Stiffness and Low-Temperature Behavior of Selected Warm Asphalt Mixes

J. Valentin, P. Mondschein
Department of Road Structures, Czech Technical University in Prague, Czech Republic

M. Varaus, P. Hýzl
Department of Roads, Faculty of Civil Engineering, Brno University of Technology, Czech Republic

ABSTRACT: Warm asphalt mixes are since several years a developing technique which has been primarily motivated by environmental benefits. Nevertheless these mixes are noted for improved stiffness behaviour and higher resistance against permanent deformations, especially due to modified (low-viscosity) bituminous binders used. On the other hand decrease of bitumen penetration due to viscosity improving additives can cause reduced flexibility behaviour of the asphalt layer in the range of lower temperatures. As part of the ongoing research asphalt mixes where bituminous binders with various viscosity improving additives were applied have been analyzed regarding stiffness modulus and low temperature behaviour by simple bending beam test. Gained results and recommendations are presented in this paper.

KEY WORDS: warm mix asphalt, bitumen, stiffness modulus, bending beam test, low temperature behaviour.

1 INTRODUCTION

The aspects of decreasing working temperatures in asphalt production and processing have been in the focus for a number of years. Attention was paid to the issue already in the 1980’s and 1990’s with mastic asphalt mixes which are characterised by a need for high temperatures for production and processing due to its composition. In this regard, experience with using an additive of Montana wax in the bitumen or the resulting mastic asphalt has been relatively well known. Based on the experience, other development activities were initiated in the 1990’s which resulted in the gradual practical implementation and verification of other additives which were generally termed “intelligent filler” or “viscosity improving additives” (Damm et al. 2002). Simultaneously, other technologies were gradually developed and refined; these are summarised for instance in (Prowell and Hurley 2007).

Since the Czech Republic ranks with countries with long-term mastic asphalt tradition the original trends using Montana waxes (most frequently the Hostamont filler in the 1990’s) were originally well known here; they were tested by some laboratories to a limited extent for basic physical and mechanical properties. The testing of the new generation of viscosity improving additives started in the Czech Republic with hot mix asphalt (HMA) in 2003-4; at that time, the first test sections were laid which have been monitored until this day. This period saw the first laboratory mix design within the road laboratory of the Civil Engineering Faculty of the Czech Technical University (CTU), too. Attention was paid particularly to the use of low-viscosity bituminous binders applying the Fischer-Tropsch paraffin (FTP). The effect of the additive on the asphalt characteristics was verified with AC mixes for wearing and base courses using common distilled bitumen. Later, based on the findings from Germany, more mixes were designed where a polymer-modified binder with an addition of FTP was applied. The dosage of the FTP additive used in all mixes was identical at 3%-wt. of the bituminous binder. From the perspective of laboratory testing, attention was paid to physical and mechanical properties (Marshall stability or void content of the mix) as well as to verification of resistance to permanent deformation. The results of the experiments were published for example in (Valentin et al. 2004).

Gradually, the warm mix asphalt technology application spread further and individual producers applied primarily the mix designs and findings of their respective foreign mother companies. The possibilities of synthetic zeolite application were tested as well as a few sections completed with a combination of bituminous binders including an FTP additive and reclaimed asphalt material (RAP) in the resulting mix. The CTU Civil Engineering Faculty's Road Laboratory performed several tests with laboratory designs of binders and asphalt mixes involving addition of amide wax in 2005-6; the tests monitored both the effects of the additive on the bitumen properties (penetration, softening point, viscosity, force ductility) and mechanical and physical properties of the asphalt mix with a distilled bitumen and this additive (Valentin and Mondschein, 2006). In this period, the first tests of functional properties of selected warm asphalt mixes were conducted; the experiments have been ongoing till the present. In 2008, the activities were extended by measurements performed by a scientific team at the Brno Technical University (Hýzl et al., 2009) where attention was initially paid to determining the stiffness modulus according to ČSN EN 12697-26 and confirmation of low temperature properties using a method developed by this university.

Since 2009, both teams have been involved in the work on a three-year research project, "Rheology and experimental determination of functional characteristics of warm asphalt mixes". The focus of the project can be summarised in the following items:

- determination of available techniques for warm (low energy) asphalt mixes including basic technical parameters, design and processing;
- optimization of the design for selected warm asphalt mix (WMA) techniques with respect to the conditions in CZ (additives used, proportion of the additives, bituminous binder content, recommended processing temperatures);
- experimental analysis of mechanical characteristics (indirect tensile strength, air voids content), dependence of the selected processing temperatures on the values of selected mechanical characteristics;
- assessment of selected performance characteristics for miscellaneous variants of warm asphalt mixes (determining stiffness modules in the temperature range of 0-40°C, study of complex modulus, researching fatigue characteristics in the temperature range of 0-30°C, researching characteristics of asphalt mixes under low temperatures including asphalt mix relaxation (0-5°C), researching resistance against permanent deformations under the temperature of 50°C);
- determination of limiting values of odd parameters suitable for numerical pavement construction design calculation;
- development of a basic model for WMA microstructure from the perspective of its performance characteristics and use of numerical simulation;
- gradual optimization of the model based on extending the measured values group and comparing the modeled values with values obtained from samples gathered from road pavement structures.

2 CURRENT EXPERIENCE IN CZECH REPUBLIC

As has been mentioned in the previous part, warm asphalt mixes cannot be considered an innovation that has not been put to use in road structures in the Czech Republic so far (Hanzík et al., 2009; Dvořák 2009). Rather the contrary; an increasing trend of applying this type of mix is obvious; the primary factor is not an effort to reduce working temperature but to increase the time interval for good-quality laying and compaction of the asphalt layer completed. In many cases, this fact is motivated by the allocation of public funds in the third and, particularly, fourth quarter of the year which result in completion of works under deteriorating weather conditions. Another motivation for the application of low-viscosity bituminous binders in particular is the production of asphalt mixes with higher stiffness modules intended primarily for base and sub-base asphalt layers. A partial reduction of energy demands and the ensuing reduction of greenhouse gas production can only be quoted as a tertiary motivation element.

At present, the most widely spread method is the application of FT paraffin which is most frequently dosed at 3%-wt. and used in a ready-mixed (industrially prepared) bituminous binder. Amide wax is applied based on a similar principle; it is usually dosed at the same quantity straight in the mixing plant. Last but not least, the use of synthetic zeolite should be mentioned; this is dosed in quantities not exceeding 1%-wt. of the asphalt mix.

A separate field is the foamed asphalt technology. In comparison to the experience from e.g. USA (Prowell and Hurley 2007), the production of foamed bitumen is applied to a limited extent, exclusively in the cold recycling field. In this group of technologies, 3-5%-wt. of foamed asphalt is usually dosed in the resulting recycled mix; a combination of the binder with cement is very common. The reason is the fact that the recycled mixes are very often used in structures where increased load bearing capacity is desirable. The use of foamed bitumen in common asphalt mixes has not been verified in the Czech Republic so far.

3 EXPERIMENTAL MIXES – DESIGN AND SPECIMEN PREPARATION

Within the framework of the research done at the CTU in Prague, individual additives were used in combination with the 50/70 distilled bitumen as well as with selected PmBs. This paper deals only with mixes, where the 50/70 bitumen was used. During last four years different AC mixes as well as SMA11 have been evaluated. To verify all alternatives and effects of odd additives in an asphalt mix, two similar asphalt concrete type mixes ACL 16S and ACL 16 (asphalt concrete for binder courses) were selected. These mixes were designed according to the CSN EN 13108-1 standard. The quantity of binder in the first mix was designed as 4.2 %-wt., what can be considered as relatively low, especially if compared with experience in some neighboring countries. In the case of ACL 16 mix the binder content was 4.4 %-wt.. Assessed mixes are described in the following tables. All mixes have been produced and compacted at 150°C.

Table 1: Determination of assessed asphalt mixes, type ACL16S.

Mix	**REF**	**WMA1**	**WMA2**	**WMA3**	**WMA4**
Used additive	-	FT-paraffin (3 %)	Amide wax (3%)	PPA (3%)	PPA (1.5%)
Mixing temperature (°C)	150				
Voids content (%-vol.)	7.9	7.8	7.8	7.2	7.4
ITSR (-)	0.87	0.91	0.60	0.96	0.97

It should be emphasised that the WMA3 mix was not considered in the testing using the tests listed below with respect to the excessive quantity of the polyphosphoric acid (PPA) dose which does not observe the recommendations of the additive producer and which could have an adverse impact on the properties of the final asphalt mix.

Table 2: Determination of assessed asphalt mixes, type ACL16.

Mix	REF2009	2009_2	2009_3	2009_4	2009_5	2009_6
Used bitumen	50/70	70/100	50/70			
Used additive	-	FTP (3 %)	PPA (1%)	PPA (0.5%)	Amide wax (3%)	FTP (3 %)
Mixing temperature (°C)	150					
Voids content (%-vol.)	4.1	4.6	4.3	3.2	4.0	3.5
ITSR (-)	0.85	0.75	0.87	0.95	0.93	0.65

The team of Brno Technical University (VUT) focused on designing an asphalt mix of the ACL 16 type with binder of 50/70 gradation of foreign origin. The optimum dosage of the binder in the mix was determined at 4.4 %-wt. and the mix thus produced was marked as the reference mix; the production and subsequent compaction occurred under standard working temperatures (test specimen production temperature of 160°C and compaction temperature of 150°C). Besides, two mixes of identical grading and with the same doses of the bituminous binder were produced; these were marked as warm asphalt mixes. In the first case, the mix included bituminous binder containing 3 %-wt. of amide wax (Licomont BS 100). Working temperatures were reduced by 10°C for this mix. In the other case, bituminous binder with an addition of FT paraffin (Sasobit), again to the dose of 3 %-wt. was used under working temperatures reduced by 20°C.

In mixes tested by the CTU team in Prague, 8-10 cylindrical test specimens were made using an impact compactor according to ČSN EN 12697-30+A1 to determine the stiffness modulus; 2 plates with the dimensions of 260x320x50 mm which were subsequently cut into test specimens of 50x50 mm cross-section were made by a segment compactor to determine the tensile bending strength.

Four plates of the dimensions of 260 x 320 x 50 mm were made of each mix; subsequently, these were cut into test specimens in the shape of trapezoid and prisms with a diamond saw to determine the stiffness modulus by a 2PB test and properties under low temperatures within the framework of the activities of the VUT team in Brno.

Figure 1: Preparation of trapezoidal specimens for stiffness modulus assessment.

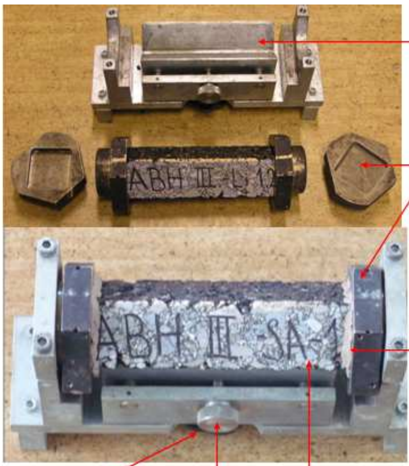

Figure 2: Detail of specimen preparation for low temperature testing by the method modified by VUT Brno (based on prEN 12697-46).

4 EXPERIMENTS AND RESULTS

All the mixes were assessed first from the perspective of their mechanical and physical properties – determination of voids content, indirect tensile strength ratio, bulk density, specimen dimensions. From the point of view of the conditions listed in the national appendix to the CSN EN 13108-1 standard for the first two of the aforementioned characteristics in particular, the mixes met the requirements. In the case of test specimens obtained from the laboratory plates, the degree of compaction fell in the 100 ± 1% range. In this context, the experimental assessment repeatedly proved that mixes with low-viscosity binders had a 5-15 % reduction in the void content value in the HMA under identical temperature of test specimen production. In the case of strength characteristics, the results usually supported increased strength which corresponds relatively well with the results of the stiffness modules as presented below. In contrast to that, the indirect tensile stress (ITS) ratio comparisons were not always unambiguous.

4.1 Stiffness modulus

Dynamic stiffness modulus is generally defined as a ratio of stress and strain at a defined temperature for which factual specific Poisson's ratio is given. The modulus characterizes the ability of tested material to resists the loading effects. With increasing value of stiffness modulus the ability to transfer larger loading effect increases as well. Values of stiffness modulus are determined and calculated by application of repeated load. In the Czech Republic the value of stiffness modulus at 15°C is specified as one of the basic designing characteristics for pavement structure design.

The stiffness modulus values were determined using two methods permitted by the CSN EN 12697-26 standard. The CTU team in Prague applied the repeated indirect tensile stress test determining the stiffness modulus under 5°C, 15°C and 27°C. Moreover, the temperature of 40°C was also selected for some mixes. The stiffness modulus value was determined in controlled deformation mode where a deformation on the 5 microstrain level was required. Each specimen was subjected to five load pulses in two directions perpendicular to each other.

The test was performed on a universal asphalt tester (Cooper Technology). The results of stiffness determination for the mixes as specified above are summarised in table 3. The VUT team in Brno prefers the 2PB test with trapezoidal specimens under 15°C and frequency of 5, 10, 15, 20 and 25 Hz for the testing. The results of stiffness modulus determination for the mixes researched at VUT are given in table 5 and figure 4.

Table 3: Stiffness modules of assessed ACL 16S mixes (ITT Test).

Temperature/Mix	REF	WMA1	WMA2	WMA3	WMA4
T=5°C	17,000	20,300	13,200	11,000	20,500
T=15°C	10,600	13,200	9,900	8,300	13,200
T=27°C	2,600	3,200	2,100	1,900	5,800
Thermal susceptibility, (-)	6.54	6.34	6.29	5.79	3.53

Table 4: Stiffness modules of assessed ACL 16 mixes (ITT Test).

Temperature/Mix	REF2009	2009_2	2009_3	2009_4	2009_5	2009_6
T=5°C	21,400	17,900	17,100	20,600	26,900	27,300
T=15°C	8,800	8,500	9,800	11,200	11,900	13,800
T=27°C	2,000	2,200	3,300	2,800	3,900	5,200
T=40°C	400	600	700	900	1,200	1,600
Thermal susceptibility, (-)	10.7	8.14	5.18	7.36	6.90	5.25

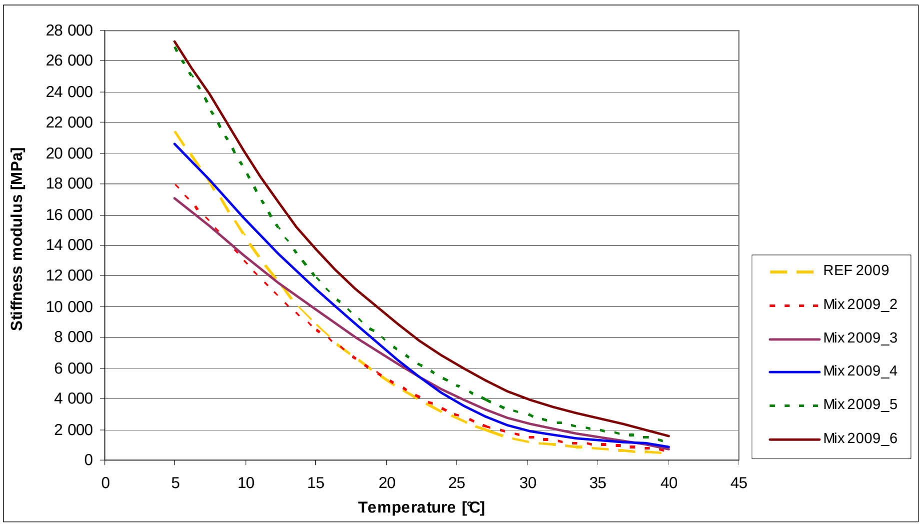

Figure 3: Graphic representation of the relationship between temperature and stiffness modulus.

Table 5: Stiffness modules of assessed ACL16 mixes (2PB Test).

Mix/Frequencies	5 Hz	10 Hz	15 Hz	20 Hz	25 Hz
ACL 16 reference	7,479	8,153	8,256	8,653	8,662
ACL 16 + 3% Licomont	7,194	7,860	7,982	8,406	8,542
ACL 16 + 3% Sasobit	7,196	7,831	7,888	8,282	8,388

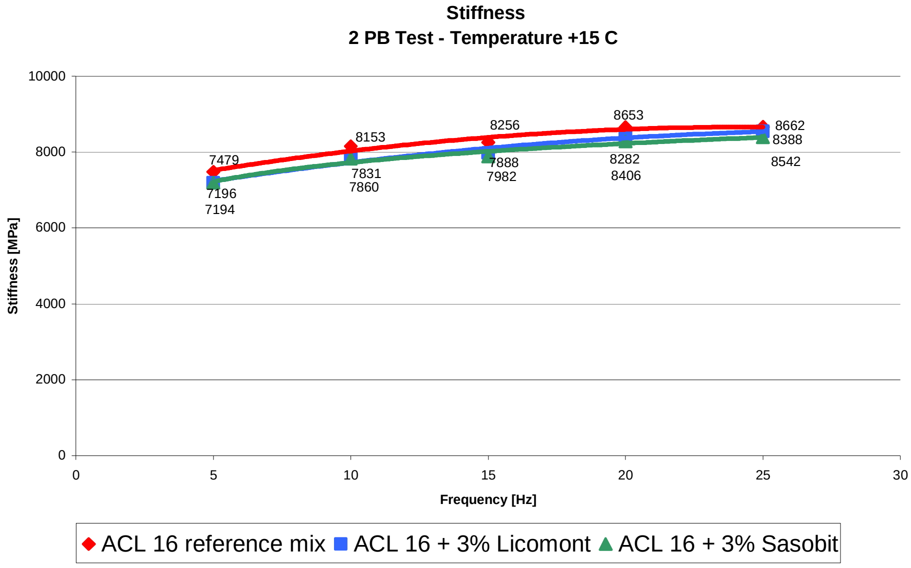

Figure 4: Graphic representation of the results of measured stiffness modules according the ČSN EN 12697-26 standard.

Gained values of stiffness modulus, which were assessed by indirect tensile test on at least 4-6 test specimens for each testing temperature, can be interpreted in following conclusions:

- the mixes meet the requirement for the minimum stiffness modulus value at 15°C as specified in the Czech pavement design specifications TP170 for Asphalt Concrete (7,500 MPa) and High Stiffness Modulus Asphalt Mix (9,000 MPa) – in this case, with the exception of mix WMA3 (a mix with the addition of 3 %-wt. of PPA) and reference mix REF2009 as well as mix with 70/100 bitumen and addition of FTP;
- generally mixes with FTP lead to highest stiffness modulus improvements (around 25 % @ T=15°C);
- there is a good comparability between the reference mix (with 50/70 bitumen) and the asphalt mix 2009_2;
- the dependence of temperature and stiffness modulus can be for statistical reasons quite good explained by exponential regression curve (regression coefficient in the range of 0.97-0.99);
- the effect of viscosity improving additives is visible not only in case of stiffness modulus but can be found for thermal susceptibility as well. Nevertheless the influence is not definite, if comparing ACL 16S and ACL 16 mixes. In the latter case the thermal susceptibility is improved by 25-50 %;
- in case of PPA additive the proper dosing of the additive can be demonstrated comparing mixes WMA3 and WMA4;
- analyzing the ACL 16 mixes it can be found, that stiffness modulus is more improved by lower portion of PPA;
- for the calculation of thermal susceptibility a modified equation has been used with 5°C as minimum and 27°C as maximum temperature.

When interpreting the results achieved during the measurements involved in the 2PB test on trapezoidal specimens at the VUT I Brno, the following findings may be formulated:

- all mixes confirmed the expected trend of the stiffness modulus increasing with the load frequency;
- relatively good comparability of the results of the 2PB test and the non-destructive

repeated indirect tensile stress test on a cylindrical specimen is obvious; the results obtained from the first method are lower by approx. 6-8 % with the reference mix and up to 40 % with the selected warm asphalt mixes.

4.2 Low temperature characteristics

Low temperature characteristics of asphalt mixes in the Czech Republic have not been specified for all types of used mixes so far. This fact reflects the overall situation in Europe, where a uniform standardized testing method has not been defined yet. Experimentally low temperature characteristics are determined mainly for asphalt mixes with high stiffness modules and for stress absorbing layers using three different test procedures – the tensile bending strength test, the relaxation test (both described e.g. in Mondschein and Valentin, 2009) and the test developed by the Brno Technology University using Cyclon -40 thermal chamber.

The tensile bending strength test uses beam specimens with dimensions of 50x50x300 mm. For each test conditions at least four beams are used. The test is carried out in a special air-conditioned bath at a temperature of 0±1°C. While measuring the tensile bending strength, the specimen is loaded until failure, where the maximum reached force (stress) and the corresponding deformation are recorded. An important factor strongly affecting the stress value is the loading speed therefore the test is carried out at 50 $mm.min^{-1}$ and 1.25 $mm.min^{-1}$. At present, the preliminary flexural strength threshold value of 6 MPa is stipulated for asphalt mixes with high stiffness modulus. In the test performed by the road laboratory at the VUT in Brno, test specimens of HMA in the shape of prisms to the dimensions of 50 mm x 50 mm x 200 mm are subjected to tensile stress which is caused by thermal shrinking when shortening of the specimen is prevented ($\varepsilon t = 0$). The maximum tensile force (stress) and the critical temperature for frost cracking are determined.

Results gained by the tensile bending strength test are shown in following figure 5. The following conclusions may be formulated for the aforementioned mixes:

- the preliminary threshold value of tensile bending stress for both loading speeds is only reached by the mix with FT paraffin additive;
- all warm asphalt mixes demonstrated a higher tensile bending strength value with the higher loading speed; from the perspective of lower loading speed, an improvement is obvious with the application of FT paraffin and PPA;
- the asphalt mix with the binder where 3 %-wt. PPA was applied was not subjected to this test with respect to the unsuitability of the dosage.

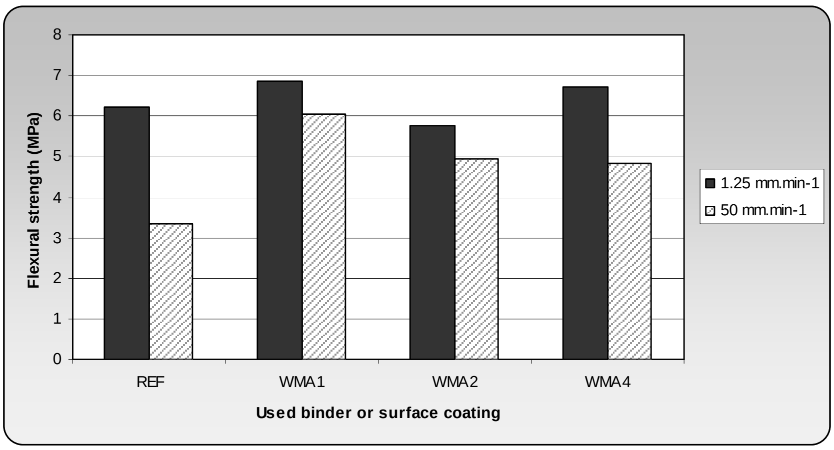

Figure 5: Results of tensile bending strength test.

The results of measurement of the mixes researched at the VUT in Brno are given in table 6. The values presented are always the average of at least three test specimens; in contrast to the aforementioned results of the tensile bending strength they allow determining the limit temperature of frost cracking. The results also show that the application of additives which reduce the viscosity of the bituminous binder does not cause any deterioration of low-temperature properties. The average temperatures of the sample at the point of deformation are basically identical; from the perspective of the maximum force and maximum stress upon fracture (cracking) of the specimen it is obvious that both characteristics have increased. Again, this confirms the probable stiffening effect of the additives.

Table 6: Results of low temperature characteristics assessment.

Mix	**Maximum load at fracture (kN)**	**Maximum strain at fracture (MPa)**	**Specimen temperature at fracture (ºC)**
ACL 16 reference	8.48	3.32	-18.8
ACL 16 + 3% Licomont	11.82	4.76	-19.7
ACL 16 + 3% Sasobit	9.29	3.71	-19.0

Figure 6: Specimen (ACL 16 + 3% Licomont) after test termination.

5 CONCLUSIONS

From the perspective of stiffness modulus values and WMA properties, the experimental results so far have not proven any negative effects of the viscosity improving additives to the bituminous binder. In the case of adding FT paraffin, the effect of increasing stiffness as previously found has been confirmed; the change caused concern with respect to the increased susceptibility to frost cracking. The results presented demonstrate no such phenomenon. On contrary, it has been proven that identical or improved values of selected performance characteristics can be achieved both under working temperatures identical to those used in case of mixes designated as reference mixes in this paper, and for asphalt mixes with added amide wax or FT paraffin where the working temperatures were lower. From the perspective of stiffness modulus values, the parameters even increased by up to 40 % with some of the mixes; this puts the selected type of mix ACL 16 significantly closer to mixes with high stiffness modulus.

It must be emphasised that from the point of view of practical application, low-viscosity binders and WMA where those are involved require precision in production as well as application; although a number of positive aspects can be identified with them they are certainly no “aspirin for the road construction industry”. They require verification of other useful behaviour characteristics focusing particularly on the durability and resistance to the changeable effects of climate and traffic. In this regard, further experiments concentrate on testing complex modules, fatigue behaviour by various methods and determination of resistance to permanent deformations in particular.

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