Selected Performance-Based Characteristics of Viscosity Improved Bituminous Binders

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ABSTRACT: Warm mix asphalts present a trend of last decade with a focus on reduced energy demand and released emissions and bituminous vapours. One of the used techniques is application of suitable organic or chemical additives or surfactants which are used as dopes for bituminous binders or are added during mix production directly to the asphalt production. Research done on the Czech Technical University focused on the use of such additives in combination with bituminous binders. Several additives have been used together with 50/70 and 70/100 bitumen and experimentally tested with respect to their performance characteristics. The influence on viscosity (dynamic viscosity), deformation behavior (complex shear modulus, master curves) and performance in low-temperature range (bending stiffness by Bending Beam Rheometer) has been assessed. Gained results and influence of selected and tested additives is presented in this paper.

KEY WORDS: bituminous binders, viscosity improving additives, low-viscosity binders, ageing, complex shear modulus, bending stiffness, viscosity.

1 INTRODUCTION

The reason behind the research of performance behavior of low-viscosity bituminous binders and warm mix asphalts (WMA) along with defining the functional characteristics at the same time is the trend of increasing implementation of the individual technological options aiming to reduce the energy requirements and restrict emission production while maintaining the technical behavior parameters expected from traditional asphalt mixtures. With respect to the fact that the use of suitable chemical additives usually results in a price increase the application of WMAs is expected to even improve some performance characteristics determining the durability of the mixture.

The traditional compacted asphalt mixtures which stand for approx. 80-90% of all road pavement surfacing structures in the Czech Republic as well as a number of other European countries are produced and processed under the temperature range of 140-180°C depending on the bituminous binder applied (for mastic asphalt the temperature reaches even values above 240°C). Such temperatures are needed to reach a sufficient balance between the bituminous binder viscosity necessary to achieve sufficient coating of aggregate grains, suitable processing characteristics in asphalt mixture paving and compacting, rapid mechanical strength increase and structural durability under repetitive traffic loading and local climatic conditions. The traditional technological methods are usually energy-intensive and constitute sources of greenhouse gas and other hydrocarbon compounds and vapours emissions. Although, according to the current findings of the latest IARC (International Agency for Research on Cancer) epidemiologic study (Boffetta, 2008), such vapours do not possess carcinogenic effects they still remain the subject matter of debate and close monitoring. Lowering the necessary working temperature reduces both the vapour concentration and the qualitative composition thereof.

Of the reasons listed above, alternative or modified techniques and production methods have been studied intensely in the last decade, aiming to reduce the energy requirements and quantities of emissions as much as possible while maintaining the required operation properties and improve processing characteristics. In all cases of alternative methods, the intention is providing sufficient viscosity or adhesion of the binder applied during processing on one hand and enabling the production of a mix that can achieve the required stiffness and operation strength relatively quickly on the other hand, while ensuring sufficiently long life as well. The effort to make reducing the consumption of non-renewable resources or replacing some ingredients by renewable components, particularly through recycling, gradually possible must also be mentioned. The basic technologies developed nowadays in this context include low-viscosity bituminous binders and application thereof in WMAs, emulsion-based or foamed bitumen-based cold asphalt mixtures as well as semi-warm asphalt mixtures using the technology of foamed bituminous emulsions or various additives added to the binder or mixture to allow application of even cold or damp aggregate (techniques based on application of various surfactants technology etc.).

2 TRENDS IN THE FIELD OF LOW-WISCOSITY BITUMINOUS BINDERS

The field of low-viscosity bituminous binders this paper deals with is currently the probably most wide-spread method of reducing processing temperatures of asphalt mixtures in Europe. The principle is based on decreasing viscosity under standard processing temperatures which allows the manufacturing and paving under lower temperatures, or in other words, such additives work either on the principle of surfactants or as special additives characterized by a fast conversion between the solid and liquid forms with the melting point within the range of 80 to 120°C. When the temperature of the melting point is reached viscosity is reduced.

The first group of agents that reduce viscosity or improve workability based on a modification of the surface activity of the aggregate includes organic amine-based organic tensides. These are added in a quantity of 0.3 to 1.0 %-wt. of binder; the basic characteristics of the binder will not be changed significantly by those additives although the viscosity is reduced and the mixture is easier to process. An analogous principle is used in the chemical additive based on 30-60 % of natural plant oil, fatty acid and reactive products based on tetraethylenepentamine together with 1-5% of ethanediamine. The additive is usually applied to the bituminous binder to the quantity of 0.2-0.5 %-wt. of bitumen. The experience has proven so far that no fundamental change of rheological properties of the bituminous binders (viscosity or $G^*/\sin\delta$) occurs. Mechanical properties of asphalt mixtures with bituminous binders containing such additives are usually comparable to the properties of mixtures produced with no additives and under higher temperatures. This type of chemical additives plays a role in the bituminous binder-aggregate interaction at the time of asphalt mixture processing. There are no changes to the bituminous binder viscosity. The second group of substances includes various forms of synthetic waxes like Fischer-Tropsch paraffins (FTP) and Montana waxes or some fatty acid amides (FAA). Adding those to the asphalt mixture usually puts the mixture melting point higher on the other hand, the addition of the usual quantity of binder (2-4%-wt.) results in reducing the binder penetration and overall improvement of its stiffness. Fatty acid amides work on a similar basis like Montana waxes. This is a synthetically produced, fatty acid-based agent with long chains which has been used to reduce viscosity of bituminous binders in the past years. Practical experience proves the ability to process (compact) mixtures up to the temperature of 95°C. Under temperatures exceeding 140°C they dissolve in the bituminous binder completely and are homogenized by mixing with the initial bitumen. Identically to the case of FT paraffins, which crystallize when cooled down; stability and resistance to permanent deformation increase. When added to the bituminous binder, they resulting product remains homogeneous and stable.

N-per cent organic polyphosphoric acid (PPA) based solutions have been used as a modifying additive primarily in relation to the so-called "green highways" program in the last ten years especially in the United States. The organic acid cannot be a priori classified as an additive helping to reduce the working temperature of bituminous binder or mixture processing; the scope of its benefits is broader. PPA has an impact on the increased consistency of the binder, primarily increased stiffness and resistance against permanent deformation. At the same time, improved flow number has been proven. The higher value of the characteristic explains the improved ability of the asphalt layer to regenerate after loading. When the additive is used, a reaction with the asphalthenic base occurs, which affects viscosity at higher temperatures. At present, this group of chemical additives includes primarily American products with a PPA solution concentration ranging from 75 to 85 %, (Phosphate Forum of the Americas, 2009).

3 SOME ACTUAL EXPERIENCE IN THE FIELD OF WMA TESTING

In contrast to a number of other technologies in road construction, the sequence was in case of WMAs from the practical needs back to the gradual identification of physical and rheological functionalities and characteristics of this type of construction mix. The development of the WMA-type mixes in the last ten years has been rather interesting. Although in Europe, where the WMA concept was originally developed more than 15 years ago and various options subsequently tested, the mixes still make up to approx. 2.5 % of the total volume of asphalt mixes produced and processed annually. In North America, there is a development with a significant growth trend although the WMA-type mixes were first introduced there in 2003-4. With an annual production of approximately 360 million tonnes of bitumen, a volume of 2 % was applied in the form of warm or semi-warm asphalt mixes already in 2005/2006. In 2009, the total WMA production reached 19.2 million tonnes; in 2010 there was another great increase to 47.6 million (13.2 %) (Beuving, 2011). It is assumed that a proportion of 20-25 % WMA in the total production will be achieved by 2012 at the latest. In USA, technologies for semi-warm or warm asphalt mixes as gradually developed and established are summarized rather well for instance in (Prowell & Hurle, 2007).

This corresponds with the increased activity in the field of research, experimental verification and definition of the performance behavior as well as a search for new, innovative potential of this group of technologies. Some of the latest findings presented in 2011 have increasingly dealt with comparison of the technologies as currently available, predominantly from the point of view of mechanical as well as functional characteristics of asphalt mixes. To an increased degree, attention has been paid to water susceptibility of the asphalt mixes. In a number of cases, one can encounter the analysis of indirect tensile strength under various temperatures and including the effects of water or water and frost (Bueche, 2011; Epps et al., 2011; Kim et al., 2011). For instance, BUECHE mentions that in indirect tensile strength tests, all warm mix asphalts recorded a lower strength than the reference mix. In case of bitumen complex modulus values, it can be indicated that only for waxes the resulting values are higher than for reference bitumen (Fig. 1). Less than 40°C, a relatively big difference was detected between particular WMA technologies. The lowest strength was registered for the low-energy asphalt (LEA) mix. The effect of maturing was little in all cases.

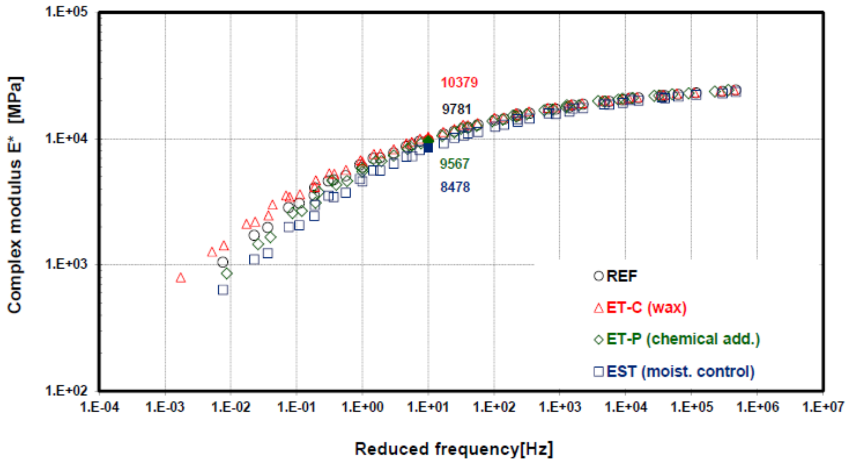

Figure 1: Example of a master curve for bitumen complex shear modulus with reduced frequencies @ 15°C, (Bueche, 2011).

In other research ZELELEW (Zelelew, 2011) compared two technologies with foaming additives (Advera®, Gencor), semi-warm mix LEA and a warm mix asphalts with FT paraffin. In the case of the foaming additives the substances used are synthetic zeolites. According to the American specification, the basic bitumen was classified as PG 64-22. In case of low-viscosity binder used for WMA, the FTP was dosed at only 1.5 %-wt. bitumen. Similarly to the preceding research, the FTP increased binder stiffness under high temperatures; however, there was no deterioration of binder characteristics under low temperatures. The remaining additives had practically no impact on the bitumen behavior.

At the same time, the complex shear modulus was measured for various frequencies and temperatures with the subsequent application of time and temperature superposition and definition of the master curve. This is a generally popular method of expressing performance behavior of asphalt mixture and an approach defining the master curve can be found in other expert papers, too (Visconti et al., 2011; Kim et al., 2011; Bennert & Brouse, 2011). In contrast to BUECHE approach, ZELELEW chose as reference temperature 21.1°C which is used relatively frequently in USA. The results are comparative for a frequency interval of 0.1-100 Hz. For higher frequencies, the measurements presented in Fig. 2 reached significantly higher values. This could be caused by the choice of different temperatures for measurements, or by the properties of the initial binder although this should not be relevant in the case at hand considering the fact that it was binder PG 64-22 that was applied in both cases.

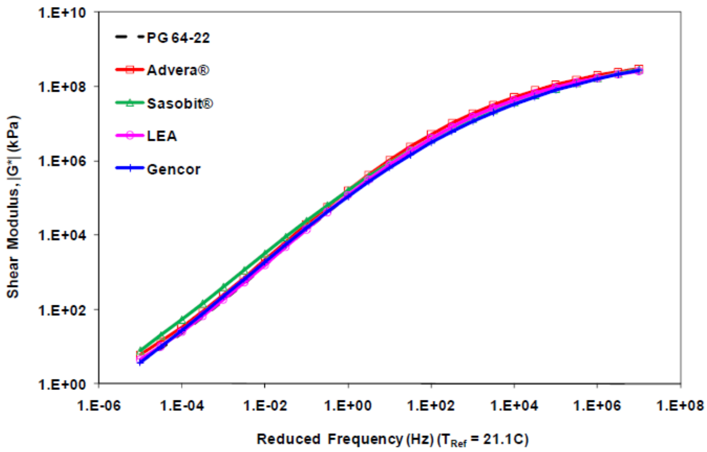

Figure 2: Example of master curves of binders with viscosity improving additives, reference temperature 21.1°C, (Zelelew, 2012).

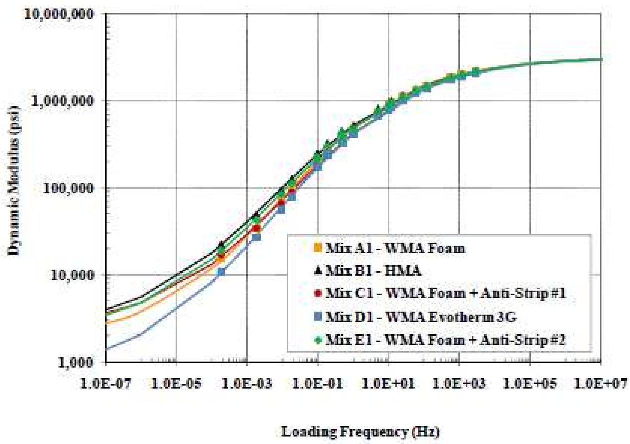

Figure 3: Examples of asphalt mix master curves with different temperature reducing techniques, reference temperature 20°C, (Bennert & Brouse, 2011).

For the dynamic stiffness modulus tests frequencies of 25; 10; 5; 1; 0.5 and 0.1 Hz were chosen and measurements carried out in three test specimens under the temperatures of 4.4°C, 21.1°C, 37.8°C and 54.4°C while 21.1°C was chosen as the reference temperature for the subsequent plotting of the master curve. In this case, the information for determination of the regress coefficients for the logistic functions is interesting; none of the available rheological software programs was applied but the Solver function in MS Excel was used to conduct the sensitivity analysis and optimisation calculation.

Last but not least, some up-to-date findings concerning the application of FTP in Germany should be mentioned, even with respect to the fact that in the past, it was Germany where the additive was applied for the first time in WMA and, to a degree, started increased focus on the field of this type of mixes. In this context, current findings can be referenced (Damm, 2011) who dealt with combining polymer-modified bitumen and low-viscosity additives of the FTP type or fatty acid amides in the asphalt layers where there was a requirement for a higher resistance to permanent deformations. With respect to that, it was discovered that from the point of view of stiffness improvement, it is primarily FTP that is effective when dosed at 2-4 %-wt. of the binder. Attention was paid both to the values of complex shear modulus of the bituminous binder (|G*|) and to the value of bending stiffness that characterize the behavior of the binder under low temperatures. As is obvious from the first characteristic, the application of a synthetic wax or FAA-based additive results in the initial values being higher than in the traditional, polymer-modified bitumen (PMB). The operation period results in further increase of the |G*| value in the binder in case of additives for reducing viscosity. For PmB, the effect is the opposite. From the point of view of bending stiffness and the m-value characteristic, it is PmB that reaches the best values; however, there are two other binders compared which also meet the requirements. In this regard, the very good stability, primarily in the case of binders with FAA, is interesting.

Table 1: Comparison of bitumen characteristics with various modifications; (Damm, 2011)

	FTP		**FAA**		**PMB 45**	
Voids content in the mix	4.2		4.7		6.2	
Year of done analysis	2004	2008	2004	2008	2004	2008
Softening point R&B (°C)	84.4	78.0	104.3	97.1	62.2	63.6
Penetration @25°C (dmm)	30	16	33	24	35	29
$G^*_{60°C}$ (Pa)	18,300	22,810	25,400	47,600	15,800	12,905
$\delta_{60°C}$	73.8	73.3	68.5	65.0	37.1	37.4
Stiffness @-16°C (MPa)	212	252	182	175	133	165
m-value	0.38	0.29	0.32	0.30	0.39	0.37

4 EXPERIMENTS AND RESULTS

Within the research of impact assessment of additives reducing the viscosity in the bituminous binder series of testing have been performed using several sets of similar binders which have been modified by various additives used in the WMA concept. Basic evaluation of required fundamental characteristics has been done as well as assessment of deformation energy in force ductility test, ageing, dynamic viscosity determination or complex shear modulus testing. In the following parts results of the broadest set of bitumen samples are discussed and accomplished by additional findings from the other test series. As initial bitumen typical binders of 50/70 and 70/100 penetration were used. All reference binders fulfilled the specifications given in CSN EN 12591, differences were found only for 50/70 of first test set, where binders of various producers have been used and different penetration values have been measured. With the reference binders two groups of low-viscosity binders have been prepared for further comparison in the laboratory. In one set different additives have been tested and evaluated, in the second set the impact of initial bitumen (produced in different refineries) on resulting properties of the low-viscosity binder was evaluated.

In following tables and presented figures the listed abbreviations of used additives has following meaning: FTP = FT paraffin; FAA = fatty acid amide; IL-T = IterLow-T/Hypertherm; PPA = polyphosphoric acid; ZC = Zycosoil; DC = Densicryl. Additive DC represents an improved component, which should be according to the producer applied together with the nanochemical additive ZC directly to the asphalt mixture. For validation of characteristics and impacts of this additive separately each of both additives has been analyzed in combination with bitumen.

Table 2: Basic characteristics of selected experimentally assessed bituminous binders

Original binder (before ageing)	**Softening point** (°C)	**Penetration @25°C** (dmm)	**Penetration index (PI)** (-)
50/70	50,5	53	-0,93
50/70 + 2% FTP	75,0	31	2,40
50/70 + 3% FTP	65,8	32	1,05
50/70 + 3% FAA	101,9	37	6,08
50/70 + 0,5% PPA	52,7	38	-1,16
50/70 + 1% PPA	61,6	34	0,46
50/70 + 0,5% IL-T	51,2	48	-1,01
50/70 + 0,75% IL-T	53,9	45	-0,53
50/70 + 0,1% ZC	51,6	50	-0,85
50/70 + 0,3% ZC	50,9	52	-0,88
50/70 + 0,5% DC	50,6	53	-0,91
70/100	46,2	82	-1,02
70/100 + 2% FTP	67,0	33	1,31
70/100 + 3% FTP	65,7	37	1,35
70/100 + 3% FAA	78,9	52	4,27
70/100 + 0,5% PPA	54,0	46	-0,48
70/100 + 1% PPA	57,2	45	0,19
70/100 + 0,5% IL-T	48,7	57	-1,23
70/100 + 1% IL-T	50,8	54	-0,81
70/100 + 0,1% ZC	52,1	45	-0,91

From the viewpoint of fundamental bitumen characteristics – softening point and penetration – especially the influence of FTP and FAA has been repeatedly approved. For softening point of all tested binders the average deviation was ±0.4°C, for penetration ±1dmm. Generally with these two additives it comes to relatively significant decrease in penetration value and increase in softening point, which is influenced by the melting point of the wax or fatty amid acid. The binder becomes stiffer. Moderate impact on both characteristics has PPA as well, where it is always crucial to observe the added quantity of this organic acid – not overrun the recommendations by the PPA producers. In this case the binder characteristics are influenced by deflocculating (deaglomeration of asphaltenes), i.e. change in ratio between maltenes and asphaltenes in the binder (Valentin V., 2011). The other additives have shown no impact on softening point and penetration.

In case of both characteristics it is proper to draw attention also on the results of relative ratio related from both characteristics and generally know as penetration index. The aim should be to reach a value below 2. According to the results gained during laboratory assessments this criterion has not been fulfilled for binders with higher content of FTP and for binders with FAA. This result was displayed repeatedly.

Besides presently most frequently used additives like FTP and FAA the impact of chemical additives PPA, IterLow-T and Zycosoil was evaluated especially for the basic bitumen 50/70. From the results summarized in table 2 it is noticeable, that for distilled bituminous binders FTP has the most significant influence on penetration shift, FAA on the other hand because of higher melting point leads to higher increase in binder softening point. Additives PPA and ZC if applied with dosing as recommended by producers have in principle no impact on penetration or softening point. In this case viscosity and workability of the asphalt mix is influenced without change of softening point. In case of IL-T additive so far no change in softening point was observed, on the other hand penetration decrease was registered.

Force ductility and resulting bitumen performance properties are required generally only for PMBs. The test was carried out on selected low-viscosity bituminous binders, whereas higher starting test temperature (min. 15°C) was applied. The reason for deciding on this temperature was the target to reach a 400mm bitumen fiber extension as required for standard PMBs. The test has been conduced in accordance with CSN EN 13589 followed by the calculation of deformation energy as required by CSN EN 13703. Within the performed measurements for each binder results always for at least two different temperatures were gained in form of deformation energy values defined by E_s (for maximum load), E_{20} (for extension of the bitumen sample to 200mm), E_{40} (for extension of the bitumen sample to 400mm) a E_{20-40} (for the difference between energy calculation after 200 and 400mm).

From further listed results for bituminous binders based on initial bitumen 50/70 and 70/100 following experience can be made:

- With increased content of FTP additive the deformation energy is raised t the same test temperature, confirming expected higher stiffness of this type of low-viscosity binder;
- Highest values at reference temperature of 15°C was gained for binders with 3% FTP;
- FAA, PPA and both presented chemical additives are from the viewpoint of deformation energy value after extension to 200 mm more or less comparable. In case of the quality indicator of deformation energy between 200 and 400mm the highest potential has been observed in case of IterLow-T additive. On the other hand the additive ZC reach in this evaluation only half value;
- If comparing bituminous binder 70/100 + 3% FAA and more advanced binder of 70/100 + 3% FAA + 0.5 PPA it is obvious, that the combined additive does not result in any improvement of deformation energy. The reasons for such combined modification were considerations by the industry for specific performance binders;

- On the other hand comparison of 70/100 + 3% FAA and 50/70 + 3% FAA is more interesting. The later binder gained worse results if assessed by E_{20-40} parameter.

As a next assessment dynamic viscosity measurements have been done. For this type of testing crucial is correct determination of input parameters. With respect to the utilization of bituminous binders, their pumping or later spraying shear rates from the interval 0.1-10 s^{-1} have been chosen. Experimental testing has been done on rotational viscometer Brookfield DV-II+Pro with use of testing spindle SC4-27. Dynamic viscosities have been determined for selected shear rates in temperature interval between 100°C and 160°C, as well as separately for a shear rate interval at test temperature of 135°C. Further comparison of neat and aged binders has been done.

Table 3: Selected results of force ductility assessment

Bituminous binder	T (°C)	E_s (J/cm²)	E_{20} (J/cm²)	E_{40} (J/cm²)	E_R (J/cm²)	E_{20-40} (J/cm²)
50/70 +1 % FTP	20	0,048	0,497	0,548	0	0,051
	15	0,120	1,876	2,168	0	0,292
50/70 +2 % FTP	20	0,074	0,679	0,745	0	0,066
	15	0,166	2,270	2,557	0	0,288
50/70 +3 % FTP	20	0,280	0,952	1,038	0	0,086
	15	0,188	2,655	3,291	0	0,636
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% FAA	20	0,074	0,682	0,746	0	0,064
	15	0,103	1,801	2,047	0	0,246
50/70 +0,1% ZC	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% IL-T	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

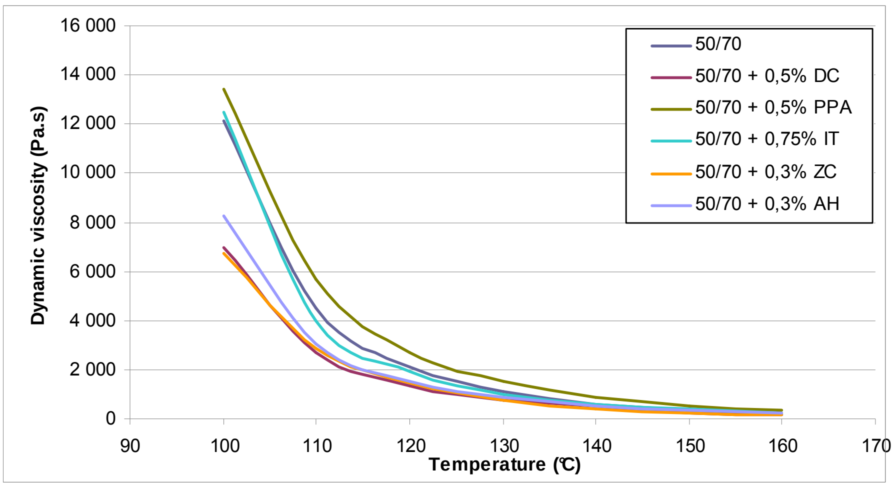

Figure 4: Dynamic viscosity of 50/70 bitumen modified by various additives, shear rate 1 s^{-1}.

Thereinafter as example of gained findings results for compared variants of low-viscosity bituminous binders at shear rate 1 s^{-1} are presented. It is obvious, that in case of 50/70 bitumen except of the alternative with PPA modification in all cases viscosity decrease could be observed in the interval of 100-130°C. For higher temperatures the effect of reduced viscosity more or less disappears and for all bituminous binders the value approximate to zero level. In the case of 70/100 binder the viscosity issue can be divided in interval 100-110°C and 110-130°C. In the first interval most of the additives, except of PPA and FAA, reduce viscosity value of resulting product and therefore allow better workability. Rather difficult is the interpretation of FAA additive results. In this case it has been expected that also this additive will have a positive effect on viscosity decrease in the given interval. Nevertheless comparing viscosity curve and gained value of softening point it is obvious – even for repeated measurements – that for temperatures lower than 120°C the effect of FAA additive is with respect to asphalt mix workability rather negative. In the second temperature interval positive effect on bituminous binders based on 70/100 bitumen and assessed additives was achieved only with FTP (with visible benefit even if the different in doping is one percent) and the nanochemical additive Zycosoil.

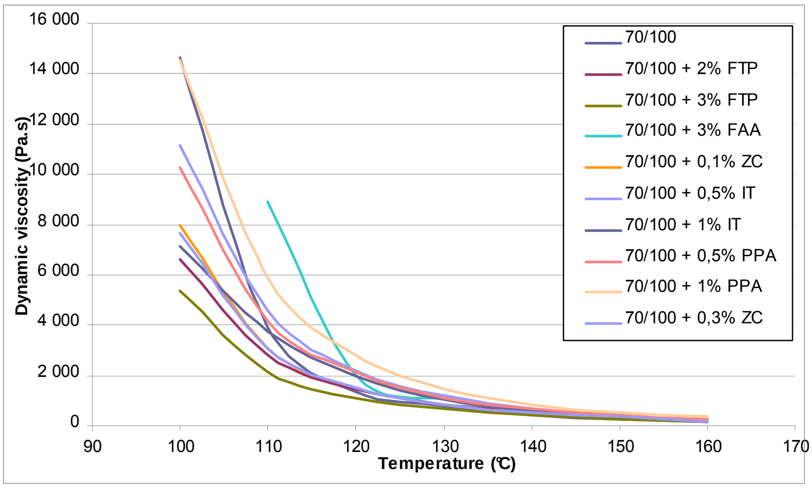

Figure 5: Dynamic viscosity of 70/100 bitumen modified by various additives, shear rate 1 s^{-1}.

Behavior of bituminous binders in the low temperature rang was analyzed by another dynamic test on Bending Beam Rheometer with determination of bending stiffness and the tangent to exponential progression of stiffness S(T), which is generally known as so called m-value. The measurements have been done for three different temperatures with the target to derive critical temperature at which S(T) = 300 MPa and m(T)=0.300 is valid. As a result, securing corresponding resistance of the binder and asphalt mix to crack origin caused by material brittleness, higher of both temperatures was used.

Figures 6 and 7 show results for particular low-viscosity binders. Reference binders have unfortunately not been tested. From the viewpoint of S(T) it was found out, that with respect to used additives the most favorable result was gained for adhesion promoter as well as for PPA. In the case of second additive it should e stressed out, that with increased content of PPA in the binders the critical temperature slightly worsens. The most unfavorable behavior in low-temperature range showed binder with FAA additive. Nevertheless labeling “unfavorable” is in this case relative, because values of all evaluated binders were within a range of 3.4°C. With respect to m-value typical logarithmic progression can be registered with a correlation coefficient declaring a reliability level of 0.94-0.98. From the gained results it is visible, that best values are reached by bituminous binders with PPA and tensides application. However, also in this case the negative impact on gradual decrease in critical temperature if higher PPA content applied has been observed. From the viewpoint of m-value the worst behavior has been reached for binder with FTP content. In this connection it should be stated, that in comparison with S(T) the difference between the best and the worst result of m-value was 6.8°C, i.e. a double value. In fine it should be pointed out, that the final critical temperature has been set on comparisons of both criteria. Only in case of FTP this temperature was driven by m-value, i.e. by the tangent to the exponential curve of S(T) and has higher importance then the stiffness value. For all other bituminous binders the determinant criterion with respect to setting minimum temperature of binder resistance in low-temperature range is reaching the bending stiffness of 300 MPa.

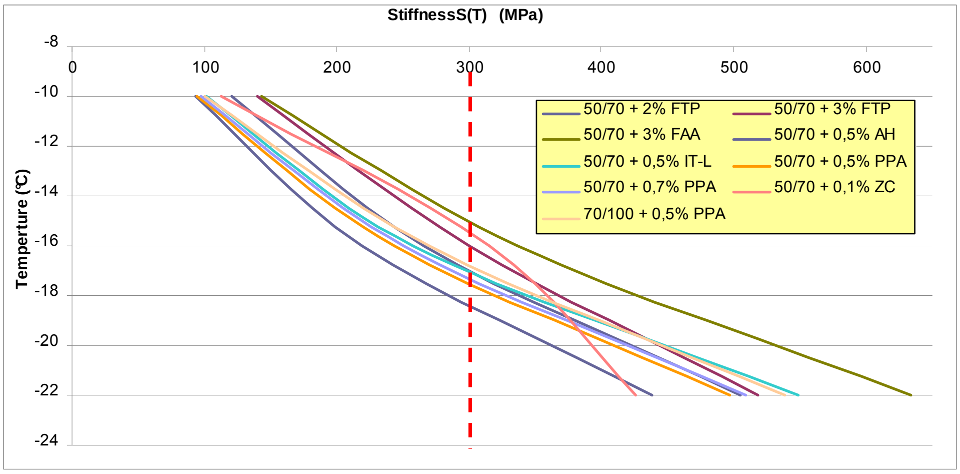

Figure 6: BBR Stiffness curves for assessed binders

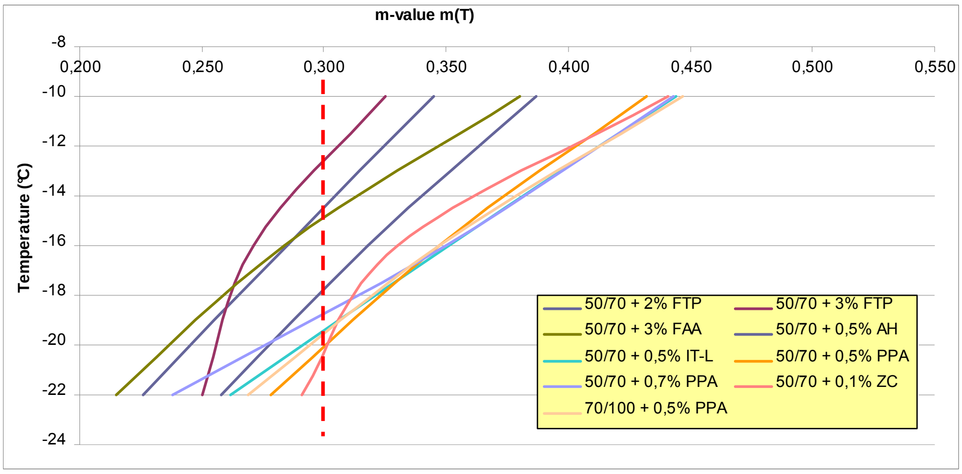

Figure 7: BBR m-value curves for assessed binders

Table 4: Results of critical temperature of assessed binders

Bituminous binder	**Temperature (°C) at which following condition is valid:**	
	S(T) = 300 MPa	**m(T) = 0.300**
50/70 + 2% FTP	-16.0	-14.5
50/70 + 3% FTP	-15.3	-13.2
50/70 + 3% FAA	-14.3	-15.5
50/70 + 0.5% AH	-17.7	-18.0
50/70 + 0.5% IL-T	-15.9	-19.4
50/70 + 0.5% PPA	-16.7	-20.0
50/70 + 0.7% PPA	-16.4	-18.5
50/70 + 0.1% ZC	-15.4	-18.2
70/100 + 0.5% PPA	-15.9	-19.7

Last but not least important performance characteristic within the bitumen assessment and correct utilization of low-viscous binders in WMAs is the complex shear modulus. Therefore separate evaluations on DSR have been done for temperatures of 25-90°C and for frequency sweep of 0.1-10 Hz. The aim was to describe in detail dynamic strain behavior. Test results have been interpreted by master curves with reference temperature of 60°C.

To gain reliable results, the measurements have been done firstly in temperature interval of 25-60°C, then separately only for 60°C and at the end in the temperature interval of 65-80°C. The DSR measurements were always repeated. During the testing the focus has been closely laid on results at 60°C because of preferences given by the standard CSN EN 14770. Normally, if dynamic strain testing on DSR required for bituminous binders the complex modulus values at 60°C is required in the European standards (Fig. 8 and 9).

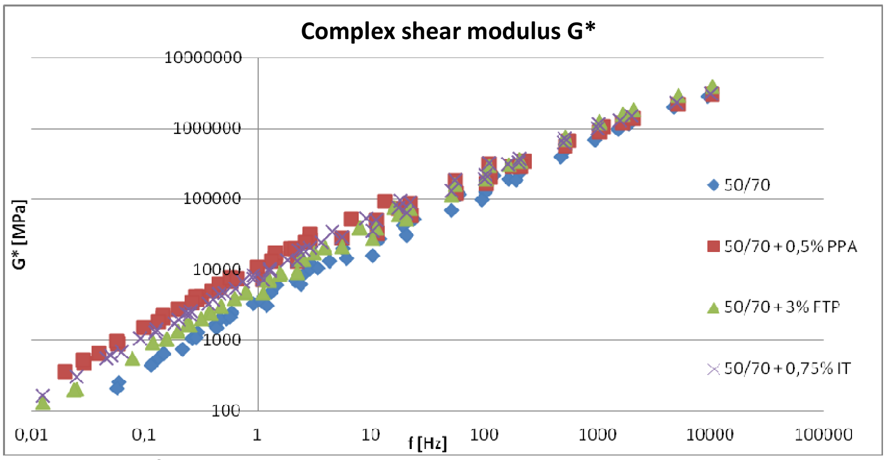

Figure 8: Comparison of various viscosity additives on complex shear modulus of a binder in the interval of 25-80°C; reference temperature 60°C

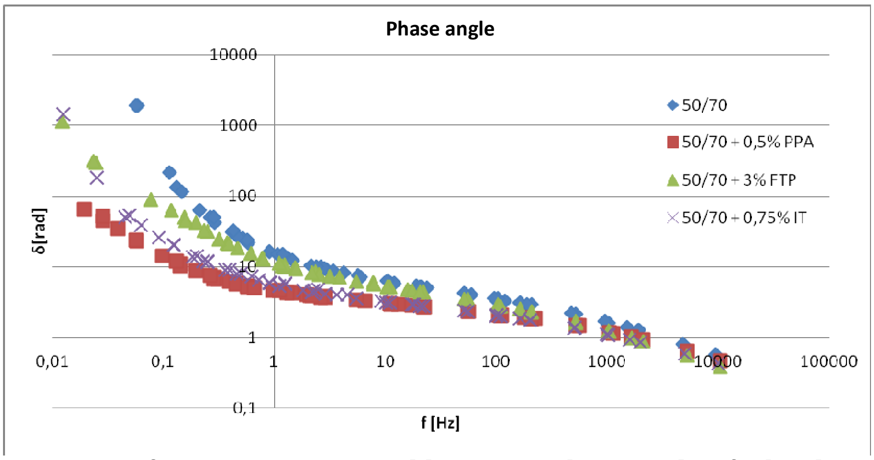

Figure 9: Comparison of various viscosity additives on phase angle of a binder in the interval of 25-80°C; reference temperature 60°C

For the reference bitumen of 50/70 penetration firstly the linear viscoelastic domain has been determined. Bitumen samples have been loaded for four different temperatures from the interval of 40-70°C. This can be seen as a domain, where the viscoelastic material behavior can be correctly observed and described without non-clarified fluctuations. In the case of the presented research finally shear stress of τ = 4,000 Pa has been selected for all frequency sweep testing.

From the viewpoint of compared master curves designed for complex shear modulus (|G*|) and phase angle (δ) benefit of several viscosity improving additives is visible. For binders with such additives also an added value for mix temperature reduction can be seen. Most apparent is this benefit especially in temperature interval of 40-80°C where permanent deformations in the asphalt pavement play the critical role. At the same time evident benefits are obvious for lower frequencies. This can be quite good approximated to demands of material behavior in pavement structure in hot summer seasons.

Comparing the effect of particular additives in the bituminous binder with respect to increased resistance permanent deformations of an asphalt mixture application of PPA and IterLow-T have been observed as most favorable alternatives. In the later case the used content of the additive should be 0.5-0.75 %-wt. in the bitumen. Modified binders in this case reach lowest phase angle and improved viscoelastic behavior can be expected. On the other hand complex shear modulus has higher values especially in the domain of lower frequencies. Surprising to a large extent in this connection is the FTP additive, which is well known for its stiffening effect. Mentioned should be also a slight change, which has been observed in the domain lower temperatures (higher frequencies in the master curve chart), where results of all modified binders are more or less similar. In this case a gradual decrease of PPA effect and increased positive effect of IterLow-T and FTP has been observed.

5 SUMMARY

From the performed experimental assessments of various binders applicable for warm mix asphalts some so far valid findings could be validated. Additives based on synthetic waxes lead to bituminous binders with decreased penetration and higher softening points. In consequence of this fact usually resistance against deformation is improved as expressed for bituminous binders by complex shear modulus and deformation energy gained from the force ductility test. In comparison with the strain behavior more significant bitumen behavior decline in the range of low-temperature was not apparent and affirmed by performed tests. Benefits in strain characteristics were gained also in case of chemical additives based on surfactants and PPA application. For these binders usually only a very small change in basic physical and mechanical properties comes out and the behavior in low-temperature range is in general not affected. Nevertheless strain behavior is improved and should impact the asphalt mix behavior. If the assessment would be done based on dynamic viscosity results, then it can be stated, that according to starting expectations the chemical modifier PPA does not improve viscosity, on the contrary in the domain of low temperatures slight increase in viscosity values was observed. However in case of experimental asphalt mixture production as reported e.g. in (Valentin, 2012) an improvement in workability for temperatures between 140°C and 150°C was followed without negative impacts on overall mix performance. In comparison with the initial assumptions worse viscosity parameters were gained for binders with FAA additive in the temperature domain <120°C. In case of other synthetic wax and chemical additives applications it was verified that there is an improvement in workability given by lower viscosity values and the processing temperatures for asphalt mixtures get larger space for safe mixing and paving.

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