

WARM MIX ASPHALT – TOO COLD TO HANDLE? LEARNING TO DEAL WITH THE OPERATIONAL CONSEQUENCES OF WARM MIX ASPHALT

Frank Bijleveld¹, Seirgei Miller², André Dorée¹

¹University of Twente, Civil Engineering & Management Department, the Netherlands

²Vusela Construction, South Africa

ABSTRACT

Governments, regulation and road authorities push for sustainability. Firms respond with strategies to reduce their carbon footprint. Beside optimization of HMA production and logistics, firms invest in the development of Warm Mix Asphalt (WMA). WMA is an asphalt mixture produced at lower temperatures.

The majority of the research deals with the production of WMA, while less research effort is put into the operational consequences for the asphalt team. WMA have expected workability problems, because of higher mixture viscosity and less time to compact. Through reducing the viscosity by modification, the mixture is more flexible at lower temperatures in order to stretch the compaction window: the time available for compaction. This paper describes the consequences of this strategy to reduce the viscosity on the paving and compaction process. It describes two WMA-projects where the temperature of the mixture during the process with laser linescanners, infrared cameras and thermocouples are monitored and the movements of the machinery were observed with GPS. Also, based on interviews conducted with operators the operational handling of WMA is studied. Finally, the paper will describe the lessons learned from this case studies and describe the implications for the industry.

Keywords: Warm Mix Asphalt, Workability, Compaction, Temperature, Viscosity, High-tech instruments

1. INTRODUCTION

Presently, sustainability is more and more important in the asphalt industry. Governments and road authorities set and publish their goals to reduce their carbon footprint, for example in reducing fuel consumption and reducing important emissions. This is regulated in for example the Clean Air Act (1970), Kyoto treaty (1997), etc. Contractors respond with strategies to reduce their carbon footprint. These strategies vary from optimization of hot mix asphalt, constructing perpetual pavements, and improving logistics. Warm Mix Asphalt (WMA) is also one of the strategies to reduce the carbon footprint and reduce emissions. WMA is a group of asphalt mixture technologies which allow a reduction in the temperatures at which asphalt mixtures are produced and placed (NAPA, 2011).

The majority of the research about WMA deals with the production technologies itself, the benefits from WMA, how the production can be improved and if it is also possible to use recycled asphalt pavement (RAP) in WMA (NAPA, 2007, 2011). However, less research effort is put into determining and quantifying the consequences during the lay-down and compaction phase, especially not from an operational perspective, like the individuals of the asphalt team. Although WMA may appear workable and easily compactable in the laboratory and when produced at the asphalt plant, it should remain workable at the paving site as well. A characteristic for the asphalt industry is that the paving process is based on craftsmanship and experience (Miller, 2010; Ter Huerne and Dorée, 2004). So questions arise, such as: Is the laying and compaction process of WMA unaffected and similar to the established HMA working practice? And is the compaction process as effective as operators used to with HMA? Also, the manual handling of the asphalt mixture (an occupational burden) is an issue, because due to the lower temperature the critical temperature for manual handling is reached faster. Moreover, the sensitivity to variability within key parameters, working methods and project conditions are important for the workability of WMA. How should the asphalt team deal with all these changes? This paper will discuss the workability of WMA at the construction site from an operational perspective.

One of the key principles of WMA is to reduce the viscosity of the asphalt mixture. The aim to reduce this viscosity is driven by the urge to stretch the available time for compaction of the asphalt layer. Researchers postulate that WMA can be compacted during a longer period of time and that it is possible to pave during cool ambient temperatures without sacrificing quality (Tanghe, 2009; Newcomb, 2000; NAPA, 2011; etc.).

However, traditionally the compaction temperatures (compaction window) are determined through plotting the log-viscosity vs. the log-temperature, where the ideal compaction temperature was the temperature at a viscosity of 1.7 poise. But nowadays researchers suggest that this method for determining the compaction temperature, only based on viscosity is not appropriate anymore (Decker, 2006; Bijleveld, 2010; Miller, 2010). The main problem with these methods is that they are based on viscosity and the density that can be reached at this viscosity, but they do not take into account the workability of the mixture and the final quality (mechanical) characteristics, such as resistance against fatigue, rutting and cracking.

So, the current WMA assumption is that by reducing the viscosity, the paving process can stay the same. This paper will describe two WMA projects, make the paving and compaction process explicit and analyses if this process stays the same. Based on these measured data, it is possible to analyse the process and search for possibilities to improve. The paper starts with a brief introduction about the theoretical background of WMA and the operational issues regarding temperature and compaction. Next, the results of the empirical research will be described: Two monitored field studies. Based on these results, the lessons learned, are discussed. Finally, the conclusions plus implications for operators and decision makers and the possibilities for future research are considered. The study aims to guide operators and decision makers towards better informed decisions about the use of WMA related to the paving process and specific project conditions.

2. WARM MIX ASPHALT

2.1 Warm-mix asphalt

WMA is a group of asphalt mixture technologies which allow a reduction in the temperatures at which asphalt mixes are produced and placed (NAPA, 2011). These technologies tend to reduce the viscosity of the asphalt mixture to provide complete aggregate coating at lower mixing temperatures. Hot Mix Asphalt (HMA) is produced at approximately 160-170 °C, whereas WMA is produced at temperatures 20-55 °C lower.

Generally, three techniques to produce WMA are commonly known (NAPA, 2001):

- Organic additives: Organic additives are mostly waxes, where aggregate will be coated and changes the visco-elastic characteristics of the bitumen.
- Chemical additives: The chemical additives can be a chemistry package mainly to enhance coating, adhesion and workability at reduced temperatures.
- Foaming techniques: At the foaming techniques a little amount of water (possible combined with zeolites) is added under pressure to the hot bitumen in a controlled way. This will expand the bitumen and increase the volume in order to enclose the aggregate.

Several researchers postulate advantages of WMA: it aids compaction for stiff mixtures, companies are able to pave in cool conditions, it is possible to pave faster, there is a reduction of fuel consumption and emission, and there are

possible better working conditions (NAPA, 2011). However, there is not much data available that contributes to these statements. This paper will monitor two projects, and analyse some of these advantages from an operational perspective. One of the possible negative points of WMA because of the lower viscosity, can be the manual handling of the mixture. Regarding working conditions NAPA (2008) reported that the workability seemed to vary depending on the process, but seemed to be good in most cases. In Norway, operators did not have any problems with the manual handling of WMA. The teams seemed to prefer WMA, particularly in the summer because of the lower handling temperature. NAPA (2008) also reports on the European practice of WMA. Interestingly, it focuses on the benefits of WMA and the WMA technologies, but hardly reports about operational issues. They state: *'Although some differences in placement practices were observed, placement practices did not differ between HMA and WMA; only the temperature was lower'*. However, this difference in temperature should have implications for the rest of the process, but they do not report about this. So, on the one hand researchers postulate that the paving process can be the same as with HMA because it is possible to compact at lower temperatures, while other researchers say the paving process can be conducted faster than the traditional HMA process.

In the last decennium more and more roads are paved with WMA and most of them are monitored from a material and density perspective. The majority of the literature focuses on WMA from a material-perspective and from a production-perspective. However, less research effort is put into paving and compaction from an operational perspective and the operational handling of the WMA for the asphalt team. In HMA literature two parameters are repeatedly mentioned from a process-perspective: 1) the temperature of the asphalt mixture during the lay-down and compaction phase and 2) the consistency of the compaction process by rollers. NAPA also wrote a 'Material test framework for warm mix asphalt trials' in order to provide a minimum level of uniform data collection which can be shared between contractors and agencies. They also advise to collect data about temperature behind the screed and during the process and roller patterns. This paper will focus on these two aspects. The two parameters are described in more detail in the next sections.

2.1 Temperature of the asphalt mixture

In the asphalt paving industry, both researchers and practitioners, propose 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 $\pm 130^\circ\text{C}$ (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 Asphalt 2000; Gudimettla et al. 2003; Wise and Lorio 2004; Mieczkowski 2007). If the material temperature is too low during compaction, the bitumen cannot grease the mixture anymore with an open surface as a result. 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 roller drums, and the roller drums sink into the mixture (NCAT 1991; VBW Asphalt 1992; VBW Asphalt 2003). Kari (1967) describes these minimum and maximum temperature as a understressed and overstressed condition.

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 viscosity of 1.7 poise (Corlew and Dickson (1970). Decker (2006) suggests that determining the compaction temperature with the viscosity-temperature plots is not always appropriate anymore. 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). Also NAPA (2011) states that for the wide range of WMA processes, the viscosity-based mixing and compaction temperatures cannot be used to control coating, workability, and compactability anymore. Therefore, new mixing, laydown and compaction procedures and methods should be developed to determine the ideal compaction temperatures, in relation to the compactability and resulting density and quality parameters.

The first step is to measure the cooling rates of WMA, measure density progression after every roller passes and determine the resulting quality parameters. To predict the cooling rates of asphalt mixtures already some models are available, like Pavcool (Chadbourn, 1998) and Calcool (Timm et al, 2001). The output of these models include the theoretical cooling rate for the mix and recommended starting and ending time for compaction after lay-down. The goal of these models and programs is to provide asphalt teams and decision makers with information about the temperature profile throughout the duration of the project in order to determine the optimal time frames, to minimize construction delays and improve the efficiency. There are many parameters that influence this cooling rate of the asphalt mixture (the input of these models), including the ambient temperature, the temperature of the underground, the compaction process and roller regimes, layer thickness, wind speed, rain, etc. This makes it really difficult for operators to predict the material temperature and adjust their action to this information and to compact in the 'ideal compaction window'. Vasenev et al (2012, forthcoming) conducted research to provide real-time information about this temperature at the asphalt team, instead of predicting this cooling rate on beforehand.

To conclude: The temperature of the asphalt mixture is crucial to both density and the overall time available for compaction to reach a certain quality level. If the initial temperature and cool-down rates are known, the temperature of

the mixture at any time after paving can be calculated. Based on this calculation, appropriate compaction equipment and appropriate rolling patterns can be determined with existing models and methods. However, existing models and methods to determine the compaction temperatures and times are not applicable to WMA. Therefore, more insight is necessary into the temperature characteristics of WMA during the paving process and the compaction process.

2.3 Compaction of WMA

The Asphalt Institute (2007) defines compaction as the process of compressing a given volume of the mixture into a smaller volume. The goal is to produce a mixture of specific density, to provide a smooth riding surface and to increase the load-bearing capacity of the layer. Compaction of a newly paved mixture is a critical component of the construction process. And the compaction process is probably the most important noticeable process that may negatively affect the final quality layer, because it is the last activity before opening the road. Several authors recognise that proper compaction is important for achieving satisfactory pavement service life (Alexander and Hughes 1989; Elhalim et al. 1993; Fitts 2001).

The compaction process is attained by a set of compactor rollers in the field. Important influencing parameters are the physical properties of the mixture, like mix characteristics, the temperature during laydown and the cooling rate, layer thickness, and the surrounding environmental conditions, such as air temperature, wind velocity and humidity, and solar radiation (Roberts et al. 1996; Asphalt-Institute 2007). So, compaction is a complex task that should be conducted under frequently changing conditions. Variability in compaction practices with inadequate compaction in vital areas of the road cross section leads to premature failure in those areas. Therefore, the consistency of compaction operations is really important.

The term compactability is often used to describe the temperature dependent characteristic of increasing the density of an asphalt mixture under the influence of compaction effort. Easily compactable mixtures show a high increase in density right at the beginning of the compaction process, followed by an early end to this process. Relatively low density increase rates from the beginning right to the end of the compaction process are a characteristic of difficult to compact mixtures. So, temperature of the mixture is really important and has a direct effect on the viscosity of the binder. As the temperature decreases, its binder becomes more viscous and resistant to deformation, which results in a smaller reduction in air voids for a given compactive effort. As the mix cools, the asphalt binder eventually becomes stiff enough to effectively prevent any further reduction in air voids regardless of the applied compactive effort.

So, the different techniques for WMA tend to reduce the viscosity of the asphalt mixture, but on the other hand the temperature of the mixture is lower, which increases this viscosity again. Also, NAPA (2007) states that the compaction process of WMA is not different from HMA, yet they state that of course the starting temperature is lower, in most cases it is easier to obtain target density, and it required a greater compaction effort to reach the target density. Additionally, NAPA (2007) states that the whole process for WMA (laydown and compaction) can be faster than at HMA. NAPA's sentiments raise an overarching practical question. What are the practical implications for the paving and compaction process of WMA? The next section will describe two projects in The Netherlands with specific attention paid to the monitoring of the WMA temperature during the lay-down and the compaction phase; and the monitoring of compaction operations for those two projects.

3. RESULTS EMPIRICAL RESEARCH

During this empirical research two WMA-projects are monitored. The initial surface temperature and the temperature of the asphalt mixture during the process were respectively monitored with a laser linescanner and thermocouples. The movements of the machinery are monitored with GPS in order to analyse the compaction procedures and strategies. Density progression was monitored at fixed positions. A combination of nuclear density measurements after every roller pass, combined with surface and in-asphalt temperature measurements, was used to analyse the impact of roller passes on the density during certain temperatures.

3.2 Case study 1

The project was an approximately 210m long section of freeway where both (1) HMA and (2) WMA with a foaming technique were to be constructed. The mix composition for the HMA and WMA were identical. The HMA was produced at approximately 165°C. However, for WMA the temperature at production and start of the construction, remains around 100°C. According to the contractor, it delivers an energy saving of up to 40% and a CO₂ emission reduction of between 20 to 40%.

The contractor's objective was to compare the construction of the two 8cm layers to ascertain whether any process improvements were possible from a construction perspective. The issue here was whether the HMA construction team applied the same operational strategies to the two mixes given differing temperature characteristics. Five lanes were constructed on one day, three 210m long lanes with the HMA; and an adjoining two 160m long lanes with WMA. In the next sections the temperature profiling, the compaction procedure and some density results are discussed.

Temperature profiling

The average surface temperature directly behind the paver screed is measured with a laserlinescanner (figure 1). The result is a temperature Contour Plot (TCP). An example is shown in figure 2, for lane 1 (HMA). A few operational aspects are noteworthy:

- For lane 1 (HMA), short paver stops when new HMA loads arrive at the hopper results in small temperature differentials as the colder mix left in the hopper is mixed with the new, hotter HMA (see 2). These stops, less than 2 minutes, result in the surface temperature dropping from an average of 141°C to an average of 126°C at the stop area.
- The TCP also shows longitudinal thermal streaks corresponding to the positions of the conveyor belts transporting the asphalt from the hopper through to the augers of the paver. These differentials were mostly less than 10°C.
- For Lane 2 (HMA), two lengthy 35 minute stops as a result of the paver waiting for asphalt to be delivered to the site, result in greater drops in surface temperature from 134°C to approximately 82°C. No temporary transverse joints were constructed for these stops with the paver merely continuing after the lengthy stops.



Figure 1: Linescanner behind paver

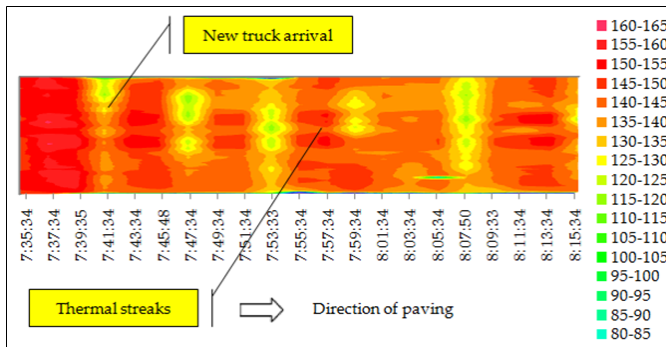


Figure 2: Temperature contour plot initial surface temperature lane 1

As expected, the average temperature for the WMA varies between 102 and 105°C. Two paver stops, each approximately 10 minutes in duration, results in the surface temperature dropping from approximately 105 to 75°C for one of the two lanes, a differential of 30°C in a 10 minute period. As was the case with the HMA layer, new truck arrivals also result in temperature differentials. However, these are not as pronounced with the surface temperature cooling off to approximately 95°C during the average 2-minute stop.

At certain fixed positions the in-asphalt temperature was measured using thermocouples, together with an infrared camera used to measure the surface temperature (see figure 3). This was done to determine the relationship between in-asphalt and surface temperature and the cooling rates of the asphalt mixtures. A comparison of the surface and core temperature cooling rates for the two mixes shows that both mixes cool off at similar rates and that there is consistency between the two measurements (see figure 4 and 5). This is not surprising given that the mix characteristics are similar.



Figure 3: Measuring cooling

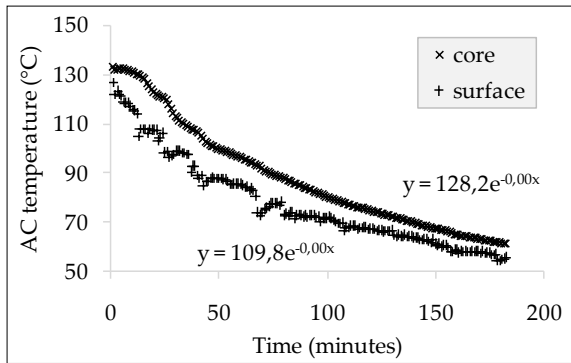


Figure 4: Cooling rate HMA layer

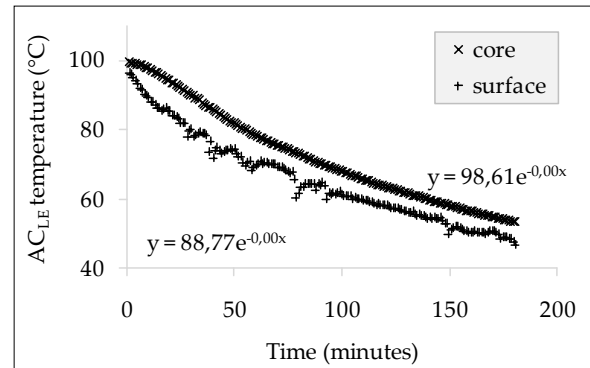


Figure 5: Cooling rate WMA layer

Monitoring machine movements

Monitoring of the movements of the machinery is carried out with differential-GPS (DGPS), using a local base station, that increase the accuracy of the measurements. Figure 6 shows the GPS mounted on a tandem roller (to also monitor the crabwalk of this roller).



Figure 6: Two GPS rovers on a tandem roller (to measure crabwalk)

The paver speed was consistent for all lanes with average operating speeds of 5.0m/min and 4.5m/min for the HMA and WMA layers respectively. Note that the average width of the lanes is about 3.5m.

Note that lanes 1, 2 and 3 were paved with the “normal” HMA and lanes 4 and 5 with the WMA mix. For the final compaction, a 10ton tandem roller performs a breakdown compaction function and the 14ton three-drum deadweight roller applies the final compaction. There is no discernable consistency in compaction for both rollers.

- The tandem roller applies the most roller passes to Lane 1 ($\mu = 14.9$) and the average number of passes gradually decreases from Lane 1 to Lane 3 where $\mu = 4.9$ passes. Also, there are two easily identifiable gaps in compaction viz. the operator has failed to compact the longitudinal joint area between lanes 2 and 3 and the last 40m of Lane 5 (see 7).
- A similar pattern emerges for the three-drum roller. The operator applied most passes to Lane 1 and the number of passes gradually decreases from Lane 1 ($\mu = 13.7$) through to Lane 5 ($\mu = 6.3$). In addition, two operational patterns emerge.
 - Firstly, the operator tends to apply more compaction passes to the first ± 100 m, the result of which is that there are compaction gaps at the end of each lane.
 - Secondly, the operator appears to concentrate on the middle of the lanes and consciously avoids compacting the longitudinal joints. If the assumption is that the two operators were working cooperatively, the longitudinal joint area should have been compacted by the tandem operator. However, this is not the case for all longitudinal joint areas.

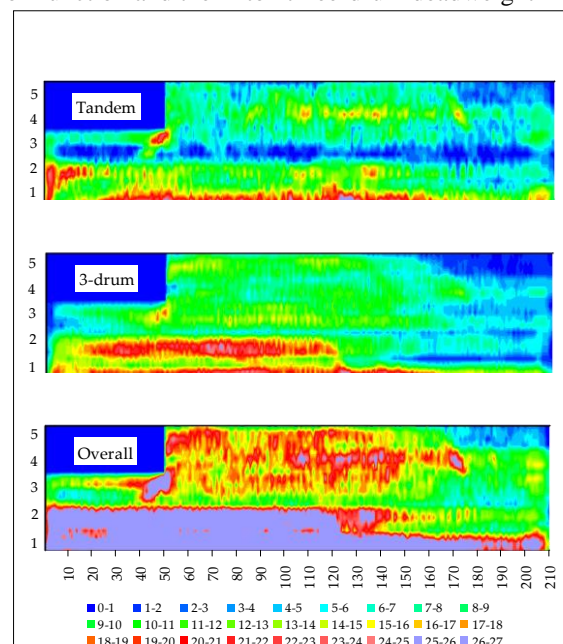


Figure 7: Compaction contour plots

- Whilst it is clear what functions the two roller types were supposed to fulfil during compaction, there are a few occasions when the roles are confusing. First breakdown rolling is undertaken by the tandem roller whilst compacting Lanes 1 to 4. However, there are three occasions where this role is reversed. The first two occur when the paver stops for approximately 35 minutes each in Lane 2 whilst waiting for asphalt. The three-drum assumes the breakdown roller function and compacts the area closest to the paver. This function is taken over by the tandem roller after a few minutes. For Lane 5, the three-drum assumes the breakdown role from the start and does so for most of the lane.
- Both operators tend to cross lanes repeatedly. An example is that whilst compacting the newly paved Lane 3 where the surface temperature behind the paver screed is approximately 135°C, both operators repeatedly applies patterns that move them across to Lane 1 where the core temperature has already dropped to approximately 70°C after 2 hours. This same behaviour is evident when the tandem roller returns to compact the Lane 1/Lane 2 transverse joint approximately 30 minutes after both rollers have previously compacted the joint.

There appears to be little difference in operational strategies applied to the two layers despite the more than 30°C difference in the asphalt's delivery temperature. For the AC layer, breakdown rolling commenced an average of 9 minutes after paving with the core temperature at the start of compaction approximately 123°C. Final rolling commenced approximately 27 minutes later with the AC layer's core temperature cooled off to approximately 98°C. The starting times for compaction are within the recommended temperature "window of opportunity" determined using the PaveCool software. For the given weather conditions and mix properties, PaveCool recommends that compaction be carried out within upper and lower temperature thresholds of 120 and 80°C respectively and that the operator has approximately 50 minutes for compaction. Both operators have started within the recommended time and temperature limits. It is unclear when exactly compaction operations ended for specific lanes given operators' tendencies to move across lanes. For the WMA layer, compaction has generally started within PaveCool's recommended limits of 105 and 80°C and the 23 minutes available for compaction. An exception is that the final rolling for Lane 4 (WMA) only started 33 minutes after paving when the core temperature already cooled off to 76°C. Analysing, the start of paving and compaction for all lanes shows variability in compaction procedures for both HMA and WMA. For the WMA lanes, the tandem roller starts compaction in lane 4 after paving while in another lane it starts 14 minutes after paving.

Also, a combination of core temperature, surface temperature measurements and nuclear density readings were recorded at eight locations. The nuclear densities were measured after each roller pass and the use of static or dynamic compaction recorded. Paver screed pre-compaction was consistent for both layers with average densities of 2084 kg/m³ (HMA) and 2075 kg/m³ (WMA) before the first roller pass. For the HMA layers, whilst mostly using static compaction, the target density of 2375kg/m³ was achieved after 20 passes with the core temperature at 80°C. When mostly dynamic compaction was used, the 2375kg/m³ target density was achieved after 7 passes with the core temperature at 120°C. Only static compaction was applied to the WMA layers with the 2375kg/m³ target density achieved after 14 roller passes and the core temperature at approximately 70°C.

3.2 Case study 2

The second case study was a project on a provincial road in Rotterdam. The local authority chose WMA because of sustainability reasons. Two WMA mixtures were constructed, one mixture produced with the foaming technique (WMA-F) and one with a wax-addition (WMA-W). For comparison one HMA section was constructed. All the sections were ca. 300 m. long with a width of approximately 5 m. In the next sections, the asphalt temperature during the process, movements of the machinery and some results (densities) are discussed.

Temperature profiling

The surface temperature was again measured using the laserlinescanner. No clear comparison could be made between the WMA's and the HMA mixtures, because the weather conditions were really different over the 2 days construction period.

Most important results of these measurements are:

- The surface temperature for the WMA-W is more consistent and homogenous than the surface temperature of the WMA-F. WMA-F had 7 stopping places of the paver of approximately 6-7 minutes and 5 colder spots, while WMA-W had 5 stopping places of approximately 3-4 minutes and 3 colder spots. The more number of stopping places in the WMA-F section can be explained through the road geometry, because trucks needed more time to put their truck in front of the paver. The reasons for the extra colder spots are unclear: Maybe the temperature already varied at the plant, but it is also possible that the WMA-F is more vulnerable for colder spots.
- Rain and wind have a great influence on the surface temperature of all the layers. Theoretically this can mean that within the asphalt layer, different temperature layers can exist. This can for example mean that the top of the layer is relatively cold, and highly viscous, while the middle of the later is still too hot, has low viscosity, and is difficult to compact. Further research on how to deal with this problem is necessary.
- For the WMA-W mix it seems that paver stops can be critical for the quality of the asphalt pavement. The surface temperature at a stopping place cools quickly down to 90-70 °C. The use of the WMA-W mix, and possibly other wax-mixtures, is therefore dependent on the location: When the continuity of the paver process is uncertain, the quality seems more vulnerable.

- At the WMA-W section there was also one long paver stop of approximately half an hour. At this stopping place the density was structurally lower. However, from other longer stopping places a possible solution appeared: Treat the longer stopping places like the day-joints or lunch-joints, because at these joints no density problems appeared. Further research at this point seems wise.

Also, the cooling during the process was measured at two fixed location per section. Most important results of this monitoring are:

- The cooling behaviour of WMA's exhibit similar cooling characteristics to that of the measured HMA cooling. Whilst the delivered temperature of the asphalt is different, the cooling rates are similar after a while. Note there is a difference in that the temperature over the layer thickness for the WMA is pretty homogenous, while for HMA at these lower temperatures, there is a difference between the surface and the in-asphalt temperature.
- The resultant cooling curves are compared with the results from the Pavcool software. In general, Pavcool predicts the cooling of the mixture too slowly. This means that cooling in practice is faster than that predicted with the software.

Monitoring machinery

Again, the machinery movements are monitored with DGPS. Based on these measurements, the paver speed and the compaction procedures are analysed.

In figure 8 the paver speed for is shown for an approximately two hour period. The change of trucks loads is clearly visible in this graph. With the laserlinescanner it is possible to measure the decrease in surface temperature. Also, longer stopping places are visible – for example between 8.17 and 8.49 hr. After comparison of the paver speeds, we conclude that again the speed at WMA is not higher than at HMA.

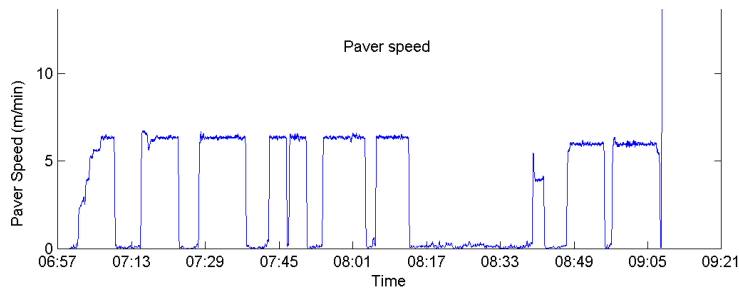


Figure 8: Paver speed during the project

Next the compaction procedures the of rollers are analysed:

- More roller passes have been carried out for the middle of the road than at the sides of the road.
- As well as at the WMA-F as the WMA-W there are just a few roller passes conducted in the first 20 m. in comparison to the rest of the section. An example is shown in figure 9.

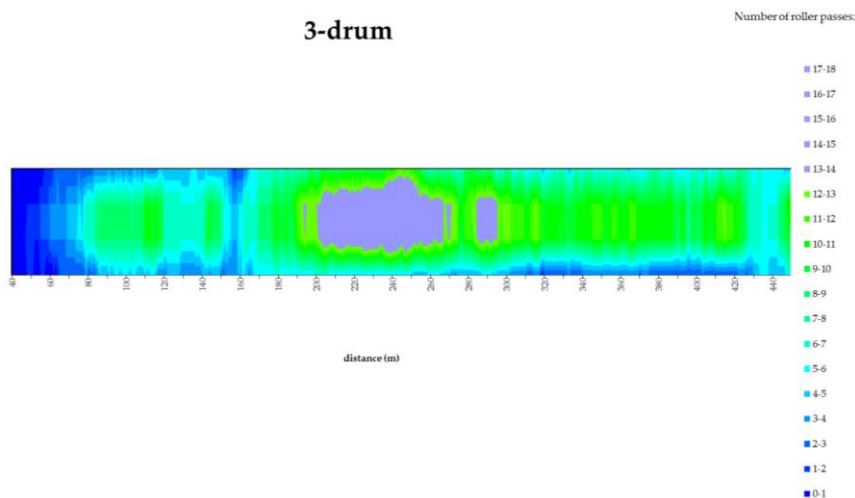


Figure 9: Number of roller passes 3-drum roller

The cooling curves in relation to the density progression at the fixed positions are analysed next.

- The roller regime of the WMA-F exhibits a degree of variability, while the regime of the WMA-W is consistent. At the first measuring point within WMA-F section 10 roller passes are undertaken in 24 minutes, while at the

second measuring point 12 roller passes are undertaken in 14 minutes. At both positions the screed compaction was about the same. Within the WMA-W section at both measuring points 12-14 roller passes were undertaken in 21 minutes.

- The roller regimes for the HMA were also really different. At the first measuring location 8 roller passes were undertaken at a constant speed, while at the second measuring location, first 4 roller passes were undertaken and after a break of 20 minutes, 8 passes were undertaken.
- Overall for the WMA's between 10 and 14 roller passes were used to achieve density, while for the HMA between 6 and 12 roller passes were used. So, for the WMA's about 50% more roller passes were undertaken (8 vs. 12).
- The total compaction time at the WMA's is approximately 7 minutes shorter than the total compaction time for the HMA. Yet, this difference is relatively small given a total compaction time of between 90 and 120 minutes.
- For the WMA's the average time between the different roller passes is about 2,5 minute shorter than that for the HMA. Apparently, the operators already take into account that less time is available for total compaction and compact a little bit faster.

An example of the different roller regimes are shown in figure 10 and 11. These are two positions in the same (WMA) section, where it is clear that at the second position the roller passes are conducted in a shorter time period and at faster intervals.

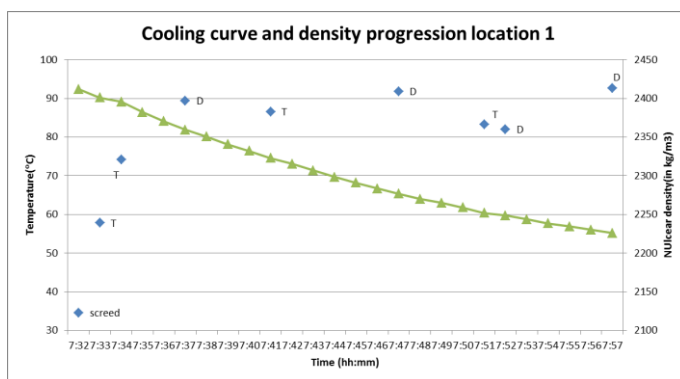


Figure 10: Cooling and density location 1

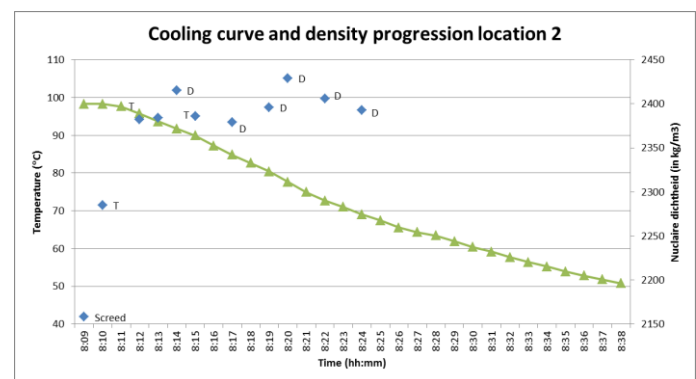


Figure 11: Cooling and density location 2

Asphalt cores were taken at the temperature monitoring locations with nuclear density measurements preceding this activity. The cores were analysed in the laboratory and their densities compared. The most important results are:

- The target density of the WMA-F is hardly reached, while the target density of WMA-W is reached. Also, the spread in density results for the WMA-F is higher than the other mixtures.
- Within the WMA-F section where manual work was conducted and at the longer stopping place mentioned earlier, the density was significant lower than that for the other mixtures. Note that the mixture cooled down to approximately 50°C.
- The target density was reached at the joint made prior to the lunch period within the WMA-W section. The target density was also achieved for the WMA section undertaken with manual labour.

Finally, interviews were conducted with the asphalt teams after construction. In general, the asphalt teams are positive about the use of WMA, because of the environment, climate and the lower temperature of the asphalt mixture exposed to the operators. The asphalt teams were not really unanimous in their opinion regarding harmful fumes. Some operators felt that working with WMA was healthier, others said they did not care and that they were used to the fumes. Regarding the operational / manual handling of WMA, the operators were clear: the handling of WMA is much more difficult than HMA. It may be useful to conduct further research to decrease the physical intensity for the operators of the asphalt team.

3.3 Lessons learned

Based on the two monitored projects there are lessons learned regarding temperature of the mixture during the WMA process, working methods of the asphalt team and the workability of WMA. This section will describe the most important lessons learned from these case studies.

The temperature differentials at these WMA-projects due to for example stopping places of the paver, truck changes, segregation and thermal streaks seem not really different from the differentials at HMA. These temperature differentials can easily be noticed and analysed with 'temperature contourplots' showing the homogeneity of the initial surface

temperature behind the screed of the paver. Based on this information the asphalt team can possibly adjust their operations in order to decrease these temperature differentials and with that increasing the quality.

From the results of the temperature monitoring can be concluded that the cooling curve of WMA is nearly the same as the cooling curve from HMA, considered from the WMA temperature. The difference is of course that the temperature over the layer thickness at WMA is pretty homogenous, while at HMA at these lower temperature, there is a larger difference between the surface and the in-asphalt temperature. That these cooling curves are nearly the same, also means that current prediction models of the cooling curve (like Pavcool, Calcool, Multicool and Coolfreeze) can also be used for WMA. The cooling of the WMA can be monitored with thermocouples and infrared cameras aside the road and presented to roller operators (in real time).

Within the working methods at the WMA-projects some extend of variability encountered. In the compaction regimes a lot of variability became visible, as well as within the different sections as between the different mixtures. The data shows mainly variability in total compaction time, the temperature during pre-compaction, the first roller pass and the time between roller passes. The result is that the overall compaction varies from lane to lane with some areas that have received little or no compaction passes at all for both HMA and WMA.

Furthermore three trends became apparent: (1) For the HMA layer, it is easier to achieve the target density using a mixture of static and dynamic compaction, (2) it appears that the target density is more difficult to achieve at lower compaction temperatures with more than double the compaction passes necessary to reach the target density, (3) there is a tendency that operators continue compacting even after the target density is reached. To monitor the movements of the machinery and working methods of the asphalt team high-end GPS equipment can be used and transformed to 'compaction contourplots' to analyse the WMA process.

Additionally, the paver speeds were consistent for both projects as was the pre-compaction behind the paver screed and did not differ from HMA projects that were monitored.

Analysis of the cooling rates, nuclear density measurements and the animations of the process for both WMA and HMA provides further evidence that the variability in compaction is more caused by what appears to be a rather uncoordinated approach for the compaction process. Thus, the variability in compaction regimes are not specifically for WMA, but is more the consequence of an uncoordinated approach. And, there seems less time available for reaching the target density, which make WMA more vulnerable for quality loss and premature failure. So, application of WMA does not lead, by definition, to a lower quality. However, the paving process of WMA seems more sensitive to quality loss, than the traditional HMA paving process because there seems less time available for quality control. Monitoring and quality control during the paving process are therefore important to work towards a high quality, because the WMA—paving process is sensitive to variability's in the paving process and on the other hand because there is less time available to steer the process.

Additionally, from interviews with asphalt operators became clear that the operational handling of WMA is much more difficult than the operational handling of HMA. It is recommended to conduct further research to decrease the physical intensity for the operators of the asphalt team. Possibilities to decrease this intensity are on the hand reduce the viscosity of the mixture and on the other hand provide the team equipment to make the operational handling with WMA easier.

4. CONCLUSIONS AND FUTURE RESEARCH

This paper monitored the Warm Mix Asphalt (WMA) process for two project and analysed this from the operational perspective of the asphalt team. We addressed and presented for these both case studies firstly the temperature of the mixture during the process and secondly the paving and compaction operations.

The gathered and presented data show a lot of variability in important parameters and working methods. For example in the initial surface temperature, compaction procedures, first roller pass after the paver, density, etc. However, these variability's are not specifically for WMA, but is more the consequence of an uncoordinated approach. Nevertheless, from the gathered and presented data we conclude that WMA seems more vulnerable for variability in quality parameters like temperature and the compaction operations than HMA and therefore give the impression to be more critical for the final quality of the asphalt pavement. And of course a loss of quality of the asphalt pavement will undo the whole advantage of WMA regarding sustainability.

Additionally, there is less time available for the whole paving and compaction process, which makes intensive monitoring and quality control more important. Technologies like a laserlinescanners, infraredcameras and thermocouples are useful to monitor the temperature during the process and GPS-equipment is applicable to monitor the movements of machinery and analyse working methods of the asphalt team.

The implication for decision makers is that the planning and organisation of the project need more attention at WMA-projects and that a continuous process should be realized. For planners this means that the logistic is more critical to provide a continuous stream of asphalt for the paver. Also, project managers need to be aware that WMA is more vulnerable for loss of quality and therefore requires a more comprehensive preparation of the paving and compaction process. Additionally, road agencies should also be aware of this vulnerability to variability and this knowledge should be taken into account in the decision making process for applying WMA or HMA in a project.

Yet, we must acknowledge that still much is unknown and unclear about the consequences of producing asphalt mixtures at lower temperatures on the paving and compaction process. A number of relevant questions still cannot be answered, such as the effects of different compaction procedures or variability in key parameters on the quality of the WMA pavement. Therefore, we propose (and pursue) further research projects to further understand the relationships between compaction procedures and variability in key parameters on the final quality of WMA. These relationships can for example be simulated in the laboratory. From different studies became clear that rolling compaction in the laboratory has the most similarities with field compaction (De Visser et al, 2006; Renken, 2002). So, for future research rolling compaction equipment in the laboratory can be useful to determine the effects of different compaction strategies on the final quality of the WMA pavement.

Furthermore the operational handling of WMA appears to be problematic for operators of the asphalt team. It is recommended to conduct further research to decrease the physical intensity for the operators, for example through reducing the viscosity of the mixture or providing the operators with equipment that makes the operational handling of WMA easier. So, decision makers should take into account that the operational handling of WMA is difficult and therefore decrease the amount of handwork as much as possible.

ACKNOWLEDGEMENTS

The contributions of the contractors 'BAM Wegen' and 'Dura Vermeer Infrastructuur bv' are gratefully acknowledged for the possibility to conduct on-site data collections on their projects and their assistance and support during the measurements.

REFERENCES

- [1] Alexander, M. L. and C. S. Hughes (1989). Compaction of asphalt pavement. Washington, D.C., *Transportation Research Board National Research Council*.
- [2] Bijleveld, F.R. (2010). Op basis van mechanische eigenschappen het bepalen van temperatuur- en tijdsvensters voor het verdichten van Nederlandse asfaltmengsels [Determine temperature- and time frames for compaction based on mechanical properties] (Free download at: <http://essay.utwente.nl/59418/>)
- [3] Chadbourn, B. A., Newcomb, D. E., Voller, V. R., Desombre, R. A., Luoma, J. A., and Timm, D. H. (1998). "An asphalt paving tool for adverse conditions." *Minnesota Dept. of Transportation Final Report MN/RC-1998*, 18.
- [4] Commuri, S. and M. Zaman (2008). "A novel neural Network-based asphalt compaction analyzer." *The International Journal of Pavement Engineering* 9(3): 177-188.
- [5] Decker, D. S. (2006). "State-of-the-Practice for Cold-Weather Compaction of Hot-Mix Asphalt Pavements." *Factors Affecting Compaction of Asphalt Pavements*, 27.
- [6] Floss, R. (2001). Compaction Technology in Earthwork and Highway and Transportation Engineering. Munich, BOMAG GmbH & Co. OHG.
- [7] Gudimettla, J. M., et al. (2003). Workability of Hot Mix Asphalt. NCAT. Auburn, Alabama, National Center for Asphalt Technology: 66.
- [8] Huerne, H. L. ter (2004). Compaction of Asphalt Road Pavements Using Finite Elements and Critical State Theory, University of Twente, PhD thesis.
- [9] Jordan, P. G., Thomas, M. E. (1976). "Prediction of cooling curves for hot-mix paving materials by a computer program." *Transport and road research laboratory report*.
- [10] Luoma, J. A., Allen, B., Voller, V. R., Newcomb, D. E. (1995). "Modeling of heat transfer during asphalt paving." *Numerical methods in thermal problems*, 6 (2), 1125-1135.
- [11] Mieczkowski, P. (2007). "The effect of weather and climate factors of temperature drops in built-in asphalt mixtures." *Foundations of Civil and Environmental Engineering*(9): 95-104.
- [12] Miller, S.R. (2010). Hot mix asphalt construction – Towards a more professional approach. University of Twente, PhD thesis.
- [13] NAPA - Prowell, B.D. and Hurley, G.C. (2011). Warm-mix asphalt: Best practices. National asphalt pavement association, 2011.
- [14] NCAT (1991). Hot Mix Asphalt Materials, Mixture Design and Construction, NAPA Research and Education Foundation.
- [15] Renken, P. (2002). Verdichtung von walzasphalt im laboratorium und im Felde. TU Braunschweig, Institut für Strassenwesen, PhD thesis, Braunschweig, 2002.
- [16] Timm, D. H., et al. (2001). "Calcool: A multi-layer Asphalt Pavement Cooling Tool for Temperature Prediction During Construction." *International Journal of Pavement Engineering* 2(3): 169 - 185.
- [17] Van Dee, R. (1999). Modelling of the compaction of asphalt layers: A survey into the influence of various factors on the compaction of asphalt layers in practice, Technische Universiteit Delft.
- [18] Van Stek, P. J., en Linden, A. H. G. (1992). *Het verdichten van asfalt in de praktijk*, VBW-asfalt.
- [19] VBW-asfalt. (2000). Asfalt in wegen- en waterbouw.
- [20] Visscher J. de, Maeck, J, Vanelstraete, A. (2006). The permanent deformation law of asphalt mixtures: investigation of the effect of mix composition and material properties, Brussel, 2006.
- [21] Vasenev, A. Bijleveld, F.R., Hartmann, T. (forthcoming). A real-time system for prediction cooling within the asphalt layer to support rolling operations. Proceedings Eurobitume, 2012, Istanbul.

- [22] Wise, J. C. and R. Lorio (2004). A practical guide for estimating the compaction window for thin-layer HMA. CAPSA '04 - 8th Conference on Asphalt Pavements for Southern Africa. Sun City, South Africa. **ISBN 1-920-01718-6**.