SELECTED PERFORMANCE CHARACTERISTICS OF WARM MIX ASPHALTS WITH VARIOUS LOW-VISCOSITY BINDERS

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ABSTRACT

Warm mix asphalts (WMAs) gain currently increased focus and utilization as a standardized type of pavement materials in many countries. Several technical solutions are worldwide available and can be easily divided into bituminous binder modification or mix modification focused on improving viscosity (workability) or surface adhesion tension. In the Czech Republic so far predominantly first or second generation of viscosity improving techniques via organic additives are used, even if there are alternative solution tested and introduced as well (e.g. zeolites). As a general problem no existence of common technical requirements has been identified during last few years, what made impossible easily compare modified mixes and assess the performance potential with respect to standard requirements for traditional mixes and/or binders. As a part of three-year research project this deficiency has been partly solved by newly introduced preliminary specifications comparable to standard asphalt mixes as specified in Europe by EN 13801-x standards. Nevertheless, more important part of the research and experimental assessment can be seen in the evaluation of deformation performance-based characteristics like stiffness, dynamic modulus, creep or resistance against permanent deformation, as well as asphalt characteristics in low temperature range for WMAs with low-viscosity bituminous binders or by selected chemical additives forming rather third generation of solutions for viscosity decrease. Selected results of performed testing for various test conditions assessed on asphalt concrete type of WMA is summarized and discussed in this paper.

Keywords: Warm Mix Asphalt, Deformation Behaviour, Low-Viscosity Binders, Stiffness

1. INTRODUCTION

Increasing attention has been paid in the last decade to warm mix asphalts the processing temperatures of which range from 120 to 140°C during production and paving. The mixes have gradually become part of everyday road construction practice; this trend is reflected in the generation of technical specifications in a number of countries and the completion of many trial sections. In the Czech Republic, the interest in such mixes has recently resulted in the elaboration of preliminary technical specifications authorized by the Ministry of Transportation. The basic principles and content of the technical specification were summarized e.g. in [9], while the objective was defining uniform rules for the field of asphalt mixes the processing temperatures of which might range 10-30°C below the usual level. As evidenced by a number of international findings as well as the implementation of some innovations in the Czech Republic, there are certainly also other applications ranged in the semi-warm mixes where the potential for processing temperature decrease and, consequently, lower energy demands associated with lowered greenhouse gas production is even greater (e.g. Evotherm DAT technology or ECO^2 binders). We may expect further development and practical implementation of such mixes in the days to come.

There are a number of motivations to develop this field; this is also reflected in the fact that the European Asphalt Pavement Association (EAPA) considers semi-warm and warm asphalt mixes one of the key trends which is currently being emphasized and efficiently promoted. On one had, there are general society-wide challenges and pledges that define the requirements from the point of view of air protection, climate change or energy demands of industrial production and processes. In this context, a form of industry's social responsibility for any actions affecting the environment and health (lower greenhouse gas emissions of mixing plants, reduced evaporation and aerosol formation etc.) should be mentioned. Apart from that, there are purely economic or technical incentives. Processing temperature reduction results in lower energy consumption; with increasing prices of such resources, ever trend towards lower consumption constitutes a saving. Other motives are improved workability and technological safety during mix compaction as well as the possibility of paving asphalt layers in seasons with less suitable temperatures, particularly in the case of countries where the differences between summer and winter weather are more distinctive and public authorities plan contractual works for late autumn or even beginning winter period. Last but not least, a slight extension of allowed asphalt mix transport distances can be reached and there is also a higher potential in the field of reclaimed asphalt material utilization in combination with certain additives.

The preliminary technical specifications applicable in the Czech Republic from the point of view of the characteristics examined refer principally to common characteristics for traditional hot mix asphalt; to a lower degree, the necessity and significance of performance based characteristics continue to be emphasized despite the fact that such characteristics allow a better description of the behavior of the asphalt layer in the pavement structure. Although the tests necessary to obtain the information on performance based characteristics have higher time and economic demands they provide a much better depiction of the behavior under dynamically changing impacts, particularly if traffic load and intensity thereof is concerned. It can be said that a verification of performance-based tests will be necessary for any innovated type of mixes to be classified in the field of WMA or mixes with various activators or new types of functional binders, especially if long-life and durable pavement structures are the ultimate objective. In this regard, the experimental activity provided by universities in the Czech Republic focuses on examination of the dynamic behavior of asphalt mixes and gradual comparisons of performance based characteristics of asphalt mixes and binders including the definition of suitable models for variable parameter simulation.

2. LOW-VISCOSITY BITUMINOUS BINDERS

Within the framework of the experimental solution as such, a number of low-viscosity bituminous binders have been laboratory prepared and assessed so far. This field constitutes one of the three possibilities of achieving lower processing temperatures during asphalt mix production and application in the pavement. A relatively broad spectrum of additives currently marketed and further developed can be used; so far, synthetic waxes or fatty acid amides as well as some organic chemical additives (e.g. surfactant tenside) have been tested so far. Generally, the existing additives can be divided into several development generations. The basic group consists of bituminous binder modification by FT paraffins, fatty acid amides (FAA) or synthetic waxes which are usually applied within a range of 3-4 % by mass of bitumen. The first group has been gradually extended by new types of predominantly chemical additives which include Rediset WMX, Revix, IterLow T, Evotherm 3G or Densicryl. The doses of such additives are lower; some are applied in the binder while others prefer dosing straight during asphalt mix production. In the case of applying directly in the bituminous binder, quantities of up to 1 % by mass are used; in some cases combined dope of two additives must be mixed. A specific additive which is not primarily intended to reduce working temperatures but which has positive impact on asphalt viscosity is poly-phosphoric acid (PPA). Last but not least, there are absolutely new systems of industrial bituminous binders which manage to maintain, or even improve the characteristics of the binder under temperatures reduced by at least 40 °C in comparison to the usual conditions.

Table 1 gives a basic overview of some bituminous binders which have been applied to varying degrees in the asphalt mixes experimentally assessed and at least partly described below. At the same time, the three fundamental characteristics are given; more information is available e.g. in [2, 3] including the force ductility measurements performed, bituminous binder aging or complex shear modulus determination (see table 3) and dynamic viscosity behavior verification.

From the point of view of force ductility a comparison to pen grade 50/70 shows that the application of viscosity-improving additives increases the deformation energy under the same test temperature (15°C) which supports the expected higher stiffness of the binder. This is unfortunately according to shear modulus assessment at 60°C for 1.59 Hz frequency and controlled stress of 5,176 Pa given only for FTP, FAA and PPA additives. For force ductility it has been repeatedly proven that lower test temperatures cannot be used because in such cases the bituminous fiber failed to extend to at least 40 mm as required for PmB testing. The findings obtained by this test to compare different bituminous binders correspond relatively well with the results obtained for asphalt mixes. If we restrict ourselves to a comparison of individual additives, the following conclusions can be formulated for force ductility testing:

- by far the highest values under reference temperature of 15°C were achieved by bitumen with 3 % FTP;
- fatty acid amides (FAA), PPA and both chemical additives are almost comparable under extension to 200 mm from the point of view of deformation energy. In the case of the qualitative indicator of deformation energy difference between 200 mm and 400 mm, the greatest potential was reported for tensides based additive (IT). Contrastingly, the nanochemical additive only (ZS) reached a 50 % value in this comparison;
- when the bituminous binders 70/100 + 3% FAA and 70/100 + 3% FAA + 0,5% PPA are compared it is obvious that the combined additive does not yield any improvement from the point of view of deformation energy. In contrast to that, the comparison with binder 50/70 + 3% FAA is interesting where this binder has worse results in both deformation energy and the qualitative indicator E_{20-40}.

Table 1: Fundamental characteristics of bitumen 50/70 and 70/100 with different viscosity improving additives.

Basic binder	**Additive**		**Softening point R&B (°C)**	**Penetration @25°C (0.1 mm)**	**PEN index (-)**
	Type	**Content (%-wt.)**			
70/100	no additive	-	46	82	-1.07
	FTP	3	91	53	5.85
	FAA	3	95	60	6.64
	FAA and PPA	3 + 0.5	99	50	6.55
50/70	no additive	-	51	53	-0.82
	FTP	3	76	40	3.18
	FAA	3	94	41	5.51
	PPA	0.5	53	53	-0.34
	PPA	1.0	56	49	0.14
	PPA	1.5	64	38	1.12
	ZS	0.1	50	55	-0.99
	IT	0.5	51	40	-1.44

Table 2: Results of force ductility for selected 50/70 a 70/100 binders with different additives.

Bitumen	**T**	**E_s**	**E_{20}**	**E_{40}**	**E_R**	**E_{20-40}**
	(°C)	(J/cm^2)	(J/cm^2)	(J/cm^2)	(J/cm^2)	(J/cm^2)
50/70 + 3% FAA	20	0.042	0.440	0.478	0	0.039
	15	0.085	1.096	1.273	0	0.177
50/70 + 0,5% PPA	20	0.025	0.306	0.332	0	0.025
	15	0.163	1.133	1.318	0	0.185
50/70 + 3% FTP	20	0.074	0.682	0.746	0	0.064
	15	0.103	1.801	2.047	0	0.246
50/70 + 0,1% ZS	15	0.078	0.926	1.024	0	0.098
	10	0.207	3.580	1.313	2.407	0.074
50/70 + 0,5% IT	15	0.076	1.308	1.512	0	0.204
	10	0.209	3.819	2.147	1.968	0.242
70/100 + 3% FTP	15	0.036	0.279	0.353	0	0.074
70/100 + 3% FAA	20	0.064	0.538	0.583	0	0.045
	15	0.095	1.509	1.737	0	0.228
70/100 DE + 3% FAA + 0,5% PPA	20	0.030	0.272	0.285	0	0.013
	15	0.081	1.301	1.488	0	0.188

Table 3: Results of |G*| assessment @ 60°C and 1.59 Hz in control-stress mode.

Bitumen	G'	G"	|G*|	tan(δ)	(δ)	J'	J"
	(kPa)	(kPa)	(kPa)	(-)	(°)	(Pa^{-1})	(Pa^{-1})
50/70	1 504	8 089	8 228	5.38	79.5	0.00002	0.00012
50/70 + 3% FTP	1 246	10 280	10 360	8.25	83.1	0.00001	0.00010
50/70 + 2% FTP	2 636	14 100	14 350	5.35	79.4	0.00001	0.00007
50/70 + 0,5% PPA	1 233	6 269	6 389	5.09	78.9	0.00003	0.00015
50/70 + 1% PPA	5 877	16 990	17 980	2.89	70.9	0.00002	0.00005
50/70 + 0,75% IT	569	4 470	4 506	7.86	82.8	0.00003	0.00022
50/70 + 1% IT	331	5 058	5 069	15.30	86.3	0.00001	0.00020
50/70 + 0,1% ZS	348	4 584	4 597	13.17	85.7	0.00002	0.00022
50/70 + 0,3% ZS	253	3 591	3 600	14.19	86.0	0.00002	0.00028
50/70 + 0,5% DC	278	4 225	4 234	15.18	86.2	0.00002	0.00024
70/100	431	6 000	6 015	13,91	85.9	0.00001	0.00017
70/100 + 3% FTP	894	7 145	7 200	7.99	82.9	0.00002	0.00014
70/100 + 3% FAA	825	7 429	7 475	9.01	83.7	0.00001	0.00013
70/100 + 0,5% PPA	777	6 099	6 148	7.85	82.7	0.00002	0.00016
70/100 + 1% PPA	1 413	7 098	7 238	5.02	78.7	0.00003	0.00014

Results given in table 3 are based on oscillatory test using controlled shear stress of 5,176 Pa as recommended for linear viscoelasticity range e.g. in [13]. The temperature control was secured by Peltier system and the test temperature is following the conditions of CSN EN 14 770. Testing has been done for other temperatures as well nevertheless these will not be presented in this paper. Following the findings of the past SHRP results for neat bitumen the deformation behavior is the most important and can be well explained by the storage modulus. Complex shear modulus |G*| can be decided as another simple quality comparator if master curves or Black diagrams are not used. Based on these characteristics the difference of 50/70 and 70/100 is visible. More important are the impacts of used viscosity improving additives. From this point of view the positive impact of FTP and PPA on deformation resistance and increased stiffness has been observed and confirm later shown results of asphalt stiffness results. If analyzing different dosage of some additives in combination with 50/70 bitumen, large change in PPA addition has been found. Different situation occurred with FTP, which can not be easily explained, because the opposite was expected. Interesting is then the comparison of 50/70 sample and alternatives with tensides and some other chemical additives (ZS and DC). By using these additives, all modules decreased.

3. EXPERIMENTAL WARM ASPHALT MIXES

To assess the performance based characteristics of various viscosity improving chemical additives applied to bituminous binders with subsequent utilization in WMAs, mixes which are described in more detail in research report [4] or article [5] were selected and researched closely. In total, there are three different types of mixes – ACL16, (ACL16S) and ACP22+ which can be used primarily in the binder or base pavement courses and comply with the conditions of technical standard CSN EN 13108-1. The grading curve of individual mixes is given in [10]. With respect to several gained findings on increased stiffness values particularly when synthetic waxes, FAA or PPA are applied, the application of warm mix asphalts in binder or base courses is much more purposeful than e.g. in the wearing course. The reason is the fact that individual mixes usually reach increased resistance against permanent deformation and this characteristic advantage can be applied in particular in binder course.

Table 4: Basic specification of mix type ACL16S – set I.

Asphalt mix	**REF**	**WMA1**	**WMA2**	**WMA3**
Used additive	-	FTP (3%)	FAA (3%)	PPA (1.5%)
Temperature of specimen preparation	150°C			
Air voids content (%-vol.)	7.9	7.8	7.8	7.4

The mixes were made with no polymer-modified bituminous binders and the processing temperature was uniformly set to the 150°C level; the Marshall specimens were compacted by 2x50 blows under the aforementioned mix production temperature. Only in the case of mix ACP22+ a comparison of the effect of temperature was conducted. In this case the mixes were first produced under standard temperature; then, the temperature was reduced by 15°C and another set of test specimens was prepared. The method determining the reference temperature for warm asphalt mix production as stated in the finished preliminary technical conditions [1] or the German technical regulation [12] was only applied to a limited degree to mixes with two binders. In mix ACL16, the bitumen content was 4.2 % by mass which has proven to

be the threshold content; this supports the general trend of the Czech practice of applying as low quantity of bitumen in the mixes as possible. For second set the content was slightly increased to 4.4 % by mass.
As is obvious for the mixes in the first set, due to the design and a lower quantity of bitumen, a higher void content is achieved even under the standard processing temperature selected. Originally, contradictory to the recommendations for PPA doping, a mix with a higher proportion of the acid was prepared. The negative impact of such dosage was confirmed and resulted in heterogeneous values and obviously negative effects of the higher. This fact was pointed out already in [11]. Mixes of set I are examined to a limited degree as some results have been presented e.g. in [5].

Table 5: Basic specification of mix type ACL16 – set II.

Asphalt mix	**REF2009**	**2009_2**	**2009_3**	**2009_4**	**2009_5**	**2009_6**	**2010_2**
Used binder	50/70	70/100	50/70				
Used additive	-	FTP (3 %)	PPA (1%)	PPA (0.5%)	FAA (3%)	FTP (3 %)	ZS (01 %)
Temperature of specimen preparation	150°C						
Air voids content (%-vol.)	4.1	4.6	4.3	3.2	4.0	3.5	4.3

Table 6: Basic specification of mix type ACP22+ – set III.

Asphalt mix	**ACL22_1a**	**ACL22_1b**	**ACL22_2a**	**ACL22_2b**
Used binder	50/70		industrially produced bitumen CP-M	
Used additive	FTP (3 %)			
Temperature of specimen preparation	145°C	130°C	160°C	145°C
Air voids content (%-vol.)	2.3	8.9	1.9	5.3
Asphalt mix	**ACL22_3a**	**ACL22_3b**	**ACL22_4a**	**ACL22_4b**
Used binder	50/70		50/70	
Used additive	FAA (3%)		PPA (0.5 %)	
Temperature of specimen preparation	145°C	130°C	145°C	130°C
Air voids content (%-vol.)	4.5	7.1	2.6	1.9

From the perspective of basic tests performed for WMAs, the influence of certain additives on void content reduction is obvious in the case of the aforementioned sets of asphalt mixes. In Table 4, we can point out the mix with the binder where FT paraffin and the PPA organic additive were applied; the effect is rather ambiguous in relation to the quantity of the additive used in this case. It should be emphasized that the individual mixes were prepared, and the test specimens compacted under identical temperatures. Therefore, the effect of improved viscosity which, in itself, usually improves workability and better compaction was not taken into consideration. In contrast to that, the probable effects of low-viscosity additives can be declared quite simply in the case of mix ACP22+ by comparing the void contents at two temperature levels. In this context, the significant increases of the void content value in the mixes with a binder and synthetic wax and fatty acid amide additives should be pointed out. Based on the results given, we could conclude that under processing temperatures decreased by 15°C the mixes would not always comply with the requirements of the technical conditions for subsequently determined void content.

4. RESULTS IN THE FIELD OF DEFORMATION BEHAVIOR

4.1 Stiffness including the complex modulus assessment

From the perspective of the tests performed on asphalt mixes, attention focused primarily on performance-based deformation characteristics. In this regard, the key characteristics are the stiffness and complex modulus along with the resistance to permanent deformation. This paper does not address the water susceptibility ratio (ITSR) although, in relation to some additives, this area receives considerable critical attention in expert discussions. In contrast to that, characteristics under low temperatures are observed with respect to the potential worries, that mixes with higher stiffness and lower penetration might be to a certain extent more susceptible to frost cracking.
The results of experimentally verified stiffness modules using the IT-CY method according to CSN EN 12697-26 are given in the following Tables 7-8. For each mix and temperature, the intention was to determine the value as an average of measurements on at least 4-6 specimens. Auxiliary characteristic of thermal susceptibility was determined at the same time; defined as a proportional indicator of stiffness modulus under the minimum and maximum temperatures chosen. As known, the lower the thermal susceptibility value the better quality the mix can be considered to have.

Table 7: Stiffness of experimentally assessed mix ACL16 (test method IT-CY).

Temperature/Mix	REF2009	2009_2	2009_3	2009_4	2009_5	2009_6	2010_2
T=5°C	21,400	17,900	17,100	20,600	26,900	27,300	21,600
T=15°C	8,800	8,500	9,800	11,200	11,900	13,800	13,600
T=27°C	2,000	2,200	3,300	2,800	3,900	5,200	4,000
T=40°C	400	600	700	900	1,200	1,600	900
Thermal susceptibility*, (-)	10.70	8.14	5.18	7.36	6.90	5.25	5.40
Thermal susceptibility**, (-)	53.50	24.83	24.43	22.89	22.42	17.06	24.00

* Calculated as ratio of stiffness at 5°C and 27°C; ** Calculated as ratio of stiffness at 5°C and 40°C.

Table 8: Stiffness modules of experimentally assessed ACL22+ (test method IT-CY).

Identification	Binder	Process temperature (°C)	Stiffness modulus (MPa) at temperature T (°C)				Thermal susceptibility*
			0°C	15°C	27°C	40°C	
ACL22+_1a	50/70+3% FTP	145	25,400	10,600	4,300	1,600	15.88
ACL22+_1b	50/70+3% FTP	130	14,500	6,900	2,500	500	29.00
ACL22+_2a	CP-M	160	23,700	13,200	4,600	1,800	13.17
ACL22+_2b	CP-M	145	23,200	12,900	6,000	2,200	10.55
ACL22+_3a	50/70+3% FAA	145	26,800	15,100	5,100	1,200	22.33
ACL22+_3b	50/70+3% FAA	130	21,700	11,600	3,200	900	24.11
ACL22+_4a	50/70 + 0,5 % PPA	145	24,100	10,800	3,400	900	26.78
ACL22+_4b	50/70 + 0,5 % PPA	130	19,900	8,000	2,200	600	33.17

* Calculated as ratio of stiffness modulus at 5°C and 40°C.

The obtained results can be summarized as follows:

- the designed mixes meet the requirements for minimum stiffness values for asphalt concrete under 15°C which is determining from the point of view of stiffness modulus used for pavement structure design calculation – with the exception of the reference mix ACL16 + 50/70 as well as the mix with 70/100 + FTP. In this context, the Czech Pavement Design Manual (TP170) defines a minimum value of 7,500 MPa for asphalt concrete and 9,000 MPa for high stiffness modulus mixes (VMT);
- the stiffness value of the majority of mixes listed in Tables 7 and 8 exceeds 11,000 MPa; from the perspective of the technical requirements and foreign practice, these could be labeled as “2nd generation of VMT mix” although any further stiffness increase should be approached with caution and the fatigue parameters of the mix should be assessed in detail;
- generally, mixes with FTP demonstrated the best improvement of stiffness values (approx. 25 % under 15°C);
- very good comparability of the mixes containing 50/70 or 70/100 with FTP was demonstrated; based on that the binders could be practically substitutable;
- the dependence of temperature and stiffness modulus can be very well statistically expressed by an exponential regression with correlation coefficient of 0.97-0.99;
- the viscosity-improving additives have a positive effect which is obvious not only in stiffness values but also in the case of the qualitative indicator of thermal susceptibility. In the case of ACL16 the most suitable seems to be in this connection PPA, FTP or ZS additives. For this mix type a 25-50 % improvement of thermal susceptibility can be observed in comparison to the reference mix. It should be emphasized that to determine a modified calculation using the stiffness value under 5°C and under 27°C was selected;
- results obtained also suggest a rather promising development of a second generation of viscosity-improving additives which are dosed in smaller quantities and allow likely improvement of some other characteristics.

In the case of comparing the set of ACP22+ experimental mixes from the perspective of the effect of the binder used, it is obvious that the mix with bitumen containing added FAA achieves the highest values. This finding is close to the results of mix ACL16 as well. In contrast to that, the worst results were unfortunately recorded by binders with FTP although the term “worst” is rather relative in the case of the values achieved. Again, the asphalt mix with PPA is noteworthy; it should be emphasized that the additive is not primarily intended to reduce the processing temperature. If the mixes were assessed by means of the thermal susceptibility criterion it is obvious that the highest values are achieved by mixes with industrially produced bitumen, CP-M, while the mix with PPA-improved binder scored worst in this regard which does not entirely comply with the findings concerning experimental mixes ACL16. Moreover, the findings concerning this additive prove that the manufacturer's recommendations must be observed and the threshold as defined should not be exceeded.

When comparing mixes ACP22+ listed in Table 8 to standard laboratory mixes of the VMT type, it is obvious that warm asphalt concrete for base layers reaches higher stiffness values in most cases. On the other hand, from the point of view of thermal susceptibility, a comparable thermal susceptibility value is only reached by mixes ACP22+ 1a and ACP22+ 2a and 2b. In all other cases, this characteristic obviously deteriorates; it can be noticed that there is a distinctive difference in stiffness moduli under the highest temperature involved in the test.

The basic findings obtained from the measurement of complex modulus by the 4BP-PR method on beam specimens are summarized as an illustration of two selected mixes in fig. 1 and fig. 2. The selected mixes are the reference mix and asphalt mix with binder 70/100 + FTP. The assumption is that due to the effects of paraffin, the two mixes should be similar; this is basically confirmed by the results obtained. The measurements were carried out on five beams at least. A suitable regression to define the relationship between the complex modulus and frequency was chosen for each temperature. The logarithmic function seems very fitting for all temperatures. The correlation coefficients are over 0.90 in all cases which proves that the mathematical expression was chosen appropriately.

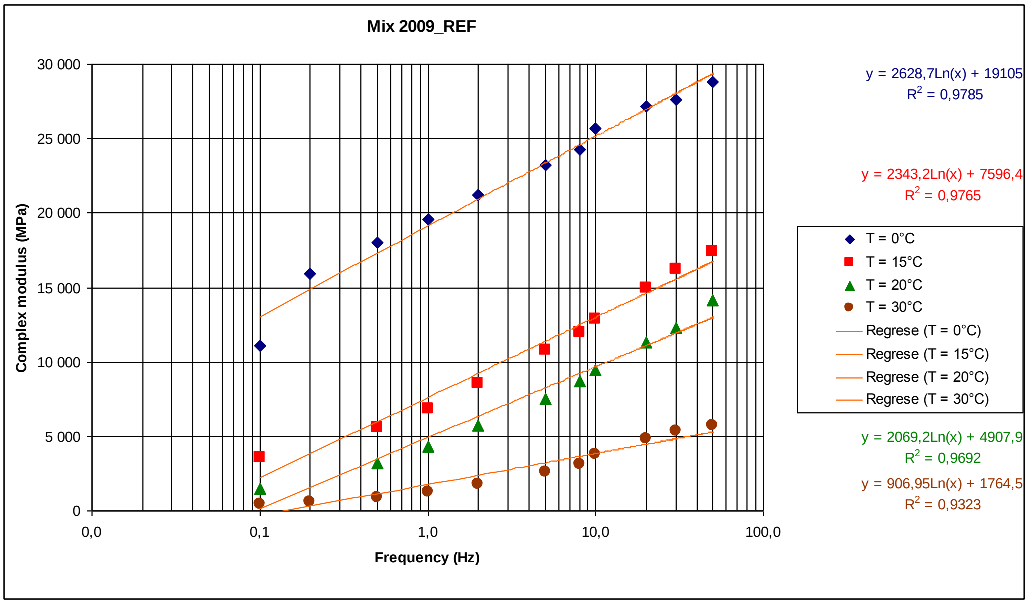

Figure 1: Complex modulus of reference mix ACL16 with pen grade 50/70.

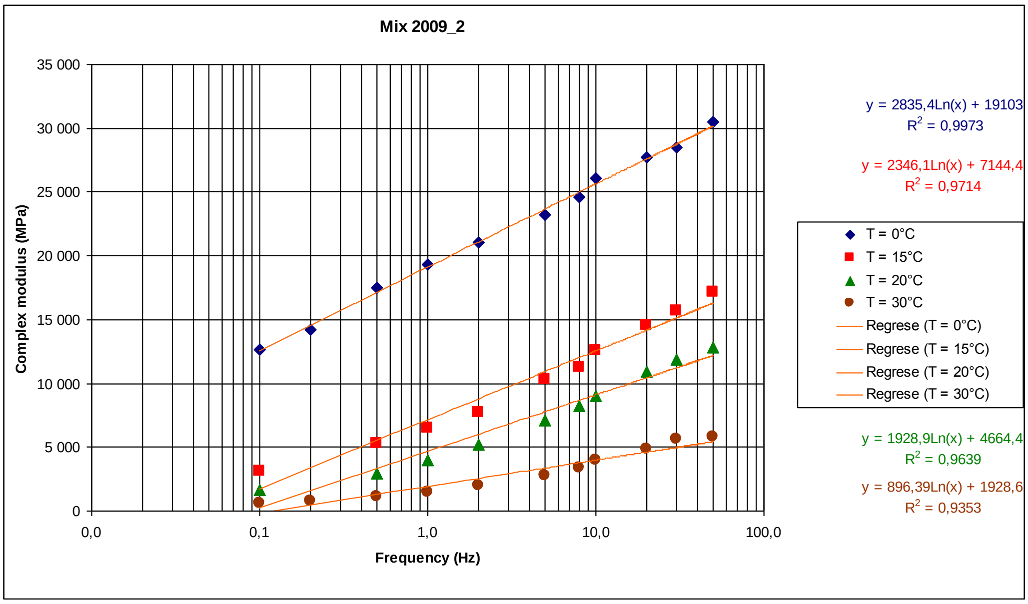

Figure 2 : Complex modulus of reference mix ACL16 70/100 + 3 % FTP bitumen.

For further comparison of deformation behavior results of stiffness testing by application of 2PB-TR method according to CSN EN 12697-26 at 15°C are shown for selected experimental mixes. If the results shown in table 9 would be compared with stiffness values summarized in table 7 and frequency of 10 Hz would be decided as the comparable loading parameter, then for mixes with bitumen where FAA or PPA has been used the results in case of 2PB-TR test are about 2,500 MPa higher. In comparison with these results for asphalt mix with FTP the measured values are different and even for the highest applied frequency the stiffness of IT-CY test method have not been reached. Following the gained results it can be with adequate caution presumed that there exist persisting question of sufficient statistical matching of values from both test methods. The repeated necessity arise to pay increased attention to the comparability of test results and set edge conditions for each test method to allow better comparison of tested values in the future.

Table 8: Stiffness of experimentally assessed mix ACL16 (test method 2PB-TR).

Mix design	**Stiffness modulus (MPa)**					
	Sample	**5 Hz**	**10 Hz**	**15 Hz**	**20 Hz**	**25 Hz**
ACL16 (50/70+3% FAA)	L1	13,477	14,093	14,614	14,876	15,049
	L2	12,673	13,240	13,653	13,908	14,018
	Average	13,075	13,667	14,134	14,392	14,534
ACL16 (50/70+1% PPA)	P1	10,929	11,478	11,796	11,985	12,133
	P2	13,003	13,840	14,283	14,565	14,815
	Average	11,966	12,659	13,040	13,275	13,474
ACL16 (50/70+3% FTP)	T1	12,107	12,887	13,364	13,655	13,773
	T2	11,629	12,220	12,652	12,920	13,016
	Average	11,868	12,554	13,008	13,288	13,395

4.2 Resistance of asphalt mixes against permanent deformation

The assessment has been done on mixes described in table 5. Standardized rutting test according to CSN EN 12697-22 at 50°C air bath with at least 10,000 cycles has been performed. The dimensions of the specimens were 260x320x50 mm. Compared to the usual testing conditions for ACL16 mixes the specimen thickness was not 60 mm to allow the utilization of specimens for further testing as well. Results are summarized in the following table 9. Because for ACL16 mixes the minimum requirements on rutting test parameters are not set it was decided to use requirements according to CSN EN 13108-1 for ACL16S mixes (PRD_{AIR} = 3 %; WTS_{AIR} = 0,05 mm/10^3 cycles).

Table 9: Results of the rutting test on ACL16 asphalt mixes.

Mix	**REF2009**	**2009_2**	**2009_3**	**2009_4**	**2009_5**	**2009_6**
Maximum relative rut depth PRD_{AIR} (%)	5.7	3.8	3.9	5.0	5.6	4.1
Maximum increment of rut depth WT_{SAIR} (mm/10^3 cycles)	0.154	0.080	0.069	0.058	0.107	0.044

Comparing the received results with standardized requirements for asphalt mixes in the class “S (superior)” it can be stated, that the condition of maximum relative rut depth has not been fulfilled by any of the mixes. The reason is firstly the type of assessed mix and secondly probably low voids content value of all experimental mixes. On the other hand the results notably impend to the threshold limit. In case of maximum increment of rut depth only the 2009_6 mix fulfill the technical requirement. Good results can be found also for mixes with PPA application.

If the influence of odd additives would be compared, it can be stated that from the view point of rutting test the additives usually have a positive effect on increased resistance. This fact was already in the past confirmed by several research studies and especially for mixes with FTP or FAA, when the stiffness of the binder is increased, these findings are logic. Similarly interesting are the results with PPA application, which is especially in the U.S. used predominantly for improving this field of asphalt mix deformation behavior.

5. NUMERICAL MODELING OF STIFFNESS WITH APPLICATION OF FEM

5.1 Theoretical background

Some of the results of the experimental measurements were applied in order to create an alternative model of warm asphalt mix deformation behavior. From the theoretical perspective, the simple numerical model applied is based on the analysis of the transformation field [14, 15] which allows describing the non-linear behavior of asphalt composites like plasticity, creep, material failure etc. The numerical model is formed by finite elements which also include the effect of indigenous parameters (deformation, tension). These parameters are both temperature changes and parameters describing Mises plasticity. The finite element method has no problem with non-linear distribution of material properties within a specimen; however, a new space in which the task is solved should be introduced in the composites. A transformation to such a space is made by means of a polarizing tensor; it is demonstrated that a fast iteration method suitable for e.g. plastic transformation in the specimen, can be offered. Sometimes it proves to be advantageous [16] to combine the Transformation Field Analysis with Desai DSC [17, 18]. A failure behavior model which may be defined according to Kachanov [19] should be introduced for this combination.

The numerical model is based on a number of experiments. The indigenous parameters allow adjusting the material properties (more precisely speaking, fine-tuning the distribution of tensity and strain fields), see e.g. [16]. The term *coupled modeling* is used for this method. The method of describing non-linear behavior of the material based on the transformation field analysis can be formulated in the following manner. The assumption is made that the material behavior is linear and elastic. This means that the classic Hooke's law applies to the entire specimen. Under such circumstances, it is rather simple to determine the fields of shifts, strains and stress tensors. In the second step, the effect of non-linear members will be added to Hooke's law and following equation can be obtained:

$$\varepsilon_{ij}(\boldsymbol{u}) = C_{ijkl}\sigma_{kl} + \varepsilon_{ij}^{\mathrm{pl}} + \mu_{ij} \tag{1}$$

where $\mathbf{u} = (u_1, u_2, u_3)$ is the shift vector, **C** is the material transformability matrix, $\boldsymbol{\sigma}$ and $\boldsymbol{\varepsilon}$ are tension and deformation tensors respectively, $\boldsymbol{\mu}$ is the tensor of deformation per se. Let us note that the deformation tensor can be replaced by the tension tensor, $\boldsymbol{\lambda}$, as follows: $\boldsymbol{\mu} = -\mathbf{C}\,\boldsymbol{\lambda}$. Now, using (1) tension can be formulated in any step in the following manner (the differential form can be used if needed):

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}^{\mathrm{ext}} + \mathbf{P}\,\boldsymbol{\mu} + \mathbf{Q}\,\boldsymbol{\varepsilon}^{\mathrm{pl}} \quad \text{or} \quad \boldsymbol{\sigma} = \boldsymbol{\sigma}^{\mathrm{ext}} + \mathbf{R}\,\boldsymbol{\lambda} + \mathbf{T}\,\boldsymbol{\sigma}^{\mathrm{rel}} \tag{2}$$

where $\boldsymbol{\sigma}^{\mathrm{ext}}$ is tension induced by external load but on the linear specimen where the linear Hooke's law applies. Causal matrices **P**, **Q**, **R** and **T** generally depend on the position; some of them might be identical because, for instance, own deformation might express plastic deformations, swelling, hydration etc. at the same time. A similar conclusion can be reached also for own tension. In our case, a constant distribution of the own parameters in the parts is assumed. The areas where the own parameters are constant are chosen according to the finite element method. If the tensor is recorded in the standard interpretation of a vector, the dimensions $\boldsymbol{\sigma}$, $\boldsymbol{\sigma}^{\mathrm{ext}}$, $\boldsymbol{\mu}$, $\boldsymbol{\varepsilon}^{\mathrm{pl}}$, $\boldsymbol{\lambda}$ and $\boldsymbol{\sigma}^{\mathrm{rel}}$ are $6m$ where m is the number of nodes in which the values are calculated, and dimensions **P**, **Q**, **R** and **T** are $6m * n$ where n is the number of sub-areas where either a temperature change or a parameter change due to plasticity is introduced.

The method of addressing plasticity by final element and regress analysis methods can be mentioned as well. The first step introduces a homogeneous and isotropic comparative specimen, V, with surface S. For this specimen, the formula (Hooke's law) applies to tension $\boldsymbol{\sigma}^{\mathbf{0}}$ and deformation $\boldsymbol{\varepsilon}^{\mathbf{0}}$:

$$\sigma_{ij}^{0} = \lambda_0 \varepsilon_{kk}^{0} \delta_{ij} + 2G_0 \varepsilon_{ij}^{0} = L_0(\varepsilon_{ij}^{0}) \tag{3}$$

The second step involves a geometrically identical specimen V with its limit S; however, now the material of the specimen generally depends on the position, i.e. $\lambda(\mathbf{x})$ and $G(\mathbf{x})$ depend on the variable **x**. Edge condition is formulated as $u_i(S) = u_i^0(S)$. This addresses the shifts **u**, deformation $\boldsymbol{\varepsilon}$ and tension $\boldsymbol{\sigma}$ in V.

Hooke's law applies in the form:

$$\sigma_{ij} = L(\varepsilon_{ij}) = \lambda\, \varepsilon_{kk}\delta_{ij} + 2G\varepsilon_{ij} \tag{4}$$

The polarization tensor $\boldsymbol{\tau}$ can be then defined as follows:

$$\sigma_{ij}(x) = L_0(\varepsilon_{ij}(x)) + \tau_{ij}(x) \tag{5}$$

At the same time, the following formula applies:

$$u_i' = u_i - u_i^0, \varepsilon_{ij}' = \varepsilon_{ij} - \varepsilon_{ij}^0, \sigma_{ij}' = \sigma_{ij} - \sigma_{ij}^0 \ \text{ v } \ \Omega, \quad u_i' = 0 \ \text{ on } \ \Gamma \tag{6}$$

If $\boldsymbol{\tau}$ and $\boldsymbol{\varepsilon}'$ are known the remaining values can be calculated.

In the next step, the H-S variational principles for the unknown $\boldsymbol{\tau}$ and $\boldsymbol{\varepsilon}'$ are formulated while defining the functional, which is not stated here, including adjacent and edge conditions. However, if the final step involves the application of the variational principle (generalized Hashin-Strikman principle), any finite elements can be formulated. Regress analysis is then based on the condition that the tensions measured and the tensions calculated are very close to one another. Therefore, the optimality condition can be formulated as follows:

$$\Pi = \sum_{x_{\mathrm{meas}}} [\boldsymbol{\sigma}(\boldsymbol{x}_{\mathrm{meas}}) - \boldsymbol{\sigma}^{\mathrm{meas}}(\boldsymbol{x}_{\mathrm{meas}})]^2 = \tag{7}$$

$$= \sum_{x_{\mathrm{meas}}} [\boldsymbol{\sigma}^{\mathrm{ext}}(\boldsymbol{x}_{\mathrm{meas}}) + \mathbf{P}\,\boldsymbol{\mu} + \mathbf{Q}\,\boldsymbol{\varepsilon}^{\mathrm{pl}}(\boldsymbol{x}_{\mathrm{meas}}) - \boldsymbol{\sigma}^{\mathrm{meas}}(\boldsymbol{x}_{\mathrm{meas}})]^2 \rightarrow \min$$

where the free parameters are represented by indigenous deformation $\boldsymbol{\mu}$. The derivation Π according to individual components of indigenous deformation will yield the value of plastic deformation increment.

5.2 Examples of results

Actual outputs can be demonstrated on the one hand by examples of model distribution of odd components of stress (tension) or strain in the test specimen and on the other hand can be formulated in comparative graphs. In these graphs it is possible to show the matching of measured and calculated values. From the achieved results an inclination in the range up to 100 kPa is evident. With respect to the place value in which usually stiffness is measured, such difference expressed by the inclination is insignificant and neglecting. On the picture 6 such comparison is shown for ACL16 mixes. The S1-S6 marking has following meaning: S1 = REF2009; S2 = 2009_2 mix; S3 = 2009_3 mix; S4 = 2009_4 mix; S5 = 2009_5 mix; S6 = 2009_6 mix.

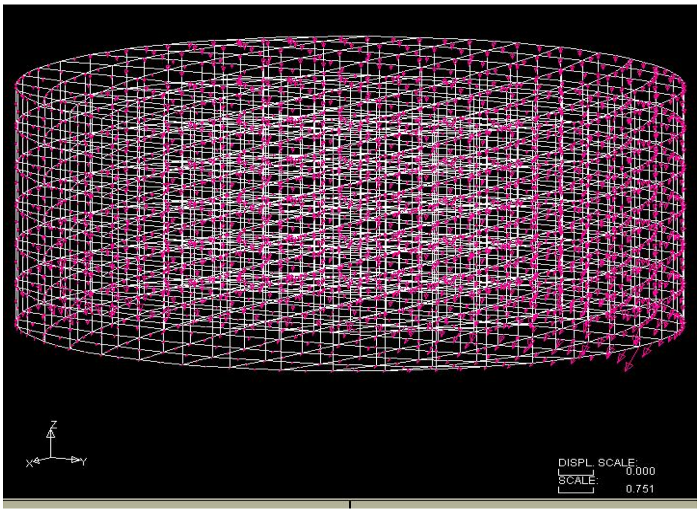

Figure 3 : Model distribution of shifting vectors used for model design for Marshall specimen.

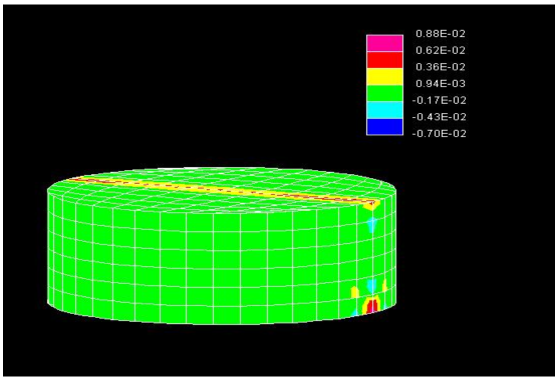

Figure 4: Example of simulation of stress σ_x distribution.

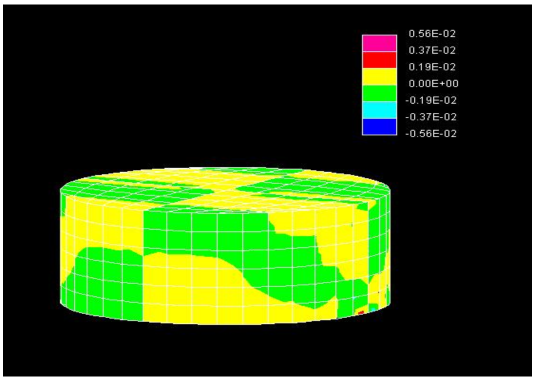

Figure 5: Example of simulation of stress τ_x distribution.

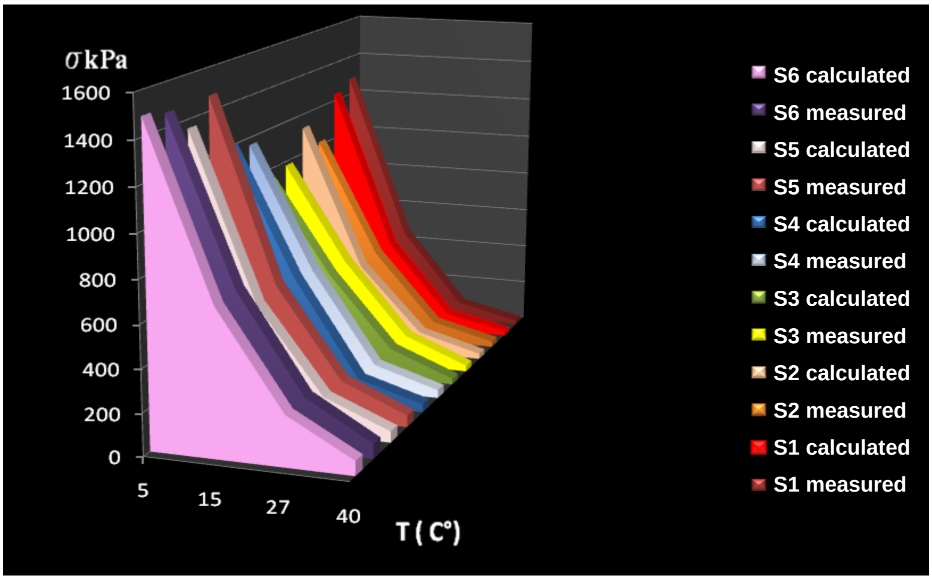

Figure 6: Graphic comparison of measured and numerically modeled stiffness values of selected WMAs.

6. SUMMARY

Experimental results gained during research focused on assessment of performance behavior of warm mix asphalts confirmed that depending on the additive used there are not only environmental benefits (reduced energy consumption and decreased concentrations of emissions) but also technical improvements especially in the field of deformation behavior. Positive effects have been found not only for rutting resistance or stiffness, but have been verified by results gained on binders as well. It has been clearly shown, that effects of various additives is not always similar for each assessed characteristic.

ACKNOWLEDGEMENTS

This research was supported by the project No. 103/09/0335 of Czech Science Agency.

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