A LABORATORY STUDY ON THE USE OF WAXES TO REDUCE PAVING TEMPERATURES

H. SOENEN[1], T. TANGHE[1], P. REDELIUS[1], J. DE VISSCHER[2], F. VERVAECKE[2], A. VANELSTRAETE[2]
[1] Nynas Bitumen AB, Noorderlaan 183, 2030 Antwerp, BELGIUM
[2] Belgian Road Research Centre, Woluwedal 42, 1200 Brussels, BELGIUM

ABSTRACT

There is considerable interest in the possibilities of producing and paving asphalt at reduced temperature. A reduction of the temperature generates a significant reduction in energy consumption, emissions and fumes. Also health and safety conditions for the road workers are improved.

This paper presents the first results of a common research project of Nynas and BRRC, in which three techniques for reducing production temperatures are considered: the addition of waxes as viscosity reducers, the addition of zeolites as foaming agent and the use of foamed bitumen. The first phase of the project aims at developing laboratory procedures for assessing the potential of each technique to reduce the production temperature. If the mix undergoes curing after compaction, procedures to simulate and possibly accelerate the curing process also need to be developed. Small field trials are planned to validate the outcome of the laboratory work. In a second phase, the performance of the mixes produced at reduced temperature will be evaluated and compared to standard hot mix asphalt, since requirements on asphalt performance (including stiffness, durability, resistance to permanent deformation and cracking) have to be fulfilled. Test sections are planned in a third phase, to extrapolate and validate the laboratory results by field data and experience. This paper describes the first phase results of the technique using waxes as viscosity reducers.

Keywords: warm asphalt, waxes, rheology, viscosity, gyratory compaction, wheeltracking

1. INTRODUCTION

Traditionally, asphalt mixtures are produced and laid respectively at temperatures between 180 and 150°C. These high temperatures are needed to achieve a low viscosity of the bitumen which facilitates a complete and strong coating of the aggregates and which allows a good workability and compactability of the asphalt mixture. In the asphalt industry there is interest in exploring the possibilities of producing and paving asphalt mixtures at lower temperatures (80-120°C), the advantages of producing at lower temperatures are obvious, including reduced energy consumption, reduced emissions and fumes, improved health and safety conditions for the road workers.

Several processes are available to reduce the mixing and compaction temperature of hot mix asphalt, one of these processes uses waxes to reduce the viscosity of the bituminous binder in the high temperature range (1-4). In order to be efficient, this wax should be solid at the highest service temperature, but at temperatures above the highest service temperature the wax should melt, become liquid, lower the viscosity of the mixture and in this way should allow production and compaction of asphalt mixes at reduced temperatures. Literature shows that waxes with a melting range between 100°C and 145°C have been used as viscosity reducers. According to the producers of these waxes, a temperature reduction of 30°C can be achieved compared to standard hot mix applications. Apart from their ability to reduce the production temperature, these waxes are also promoted as performance improvers for rutting (5, 6).

In this paper a laboratory study is presented with the aim to evaluate the potential of various commercially available waxes to reduce the production temperature of asphalt mixtures. In addition, this study aims at providing quantitative information on the range of temperature reduction that can be expected as well as on the amount of wax that needs to be added. The possible potential of waxes to improve the resistance to permanent deformation is also evaluated. The paper is subdivided into two parts: First, tests on the as-received waxes and on the bitumen-wax blends are discussed, afterwards, tests on asphalt mixes are described.

This paper belongs to a larger project between Nynas and BRRC in which three techniques for reducing production temperatures are considered: the addition of waxes as viscosity reducers, the addition of zeolites as foaming agents and the use of foamed bitumen. The first phase results of the technique using zeolites are presented in reference 14.

2. TESTS ON WAXES AND BITUMEN-WAX BLENDS

2.1 Materials

Ten commercial waxes were collected, denoted alphabetically from A to J. The bituminous reference binder is a paving grade bitumen 50/70. The temperature reduction potential, as well as the performance related properties of the wax modified bitumen (WMB), are compared to this reference binder. WMBs were prepared by adding the wax pellets to hot bitumen and by continued blending at 160°C for 1 hour. Two experimental methods were used, Differential Scanning Calorimetry (DSC) and Dynamic Shear Rheology (DSR). The DSC equipment was a TA instruments 2920

Modulated DSC. The DSR equipment was a Paar Physica MCR500, with the 8 mm and 25 mm plates. For the high temperature measurements, a Paar Physica MCR101 equipment was used with a cup-cylinder geometry.

2.2 Investigations on the as-received waxes

Differential scanning calorimetry (DSC) was used to investigate the melting and crystallization behaviour of the pure waxes. The samples were first cooled from 180°C to -70°C at -10°C/min and subsequently heated at the same heating rate. Cooling scans are presented in Figure 1. Crystallization, in most cases observed during cooling, can be followed as an exothermal signal; melting is observed in the heating scan as an endothermal signal; and a glass transition is observed as a shift in the baseline. The surface of the endo- and exothermal signals, calculated as an enthalpy, gives an indication of the amount of crystallizing material. Some important parameters are represented in table 1: the temperature where crystallization starts on cooling (Tc-onset), the temperature where melting starts on heating (Tm-onset) and the enthalpy of the crystallization signal on cooling. If more than one signal is observed, the values for the smaller signal are placed between brackets.

Table 1: Calorimetric and viscosity properties of the as-received waxes and of the reference binder B50/70.

Samples	**Tc-onset Cooling [A] (°C)**	**Tm-onset Heating [A] (°C)**	**ΔH Cooling[B] (J/g)**	**Viscosity at 150°C ($20 s^{-1}$) (Pa.s)**	**Temp. of viscosity increase (°C)**	**Remarks**
Ref. bitumen	-	-	-	2.14E-01	-	
Wax-A	140-(75)	(65)-125	127	8.79E-03	143.0	
Wax-B	140-(70)	(67)-120	139	7.90E-03	142.5	
Wax-C	140-(70)	(60)-120	141	8.42E-03	144.4	
Wax-D	110	60	268	5.43E-02	114.2	
Wax-E	100	60	247	8.35E-03	101.0	
Wax-F	100	30	226	4.05E-02	105.7	Broad crystallization range
Wax-G	100	45	234	1.07E-02	104.5	
Wax-I	47	57	27	2.54E-01	-	Low degree of crystallinity
Wax-J	36	45	20	3.37E-01	-	
Wax-H	(120)-80	86-(100)	47	7.26E-03	-	

[A] *if more than one signal, the smallest signal is placed between brackets*
[B] *only the value for the largest signal is given*

From the DSC behaviour the samples can be subdivided into five types: In figure 1, an example of each type is shown.

1. Wax-A, Wax-B and Wax-C, show a large and sharp crystallization signal on cooling, starting at 140°C, followed by various very small crystallization peaks at lower temperatures. These three samples behave very similar.
2. Wax-D shows a large and sharp crystallization onset, starting at 112°C, but the exothermal signal broadens somewhat at lower temperatures with an end-crystallization temperature at around 60°C.
3. Wax-E shows a large crystallization signal, starting at 102°C and ending around 60°C.
4. For Wax F and Wax-G the shape of the crystallization signal is very similar to Wax-E, but for these samples the sharp crystallization signal, at high temperature (around 105°C) is small and is combined with a large signal that covers a very broad temperature range, extending to temperatures below 20°C. In these samples a lot of material still has to crystallize at temperatures below 60°C, and this could cause problems at high service temperatures if these samples are to be used in asphalt mixes.
5. Wax-H, Wax-I, Wax-J show only very small crystallization signals, seen as small peaks, and have at lower temperatures, below 0°C, a shift in baseline related to a glass transition (this is not shown in Figure 1). The crystallinity of these three samples is very low, therefore these waxes will soften the binder at all temperatures, also at high service temperatures, and this can cause problems.

Viscosities of the as-received waxes could be investigated, at least in the molten state, using a bob-cylinder type rheometer in rotational mode. Dynamic viscosities were measured during cooling from 180°C to 80°C at a cooling rate of -2°C/min. Some cooling scans are shown in figure 2, together with a scan of the reference binder. The sharp increase in viscosity of these samples is caused by the crystallization onset. At this point, the measurements had to be stopped because the samples became too stiff to be measured in a bob-cylinder geometry. In table 1 some viscosity parameters, such as the temperature where the viscosity increases as well as the level of viscosity at 150°C are included. The level of the viscosity at 150°C is for most waxes below the viscosity of the reference bituminous binder. In order to achieve a viscosity reduction of the reference binder by adding waxes this is of course a necessary condition.

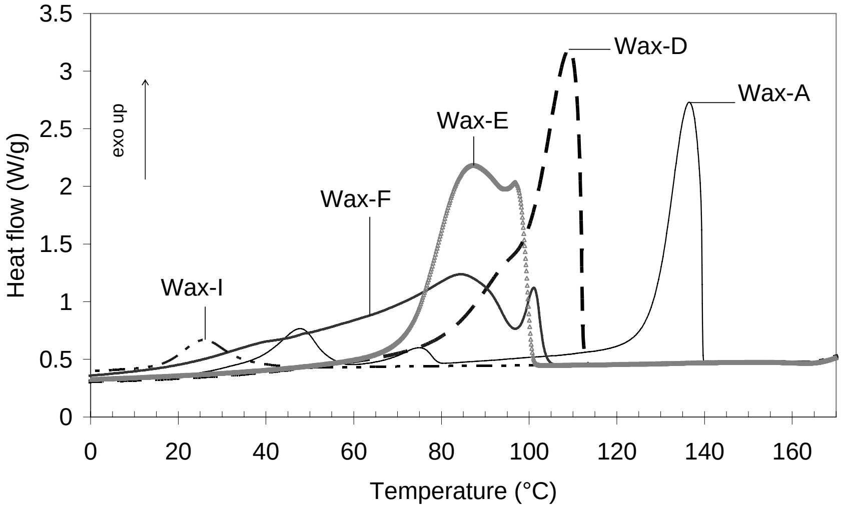

Figure 1: DSC cooling scans (-10°C/min) of pure waxes

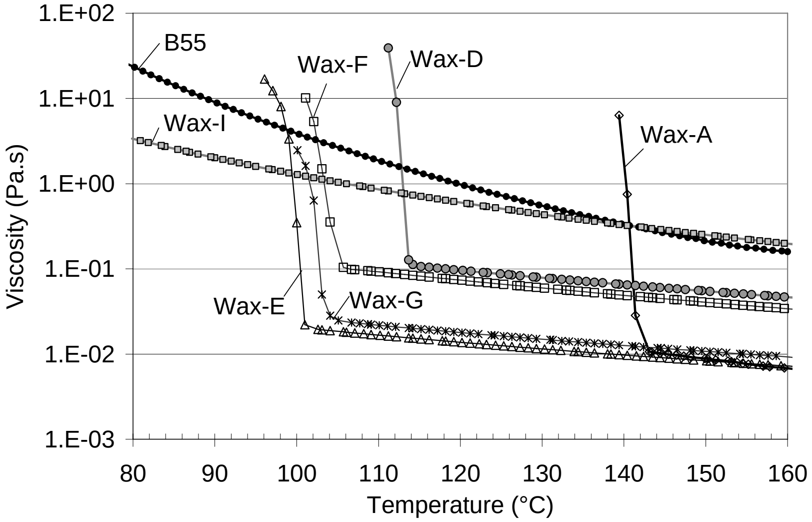

Figure 2: Dynamic viscosities of reference binder B55 and pure waxes (shear rate 20/s, cooling rate -2°C/min).

2.3 Tests on bitumen-wax blends at production temperatures

Similar tests were done on the waxes blended with the B50/70 reference binder, in a concentration of 3% wax. As this concentration is recommended by wax producers it was used as a starting point. DSC cooling scans are shown in figure 3. Compared to the pure waxes the bitumen –wax blends show a considerable decrease in crystallization temperatures, which indicates some interaction of the wax with the binder. For example, for Wax-A there is a temperature drop of about 40°C between the crystallization onset in the pure and in the blended form. For Wax-D this drop is about 20°C. The waxes (H, I, J) which showed small crystallization signals in the pure form did not show any exothermal signal anymore in the 3% blends. In table 2, some parameters for the blends are summarized.
Viscosities of the 3% Wax Modified Bitumen (WMB), with the reference binder B55 as base binder, were investigated at temperatures between 160°C and 60°C, see figure 4. As for the pure waxes, the crystallization of the wax results in a sharp increase in viscosity, and again a sometimes large temperature depression between the pure and the WMB was observed. Although most of the pure waxes have a lower viscosity than the reference binder in this temperature range, the viscosity reduction in the 3% WMBs is rather limited, especially if this decrease in viscosity is expressed as a shift in temperature. Equi-viscous temperatures are included in table 2. Compared to the reference binder the temperature shift is limited to a maximum of 6°C. Since the viscosity reduction for 3% blends is limited, higher concentrations of wax in bitumen were investigated; but even for 5% WMBs the reduction in viscosity was still limited.

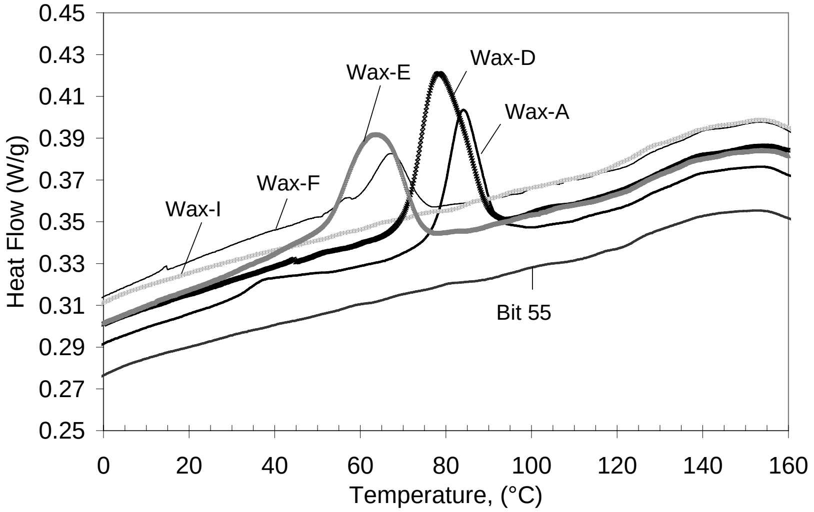

Figure 3: DSC cooling scans of 3% WMBs , compared to the reference binder (cooling rate -10°C/min).

Table 2: Calorimetric and viscosity properties of 3% WMBs and of the reference binder.

Samples	**DSC Tc-onset cooling (°C)**	**Temp. viscosity increase (°C)**	**Viscosity at 150°C ($20s^{-1}$) (Pa.s)**	**Equivisc. temp. for 1Pa.s (°C)**
Ref. binder	-	-	0.214	120
Wax-A	101	94	0.160	114
Wax-B	102	96	0.163	116.5
Wax-C	102	96	0.169	116
Wax-D	93	93	0.175	115
Wax-E	77	79	0.166	114
Wax-F	76	78	0.168	114
Wax-G	81	80	0.160	112
Wax-I	-	-	0.210	119
Wax-J	-	-	0.218	120
Wax-H	-	-	0.162	114

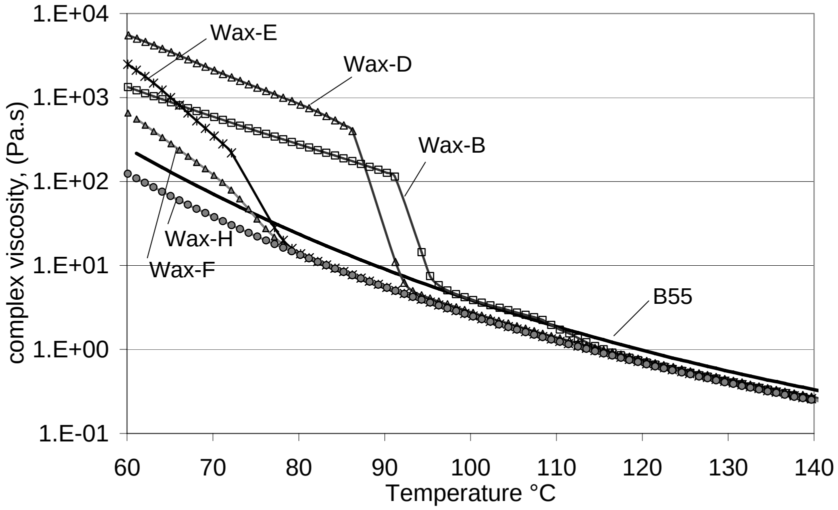

Figure 4: Complex viscosity during cooling for various 3% WMBs and for the reference binder (cooling rate -2°C/min; 1Hz, 1% strain)

Another parameter that can be varied is the penetration level of the base binder. Using a softer binder results in a larger viscosity reduction, but this can of course only be used if the stiffness at high service temperatures is not negatively influenced. Performance-related tests at service temperatures will be discussed in detail in the next section. The effect on viscosity of using more wax or a softer base grade bitumen is given in table 3. For example, the reduction in viscosity is largest after adding 5% of wax (E, in this case) to a base binder with a penetration of 180 mm/10 and corresponds to a temperature shift of about 25°C.

Table 3: Influence of wax concentration and base binder penetration on the viscosity properties of WMBs.

Pen Base binder mm/10	**Wax type and concentration**	**Temp. viscosity 1Pa.s, (°C)**	**Pen Base binder mm/10**	**Wax type and concentration**	**Temp. viscosity 1Pa.s (°C)**
55 (ref.binder)	-	120	80	+ 2% Wax E	111
55	+ 2% Wax-B	117.5		+ 3% Wax E	109
	+ 3% Wax B	116.5		+ 4% Wax E	107
	+ 4% Wax B	115.5	100	+ 5% Wax E	102
	+ 2% Wax-D	117	180	+ 3% Wax E	99
	+ 3% Wax-D	115		+ 4% Wax E	98
	+ 4% Wax-D	114		+ 5% Wax E	96

2.4 Tests on bitumen-wax blends at service temperatures

In this section, performance-related binder tests were conducted on several 3% WMBs using the reference binder B55 as base binder. Conventional tests are shown in table 4. From table 4 it is clear that the three waxes that showed only small signals in the DSC tests (Wax-I, Wax-J and Wax-H) also show a very limited increase in R&B temperature. For the two waxes with a very broad DSC signal (Wax-F and G) only Wax-G shows a considerable increase in softening point while the other sample, Wax-F, shows an increase of only 10°C. The other waxes all show large increases in softening point.

The waxes with a considerable increase in softening point were considered in DSR testing. Frequency sweeps were made from -10°C to +90°C, in order to have an idea of the low temperature performance and also the high service temperature performance. For the low temperature performance the stiffness at 1Hz and 0°C is included in table 4. One can observe that this stiffness level is never increased by more than 5% which at least indicates that the low temperature stiffness is almost not influenced by adding 3% of wax to the base binder. For Wax-E, F and G the low temperature stiffness is even slightly decreased.
To assess the rutting susceptibility, two parameters are included in table 4: the SHRP high temperature Performance Grading (PG), measured on the original binder at a frequency of 1.59 Hz, and a low frequency parameter measured at 50°C. It can be observed that the PG temperature can increase by 16°C, just by adding 3% of, for example Wax-C, to the base binder. A low frequency parameter is also given in table 4, since in reference 7 it was observed that the relation between experimentally measured rut depths and binder stiffness levels improved if the frequency was reduced to 0.01Hz. The low frequency stiffness at 50°C is increased for all the waxes added, in some cases the increase is more than a decade. A change of one decade can be compared to a change from a base binder pen 50/70 to a base binder pen 10/20.

Table 4: Conventional and rheological properties of the reference binder and various WMBs. All blends consist of 3% of the respective wax in the B50/70 ref. binder.

Samples	**Pen 25°C (mm/10)**	**R&B (°C)**	**Temp.G*/sin(δ) = 1kPa, 1.59 Hz, 1% strain (°C)**	**G*/sin(δ)- 0.01Hz & 50°C 1% strain (Pa)**	**G* - 1Hz - 0°C 0.05% strain (Pa)**
Ref. bitumen	55	49.0	68	1.13E+02	9.85E+07
Wax-A	45	100.6	79	8.49E+02	1.02E+08
Wax-B	42	93.3	82	10.26E+02	1.03E+08
Wax-C	43	100.5	84	15.04E+02	1.07E+08
Wax-D	40	102.0	79	6.63E+02	1.12E+08
Wax-E	35	78.9	76	5.85E+02	7.77E+07
Wax-F	53	59.4	70	1.39E+02	7.58E+07
Wax-G	40	90.0	72	2.46E+02	9.32E+07
Wax-H	49	52.7			
Wax-I	53	50.0			
Wax-J	56	55.5			

There are large differences in stiffening effect at 50°C between the different wax types. Those waxes which show sufficient crystalline material in the DSC cooling scan, that crystallizes at high enough temperatures (above 60°C) show the largest stiffening effects. So in practice those waxes with a large exotherm occurring over a small and high temperature range seem to be most suited to improve the resistance against rutting .

Upon analyzing the DSR behaviour in detail it was observed that the stiffness of wax modified binders is very strain sensitive, the stiffness reduces very quickly if the applied torque level increases. The authors have also shown this in reference 8. In figure 5 stress sweeps, recorded at 50°C and at 0.01Hz, on some selected samples are shown. Compared to unmodified and polymer modified binders, these WMBs can be considered as strain sensitive binders. The finding that WMBs are much more strain sensitive than unmodified or polymer modified binders at high service temperature is very important. In literature, there is a lot of discussion if performance indicators for rutting should be measured inside or outside the linear viscoselastic (LVE) range (9, 10). For unmodified and polymer modified binders the LVE range is rather large and the question is not so crucial, but for these WMBs the LVE range is limited to low strain levels, and maybe not representative of the strain and stress level(s) the binder feels when loaded in an asphalt layer in a road. For the time being it is not clear what stress or strain level should be used in binder tests and how this relates to a stress or strain level in asphalt mix tests. In reference 11 a value of 300% strain is suggested, but this depends on many factors, such as thickness of the binder film, void content and aggregate grading. In the section on asphalt mix tests some experimental rut measurements on waxy samples, loaded in an MLPC rut tester at 50°C will be discussed and related to the binder tests.

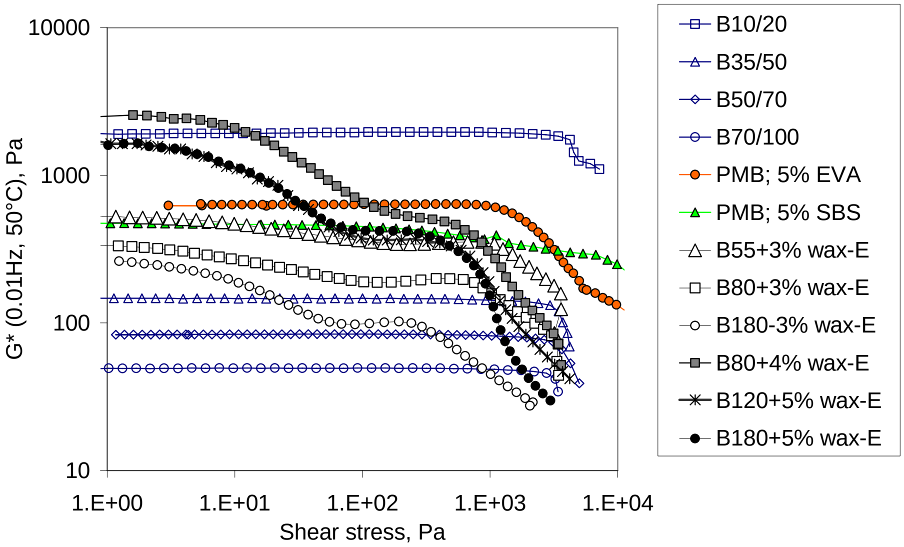

Figure 5: Strain dependency at 50°C and 0.01Hz of some selected WMBs, some PMBs and some unmodified binders.

2.5 Proposed system to select base binder and concentration of wax

In the previous sections, general properties of various waxes and WMBs were presented. In table 3, it was shown that the viscosity reduction for a specific wax and bitumen blend is dependent on the wax concentration and the penetration level of the base binder. In this section a method to estimate the reduction in temperature for one selected wax material (wax-E) is given.

The viscosities of several WMBs with wax-E at three different concentrations and with base binders with different penetration levels, were tested and the temperature where the viscosity has a certain value, in this case 1Pa.s, is plotted versus the penetration level of the base binder (see figure 6). If we assume that compactability is related to the viscosity of the binder, an assumption that is often used in literature for unmodified (12) and for modified binders (13), this figure can be used to see how a temperature reduction of 20°C, based on equi-viscosity levels, can be achieved. Several options exist: If 5% of wax is used it would be sufficient to use a softer base binder with a pen. level of around 125, if 4% of wax is added a pen base binder of 155 should be used, and if this needs to be achieved with only 3% of wax a base binder of pen 170 needs to be used. Of course, before using a base binder with a penetration of 170, one should also consider performance related parameters, as is further discussed below.

Regarding performance, the rutting sensitivity is considered as the most critical parameter, certainly if the penetration level of the base binder would be increased in order to get sufficient temperature reduction. In this study, the stiffness at 50°C and at a frequency of 0.01Hz is used as a binder performance indicator for rutting, since in a previous study it was found that this parameter is a good performance indicator for unmodified and also polymer modified binders (7). In figure 7 the level of stiffness (at 50°C and 0.01Hz), measured inside the LVE range is plotted for the base binders and various binder-wax blends. From this figure, it is clear that the stiffness of the reference binder (a value around 100Pa) is reached for all the WMBs, so this graphs would indicate that wax-E is excellent to improve the rutting resistance and also that a soft base binder (even a pen 180) could be used and would give sufficient rutting resistance. In figure 8 a similar graph is shown but now the stiffness level is measured at a much higher strain level, in this case 300% strain is used since this value is indicated in literature. Figure 8 illustrates that, in order to have the same range of stiffness as the reference binder, a base binder pen 180 could be used, provided 5% of wax is added. If only 3% of wax would be used, the penetration level of the base binder should not be higher than 140. Of course these conclusions are based on the assumption that the strain level of 300% (at 50°C and at 0.01Hz) is representative for the strain the binder experiences when loaded in a mix, an assumption which is not yet validated.

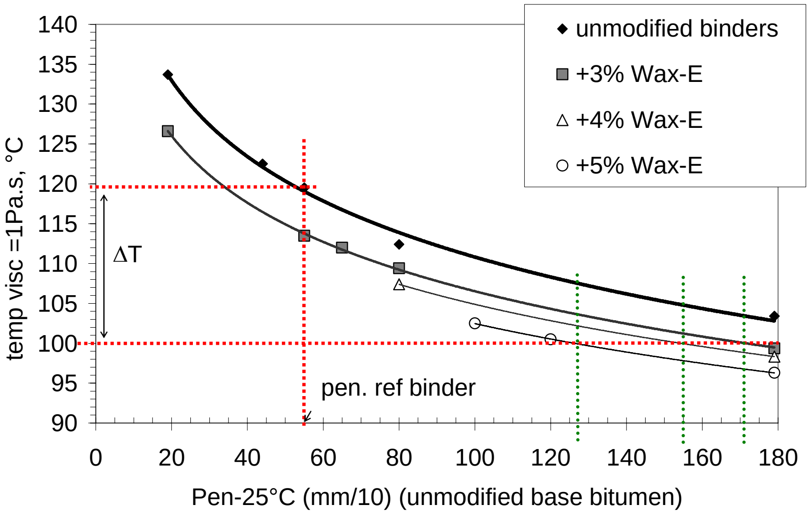

Figure 6: Equi-viscosity temperatures as a function of penetration level of the base binder

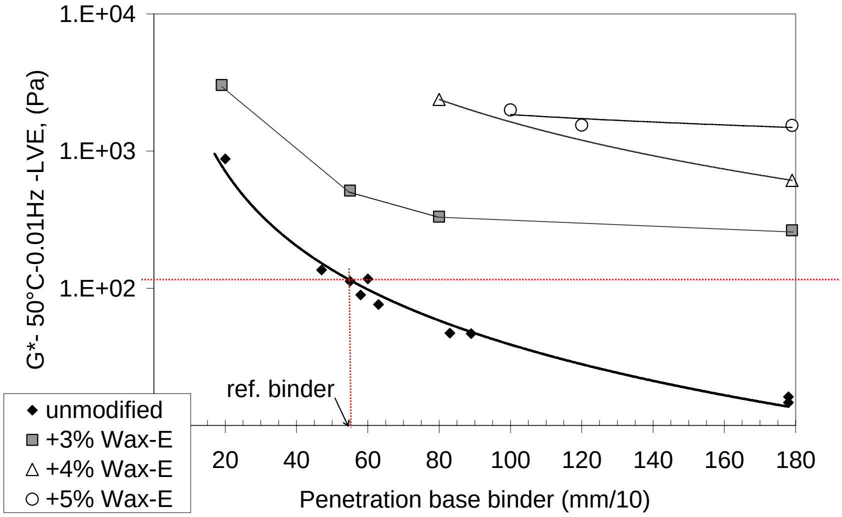

Figure 7: Stiffness at 50°C and 0.01Hz within linear visco-elastic range versus penetration of the base binder.

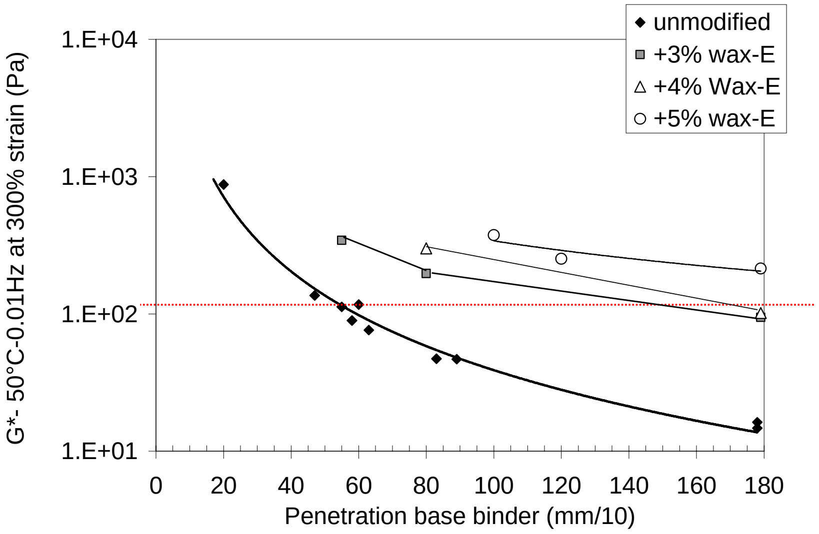

Figure 8: Stiffness at 50°C and 0.01Hz at 300% strain level versus penetration of the base binder.

2.6 Conclusions

In the previous section, a system was proposed to select the base binder and the wax concentration with the aim of achieving a given reduction in asphalt production temperatures. This system is based on, several assumptions:

- The reduction in temperature of compaction and paving is entirely related to the viscosity of the binder. Therefore, equi-viscosity temperatures measured on the binder-wax combinations can be used to predict the achievable reduction in asphalt production temperatures.
- The wax is compatible with the bitumen, so that there is no separate phase of nearly pure wax which could then keep its low viscosity. This assumption is in fact already validated by the viscosity tests on the WMBs described in the previous sections. The viscosity of a WMB relates very well to values that are expected for a compatible blend based on the viscosities of the 2 pure components.
- Regarding rutting sensitivity, the assumption is made that binders with equal stiffness at 50°C, at 0.01Hz and at 300% strain will have similar rutting resistance. This assumption is based on a rough estimation found in literature, that the strain level of the binder in a mix, if loaded at high temperature, can achieve strain levels of 300%. Of course this strain level will depend on the mix type, in particular on the amount of binder, the thickness of the binder film, the void content, angularity of aggregates, amount of coarse material, etc.

In the following section, these assumptions will be verified by asphalt mix tests.

3. ASPHALT MIX TESTS

3.1 Mix Design

The study was made with a mix type AB-4C, which is specified in the standard specifications of the Flemish region (SB 250 v2.1). This is an asphalt concrete mix for top layers, AC 0/10 according to the European standards. Use was made of the PradoWin software of BRRC. With the characteristics of the different constituents as input data, this software predicts the volumetric composition and void content of the mix for a given mix composition. Table 5 shows the dry mix composition. The grading of the mix is shown in figure 9. The binder is added in 6.2 % by mass on the aggregate mass (5.84 % by mass in the mix). The same mix design was used for the reference binder and for the wax modified binders. All wax modifications in the asphalt mix tests are made with wax-E.

Table 5: Composition of the reference mix AC 0/10 (dry aggregates)

Type	Component	Density (g/cm³)	Volume (%)	Mass (%)
Fillers	Duras II	2.61	7.7	7.4
Coarse Aggregates	porphyry 4/6.3	2.72	19.9	20.0
Coarse Aggregates	porphyry 2/4	2.71	22.4	22.5
Coarse Aggregates	porphyry 6.3/10	2.71	16.6	16.7
Sand	porphyry 0/2	2.72	25.1	25.3
Sand	Round sand	2.62	8.4	8.1

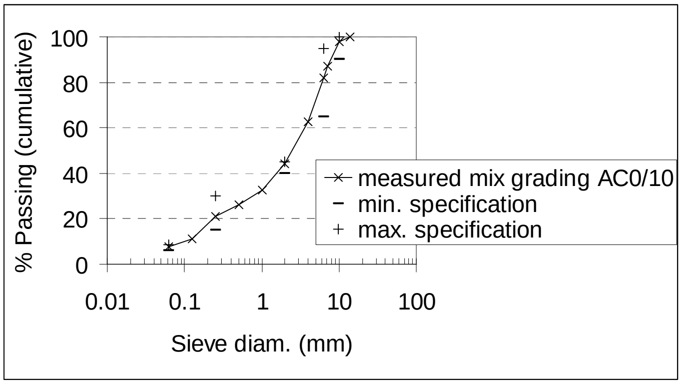

Figure 9: Grading of the reference mix AC 0/10, compared to the specifications of SB250 (Flemish standard tender specifications)

3.2 Compaction tests

The gyratory compactor was used according to the European standard (EN 12697-31). The mix preparation procedure followed EN 12697-35. According to this standard, the reference temperature (temperature at which compaction starts) of the hot mix asphalt type AC 0/10 should be 150 °C (for a bitumen B 50/70). When the compaction temperature is decreased, the viscosity of the binder increases and it becomes more difficult to compact the mix. This is seen in figure 10, where the void content increases with deceasing compaction temperature, although the sensitivity of the void content to compaction temperature is not very high. Each result presented in figure 10 is the average of three compaction tests. The temperatures on the horizontal axis are compaction temperatures. The mixing temperature was systematically 20 °C above the compaction temperature. Compaction was started when the temperature in the mix was at the compaction temperature ±5 °C. Figure 10 also shows the effect of using a wax-modified binder (a pen 80+3% wax-E) and a softer base binder (B180, without wax). The temperature reduction based on equi-viscosity levels would for these two samples be about 10°C for the waxy sample, and 18°C for the B180.

Figure 10 shows that, at 150°C and at 135 °C, the wax-modified binder gives a somewhat lower void content compared to the reference mix. At 120°C, 105°C and at 90°C the void content is almost the same. Although the effects are small compared to the standard deviations (error bars), the averages over the two highest temperatures indicate that the same void content as the hot mix can be obtained for mixes with wax and with a temperature reduction of about 10°C. These tests also show that a temperature reduction of 30 °C, as is advertised by wax producers will result in a larger void content of the wax modified mixes compared to the reference mix prepared at the reference temperature of 150°C.

For the very soft and unmodified binder, B180, the compaction was only tested at one temperature, 120°C and at this temperature clearly a larger temperature reduction would be possible, but of course this result is only based on the three repeats at one temperature and this mix would perform worse for rutting compared to the reference mix.

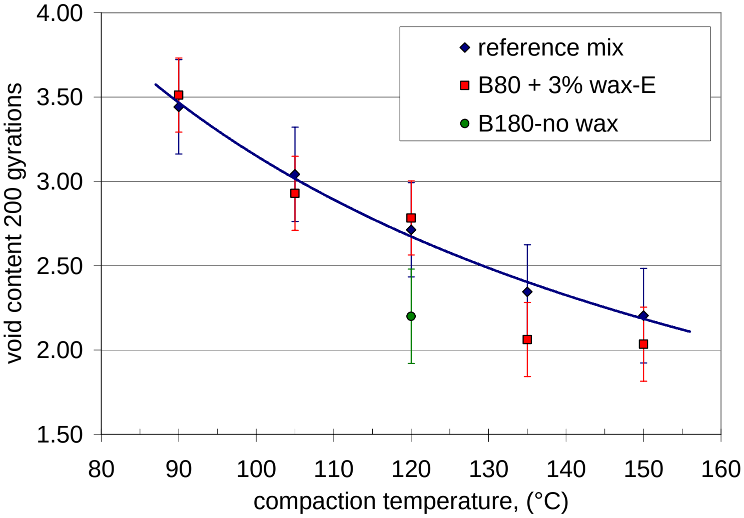

Figure 10: Void content at 200 gyrations as function of compaction temperature (mixing temperature always 20 °C above compaction temperature).

In addition, the MLPC plate compactor was used for the preparation of test plates (dimension 50x18x5 cm) to be used for the wheel tracking tests described in the following paragraph. The plates prepared with the wax-modified binder, when compacted at 135 °C, had a smaller void content than the plates prepared with the reference binder, when compacted at 150 °C. The improved compactability with the wax-modified binder is thus also seen in the plate compactor, but since the number of compacted plates is very limited, it is not possible to derive quantitative information regarding the amount of temperature reduction from the plate compaction tests.

3.3 Wheeltracking tests

A few rutting tests were performed in order to verify the assumptions made in section 2.5. The tests were performed with the MLPC rut tester at 50°C. The selected binder and binder-wax blends were:

Reference binder
B180+5% wax, B120+5% wax, B80+3% wax

With the reference binder, three sets of plates were prepared and tested: one set was compacted at 150 °C, one at 120°C, and the one at 90 °C.

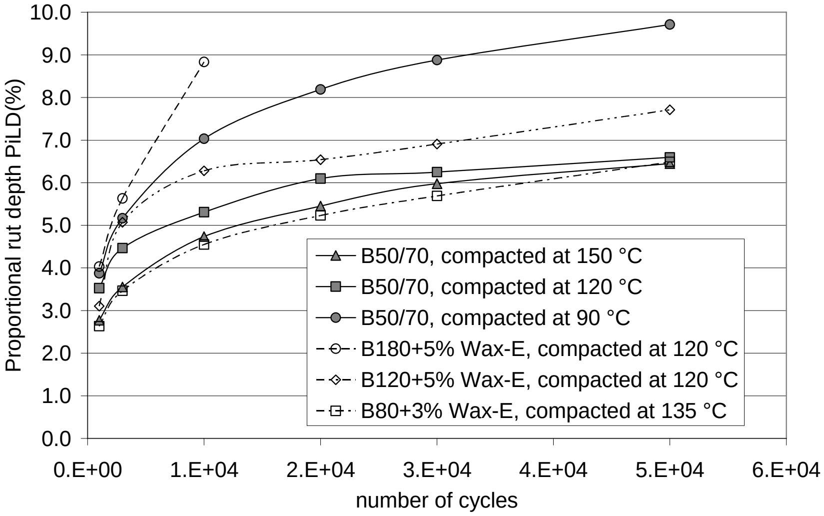

Figure 11: Wheel tracking tests on reference and some selected wax modified binders, at 50°C.

From the limited number of rutting tests that were performed, graphically shown in figure 11, we can already draw some preliminary conclusions:

- The experimentally determined rut depths of the samples modified with waxes, using the MLPC rut tester at 50°C, cannot be predicted by the LVE stiffness level and also not by the stiffness level (50°C, 0.01Hz) at 300% strain. The rut depths are much larger as would be predicted from these two stiffness levels.
- For these (few) rutting experiments, no relation between binder stiffness versus rut depth could be obtained, if the stiffness obtained at a fixed strain level was used, instead by using the stiffness obtained at fixed stress levels it was possible to have an agreement between the rut depths, obtained until now, and the binder stiffness. A stress level of 2000Pa (50°C and 0.01Hz) is at this stage still in agreement with the test results obtained in this project and also in ref 7. This stress was obtained by comparing rut depths found for the wax-modified mixes to rut depths of unmodified mixes, in the same mix design. For example the sample B180+5% wax-E has similar rut depths as a mix prepared with an unmodified B70/100 mix, and the sample B80+3% wax-E has a rut resistance similar to the reference mix. The stress level found here will certainly depend on the particular mix design used (binder film thickness, void content, angularity of aggregate material,…) and also on the particular type of rutting equipment used (load levels, rate, …), but this was not investigated in this study. For a number of other binders (unmodified and polymer modified) the stiffness level at a stress level of 2000Pa (and at 50°C and 0.01Hz) is still inside or just on the starting point of non-linearity. This would still be in agreement with the findings from our previous study (ref. 7), where rut depths could be predicted using LVE stiffness levels, since this study was only using unmodified and polymer modified binders, for which the stress level is not a crucial parameter (see also figure 5).

In figure 12 the stiffness levels at 2000Pa of unmodified and several WMBs binders are shown. Figure 12 indicates that for 3% wax added, the softest base binder that can be used without deteriorating the rutting resistance would be a pen 80 binder. For 4% wax addition, this would be a pen 90 and for 5% wax a pen 110.

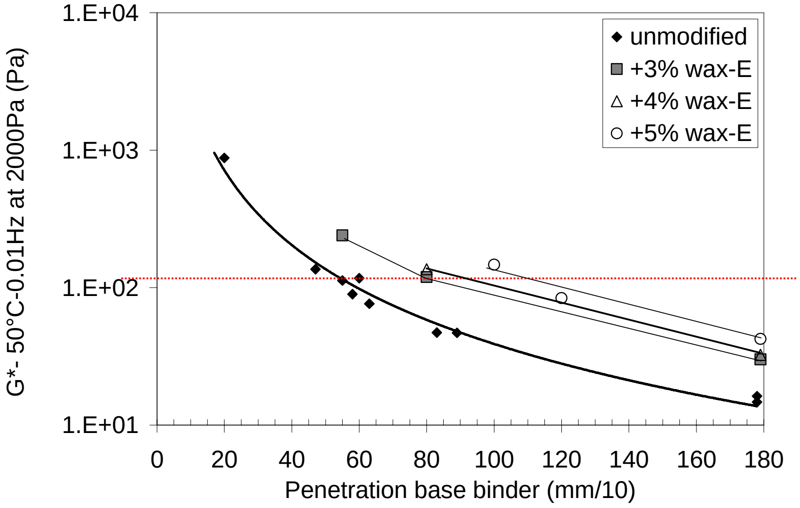

Figure 12: Stiffness at 50°C and 0.01Hz at a stress level of 2000Pa versus penetration of the base binder.

4. DISCUSSION AND CONCLUSIONS

In this paper, general properties of commercial waxes and of wax modified binders (WMBs) were shown. Most waxes (as received) show rather large peaks in the DSC signals, associated with crystallizing and melting material. The crystallization and melting temperatures can vary a lot as well as the degree of crystallinity. In some cases the crystallization and melting temperature ranges are very broad, covering a temperature range from 20°C to above 100°C. Waxes show some interaction with bitumen since upon adding wax to bitumen the melting point depression can be considerable, 20 to 40°C. For those waxes with only a small degree of crystallinity in the pure form, no signals of crystallinity in the blended form were observed, most likely these waxes dissolve completely in the bitumen. These waxes soften the base binder at all temperatures and are not suited as an additive in asphalt.

Most waxes have in the liquid form a viscosity that is below the viscosity of bitumen and therefore they can indeed be used as viscosity reducers. However upon addition of 3% of wax to a reference binder the reduction in viscosity, expressed as a shift in temperature, is limited to 6°C in the best case. Larger effects on the viscosity reduction, in the range of 15 to 20°C, can be achieved by increasing the amount of wax added (which is economically not always feasible) or by increasing the penetration level of the base binder. The viscosity reduction as a function of three wax contents (3%, 4% and 5%) and as a function of penetration level of the base binder has been evaluated in detail. But if the penetration level of the base binder is reduced the wax should stiffen this base binder sufficiently at high service temperatures where rutting can take place and should at these temperatures be in the crystalline form.

Waxes with enough crystalline material, melting at high enough temperatures, have a large effect on the R&B temperature, on the SHRP PG temperature for rutting, and also on the complex modulus at 50°C. These binder tests suggest that these waxes will improve the rutting resistance. However, it was also observed that WMBs are rather strain sensitive, so the stiffness quickly decreases if strain or stress is increased. Since, at this moment it is not clear what strain levels the binder feels when loaded in a mix, it is also not clear how waxes influence the rutting resistance.

Asphalt mix tests were conducted to verify on one hand if the viscosity changes are directly related to changes in compactibility and on the other hand to verify how the increased stiffness after adding wax to bitumen influences the rutting susceptibility. It has been shown that compactability levels measured using the gyratory compactor and the plate compactor are in agreement with the values derived from equi-viscosity levels of the bitumen-wax blend.

A limited number of rut tests have been conducted; these tests show that the linear visco-elastic (LVE) stiffness levels of wax-modified binders over-estimate the rutting performance. For the conditions used in this study (for the particular mix design and rutting equipment used) rut depths can be related to the stiffness at a given high stress level at the same temperature as the rutting test and at a low frequency of 0.01Hz. For the WMBs this stress level is clearly outside the LVE range, while for unmodified and polymer modified binders it is inside or almost inside the LVE range.

The conclusions from this paper are listed below:

- Commercial waxes proposed for mixing into bitumen vary with respect to melting temperature and melting enthalpy.
- The most effective wax for temperature reduction of bitumen is a wax with a low viscosity at the temperature of interest, and in relation to performance with a distinct melting peak at high enough temperatures and a high melting enthalpy.

- The maximum temperature reduction with 3% of wax is about 6°C (based on binder viscosity and compared to the same base binder).
- The increased stiffness of the wax modified bitumen at temperatures where the wax is solid can be used for selection of a softer bitumen to further decrease the viscosity at construction temperatures.
- Unmodified bitumen is much more strain and stress resistant than wax-modified bitumen. Thus the increased stiffness cannot fully compensate for the use of a softer binder.
- The range of temperature reduction obtained from compaction tests are in agreement with the predicted range of temperature based on equi-viscosity levels.
- The rutting resistance of wax-modified mixes (in laboratory tests) cannot be predicted by the LVE stiffness level. The LVE stiffness over-estimates the behavior of wax-modified mixes.

5. ACKNOWLEDGEMENTS

The funding of IWT (Instituut voor de Aanmoediging van Innovatie door Wetenschap en Technologie in Vlaanderen) is gratefully acknowledged. The authors also acknowledge the input of the Nynas Technology Department Antwerp, and of the laboratory of BRRC.as well as the Nynas laboratory in Nynäshamn for DSC testing.

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