Assessing temperature reduction potential of various additives on binder and asphalt mix level for mastic asphalt

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ABSTRACT: In an ongoing study, the wax concentration in a polymer-modified binder is varied for different wax types to study their impact on binder viscosity by rotational viscometer (RV) tests. In addition, mastic asphalt (MA 11) was produced with different wax-modified binders in a lab mixer. The mixer is equipped with a dynamic torque sensor to derive the mixing-torque as a measure of workability during mixing. Thus, temperature reduction potential is studied on binder and mix level. As an alternative approach for temperature reduction of mastic asphalt, crushed aggregates were substituted by rounded aggregates.
It was found that amide wax has the highest potential for temperature reduction of mastic asphalt (-23 K at 4 wt.% related to binder mass). When substituting the 0/4 fraction by rounded aggregates, a reduction of 23 K can be realized, when substituting the 0/11 fraction, a reduction of 36 K is possible without use of waxes.

1 INTRODUCTION

Among the different asphalt mix types, mastic asphalt (German: Gussasphalt) holds a special position due to its composition, application and load transfer. The main components of mastic asphalt is filler with up to 40 wt.% (CEN, 2013) and bituminous binder with around 8 wt.% to 10 wt.%. Thus, about half of the mix is considered as mastic, the other half is taken up by coarse aggregates. Due to its composition with high binder and filler content, mastic asphalt is applied in the field without compaction, it is merely poured. Different from other asphalt mix types, mastic asphalt transfers load mainly by a stiff mastic and not by coarse aggregate interaction. In addition, the mix does not exhibit air voids. There is a wide range of applications for mastic asphalt as sealing and/or surface layer on bridges (Widyatmoko et al., 2005, Medani et al., 2007), as road surface layer for city centers where compaction would endanger historic buildings or as surface layers for walk and bike ways.

Since the mastic is responsible for load transfer, usually hard and in many cases polymer-modified binders are employed for mastic asphalt. To keep the mix pourable, the viscosity of the mastic and mix has to be low enough at the construction site. Thus, high temperatures of up to 250°C are necessary for mixing and paving. Since more than 70 % of the total energy consumption for asphalt mix production are dedicated to the mixing plant (Canada, 2005), mastic asphalt is especially energy-intensive in production. Also, a number of reports show that workers health is increasingly affected when bitumen is handled at temperatures over 200°C (Hansen, 1991, Ruhl et al., 2007, Kriech and Osborn, 2014). For these reasons, a temperature reduction in mastic asphalt is seen crucial for enhanced energy efficiency and a healthier work environment. The addition of waxes to bitumen is a state-of-the-art procedure to reduce the binder's viscosity above the waxes' drop points and reduce the mixing and paving temperature of asphalt mixes (Biro et al., 2009, Silva et al., 2010, Rubio et al., 2012, Wu and Zeng, 2012). Different types of waxes are available and employed with different effects on workability of the mix during production as well as on the performance of the mix in terms of resistance to permanent deformation at high temperatures and to cracking at low temperatures. Due to wax crystallization during cooling of the mix to ambient temperatures, waxes tend to increase the high temperature stability and decrease the low-temperature cracking resistance.

This paper compares the temperature reduction potential for a mastic asphalt mix with different wax-modified binders. In addition, an economic alternative to waxes for temperature reduction is investigated as well. Therefore, crushed aggregates are partly and completely substituted within the mastic asphalt. The investigations were carried out on two levels of observation, on the binder level and on the asphalt mix level.

2 MOTIVATION AND OBJECTIVES

Within a comprehensive research project, called <E>EMA (“High Efficiency Low Emission Mastic Asphalt”), optimized mastic asphalt mixtures are developed with regard to temperature reduction, mix performance and economic efficiency. The following steps are taken by the project:

1. Bitumen is blended with different waxes and different wax concentrations to study the effect of the waxes and their concentration on the temperature reduction potential by rotational viscometer (RV) tests with temperature sweep.
2. Mastic asphalt is produced with bitumen modified with different waxes in a lab mixer. The lab mixer is equipped with a mixing torque measurement unit to assess workability of the mixes at different temperatures.
3. An alternative approach for temperature reduction is taken by substituting usually used crushed aggregates by rounded aggregates in the mix and the workability is analyzed as well.
4. Mastic asphalt slabs are produced in lab using the methods that show best potential for temperature reduction. The resistance to permanent deformation by uniaxial cyclic compression tests (UCCT) and to low-temperature cracking by thermal stress restrained specimen tests (TSRST) are assessed and results are compared to results from the reference mix.
5. Thus, an optimized mastic asphalt mixture can be recommended with a maximum temperature reduction potential while keeping the mix performance at a high level and keeping the material costs low.

This paper presents results of the first three research items.

3 MATERIALS

For the presented research a mastic asphalt with a maximum nominal aggregate size of 11 mm (MA 11) was used. The filler component is powdered limestone, the coarse fraction are totally crushed aggregates of porphyritic origin. The grading curve is shown in Figure 1. For the binder, an SBS-modified PmB 25/55-65 (PG 82-16) was used. The main characteristics of the binder are listed in Table 1.

The mix consists of 8.2 wt.% binder and shows a maximum density of 2.46 kg/m^3 which is equivalent to the bulk density since no air voids are present in the mix.

Four waxes where employed to compare their temperature reduction potential, an amide wax (AW), a Fischer-Tropsch wax (FTW), a montan wax (MW) and a polyethylene wax (PEW).

As an alternative approach to lower the production temperature, the crushed aggregate was substituted partially and completely by rounded, calcitic aggregates, respectively. The filler component remained unchanged for each tested mix.

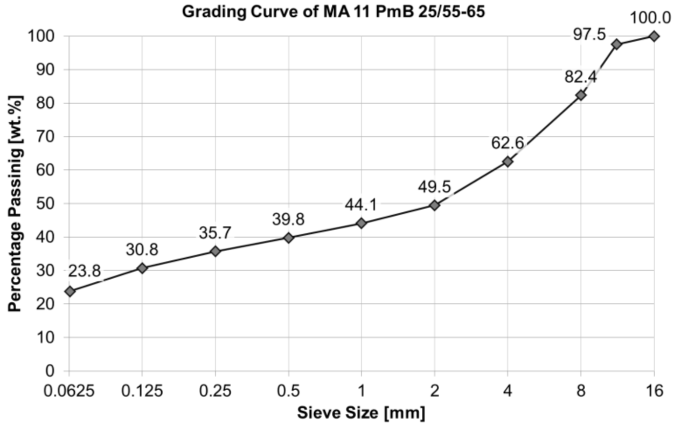

Figure 1. Grading Curve.

Table 1. Main characteristics of the PmB 25/55-65.

Parameter	Value
Needle Penetration at 25 °C	50 dmm
Softening Point Ring & Ball	77.6 °C
Performance Grade	PG 82-16

4 TEST METHODS AND TEST PROGRAM

Two test methods are applied to assess and compare the temperature reduction potential on binder level as well as on asphalt mix level: (a) the rotational viscometer (RV) for bitumen testing and (b) measurement of mixing torque in a conventional lab mixer for asphalt mix production.

4.1 *Rotational Viscometer (Bitumen Level)*

The rotational viscometer (RV) is a test device to measure the dynamic viscosity of bituminous binders. Figure 2 shows the principle of the device: It consists of a coaxial system of cylinders, a static outer cylinder (1) and a rotating inner cylinder (2). The outer cylinder is filled with bitumen (4). The radius of the spindle R_1 used for this research is 16.6 mm, the radius of the outer cylinder R_2 19.0 mm.

The momentum that is needed to keep the spindle rotating with a constant speed of 20 rounds per minute (RPM) is directly related to the resistance of the spindle to rotation and is thus, a measure of the dynamic viscosity of the tested sample. The dynamic viscosity of bitumen obtained by RV is used to describe the workability of bitumen at mixing and production temperature. (CEN, 2010)

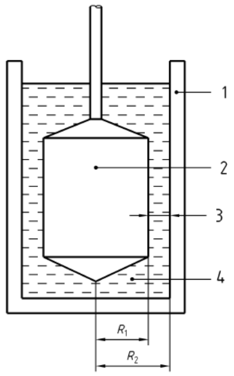

Figure 2. Principle of the RV (CEN, 2010).

4.1.1 *Test Program*

As shown in Table 2, a comprehensive test program was carried out on the original binder (PmB), as well as on binder, modified with the different waxes at concentrations ranging from 2 wt.% to 30 wt.% based on bitumen mass.

To mix bitumen with the waxes, the following procedure was carried out for all samples:

- Bitumen, sealed in cans, was heated at 180°C for 4 hours within a thermal chamber
- The respective wax was also heated in a covered way at 180°C for 3 hours within a thermal chamber to melt it, which makes the mixing process easier.
- The preheated bitumen is placed on a heated sand bath and the pre-defined mass of melted wax is added to the bitumen while the bitumen is stirred by a mechanical mixing device for 20 min to ensure a homogeneous blend.
- After mixing, the samples are filled in the outer cylinders of the RV and are cooled down to room temperature. All samples rested for 24 h prior to RV testing.

Table 2. Test Program for RV testing.

	0 wt.%	2 wt.%	4 wt.%	6 wt.%	10 wt.%	30 wt.%
PmB	3x					
AW		x	3x	x	x	x
FTW		x	x	x	x	x
MW		x	x	x		
PEW		x	x	x	x	

For RV testing, the samples were heated in the device to 135°C and the dynamic viscosity was determined at 135°C, 140°C up to 250°C with temperature steps of 10 K. At each temperature a triple determination of the dynamic viscosity was obtained. For the original binder without wax modification and for the binder modified with 4 wt.% of AW, the RV was run on three separately mixed samples to check repeatability of the mixing process and of the test itself.

4.2 *Mixing Torque Measurement (Mix Level)*

To assess the possible temperature reduction not only on bitumen level, but on larger scale, mixing-torque measurements with a temperature sweep were carried out on different mastic asphalt mix samples.

The device for these measurements is a standard compulsory lab mixer as shown in Figure 3. It consists of a rotating drum with a capacity of 30 l and a reverse rotating mixer with variable speed from 25 to 60 RPM. The drum can be heated up to 250°C. In addition, a torque measurement device records the mixing torque in Nm necessary to rotate the mixer at a constant speed. The mixing torque is used as a measure for the workability of the mix.


Figure 3. Lab mixer with torque measurement device (Infratest).

4.2.1 *Test program*

Table 3 shows the test program carried out for mixing-torque measurements on the mastic asphalt mix (MA 11). As reference sample, the asphalt mix with the PmB was taken. In addition, mixes with 4 wt.% and 10 wt.% of AW and with 4 wt.% of FTW and PEW were tested. The mix design of these mixes consisted of 100 % totally crushed aggregates (TC). As an alternative way to reduce the production temperature, an attempt was made by substituting a part of the totally crushed aggregates by totally rounded aggregates (TR). Thus, different mastic asphalt mixes with PmB and different aggregate geometries as shown in Table 3 were tested as well. For one mix the 0/4 fraction, for another mix the 4/11 fraction and for a third mix the complete 0/11 fraction was substituted by TR. It should be noted at this point, that the filler component was left unchanged and the grading curve of the mix was not altered either. For all mixes a triple or double replication of the mixing torque measurement on separate samples was run.

Table 3. Test Program for mixing-torque measurements on mastic asphalt MA 11.

TC*) / TR**)	0/11 / ---	0/4 / 4/11	4/11 / 0/4	--- / 0/11
PmB	3x	2x	2x	2x
PmB + 4 wt.% AW	2x			
PmB + 10 wt.% AW	2x			
PmB + 4 wt.% FTW	2x			
PmB + 4 wt.% PEW	2x			

*) TC = totally crushed aggregates
**) TR = totally rounded aggregates

The standardized test procedure for obtaining the mixing torque at different temperatures is as follows:

- In case of PmB with wax modification, the wax-modified binder was produced according to the procedure listed in section 4.1.1 prior to asphalt mix production.
- Aggregates, binder and the lab mixer were preheated at 170°C. The aggregates were preheated for 5 hours; the binder and lab mixer for 3 hours.
- Fine and coarse aggregates were homogenized in the mixer for 30 sec, after that the binder was added and the mix was homogenized for a mixing time of 3 min at a mixing speed of 40 RPM. In all cases a constant asphalt mix mass of 22 kg was used for testing.
- After the initial mixing process, the actual mixing-torque measurements started at 170°C and 40 RPM for 300 sec. The sampling rate is 1 Hz. Subsequently, the mixer with the mix inside was heated to 190°C with intermediate mixing of 10 sec every 60 sec to ensure a homogeneous temperature distribution in the mix. When the set temperature was reached, another mixing-torque measurement started at 40 RPM for 300 sec. This procedure was continued every 20 K until 250°C were reached.

5 RESULTS AND DISCUSSION

5.1 *Temperature reduction on bitumen level*

RV tests were carried out according to the test program listed in Table 2. To present results of RV testing exemplarily, Figure 4 shows the dynamic viscosity vs. test temperature of the PmB and of the binder modified with different percentages of AW. Since the benchmark value for calculation of the temperature reduction on binder level is the dynamic viscosity of the PmB at 230°C, this value is marked in the diagram (77.2 mPa*s). As can be seen from the diagram in Figure 4, the viscosity of the binder is reduced with increasing wax concentration in the binder. The standard deviation for the PmB and the PmB with 4 wt.% of AW is implemented in the diagram as well but due to the small scattering of results it is not visible. The maximum standard deviation from three replicates is 3.5 mPa*s for the PmB and 6 mPa*s for the PmB with 4 wt.% of AW. This proves an excellent repeatability of the test itself, as well as a good repeatability of the mixing process of wax with the binder.

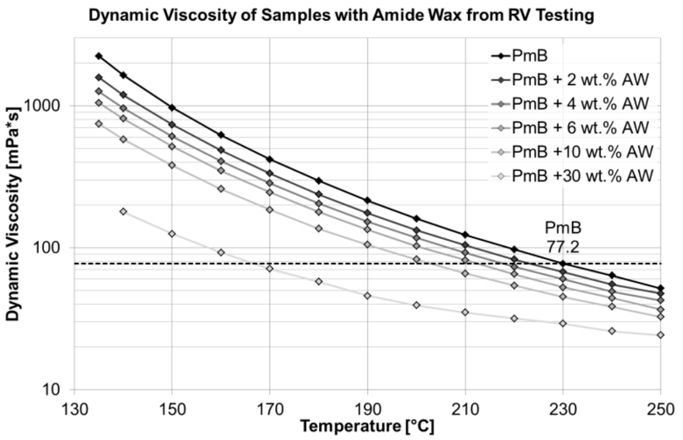

Figure 4. Dynamic viscosity vs. temperature for original binder (PmB) and AW modified PmB with different concentrations of wax.

Figure 5 shows results of all tests in terms of dynamic viscosity at 230°C vs. wax concentration for all four wax types. The presented data are mean values given in a log-lin scale. In addition, a logarithmic function of the following form was employed to give an analytical link between wax concentration and dynamic viscosity:

$$\eta(\mathrm{wc}) = \mathrm{a} * \ln(\mathrm{wc}) + \mathrm{b} \quad (1)$$

η dynamic viscosity [mPa*s]
wc wax concentration [wt.%]
a,b regression coefficients.

Coefficient *a* describes the impact of wax concentration on the change in dynamic viscosity, coefficient *b* indicates the dynamic viscosity at a wax concentration of 1 wt.%. The lower the absolute value of *b* and the higher the absolute value of *a*, the higher is the viscosity reduction potential of the respective wax. In the presented case, the highest viscosity reduction occurs for AW, followed by FTW, MW and PEW. As visible from the diagram in Figure 5, AW seems to be a class of its own, since the combination of coefficients *a* and *b* is optimal. FTW and MW exhibit similar behavior, while the PEW shows the smallest incline *a*.

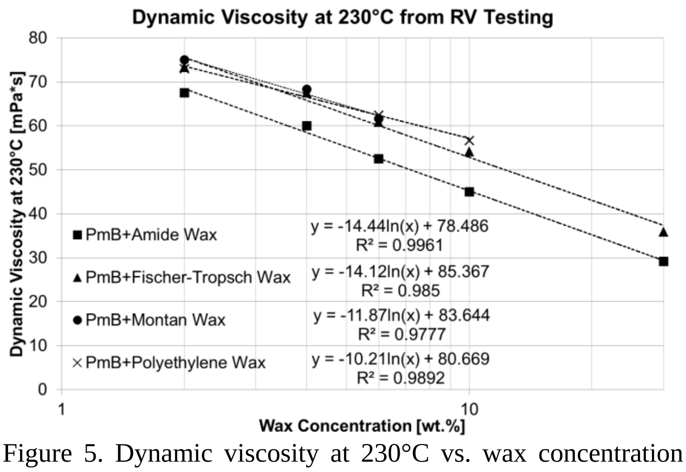

Figure 5. Dynamic viscosity at 230°C vs. wax concentration for all wax-modified binder samples.

To determine the possible temperature reduction on bitumen level, results from the PmB were used as the reference sample. Since the production temperature of standard mastic asphalt is between 230°C and 250°C, the mean value of the dynamic viscosity of the PmB at 230°C was taken as the benchmark value (77.2 mPa*s). The equiviscous temperature at 77.2 mPa*s, i.e. the temperature where the same dynamic viscosity occurs, was derived from RV test data of all tested samples. For this, the dynamic viscosity between two measured data points was considered to have a linear trend. Results of this analysis are given in Figure 6. It shows the equiviscous temperature vs. wax concentrations for all tested samples. In addition, a linear regression of the following kind was applied to the data:

$$T_{eq}(wc) = c * wc + d \qquad (2)$$

T_{eq} equiviscous temperature [°C]
wc wax concentration [wt.%]
c,d regression coefficients.

Coefficient *c* gives the impact of the wax concentration on the temperature reduction, coefficient *d* gives the interception at 0 wt.% wax concentration. In theory, coefficient *d* should be 230°C for all samples, since this is the temperature at which the dynamic viscosity of 77.2 mPa*s of the original binder occurs. The actual values of *d* range from 225.4°C to 233.6°C. One explanation for this is the fact that the evolution of the dynamic viscosity between two temperatures with recorded data was considered linear when in fact it does not exhibit a linear behavior.

Similar to the results shown in Figure 5, the best temperature reduction potential occurs for the AW modified binder, followed by FTW, montan wax and PEW. If only the incline of the linear regression *c* was taken into consideration, MW would show the best behavior. This would be true for higher wax concentrations, but since the intercept *d* is the highest for MW, the higher incline does not get effective at low wax concentrations (below 10 wt.%) which are representative for use in construction practice, where economic considerations do not allow for higher concentrations than 4 wt.% of wax.

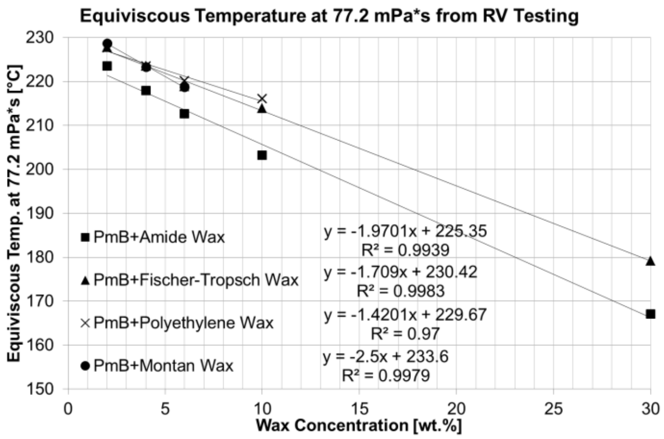

Figure 6. Equiviscous temperature at 77.2 mPa*s vs. wax concentration for all wax-modified binder samples.

5.2 *Temperature reduction on mix level*

To assess the temperature reduction potential on mix level, mixing-torque measurements were carried out on the reference mix and wax-modified mixes, as well as on mixes with partial or complete substitution of crushed aggregates by rounded aggregates.

Figure 7 shows results for the tests with wax-modified mixes. The data points shown in the diagrams are mean values at those temperatures were more than 20 single mixing-torque measurements were recorded. The benchmark to assess the temperature reduction potential on mix level is the mixing torque of the reference mix (MA 11 PmB) at 230°C, which is analogue to the assessment on the binder level. For an analytical description of the link between mixing torque and temperature, a linear regression of the following kind was carried out:

$$M_{mix}(T) = g * T + h \qquad (3)$$

M_{mix} mixing torque [Nm]
T mixing temperature [°C]
g, h regression coefficients

Coefficient *g* indicates the temperature susceptibility of the mix regarding the mixing torque. A higher absolute value of *g* means a stronger decrease of the mixing torque with increasing temperature. Coefficient *h* gives the theoretical mixing torque at 0°C. A low coefficient *h* and a high absolute value of *g* are desired for a high potential of temperature reduction on mix level. From the coefficient values and a visual analysis of the mixes with 4 wt.% wax modification, AW and FTW show the best temperature reduction potential compared to the reference mix. AW shows a temperature susceptibility of -0.222 Nm/K, FWT of -0.215 Nm/K. PEW (-0.155 Nm/K) even shows a slightly worse behavior than the reference mix with -0.165 Nm/K. The mix with 10 wt.% of AW is a class of its own with clearly lower mixing torques, although the incline of the linear regression is smaller than for the 4 wt.% AW mix. Since the intercept with the y-axis at 0°C is much lower for the 10 wt.% mix (60.6 Nm) than for the 4 wt.% mix (72.9 Nm), the higher modified mix shows lower mixing torques than the lower modified mix.

Figure 8 includes data for the mixes where crushed aggregates were substituted by rounded aggregates. The diagram is analogue to Figure 7. The results indicate that the mixes with rounded aggregates behave similarly to the wax-modified mixes in terms of temperature reduction potential. All mixes with rounded aggregates show an incline of the linear regression between -0.221 Nm/K and -0.226 Nm/K. These values are similar to the 4 wt.% AW and FTW mixes.

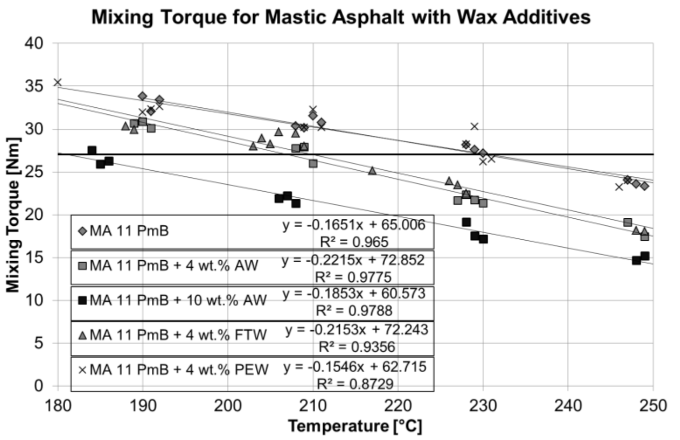

Figure 7. Mixing torque vs. temperature for the reference mix and the wax-modified mixes.

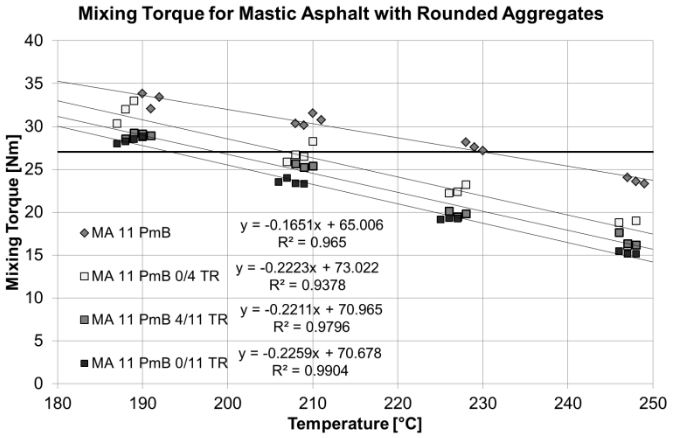

Figure 8. Mixing torque vs. temperature for the reference mix and mixes with partly and complete substitution of crushed aggregates by rounded aggregated.

In addition, the mixes with rounded aggregates where the 4/11 fraction and the complete 0/11 fraction was substituted exhibit smaller intercepts with the y-axis at 0°C (71.0 Nm and 70.7 Nm respectively) than the wax-modified mixes. Thus, these mixes show an even higher temperature reduction potential compared to wax-modified mixes.

5.3 *Comparative Analysis*

Figure 9 presents an overview of the temperature reduction potential of the tested products on binder and mix level. The reference for the calculated temperature reduction is the dynamic viscosity of the PmB at 230°C for the binder level and the mixing torque at 230°C of the MA 11 PmB for the mix level. The values given in Figure 9 show the temperature difference at the same dynamic viscosity (77.2 mPa*s) and the same mixing torque (27.2 Nm) respectively for the different tested products.

Looking at the data for mixes with wax modification, it becomes obvious that the derived temperature reduction potential on binder level deviates strongly from the reduction potential on mix level. In case of AW and FTW, the results on binder level underestimate the temperature reduction potential. The difference between binder and mix level ranges from 13.6 K to 22.2 K. In case of PEW, the results on binder level overestimate the reduction potential by 7.3 K. The ranking of the products (for 4 wt.% wax concentration) is the same for binder and mix level: PEW shows the lowest potential (a slight increase in temperature was measured on mix level), followed by FTW and AW.

Looking at the mixes with rounded aggregates instead of crushed aggregates, the reduction potential varies from -23.1 K to -36.7 K. The lowest reduction potential was obtained for the 0/4 TR, followed by 4/11 TR and 0/11 TR.

When results from wax-modified mixes and mixes with rounded aggregates are compared, it is obvious that the temperature reduction potential is equal or even higher for substitution of crushed aggregates. When only the 0/4 fraction is substituted, the temperature reduction is equal to 4 wt.% of AW, for substitution of the 4/11 and 0/11 fraction, the reduction is 8.2 K to 13.6 K higher than for wax-modified mixes.

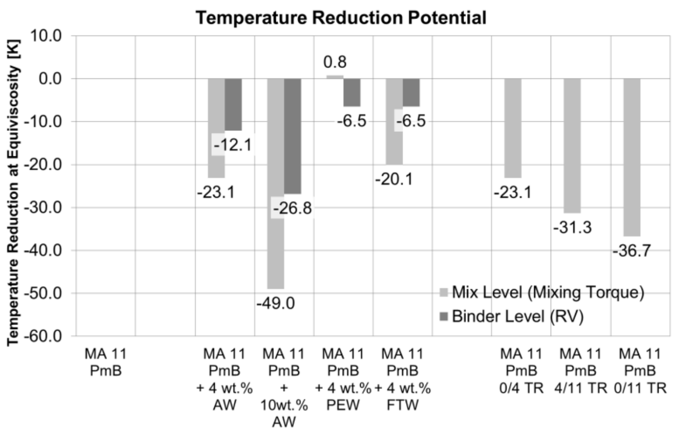

Figure 9. Comparison of temperature reduction derived from binder testing and mix testing.

6 SUMMARY AND OUTLOOK

Within <E>EMA ("High Efficiency Low Emission Mastic Asphalt"), a comprehensive research project, optimized mastic asphalt mixes with regard to maximum temperature reduction and high level of mix performance are developed. This paper contains results of investigations on the temperature reduction potential of different waxes on binder and asphalt mix level. In addition, an alternative approach for temperature reduction by substituting crushed aggregates partly or completely by rounded aggregates is analyzed as well.

To analyze the temperature reduction potential on binder level, an SBS-modified binder (PmB) with and without wax modification was tested in the rotational viscometer (RV) with temperature sweep at different wax concentrations. The temperature reduction potential on mix level was investigated by producing mastic asphalt with a maximum nominal aggregate size of 11 mm (MA 11) using PmB, as well as wax-modified binders. In addition, mixes with PmB and a partial or complete substitution of crushed aggregates with rounded aggregates were produced. The mixes were produced in a standard compulsory lab mixer that is equipped with a device to measure the necessary mixing torque at a constant mixing speed. The mixing-torque measurements were carried out with a temperature sweep from 170°C to 250°C.

To assess the temperature reduction potential, the binder viscosity at 230°C of the PmB was taken as a benchmark on binder level and the mixing torque at 230°C for the MA 11 PmB on mix level.

The following conclusions can be drawn from the results:

The evolution of the dynamic viscosity of the binder in RV vs. wax concentration can be fitted by a logarithmic function. The evolution of the equiviscous temperature vs. wax concentration can be described by a linear function. From RV tests on binder level, amide wax (AW) showed the highest reduction potential, followed by Fischer-Tropsch wax (FTW), montan wax (MW) and polyethylene wax (PEW).

The evolution of the mixing torque vs. temperature on mix level can be described by a linear function. The ranking of the waxes is the same as for the binder level. For PEW, no temperature reduction could be derived on mix level.

When the resulting temperature reduction on binder and mix level is compared, large differences between these two levels of observations were found. E.g. the temperature reduction of a 4 wt.% AW modified binder is 12.1 K on binder level and 23.1 K on mix level. The reduction potential is underestimated for AW, FTW and MW on binder level. For PEW, the reduction potential is overestimated on binder level. This shows that an assessment of the actual temperature reduction needs to be carried out on mix level if reliable values should be derived from testing.

Substitution of crushed aggregates by rounded aggregates has a high potential for temperature reduction in mastic asphalt. When the 0/4 fraction is substituted by rounded aggregates, 23.1 K temperature reduction is possible. This is an equal reduction compared to addition of 4 wt.% AW to the binder. When the 4/11 fraction is substituted, the production temperature can be reduced by 31.3 K, when the complete 0/11 fraction is substituted it can be reduced by 36.7 K. This shows that the use of rounded aggregates for mastic asphalt can be seen as an economic alternative for temperature reduction.

While crushed aggregates are necessary in other asphalt types to ensure a stable mix due to dominant intergranular contact of coarse aggregates and also to ensure a high friction value for surface layers, the situation is different for mastic asphalt. The dominant load transfer in mastic asphalt is a hard mastic with hardly any intergranular contact. Due to the binder excess in mastic asphalt, the surface has to be post processed by chip sealing with crushed aggregates after paving to realize a high friction value.

Tests on performance of the different mixes are currently running. The resistance to permanent deformation and to low-temperature cracking is investigated for the reference mix as well as for the wax-modified mixes and the mixes with rounded aggregates.

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