Laboratory assessment of new technical solutions for mastic asphalt with reduced mixing temperature

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ABSTRACT

Mastic asphalt is still an important type of asphalt mix used in several European countries especially for applications on bridge pavement structures as a waterproofing layer or even binder/wearing course. Similarly it is used for tram tracks to fix the structure in the existing road. Last but not least it is used for trafficked areas with heavy loading or very low traffic speed (parking garages, storage areas etc.). Since REACH was introduced to European legislation and bitumen including its applications was registered there is an ongoing effort to reach mastic asphalt variants where the processing temperature would be at maximum 200°C. Within the research activities of Centre for Effective and Sustainable Traffic Infrastructure, which is the only R&D centre of competence financed in this area by the Czech government a subtask was done with focus on different possibilities to design and assess mastic asphalt with reduced processing temperature. Besides the known waxes which are used since many years, some new alternatives were tested. Additionally also a surfactant and additives based on sugar cane extracts were included as well as some less known wax based additives.

Firstly bitumen (20/30) treated by these additives was analysed by standard empirical tests and mainly performance based test focusing on dynamic viscosity, MSCR test and frequency sweep test on DSR. For some additives different ratios were applied to discuss the impact of such additive. In the second stage mastic asphalt MA11 (eventually MA8) was produced in the laboratory with assessment of workability given in Czech technical standards and the stiffness test according to the EN standard. Especially because of the bridge deck applications also the rip-off test was done. The mixes were produced by different temperatures to analyse the effect of the used additives in the binder.

Keywords: Additives, Asphalt, Low-Temperature, Mastic Asphalt, Workability

1. INTRODUCTION

Mastic asphalt is a compact composite mix of bitumen, aggregate, fine-grained limestone, possibly reclaimed material and other ingredients which is – as generally known – prepared and processed under significantly higher temperatures (230-250°C) than standard hot mix asphalt (150-180°C). The mastic asphalt mix does not contain any air voids; these are perfectly filled with a higher quantity of asphalt mortar. Traffic loads are not transferred by the stone skeleton as in the case of hot mix asphalt but by the bituminous binder, of harder grading usually, reinforced by finely ground limestone. Larger fractions of aggregate act as a binder that "floats" in the asphalt mix.

With respect to the higher working temperatures, mastic asphalts have higher requirements for energy and also generate more emissions during preparation and paving. Such emissions might constitute a possible safety and health risk for the staff. The effort towards reducing the working temperatures has been a trend since early nineties. However, decreasing temperature brings increasing viscosity of both the bituminous binder and the entire mix, and mastic asphalt becomes difficult to process, particularly in case of manual application. To facilitate a reduction in the production and working temperatures, the viscosity must be reduced to guarantee good workability of the mix under lower temperatures. At the same time, resistance to permanent deformation under operation temperatures may not deteriorate.

One of the first incentives for temperature reduction for asphalt mixes in general was the introduction of a new regulation for chemicals known under the acronym REACH, within the European Union and the associated registration procedure with the European Chemical Agency (ECHA) filed for bituminous applications by CONCAWE in October 2010. During REACH registration, no bitumen product was registered as a hazard by asphalt producers. However, a recommendation was made for application under lower temperatures than had been common until then.

The bitumen and asphalt mix thus tested various additives that would allow reducing the temperatures during mastic asphalt production by 10 to 20°C. A production temperature reduction by 10°C roughly halves the emissions from bitumen and asphalt products. In connection to the development, for example Germany introduced a limit on maximum temperature during mastic asphalt product at 230°C into its regulations.

According to the presentation data [1], mastic asphalt producer in France embraced a new strategy in the course of 2013; it was assumed that in 2013 about 80 % mastic asphalt would be prepared under temperatures not exceeding 200°C. The problem aspect is the fact that the price of special additives is not offset by a reduction in the energy requirements and, therefore, costs increase by approx. 15 % in comparison to traditional mastic asphalt [2].

In the Czech Republic, preliminary technical conditions TP 238 [3] have been published for the field of low-temperature asphalt mixes so far.

2. EXPERIMENTAL STUDY

The CESTI project working group that worked with the issue of possible reductions in mastic asphalt temperatures, was composed of representatives of the Czehc Technical University in Prague, EUROVIA Services s.r.o., SKANSKA CS a.s. and TOTAL Česká republika.

The work sequence methodology which primarily aimed to create a mastic asphalt mix that would facilitate paving under temperatures below 200°C, was divided into four stages. Two tested the properties of bituminous binders modified by a number of substances. The work methods will be described in the following parts of this paper. The next two stages chose such laboratory methods for mastic asphalt mix testing that would prove the possibility of reducing the production and paving temperature while maintaining, or meeting the qualitative requirements stipulated for this type of mix.

3. LOW-VISCOUS BITUMINOUS BINDERS

Two sets of bituminous binders were assessed within the framework of searching for suitable innovative solutions for low-temperature mastic asphalts. New types of additives were used, either completely new products in development, or the application of the additive was known from the warm mix asphalt solutions. At the same time, some of the new industrial binders just developed were applied which could also be used in the manufacturing of mastic asphalts in the future, within the effort towards lowering the production temperature. The individual versions generally benefit from two effects. Either, based on the chemical composition of the additive as such, they facilitate a better "liquefaction" of the asphalt even under lower heating temperature, or they are characterised by a positive impact on the lubrication effects when the binder + additive are mixed to the aggregate commonly used for mastic asphalts.

3.1. Characterization of used binders

The results of the CESTI project are not publishable yet; therefore, the individual variants of the binders tested are described in general. Montana waxes, natural-based waxes, synthetic waxes, amide waxes, fatty acids, plant-based additives on the basis of hydrogenated ricin oil as well as industrially produced low-viscosity bituminous binders were used. Straight-run bitumen 20/30 according to EN 12591 was used as the basic control binder.

3.2. Set of test methods

The lab-prepared binders were exposed to a number of empirical and functional tests. Traditionally, penetration and softening point were tested and a penetration index was established. Dynamic viscosity was determined for bituminous binders and MSCR test was conducted for them. The results of selected tests are indicated in Tables 1-3. Some versions of additives were tested with various quantities applied to the binder. This was carried out for the additives of which the research team had not had extensive experience.

3.3. Results of the experimental tests

As is obvious from the empirical test results, the impact of additives on the basic penetration and softening point tests is very small. An exception is additive D which, even in combination with Montana wax no. 2, significantly increases the softening point. Also additive I, and additive K in a dose of 10 % by mass of the bitumen, had a noticeable effect on a change of the empirical properties.

The impact of additives on dynamic viscosity is described in Tables 2 and 3. The measurements were divided into two stages and, therefore, the temperature ranges differ. The additives tested in Stage 2, i.e. the additives listed in Table 3, were assumed to demonstrate positive dynamic viscosity results even under lower test temperatures, if they are to be applicable in practical production. As is obvious from Table 2, the differences in the values measured in the temperature range of 200°C to 250°C are minimal compared to the reference binder. It was one of the reasons why the second stage of bituminous binder testing used a temperature range of 130°C to 200°C. Out of the first group of additives tested, Montana wax no. 3 (labelled "D") affected dynamic viscosity the most.

For the second group of bituminous binders tested, good results were demonstrated by both industrially prepared low-viscosity binders (samples F2, F3) and samples H1, H2 (or K1 and K2, respectively). The impact of a greater quantity of the additive is noticeable for both binders.

Table 1: Results of empirical characteristic of tested binders

Bitumen	Additive	Additive content	Penetration	Softening point	Penetration index
		(%)	(0.1mm)	(°C)	(-)
A	control sample	-	24	59.0	-0.8
B	montana wax No.1	3	21	64.0	-0.1
C1	montana wax No. 2	1.5	21	62.8	-0.3
C2		3	22	61.0	-0.5
D	montana wax No. 3	5	17	114.0	5.5
E	montana wax No. 2 and No. 3	1.5 + 1.5	19	76.4	1.6
F1	industrially produced low-viscous bitumen No.1	-	21	63.2	-0.2
G1	natural wax	3	20	64.6	-0.1
G2		5	23	67.2	-0.6
H1	synthetic non-polar polyethylene wax	3	16	60.2	-1.2
H2		5	16	58.4	-1.5
I	Amid wax	3	22	78.2	2.2
J	Fatty acids and other ingredients	0.5	22	59.8	-0.7
K1	Vegetable origin based on hydrogenated castor oil	7	22	65.4	0.2
K2		10	19	68.2	0.4
F2	industrially produced low-viscous binder No. 2	-	28	64.8	0.6
F3	industrially produced low-viscous	-	26	65.4	0.6

	binder No. 3				
L1	polyethylene wax	2	23	60.2	-0.6
L2	polyethylene wax	3	23	21.4	-0.4
L3	polyethylene wax	5	36	64.8	1.2
N4	industrially produced low-viscous binder No. 4,5,6, (tested only on mixes, see table 4)	-	-	-	-
N5		-	-	-	-
N6		-	-	-	-

Table 2: Results of dynamic viscosity at 20 rpm/min. (6.8 s^{-1}) [mPa.s]

Bitumen	Test temperature (°C)										
	150	160	170	180	190	200	210	220	230	240	250
A	1350	375	225	150	113	75	63	50	38	38	25
B	600	410	280	200	140	100	88	63	50	25	13
C1	1700	375	225	150	113	75	63	50	38	38	25
C2	775	313	200	138	100	75	63	50	38	25	25
D	388	250	175	113	75	63	38	25	25	13	13
E	1688	363	225	163	113	88	50	50	38	25	25

Table 3: Results of dynamic viscosity at 20 rpm/min. (6.8 s^{-1}) [mPa.s]

Bitumen	Test temperature (°C)							
	130	140	150	160	170	180	190	200
A	-	-	1350	375	225	150	113	75
G1	10718	1413	638	363	238	163	113	75
G2	4317	911	463	288	188	125	88	75
H1	2202	1081	613	388	250	175	125	100
H2	2076	891	488	313	213	138	100	88
I	9003	1064	525	313	213	138	100	88
J	7000	1352	663	400	250	175	125	88
K1	3037	669	375	225	150	100	75	50
K2	2847	548	313	188	125	88	63	38
F2	3634	1130	588	325	200	138	88	63
F3	2049	790	425	263	163	125	88	63

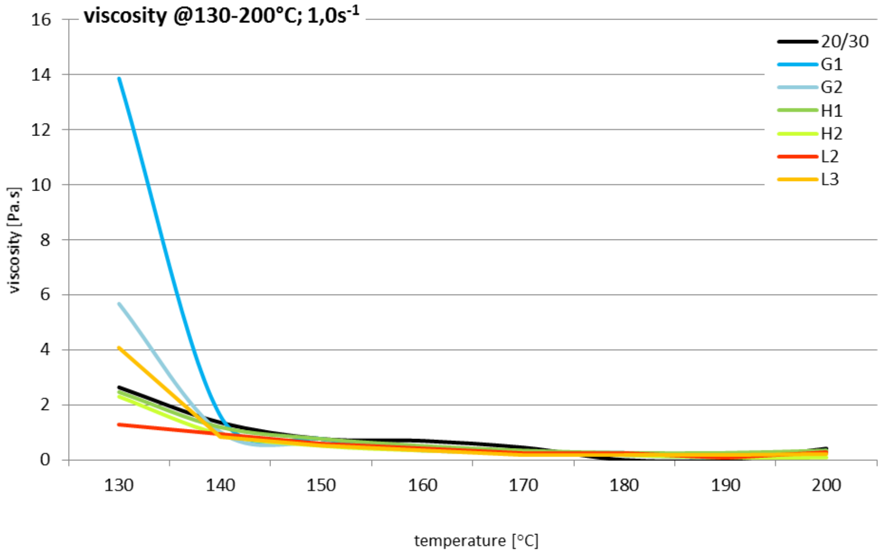

Figure 1: Dynamic viscosity in the thermal range from 130°C to 200°C, shear rate 1.0 s^{-1}

The MSCR (multiple stress creep recovery test) was conducted with unaged bituminous binder samples and demonstrates the impact of the additives tested from the point of view of elastic recovery and irreversible shear compliance – i.e. the characteristics determining the deformation behaviour of the binder. The results indicated in the following diagram present the tendency towards resistance to permanent deformation being reduced with the increasing proportion of additives (irreversible shear compliance increase and elastic recovery decrease) which is surprising with respect to the nature of individual additives (synthetic wax-based – except for additives used in “H” binders). In comparison to the reference binder, both characteristics monitored deteriorate in all cases, too. Samples using additive “G” demonstrate a smaller difference in the effects of 1 and 3 %-wt. of the additive; however, in the case of 5 %-wt., the difference in elastic recovery is quite significant in comparison to the lower quantity of additive applied (a reduction almost four times the value). The ratio between irreversible shear compliance and elastic recovery seems to be most appropriate for samples with 1 %-wt. (sample H). Both characteristics observed deteriorate also in the case of additive used in samples J and K (polyetylene wax). Even for this additive, a tendency identical to the preceding two additives is seen. The results are also supported by the values of additionally prepared option with 2 % by weight of this polyethylene wax, where the elastic recovery as well as shear compliance deteriorated slightly and correspond, basically, with the reference binder values. A great decrease of elastic recovery after ten cycles under the lower and higher strain applied in the test is observed in this case, too. To a degree, this might indicate degrading that occurs in the binder with the additive when longer loading is simulated. The values of elastic recovery and irreversible shear compliance seem illogical for 0.1 kPa in case of sample with additive “L” where the values are absolutely out of proportion to the preceding two values; moreover, there is also discrepancy between the relationship of J_{nr} to the deformation value observed where a value of 0.5 Pa^{-1} would be more appropriate.

Table 4: Results of MSCR test of assessed bituminous binders – part I

Bitumen sample	**stress = 0.1 kPa**			**stress = 3.2 kPa**		
	deformation	elastic recovery	J_{nr}	deformation	**elastic recovery**	**J_{nr}**
20/30	0.9	13	0.3	12.3	**10.4**	**0.3**
G0 (1 % of additive)	1.3	11.4	0.4	19.6	**6.1**	**0.4**
G1	1.6	17.2	0.5	27.2	**5.6**	**0.6**
G2	7.4	7.3	3.7	69.2	**1.6**	**1.6**
H0 (1 % of additive)	1.0	14.7	0.3	14.8	**8.8**	**0.3**
H1	1.3	12.3	0.4	20.1	**6.1**	**0.4**
H2	2.2	9.2	0.7	36.8	**2.6**	**0.8**
L1	0.9	14.4	0.3	15.7	**8.2**	**0.3**
L2	1.4	14.9	0.4	23.5	**5.0**	**0.5**
L3	1.6	24.1	0.5	38.5	**4.1**	**0.9**

Table 5: Results of MSCR test of assessed bituminous binders – part II

Bitumen sample	**Stress = 3.2 kPa**	
	Elastic recovery [%]	**J_{nr} [kPa^{-1}]**
B	3.6	0.71
C1	4.1	0.64
C2	2.9	0.86
D	52.2	0.04
E	7.5	0.44

The last set of results summarises the findings obtained during oscillation tests with the so-called frequency sweep test mode don in Dynamic Shear Rheometer where a bituminous binder sample is gradually tested under various temperatures for a frequency range of 0.1-10 Hz simulating various traffic load levels. A total of 5 temperatures in the range of 20-60°C was selected. The test was conducted with parallel-plate geometry (PP25). With respect to the geometry applied, and the testing of unaged bitumen samples, a gap of 1 mm was used. Measurements are taken for two samples at least every time; besides a separate summary of results for the stress frequency of 1.59 Hz and temperatures of 40°C and 60°C, the so-called Black diagrams, Cole-Cole diagrams can be plotted for each binder for the full range of temperatures and frequencies or parts thereof and, in particular, with the superposition of time and temperature theory applied, the master curves can be converted and plotted for a reference temperature of choice (20°C is used as a standard, within the framework of measurements carried out at CTU in Prague). A calculation of deformation and fatigue characteristics which have been established for over 20 years based on the SHRP research program is carried out for the data of the two higher temperatures.

Table 6: Results of complex shear modulus determination on DSR for 1.59 Hz

Bitumen sample	40 °C				60 °C			
	G* [kPa]	δ [°]	G*/sin(δ) [kPa]	G*x sin(δ) [kPa]	G* [kPa]	δ [°]	G*/sin(δ) [kPa]	G*x sin(δ) [kPa]
20/30	509.0	58	603.4	429.3	45.6	74	47.5	43.7
G0 (1 % of additive)	321.0	60	369.7	278.7	6.0	82	6.0	5.9
G1	313.1	59	365.5	268.2	8.7	78	8.9	8.5
G2	333.8	56	401.2	277.7	12.4	77	12.7	12.1
H0 (1 % of additive)	409.6	56	492.2	340.8	35.7	77	36.6	34.8
H1	282.7	63	316.7	252.4	22.8	77	23.4	22.2
H2	215.5	65	237.9	195.3	12.7	78	13.0	12.4
L1	321.9	56	386.9	267.9	20.6	77	21.1	20.0
L2	211.4	66	232.1	192.6	17.0	78	17.4	16.6
L3	139.9	68	150.5	130.0	6.5	82	6.6	6.4

The results presented in Table 6 basically confirm the findings obtained within the MSCR test. However, they depict an even greater difference between the drop in resistance to permanent deformation of binders with additives in comparison to control bitumen 20/30. In the case of variants with additives “G” and “H”, a contradicting phenomenon was noticed. Where, under 40°C, increasing doses of additive “G” does not always result in a higher modulus value (particularly when the values for 3 % by mass are compared), the opposite happens under the higher temperature; the trend is logical. From our perspective, this might confirm the limited functionality of the additive to a certain degree. The additive probably brings on a reduction of dynamic viscosity under higher temperatures, but probably does not modify penetration and causes a higher softening point; nevertheless, from the point of view of complex shear modulus, the trend is ambiguous. Contrastingly, additives “H” and “L” behave identically to the MSCR, particularly when additive “L” is compared with the logic of the link to penetration. However, generally the findings where the increasing quantity of additive with a higher stiffness results in a gradual decrease of the complex shear modulus and deformation characteristic deterioration are not desirable, particularly if the values are compared to the reference binder. Unfortunately, the trend was verified even by measurements taken for the additionally prepared binder “L1”. Moreover, this case also demonstrates a proportionally greater difference for data obtained at 40°C. The effect of increasing quantity of additive on the shift angle value is also interesting.

The following figures depict the courses of the master curves for 20°C of both the complex shear modulus and the phase angle. At least these characteristics are obviously affected by additive “H” where the curves are almost identical with the reference binder with minimum difference as clearly represents figure 3. In this case, the quantity of additive is not reflected either. The impact of additive “G” is analogous to the quantity of the additive applied. The sample G2 increases the complex shear modulus value and decreases the phase angle. Contrastingly, the sample G1 reduces the complex shear modulus value and increases the phase angle. When compared to the reference bitumen, G2 improves the complex modulus characteristic particularly in the field of very small to small frequencies (this corresponds with higher real temperatures in the diagram of frequencies up to 0.01 Hz). The last compared additive “L” has a more significant effect on the results – it reduces the complex shear modulus and increases the phase angle value. With a higher percentage of the additive applied, the phenomenon becomes more obvious; again, this is a development not envisaged for this additive. Moreover, contents of both quantities result in an obvious deterioration of the complex shear modulus course. The application of additive “H” in all quantities tested had no effect in this case; all options show courses almost identical with the reference binder.

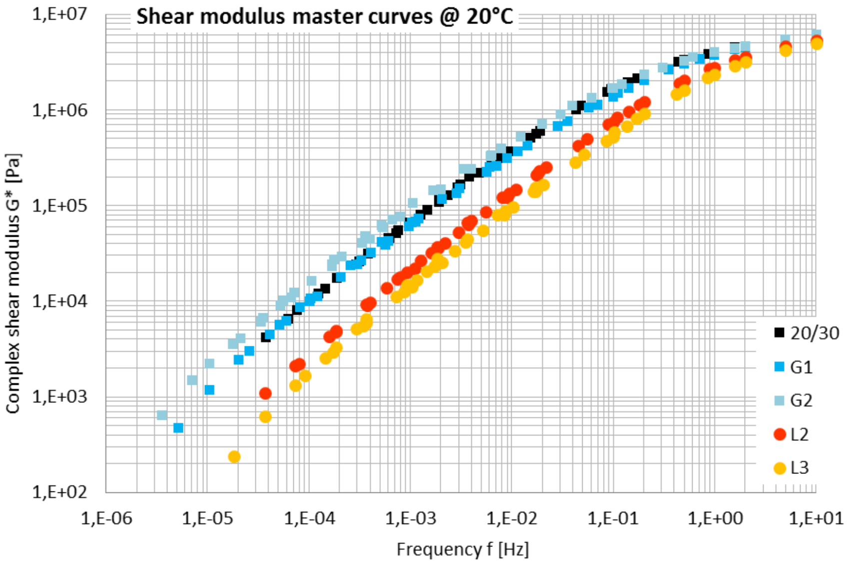

Figure 2: Master curve of complex shear modulus for additives G and L, reference T = 20 °C

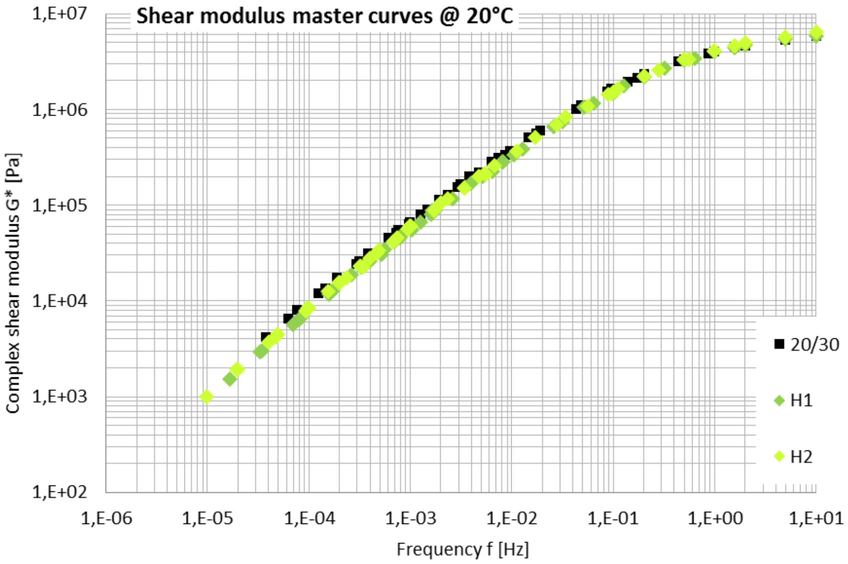

Figure 3: Master curve of complex shear modulus for additive H, reference T = 20 °C

4. TESTING OF MASTIC ASPHALT

The product standard for mastic asphalts [4] defines the aggregate grading range and minimum quantities of soluble binder. It also requires that resistance to permanent deformation be determined for mastic asphalts by stipulating the hardness number and its increments according to one of the ČSN EN 12697 test standards [5].

With respect to the requirement for reducing temperatures within the entire technological process of preparation to paving of mastic asphalts, mix workability can be modified either by varying the quantities of binder added, or adjusting the mix viscosity by introducing additives. Higher quantities of additives create a possibility of processing mixes under lower temperatures; however, this has a negative effect on stiffness of the mix under higher temperatures, and also makes the overall product more expensive. This means that to comply with the requirement for the hardness number and its increment, mastic asphalt workability under lower temperatures must be improved by applying suitable "liquefying" additives.

Laboratory testing to monitor mix stiffness and workability was performed with two mastic asphalt mixes with two groups of additives. These were expected to affect mix workability in a positive way; achieve a reduction in mastic asphalt laying temperature while maintaining mix workability and stiffness. This paper presents test results for testing performed with mix MA 11 IV. The values of basic mix characteristics, i.e. the hardness number and its increment, are indicated in Table 7.

Mastic asphalt workability was assessed according to the methodology described in [6]. Mastic asphalt workability was evaluated for mixes suitable for manual paving, with thickness of 2 to 3 cm (1), for mixes suitable for manual paving, with thickness of 3 to 4 cm and for machine paving, with thickness of 3 cm (2), for mixes suitable for manual paving, with thickness of 4 cm and for machine paving with thickness of 3 to 4 cm (3), for mixes suitable for machine paving, with thickness of 4 to 4.5 cm (4). Table 7 further shows the threshold temperature under which the asphalt mix was workable for each of the technologies concerned. If a table cell is crossed out the mix was not workable within the temperature range tested.

Table 7: Hardness number and workability of assessed MA 11 IV mixes

Mix type	**Bitumen content (%)**	**Hardness number (mm)**	**Increment of hardness number (mm)**	**Minimum workability temperature (°C)**			
				(1)	(2)	(3)	(4)
A	7.6	1.7	0.4	---	≥ 240	≥ 230	≥ 230
B		2.9	1.0	≥ 230	≥ 220	≥ 210	≥ 200
C1		1.5	0.5	---	---	≥ 240	≥ 230
C2		0.6	0.1	---	---	---	≥ 240
D		0.7	0.2	≥ 210	≥ 210	≥ 200	≥ 200
E		2.4	0.8	≥ 240	≥ 230	≥ 210	≥ 200
F1		0.7	0.2	---	---	---	≥ 240
G1	7.4	3.4	1.0	---	---	---	---
G2		2.2	0.6	---	---	---	---
H1	7.4	4.0	1.1	≥ 190	≥ 180	≥ 170	≥ 170
	7.1	1.1	0.3	---	---	---	≥ 220
H2	7.4	3.8	0.9	≥ 190	≥ 180	≥ 170	≥ 170
	7.1	3.3	0.9	≥ 210	≥ 200	≥ 180	≥ 180
I	7.4	1.9	0.4	≥ 210	≥ 210	≥ 210	≥ 210
J		3.1	0.9	---	---	---	≥ 220
K1		1.7	0.5	≥ 210	≥ 200	≥ 190	≥ 180
K2		1.9	0.4	≥ 200	≥ 190	≥ 180	≥ 180
F2		0.9	0.2	≥ 230	≥ 230	≥ 220	≥ 220
F3		1.6	0.4	---	≥ 240	≥ 230	≥ 230
N4	7.4	0.9	0.3		≥ 210	≥ 200	≥ 190
N5	7.4	3.7	0.8		≥ 180		
N6	7.4	2.1	0.5		≥ 190		

4.1. Results of laboratory tests

The workability limits of reference mastic asphalt mixes ranged from 210°C to approx. 250°C based on the type of paving, machinery exploited and thickness of the layer applied. Out of the additives used in test stage one, additive D along with additive B appeared to be the best. Both additives are commonly used in mastic asphalt preparation. Additive B is used to improve workability while D is an additive improving mix resistance to permanent deformation of the asphalt finish (see Table 7 for reduction of the hardness number and is increment). Neither is presently viewed as capable of reducing the preparation and laying temperatures in practice. The testing of mixes with additive D proved the possibility of reducing the temperature of up to 40°C in case of manual application of the mix. Additive B allows reducing the temperature by 10-30°C depending on mix type and laying technology. These results are supported by the dynamic viscosity values measured for bituminous binders, see Table 2.

The other part of experimental observation of the possibility to reduce temperatures while maintaining workability delivered rather mixed results. No possibility to reduce temperatures was proved for some combinations (F2, F3). With others, the results were satisfactory. The greatest potential for temperature reduction was observed for the variant with 10 % K (K2) and N6 where, depending on the paving technology and structural layer thickness, the temperature can be reduced by up to 50°C. For the option with N5, temperature could be reduced by even close to 60°C. However, the mix would have to be optimised to satisfy the requirements for mix stiffness. Temperature can be reduced by approx. 30°C when natural wax G is added; however, the condition of re-optimising the mix to maintain mix stiffness applies again. Without mix optimisation (maintaining stiffness with identical binder content), the mastic asphalt temperature can be reduced by 20-30°C when additives I and N4 are applied.

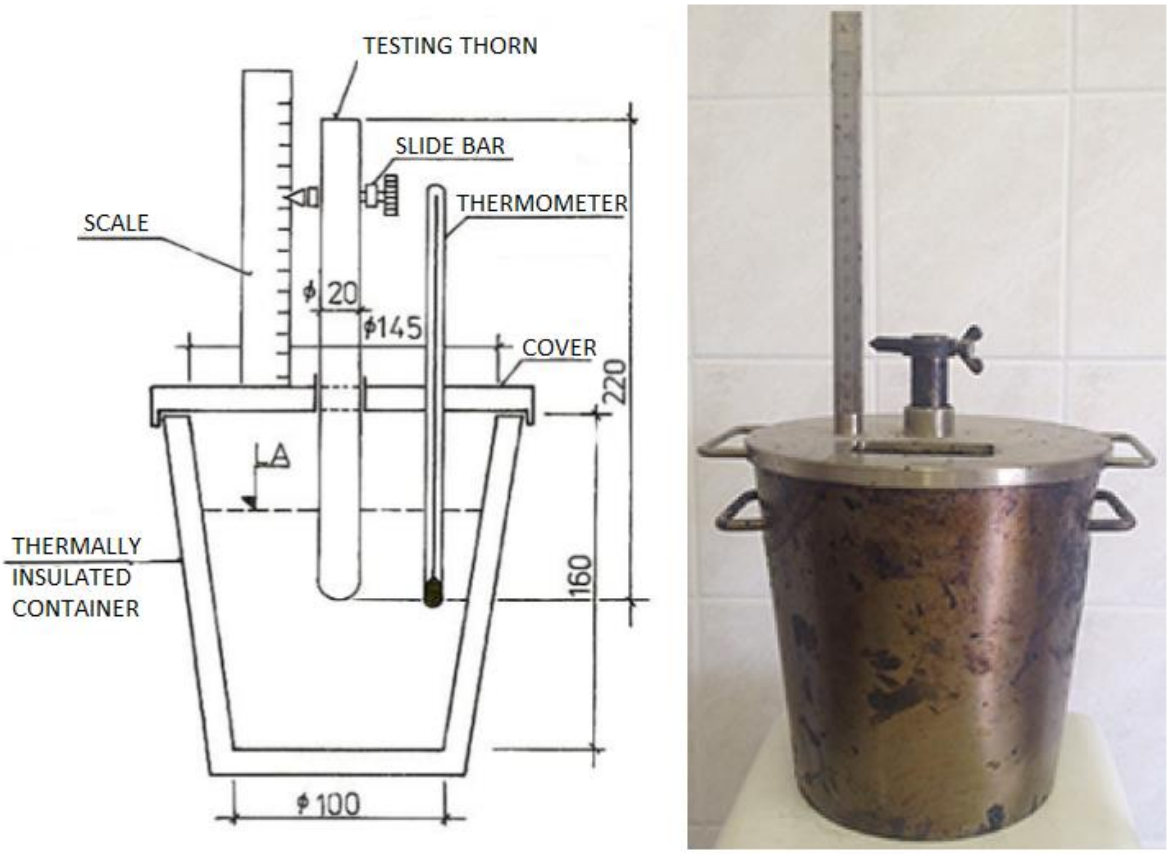

Figure 4: Test apparatus for workability determination [7, own photo]

5. CONCLUSION

The test results obtained and experience from test production show that reducing the temperature of mastic asphalt preparation to approx. 200°C is possible. Such temperatures can only be achieved with the application of additives to bituminous binders, using a new generation of additives as has been proven during the second experimental stage of testing. The dependence between mix stiffness and the bituminous binder quantity has been proven along with the dependence of mix workability and the quantity of the binder added. Both properties demonstrate an opposite tendency depending on the bituminous binder quantity; therefore, specific mixes must be optimised individually.

The results of laboratory testing showed a possibility of reducing the production temperature to the 200°C limit during asphalt preparation. However, the conclusions will have to be verified in real-life application in trial sections (summer/autumn 2015) which are expected to be completed in the course of 2015 and monitored for at least 5 years. Mix workability is affected by the temperature. During paving, the mix cools down depending on the temperature of the base and environment. It will be necessary to verify the possibility of paving the mixes even under adverse weather conditions.

We hope to be able to present experience from the completion of both test and standard applications of low-temperature mastic asphalt mixes at the conference next year.

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[6] HANZÍK, V., PSVS a.s. Praha, Měření zpracovatelnosti litých asfaltů, Inženýrské stavby 11, 1979

[7] ČSN 73 6160 Zkoušení asfaltových směsí, Český normalizační institut, 2008