there is an ideal window of temperatures to compact the asphalt mixture, where the desired mechanical characteristics can be achieved with a high degree of probability. Depending on the cooling rate of the asphalt mixture, this also means that there is an optimal time window to compact. If the asphalt mixture is compacted outside of these windows the asphalt mixture will be understressed (if the mixture is compacted at too low temperatures) or overstressed (when the mixture is compacted at too high temperatures). These conditions are illustrated in figure 1, which schematically shows the temperature of the mixture as a function of time. For different mixtures and different conditions, the ideal compaction window shifts along the timescale.
Using the ASPARi-equipment (GPS, laserlinescanner, thermocouples and infraredcameras), it is possible to register the lay-down temperature, the cooling rate, the number of roller passes, the temperature at certain roller passes, etc. for the entire paved road. However, the measured data and its relationship with the mechanical and the functional quality will not be directly clear. Hence, the ASPARi-approach as reported by Miller (2010) as yet does not determine the effects of different compaction temperatures on the final density and quality of the pavement.

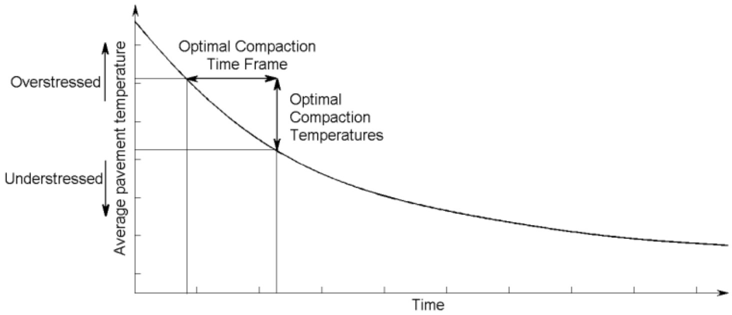

Figure 1: Cooling rate asphalt mixture and optimal compaction temperature and time frame

So, the basic assumption is that both density and compaction temperature are important for the final quality of the pavement. But what if the desired density is reached while the mixture is compacted at too low or too high temperatures? Is this possible and what are the consequences? This paper will deal with these questions. The approach used to answer these questions is conducting advanced experiments in the laboratory and measurements taken at a construction site. The paper will focus on the causal effect of the compaction temperature to the density and the mechanical properties of the asphalt mixture. Specifically, this means that asphalt mixtures will be compacted at different temperatures after which the density and the mechanical properties will be determined. The next section will describe the theoretical framework and in section 4 the results of the empirical tests will be discussed. Section 5 describes the consequences of this research and explores some possibilities to further professionalise the paving process. The paper concludes with the main findings, and an outline of further directions for this line of research.

3. THEORY OF ASPHALT COMPACTION

3.1 Density and compaction

To successfully use asphalt as a construction material in a pavement, it is necessary to force the different particles of the material more close to each other. During this process a rearrangement of the particles take place, while air is expelled. This process is known as compaction (Ter Huerne, 2004). The Asphalt Institute (2007) defines compaction as the process of compressing a given volume of asphalt into a smaller volume. Reaching the correct density will optimize the desired mixture characteristics including strength, durability, resistance against deformation and moisture, etc. (Decker, 2006). The most important factors to influence the density are the gradation and the composition of the asphalt mixture, the moist in the underground and the loading that is placed on the mixture (Asphalt-institute, 1989; Van Stek & Linden, 1992; Ter Huerne 2004).
Ter Huerne (2004) gives several methods to determine the density, such as ‘The volume of voids in the material related to the total volume of the material (inclusive voids)’, ‘Weight of the material divided through the volume of the material’, ‘The amount of space in mineral aggregate related to the total volume of the material’, etc.
The asphalt compaction process takes place through loading the mixture. A material that is loaded, in principle wants to deform. This deformation is prevented by counter pressure and internal cohesion (Van Stek & Linden, 1992). To reach progression in density, the aggregate skeleton needs to be pushed closer to each other. This can only be reached if surplus air is driven out of the mixture (Van Stek & Linden, 1992). Through loading a relatively uncompacted material,

the particle arrangement will change. The volume will reduce and the density increases. The fluid in the asphalt mixture (bitumen) will grease the contact areas between the particles and makes sliding against each other easier (Ter Huerne, 2004).

If the mixture is over-compacted, or if there are little or no voids present, the mixture becomes overfilled and can lose its stability. Certain mixtures, mainly so-called aggregate rich mixtures, also need horizontal forces to reach the desired particle rearrangement. This horizontal movements originates through vertical loads in combination with horizontal confinement. Through differences in horizontal and vertical tensions, sliding tensions originate. Through variations in sliding tensions against the vertical tensions a kneading compaction arises (Ter Huerne, 2004). If there is insufficient confinement, the roller can displace the mixture (shove) and roll out the mixture, with possible micro-cracking resulting.

Therefore, the goal of compaction is to achieve an optimum air void content, to provide a smooth riding surface and to increase the bearing capacity of the material. The task of roller compactors is to reduce the void content to a certain level. Usually the machinery for compaction consists of several type of rollers, all with different roles during the process, for example, squeezing, kneading or smoothing the surface.

Van Stek and Linden (1992) and several roller operators observed in actual construction projects that the compaction process scan be divided into three phases:

1. During phase 1 the particles need to be arranged. Stones need to slide against each other, so the mortar (bitumen and filler) needs to be sufficiently flexible (warm). If loading forces are applied, air can be expelled. The mixture must not be too tough.
2. In phase 2 the asphalt mixture will behave differently. Through increasing density, and increasing stiffness through cooling, air present in the mixture will be trapped. As a result, the asphalt mixture will behave more elastic and the compaction effort (density progression) is negligible. In this phase horizontal forces cannot be too high, because the chances for shoving and micro-cracking are high during this phase.
3. During phase 3 the compaction process can be continued again during further increasing stiffness of the mixture and decreasing the volume of bitumen and air (shrinkage). Through this shrinkage the skeleton can be compressed further with very high forces are necessary to achieve relatively high stiffnesses and density. Finally, unevenness's and prints of the roller compactors can disposed of in this last compaction phase.

3.2 Behaviour of the asphalt mixture during compaction

Figge (1987) studied the possible movement of particles in the asphalt mixture during compaction. In a non-compacted mixture the individual particles are reasonably free to move and during the compaction process these possibilities to move are greatly reduced. The rollers must be able to create such loads that it results in movement of the individual particles. The sooner this is conducted, the faster one will arrive at a situation where no more particle movement can take place. During this compaction process, the forces needed for achieving particle movements increases (Ter Huerne, 2004).

Figge (1987) also studied the rheological behaviour of the asphalt mixture during the compaction process. The results show that the behaviour at the start of the compaction process is mainly plastic and during this process (when the material becomes more compacted), this behaviour turns into mainly elastic behaviour. During the whole compaction process the viscous behaviour is relatively constant. According to Ter Huerne (2004) the behaviour of the mixture during compaction can be characterized as elastic (before the particles start shoving) and plastic (during shoving of the particles).

Nijboer (1942, 1948) and Paulmann (1969) studied the forces needed to achieve the described particle movements by Figge from the perspective of the characteristics and amount of fluid in the mixture. The fluid acts as a lubricating agent between the particles and reduces friction. He claimed that inside the voids of the mixture a fluid-air menisci exists. The surface tension of those fluid-air menisci pulls aggregate particles towards each other. The result is a pre-compression stress in the particle matrix and this gives the matrix shear strength. The magnitude of this stress in the sample is proportional to the surface tension and inversely proportional to the diameter of the voids between the articles. When the voids are completely filled (saturated material), the stress disappears. In such a situation the material behaves hydraulically. The results of Nijboer indicate that for asphalt mixtures the hydraulic region starts at void contents of 2 to 4% (Ter Huerne, 2004).

The conclusion drawn is that the asphalt mixture exhibits components of elastic, plastic and viscous behaviour. Some characteristics can dominate, depending on the compaction phase. Thus, during the empirical research we need to take into account that the mixture can have an elastic effect after compaction, and influencing the final density.

3.3 Temperature during compaction

In the asphalt paving industry, both researchers and practitioners, postulate that the temperature of the asphalt mixture during compaction is important for the final quality of the pavement (Floss, 2001;Chadbourn et al, 1998, Timm et al, 2001). Some authors suggest that compaction should be completed in specific temperature ranges for example, 90 to 100°C (Floss 2001) or have specified either high cut-off temperatures of ± 130°C (Commuri and Zaman 2008) or low cut-off temperatures of between 70 and 80°C (Alexander and Hughes 1989; Van Dee 1999). However, there is general agreement that cessation temperature (minimal compaction temperature where the mixture is stiff enough to prevent further reduction of air) varies depending on the mix properties, layer thickness and environmental conditions (VBW

Asfalt 2000; Gudimettla et al. 2003; Wise and Lorio 2004; Mieczkowski 2007). If the material temperature is too low during compaction, the bitumen cannot lubricate the mixture anymore resulting in an open surface. The same prevails for the maximum temperature: if the binder is too fluid and the aggregate structure is weak (at high placement temperatures), roller loads will simply displace or “shove” the mat rather than compact it, cracks originate behind the rollers, the mixture sticks to the rollers, and the rollers sink into the mixture (NCAT 1991; VBW Asfalt 1992; VBW Asfalt 2003). Kari (1967) describes these minimum and maximum temperatures as understressed and overstressed situations.

There are many parameters that influence the temperature of the asphalt mixture. These include the ambient temperature, the temperature of the underlying surface, the compaction process and roller regimes, layer thickness, wind speed and rain. This makes it difficult for operators to predict the material temperature and adjust their actions to this information and to compact in the ‘ideal compaction window’.

Traditionally, the optimal compaction temperature was determined through plotting the log-viscosity vs. the log-temperature, where the ideal compaction temperature was the temperature at a bitumen viscosity of 1.7 poise (Corlew en Dickson (1970). Subsequently, Jordan and Thomas (1976), Daines (1985) and Luoma et al (1995) developed tools to predict the temperature window, and the starting and ending temperature to compact. Also, Van Dee (1999) conducted research to model the cooling rate of the asphalt mixture. He concludes that modelling the effects of rain and wind are difficult and these situations are mainly outside the experience domain of the operators.

Decker (2006) postulates that determining the compaction temperature with viscosity-temperature plots is no longer appropriate. For example, more viscous bitumen can increase the compaction temperature, while there is not always enough time available to compact the mixture. The main problem with these methods is that they are based on viscosity and density, but not on the final quality characteristics (like resistance against fatigue, rutting and cracking).

Subsequently, Chadbourn et al (1998) developed a Windows-based computer program, PaveCool. This is a one-dimensional solution to predict the pavement cooling phenomenon. This program take into consideration: the type of existing surface, its properties and temperature; the type of HMA mix and mix temperature; the lift thickness; various environmental conditions including ambient temperature and cloud cover; and the time of the year and time of day. The output includes the theoretical cooling rate for the mix and recommended starting and ending time for compaction after lay-down. However, PaveCool is limited because it only considers one HMA pavement lift. Often more asphalt layers are constructed on the same day, where the previously laid lifts may act as residual heat sources and slow the overall cooling of the newly placed lift. In response, Timm et. al. (2001), developed CalCool, a program that takes the multi-layer construction into consideration. Later, researchers developed practical guides to estimate compaction windows based on local conditions (Wise and Lorio 2004; Pilate 2006; Mieczkowski 2007).

The goal of all these models and programs is to provide asphalt teams and decision makers with information about the temperature profile throughout the duration of the project and in addition, to determine the optimal compaction time frames, to minimize construction delays and improve the efficiency of the compaction process.

However, a practical problem is that the temperature over the height of the asphalt layer is rarely constant. This is because the surface of the layer cools down faster than the middle of the layer and the temperature of the bottom of the layer can decrease faster depending on the temperature of the base layer. So, different layers within the height of the asphalt mixture can have different optimal temperature windows. At the extreme, it can also happen (theoretically) that these different layers have such different temperatures, that the different optimal compaction windows do now overlap. For example if the middle of the layer is still too hot to compact, while the surface of the layer is already too cold too compact. Thus, not only is the absolute temperature important, but also the variability within the height of the layer as well as over the whole length of the road.

In conclusion, the combination of bitumen and aggregate needs to be viscous enough to allow compaction but stiff enough to prevent excessive shoving. This means that HMA mat temperature is crucial to both the actual amount of air void reduction for a given compactive effort, and the overall time available for compaction. If the initial temperature and cool-down rate are known, the temperature of the mat at any time after paving can be calculated. Based on this calculation, compaction equipment and appropriate rolling patterns can be determined.

4. EMPIRICAL RESEARCH ON THE EFFECT OF DIFFERENT COMPACTION TEMPERATURES

What is the relation between the compaction temperature and the resulting density and mechanical properties of the asphalt mixture? By answering this question, it is possible to determine a compaction window based on the desired mechanical properties. This is different from the traditional approaches where this compaction window is based on viscosity-properties and the density that can be reached at this viscosity. To determine the compaction window based on mechanical properties, laboratory experiments and a field study are conducted. This empirical research is conducted for an asphalt mixture with 16 mm maximum size coarse aggregate, 4,5% bitumen (pen 40/60), without recycled asphalt (AC 16 base 40/60 pen). This mixture was chosen since it is often constructed under less than ideal circumstances in The Netherlands. The reason for choosing a mixture without recycled asphalt, is to increase the homogeneity of the mixture. In the next sections, the set-up of the laboratory experiment and the field study are described, and the results of these empirical studies are discussed.

4.1 Laboratory experiments

For simulation of field compaction in the laboratory the European standard (EN-12697) describes four compaction methods: Impact compaction (Marshall), kneading compaction (gyratory), vibration compaction and rolling compaction. From different studies it became clear that rolling compaction has the most similarities with field compaction (De Visser et al, 2006; Renken, 2002). Also, the instrument can be pre-heated and can produce more test-samples at the same time. Given these reasons, a decision was made to compact the asphalt mixtures with the Freundl, Roller Sector Compactor (RSC), type: WSV-2008-KW50/500. Figure 2 shows respectively a picture of the instrument (a), the principle of the compaction method (Mollenhauer, 2009) (b), and the result of the compaction, an asphalt sample of 50 by 50 cm, with a height of approximately 8 cm (c).

Figure 2a: Roller Sector Compactor

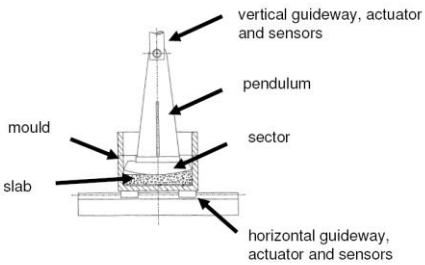

Figure 2b: Principle

Figure 2c: Result

Mollenhauer (2009) developed two standardized compaction procedures with this instrument: One procedure to reach a certain height and density (position steered) and one to simulate real compaction effort (force steered). These procedures are used in this research. The principles of the applied procedures are as follows:

Position steered:

1. Pre-compact with 0.5 mm per roller pass till reaching a height of 80 mm;
2. Keep the height constant for 5 roller passes;
3. Relieve the compaction power with 0.5 mm per roller pass till the power is reduced to 0 kN.

Force-steered:

1. Pre-compact during 15 roller passes from 0.02 kN to 0.1 kN/cm slab material;
2. Level the asphalt sample during 15 roller passes with 0.02 kN/cm slab material;
3. Raise the force during 15 roller passes constantly till 0.75 kN/cm slab material;
4. Relieve the force during 15 roller passes till 0 kN.

This procedure produced 18 slabs: 12 position steered and 6 force-steered slabs. These samples are compacted at temperatures varying from 80 °C till 170 °C. Afterwards, they are separated into four categories: Slabs compacted in the temperature range 160-170 °C; 140-150 °C, 100-130 °C and 80-100 °C.

From these 50 by 50cm slabs, 9 cores (100mm in diameter) are drilled to determine its mechanical properties: 6 cores for the indirect tensile strength test (for resistance to cracking) and 3 cores for the cyclic compression test (indication for resistance against rutting). These tests were chosen since they determine parameters for the normative damages for this kind of mixture (AC 16 base), 9 cores could be drilled from one slab, and because this equipment was readily available. The tests are conducted on samples with a diameter of 100 mm and a height of 60 mm. The ITS-test is conducted according to EN-12697-23 (4 hours conditioned at 5 °C). The CC-test is conducted according to the Dutch national norm (test 250), loaded with a block pulse instead of a sinus pulse (so twice as much loading). To reduce friction, two layers of plastic were used with silicon oil in between the two layers (Erkens, 2002). During the compaction the temperature is monitored with 3 thermocouples in the height in the layer (see figure 3).

Figure 3: Inserting thermocouples

4.2 Field study

The results obtained in the laboratory were then checked in a practical setting during a field study on a project of Ooms Construction bv. The field study was located in the city Dirkshorn (in the North of the Netherlands). The construction of a 1600 m^2 area surrounding an agricultural warehouse formed the setting for the field study. The movement of the paver and rollers were monitored with high-end GPS equipment (figure 5). Using a laser linescanner behind the paver (figure 4), infrared cameras and thermocouples, the asphalt temperature during the entire paving and compaction process was monitored. Three 86m long lanes, were surfaced with an 80 mm base layer (AC 16 base). The underlying layer consists of a well-compacted 350 mm recycled concrete granulate.

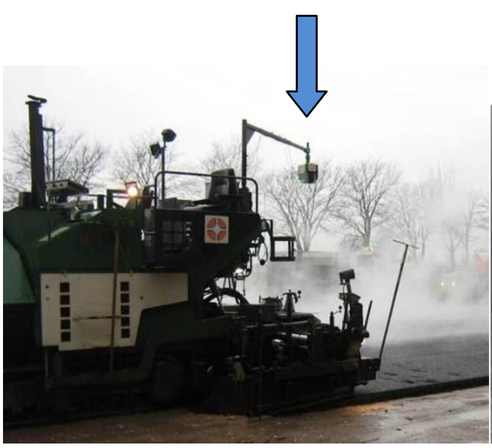


Figure 4: Laser linescanner on the paver **Figure 5: GPS-equipment on a roller**

Keeping in mind the aim of the project, to study the influence of the compaction temperature on the mechanical properties, required that the compaction process should be partly guided. This meant that on the one hand, the compaction temperatures and time frames would be specified with roller operators instructed when to start and when to finish compacting. On the other hand, the rolling patterns employed by operators would not be influenced in any way. The compaction of lane 1 started in the region of 150 to 160°C. Lane 2's compaction would start at approximately 130°C and the compaction of lane 3 would start at the lower temperature of approximately 100°C.
From each lane 14 cores were extracted to provide insights into its properties. The cores were polished again to a 100mm diameter and a 60mm height as in the laboratory research part. Next, the core densities were determined and ITS tests were conducted to determine the resistance to cracking.

4.2 Results

The effects of the compaction temperature on (1) the compaction effort and energy, (2) on the mechanical properties and (3) on the elastic recovery are described from both laboratory experiments and field study perspectives. No direct comparison is made between the results of the laboratory experiments and the field study, because the mixture from the field study appeared to be coarser than the mixtures in the laboratory and it rained heavily the night before and the granulate layer was saturated during the field study. This contributed to difficulties in comparing results of the practical case with the laboratory results.

Effect of compaction temperature on compaction effort and density

With respect to the required compaction force and compaction energy we can conclude that more force and energy is required, if the compaction temperature decreases. This is illustrated in figure 6, where the compaction energy (in Nm) is shown for all the compaction temperatures (of course only for the position steered compaction, since the energy for the force-steered is the same for all samples). The most logical explanation for this result is that the bitumen is more viscous, and as a result more force is necessary to bring the particles in the mixture closer to each other.

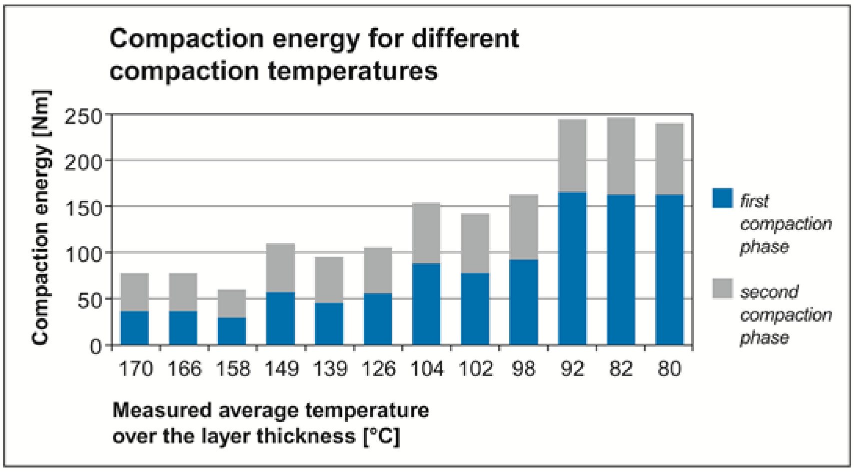

Figure 6: Compaction energy for different compaction temperatures

Next, forces in the RSC above 30 kN are hardly possible in practice and unlikely given current roller compaction technology. This is the case at compaction temperatures lower than 100 °C. At compaction temperatures higher than 150 °C less force is necessary and is it possible to use a smaller roller in practice, otherwise the bitumen will be pushed through the skeleton to the surface.
Subsequently, from the determined densities it seems that at all compaction temperatures the desired density can be achieved, even at a low 80 °C. However, a large amount of force and energy is required to reach this density. The field

study showed that although it became more difficult to compact at the lower compaction temperatures, it was still possible to reach the target density.

Effect compaction temperature on mechanical properties

The mechanical properties within a slab (9 cores) was found to be homogenous. From the results of the mechanical tests we can conclude that despite the target density being reached, the mechanical properties vary depending on the compaction temperature. This variability is highest for the properties cracking toughness and crack propagation rate (determined according to Molenaar 1983; De Bondt, 1999). This is illustrated in figure 7 where the relative cracking toughness (%) is shown for the different compaction temperatures. From the test results it became clear that the samples compacted in the temperature range 140-150 °C have a significantly higher cracking toughness than the samples compacted in the other temperature ranges. The cracking toughness in the 140-150 °C range is approximately 1,0-2,0 (N.mm)/mm^2 higher than in the other temperature ranges, which is approximately 20-35% higher. Thus, starting with the compaction process outside the temperature range of 140-150 °C, can decrease the cracking toughness with 20-35%, despite the target density being achieved.

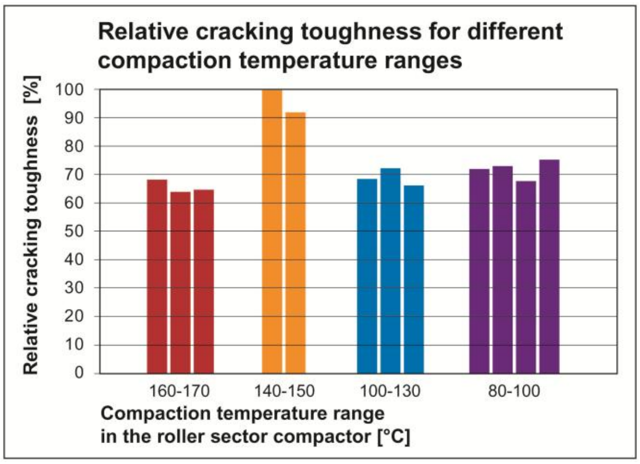

Figure 7: Relative cracking toughness for different compaction temperature ranges

Also, the field study shows that the cracking toughness and the crack propagation rate can significantly differ depending on the compaction temperature, this despite the target density being reached in practice. Moreover, the lane where operators started compaction at approximately 150 °C shows significantly better results for resistance against cracking. Thus, compaction temperature is a very important parameter for the resistance to cracking for this specific asphalt mixture.

The results of the cyclic compression test do not show a clear relationship between the compaction temperature and the resistance against rutting. Also, the standard deviation of the results within one slab was pretty high. Therefore it was also difficult to determine a clear relationship.

Effect compaction temperature on the elastic recovery

From theory it is well-known that the behaviour of an asphalt mixture has elastic characteristics (Van Stek&Linden, 1992; Asphalt-Institute, 2007, VBW-Asfalt, 2000). This also became clear in the laboratory tests and the field study. The samples in the laboratory were compacted to a height of 80 mm. However, after cooling down and conditioning, the sample turned out to be 81.5 – 82.5 mm. Also, during the field study, measurements taken with the nuclear density gauge shows that the density first increases, then decreases and after a certain temperature, again increases. Additionally, for the laboratory samples, the elastic recovery measured after 23 hours is the same as the elastic recovery after 110 hours, so the assumption is that the elastic recovery is finished 23 hours after compaction. Then the layer thickness per compaction temperature was analysed. From this analysis it became clear that the elastic recovery is higher at the higher compaction temperatures than at lower compaction temperatures. It was not possible to precisely determine a relationship since the measurements were not precise and structured enough, but the phenomenon is observed both in the laboratory and the field study.

4.3 Conclusion

The results of the empirical studies show that the compaction process for an AC 16 base (conventional bitumen 40/60 pen) should be started at a temperature between 140-150 °C. When the compaction process starts outside this window, it is still possible to reach the target density, but a lower cracking toughness and a higher crack propagation rate should be expected. Despite reaching the target density, compacting outside the optimal compaction window can decrease the cracking toughness to a maximum of 30% and increase the crack propagation rate to a maximum of 40%. So, it is certainly important at which temperatures are compacted. Consequently, if during quality control only the density is used as a criterion, detecting the reduction in quality due to compacting outside the optimal compaction window is not possible. Therefore, it is not sufficient to only steer the process based on the density. The compaction temperature should be taken into account depending on the indicative damage mechanisms.

5. CONSEQUENCES FOR THE ASPHALT INDUSTRY AND FURTHER PROFESSIONALISATION

5.1 Consequences for the industry

What will bring these results us?
To start with: The asphalt industry needs to realize that the mechanical properties of an asphalt mixture are (heavily) influenced by the compaction temperature. Therefore, it is important to monitor this temperature during the process and if necessary to steer the paving and compaction process based on this temperature. Compaction outside the optimal temperature window can lead to a decrease in quality and a shorter life span of the pavement. And: Earlier damages to the pavement, means higher costs for repairs and maintenance and possible penalties for decreasing availability of the road during repairs. The resources (equipment) to monitor the temperature during the paving process are available, namely laser linescanners, infrared cameras and thermocouples. Rollers can also be tracked with GPS to determine the number of roller passes at every location. Additional quality control and process steering based on these parameters can be used to work towards more controlled and directed quality.

Who affect these results?
It is clear that the operators of the asphalt team need to realize that compaction outside the optimal compaction window increases guarantee risks. But there is more. Working with compaction windows based on mechanical properties is important for different phases in a project, for different disciplines and for both contractors and agencies. A (technical) designer should take into account the variability in temperature of the asphalt mixture and which consequences this can have for the quality of the pavement. Asphalt mixtures with a short compaction window (for example thin surfaces) require more attention during the paving process and are therefore more vulnerable in terms of variability in temperature and thus in quality. The layer thickness is also really important for the cooling rate of the asphalt mixture, so a designer should take this into account. A designer of the logistics process should realize that delays in the supply of asphalt, can lead to a lower lay-down temperature, possibly outside the compaction window.
The results are also important within the framework of the delivery of the road or acceptance of a project. If the road or project is accepted through the client, without knowledge that the compaction temperature can be important for the final quality of the pavement, it is possible to accept a road that does not match the intended quality goals. A client can for example ask the contractor if the compaction is conducted inside the compaction window. If a client wants to reduce this risk, the client can demand that the contractor should monitor the temperature and that he should carry this information over in a delivery file. Putting the right requirements in contracts, can reduce the risk of undesirable acceptance of a project.
Résumé: The compaction temperature (significantly) influences the final quality of the pavement. Risks for contractors are a shorter lifespan of the pavement, and at contracts with longer guarantee periods possibly discussion about the guarantee itself. Risks for clients (agencies) are undesirable acceptance of a project that does not fulfil all the quality goals. Reducing the risks for a shorter life span of the pavement are important for the durability of the pavement and automatically have a positive effect on the sustainability of the pavement. This understanding should as a result, have pro-active handling within the frameworks of contracting, designing (asphalt mixtures, but also to logistics) as in the construction of a project.

5.2 Further professionalization
Earlier ASPARi work showed that with GPS, infrared- and laser technology, it is possible to make the paving process more explicit and monitor important parameters during the process (Miller, 2010; Miller & Dorée, 2008). It improves process control, and improvements in process control reduce the variability in quality. Besides, it now appears that the compaction temperature is important for the quality of the pavement and guarantee risks. To work towards controlled quality, a few next steps within process control are necessary in the near future. A logical next step in this professionalization, now that we know that the process can significantly influence the quality of the pavement, is to determine more relations between paving process and the quality of the pavement. What for example is the effect of the speed of the roller? And what is the effect of more roller passes in a shorter window or less roller passes in a larger window? And does the sequence of different types of roller matter? Understanding these relationships is important for asphalt contractors, because they need to work towards a certain quality level under a controlled construction process. For clients (agencies) this understanding is important for improving their contracts (setting the right requirements) and reducing the risks of undesirable acceptance of projects.

6. CONCLUSIONS AND FURTHER RESEARCH
This research into the relationship between the compaction temperature and mechanical properties of the asphalt pavement provides several valuable outcomes and insights:

- The changes in the paving industry stimulate asphalt contractors to professionalize. Within this professionalization, process control during the paving process is an important issue.

- The compaction temperature of an asphalt mixture is important for the final quality of the pavement. Compaction outside the compaction window can reduce the cracking toughness by 35% and increase the crack propagation rate by 40%, despite the target density being reached.
- In quality control it is not sufficient to only check and steer on density, but also the compaction temperature and the representative (mechanical) properties should be taken into account. Technologies, like laser linescanners, infrared cameras and thermocouples are available and can be used.
- It is advisable to determine the compaction window based on temperature and the resulting mechanical properties instead of bitumen viscosity and the density that can be reached at this viscosity.
- These results are important in quality control and the final durability of the pavement. Improvements for the durability of the pavement will automatically have a positive effect on the sustainability of the pavement.

Recommendations for future research are:

- Investigate the possibilities to simulate different roller regimes in the laboratory with the Roller Sector Compactor. If it is possible to closely simulate field compaction, optimal compaction regimes for different asphalt mixtures can be designed in the laboratory.
- Search for possibilities to monitor and steer the compaction process in real-time based on the (mechanical) properties of the asphalt mixture.
- Besides research about process control, it is important to conduct research about the impact of operational procedures and routines and the circumstances of a project on the final quality of the pavement. Thus, connect the search for process control with (technical) research about the quality of the pavement.

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