DEFORMATION PARAMETERS OF THE ASPHALT MIXTURES IN PAVEMENT CONSTRUCTION LAYERS

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ABSTRACT

The quality of the road is affected by the correct design, materials used appropriately, climate impacts and technological discipline. Deformation properties of mixtures used for construction of pavement construction layers detected by dynamic methods and fatigue - as a functional test - allow to design the road to suit the anticipated traffic load throughout its life. Quality of mixtures is also expressed by the resistance to permanent deformation. Complex modulus of stiffness, principal curves and fatigue can reliably characterize the proposed mixture of asphalt bonded aggregate and additives. On the circular test track were evaluated mixtures with conventional asphalt binder, modified binder and additives.

1. INTRODUCTION

Various procedures of asphalt mixtures testing, which correspond to the model of viscoelastic matter are being verified in the road construction. Dynamic test allows better assessment of mixtures used in the road construction. The axle of the car when driving over the road surface generally oscillates at the frequency from 6 to 25 Hz, which corresponds to impact of moving vehicles during normal operation [1]. For purposes of design of pavement construction layers in Slovakia is used the dimensioning method, which considers the dynamic modulus of elasticity (E), Poisson's ratio (μ) and flexural strength (Ri,t). Dynamic modulus of elasticity is determined by the impact test.

Rheological properties of road construction materials are characterized by the mass models which express properties of asphalt mixtures in the system of flexible pavement structure [1], [2]. Materials and binders for pavement wearing course create viscoelastic substance. Quality of the mixture can be assessed by

- static creep modulus which is used to verify the deformation properties of asphalt bound materials.
- complex modulus which better represents, in the field of complex numbers, the behaviour of viscoelastic materials which form pavement bearing and wearing courses. It is expressed mainly in dependence on the size of acting harmonic force, temperature of the sample and environment, load frequency of harmonic force. Testing should proceed at the same frequency as the oscillating axle of the vehicle when moving on the road under the normal conditions.
- durability of bound materials, expressed by the material fatigue at the testing frequency and temperature, depending on the same strain or tension in the test [9].

2. DEFORMATION PROPERTIES

Operational capability of the road is substantially dependent on deformation and strength characteristics of materials forming the wearing course of flexible pavements. The basic deformation characteristics include modulus of elasticity, deformation modulus, modulus of stiffness, creep modulus, Poisson's ratio. The basic strength characteristics are stability, compressive strength, flexural strength and splitting tensile strength.

Test methods for design and control of pavement construction materials determine the basic conditions valid for flexible matter. Materials in terms of deformation properties are divided into solid, viscous and plastic. *Stiffness* of the material is characterized by the directly proportional dependence of tension and strain. *Viscosity* is expressed by the direct proportion of the resistance force (tension) to the strain rate. *Plasticity* is characterized above the yield strength limit and has no direct relation between stress and strain. It is anticipated that road construction materials, act as perfectly flexible substances and that their deformations are immediate and reversible [12].

Activity of majority of road construction materials loaded short or long term is expressed by the Boltzmann theory of linear viscoelastic materials, which better reflects the effects of repeated stress (fatigue). Most road construction materials are characterized as a linear viscoelastic matter, which is simplified in the Boltzmann theory by the mechanical model, consisting of a system of springs (flexibility) and silencers (viscosity), located behind or next to each other, which may be deformed by the reversible (immediate, delayed) or variable permanent deformations.

For linear viscoelastic matter [10] stressed by the harmonically variable stress $\sigma = \sigma_0 \cdot \cos(\omega t + \varphi)$ is also the deformation at forced oscillation harmonically variable. However, there is even a phase delay ε and σ, consequently
$\varepsilon = \varepsilon_0 \cdot \cos(\omega t + \psi)$, where $\varphi \neq \psi$

Complex modulus $E^*_{(i\omega)}$ is a complex number, which has the form

$$E^*_{(i\omega)} = E_1 + iE_2$$

$$E_1 = \frac{\sigma_0}{\varepsilon_0} \cdot \cos(\psi - \varphi)$$

$$E_2 = \frac{\sigma_0}{\varepsilon_0} \cdot \sin(\psi - \varphi)$$

E_1 - real component, which characterizes the elastic properties [MPa]
E_2 - imaginary component, which characterizes the viscous properties [MPa]

$$\alpha = \psi - \varphi = arctg \frac{E_2}{E_1}$$

Share $\frac{\sigma_0}{\varepsilon_0}$ equals to the absolute value of the complex modulus and expresses the module of stiffness S

$$S = \frac{\sigma_0}{\varepsilon_0} = \left| E^*_{(i\omega)} \right| = \sqrt{E_1^2 + E_2^2}$$

For evaluation of mixtures were used:

- *creep modulus* - the ratio of permanent tension and time-variable deformation
- *complex modulus* - the ratio of tension and deformation at steady, harmonically variable oscillation in consideration of their mutual time shift.

Absolute value of complex modulus (modulus of stiffness) is equal to the creep modulus for the load time $t = \frac{1}{\omega}$ and allows reciprocal comparison of results of measurements obtained from static and dynamic tests.

It is better to use dynamic methods to measure deformation characteristics of asphalt mixture which forms pavement construction layer.

Measurement of the complex stiffness modulus is performed at the short-term alternating harmonic load. It expresses the proportion of maximum amplitudes of excitation tension (σ_0) and deformation induced by it (ε_0) and their phase shift (φ). The stress (force), which varies sinusoidally in time, is applied on to the element of linear viscoelastic material, the strain (deformation) varies in time with the same frequency as the stress, but it lags behind by the phase. Graphical representation of measurement and complex modulus evaluation is represented in Fig. 1 and [10].

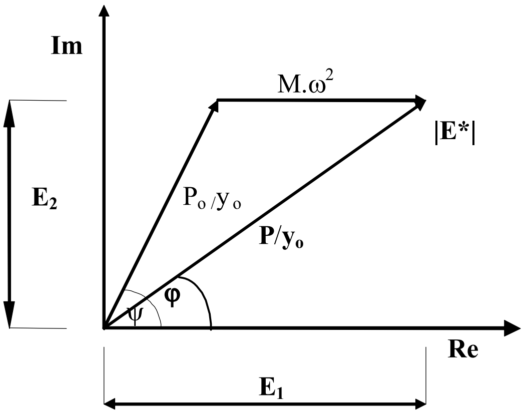


Figure 1 - Complex modulus [10]

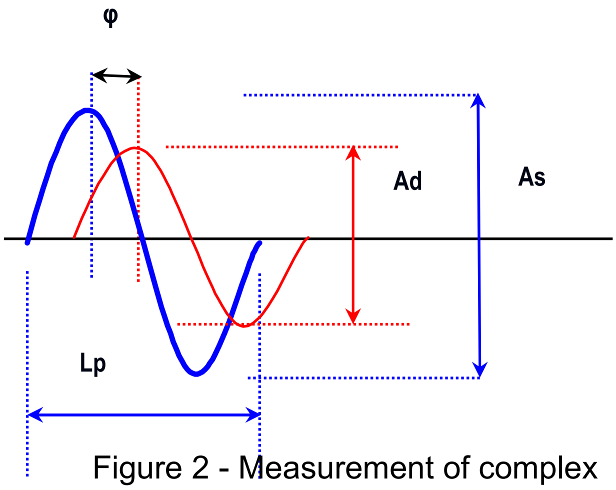


Figure 2 - Measurement of complex modulus

Lp - length of period, φ-phase-shift, As-amplitude forces; Ad-amplitude deformations

For measurement and evaluation was used the module of Burgers solid (Figure 3) trapezoid-shaped samples (Figure 4) [10]

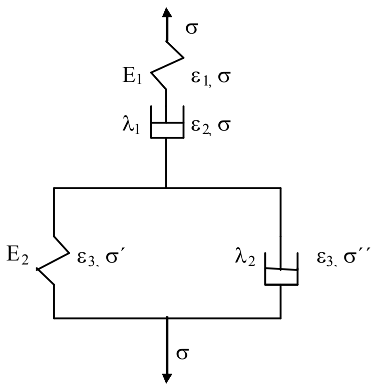


Figure 3 - Burgers solid

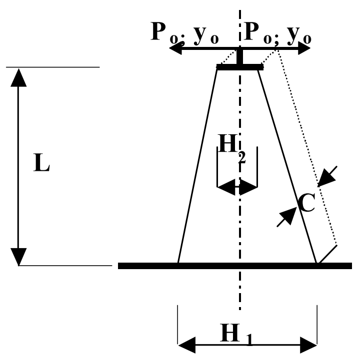


Figure 4 - Testing sample trapezoid-shaped

Circular test track (Figure 5) was divided into 6 sections (Figure 6) with various pavement construction [12]. Simulated load was created by the three-arm testing device. At the end of each arm the load of 100 kN could have been simulated and later, at different pavement composition it was 115 kN. Arms allowed the loading at different distances from the axis. Therefore, some lanes (in the road width arrangements) were loaded with different number of driving over. Construction layers with asphalt binder were placed on unbound materials or bound materials on the basis of hydraulic binders.

The procedure and method of measurement was selected:

- blocks were cut out from individual sections in the trail pass of the loading wheel and from the other part of the wearing course, where pavement was not loaded (only climate conditions effected the pavement)
- trapezoid shape testing samples were cut out from the blocks and evaluated were:
    - deformation properties - static modulus and complex modulus (of stiffness)
    - fatigue.

Measurement and evaluation were carried out at temperature corresponding to the design method used in the Slovak Republic 0 °C, +11 °C, +27 °C and at different frequency of the loading force.

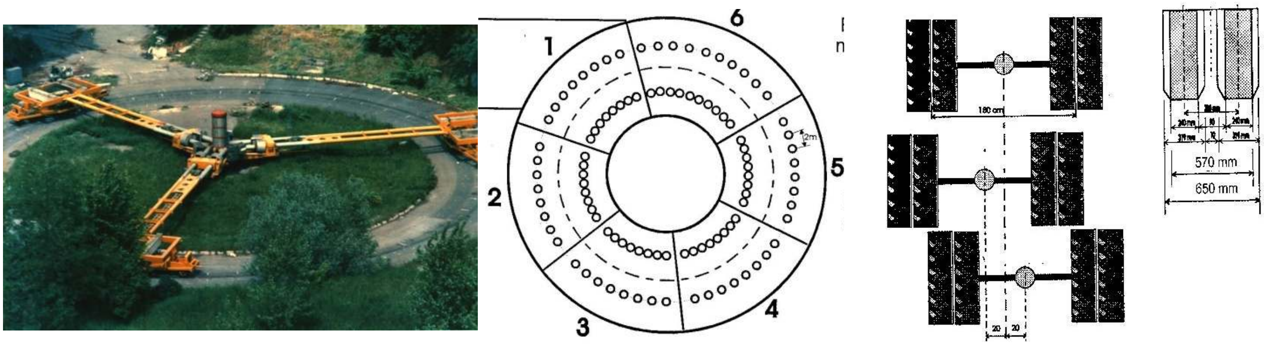


Figure 5 - Scheme of the circular test track

Legend: bias tyre construction 12,00-20; tire profile MP600; average 1130 mm; truck rim 8,50; loading capacity 3250 kg; inflation 700 kPa

1 Comparative pavement	2 Cold technology	3 Cold technology	4 Hot asphalt mixture	5 Hot asphalt mixture	6 Experiment (road base)		± 0.00
ABSI 40 mm	AKMS 25 mm	AKMS 25 mm	AKMS (PmB) 40 mm	AKMS (PmB) 40 mm	AKMS 40 mm		-40.00
ABVHI (PmB) 70 mm	ABVHI (PmB) 70 mm	ABVHI (PmB) 70 mm	ABVHI (PmB2) 70 mm	ABVHI (PmB2) 70 mm	ABVHI (B) 70 mm		-110.00
SCI 200 mm	SCI 200 mm	SCI 200 mm	SCI 200 mm	SCI 200 mm	SI 200 mm PTS	SII 200 mm PTS	-310.00
SD 200 mm	SD 200 mm	SD 200 mm	SD 200 mm	SD 200 mm	SD 200 mm		-510.00
Ep 45 MPa	**Ep 45 MPa**	**Ep 45 MPa**	**Ep 45 MPa**	**Ep 45 MPa**	**Ep 45 MPa**		
16 m	**16 m**	**16 m**	**16 m**	**16 m**	**16 m**		

ABS - ACsurf; ABVH (PmB)-ACbin; AKMS – SMA; SD – crushed material

Figure 6 - Pavement construction in sections

On the circular test track were identified the sections, in which were used mixtures intended for experimental tests. Mixtures were designed with traditional binders and modified binders or construction layer with unconventional materials. Tested were mixtures loaded (symbol p) and not loaded (symbol n) by the traffic load (Table 1 and 2)

3. MEASUREMENTS RESULTS

The resulting measurements of selected mixtures incorporated into pavement construction layers of the round test track are shown in Table 1.

3.1. Static Creep Modulus ($S_{i,t}$)

Average values of static creep modulus $S_i(t)$ for mixtures SMA 11, AC 11 and AC 22, measured since 1999 till 2001 are listed in Table 1. The measured results imply mainly the following conclusions:

- the greatest effect of temperature on the course of dependence of the value Si(t) on the temperature is in the temperature range from + 11 °C to +27 °C, which is demonstrated by the greater decline of the value $S_{i(t)}$ than in the range from 0 °C to +11 °C
- changes in values within a temperature range +27 °C to + 40 °C are insignificant, more favourable are the results with the use of modified binder
- the best properties of mixtures were observed at using the binder PmB2.

Measurements were carried out also at the temperature + 40 °C - in addition to the design method. Differences versus temperature +27 °C are irrelevant.

Table 1 - Example of assessment $S_{i(t}$ mixtures SMA and AC 22 (without traffic load)

Mixtures with modified binders	Static creep modulus in flexural strength $S_{i(t)}$ [MPa]			
	0 °C	+11 °C	+27 °C	+ 40 °C
SMA 11,4n97 (PmB)	491.0	44.4	11.5	-
SMA 11,4n98 (PmB)	412.0	130.0	50.5	25.9
AC 22,4n98 (PmB2)	736.9	392.0	84.3	30.8

3.2. Complex Modulus

Observed values of complex modulus were evaluated as the average for temperature of 0 °C + 11 °C + 27 °C and for selected mixtures for +40 °C and at different frequencies of acting force. The results obtained from measuring construction layers unloaded and loaded by the effects of moving cart weighing 100 kN imply that:

- by reducing the temperature, the value of E^*, E_1, E_2, σ_0 rises and vice-versa, the phase angle φ (FI) decreases
- the largest value of E^* was reached at the temperature 0 ºC (8377 MPa at mixture SMA11,p97)
- value of phase angle (φ) is temperature dependent, lower values were obtained at ±0 ºC, when a flexible component of viscoelastic material is demonstrated. Higher values of phase angle were detected at +27 ºC, where the impact of plasticity is greater
- value of maximum tension (σ_0) expresses the size of the harmonic excitation force (P_0) which effects the free end of the testing sample. According to the standard STN 73 6160 was the displacement ± 0.1 mm (for all measurements)
- evaluated mixture was SMA 11,4n98 not loaded by the impact of driving over and the same mixture loaded by the impact of driving over by cart weighing 115 kN (SMA 11,4p98)

- by increasing the temperature, the value of E^{*}, E_1, E_2 at both mixtures decreases and vice versa, value of the phase angle increases. Unloaded mixture has higher levels of E^{*}, E_1, E_2 which corresponds to material fatigue.

Selected final evaluation of mixtures loaded and unloaded by the traffic load (the loading cart 115 kN) is in the Table 2.

Table 2 Evaluation of deformation properties of selected mixes SMA 11

Mix	Temperature [°C]	Frequency [Hz]	Complex modulus [MPa]			φ [°]	$S_{i(t)}$ [MPa]
			E_1	E_2	E* (S)		
SMA 11p (PmB)	40	8.3	344	254	430	36.3	20.5
	27	8.3	1469	982	1769	33.6	32.4
	11	8.3	4684	2096	5139	24.1	88.4
	0	8.3	5432	1726	5587	17.7	376.4
SMA 11n (PmB)	40	8.3	357	288	459	38.7	25.9
	27	8.3	1655	1030	1951	31.6	50.5
	11	8.3	4810	2132	5261	23.9	130.2
	0	8.3	6771	2390	7180	19.4	412.9
SMA 11n (PmB)	0	5	6080	2312	6505	20.2	412.9
	0	8.3	6771	2390	7180	19.4	412.9
	0	10	7217	2413	7612	18.6	412.9
	0	15	7562	2420	7942	17.8	412.9
SMA 11,4n98	40	8.3	357.4	288.1	459	-	25.9
SMA 11,4p98	40	8.3	343.8	254.1	429	-	20.5
AC 22,4n98	40	8.3	617.3	404.6	738	-	30.8
AC 22,4p98	40	8.3	454.0	318.9	554	-	30.6
SAM 11-1.3	40	5.0	239	149	282	-	14.0
	40	8.3	294	222	370	-	14.0
	40	10.0	333	225	404	-	14.0
	40	15.0	386	304	493	-	14.0

For evaluation by means of principal curves - after introducing the gas constant - at the frequency of 3 to 97 Hz is valid the relation [16]

$$\alpha_T = \exp\frac{\Delta H}{R}\left(\frac{1}{T}-\frac{1}{Ts}\right)$$

where ΔH - the apparent energy activation ($2*10^5$ $Jmo1^{-1}$)
R - universal gas constant (8.31434 $Jmo1^{-1}$°K^{-1})
T, Ts - temperatures expressed in °K (*Ts* is the reference temperature).

Figure 7 shows the change of the complex modulus at different temperature and the frequency of excitation force (continuous lines). Discrete values (Fig. 7) show the change in the complex modulus at constant temperature but various frequency of excitation force and various mixtures verified at the constant temperature and frequency.

The measured results imply the knowledge [9]:

- at increasing frequency of the excitation force the values of the complex modulus are increasing in the real, imaginary and absolute value
- complex modulus values are substantially dependent on air temperature and temperature of the sample. With increasing temperature significantly decreases the value of the complex modulus

- phase angle (expresses the delay of deformation and acting force due to inertia forces in excitation force antiphase) increases with increasing temperature. Its change is not significant at changing the frequency of excitation force and at the constant temperature,
- modified asphalts used for creation of the mixture contribute to the improvement of deformation properties. Mixtures are less temperature sensitive, which causes improvement in terms of:
  - low temperatures - extended flexible region at lower temperatures during the frost period
  - high temperatures - mixtures are more resistant to permanent deformation at higher temperatures in the summer, what is in he climate zone of the Slovak Republic very important given the frequent rotation of pavement temperatures in the summer (above 60 °C) and winter (below -20 °C).

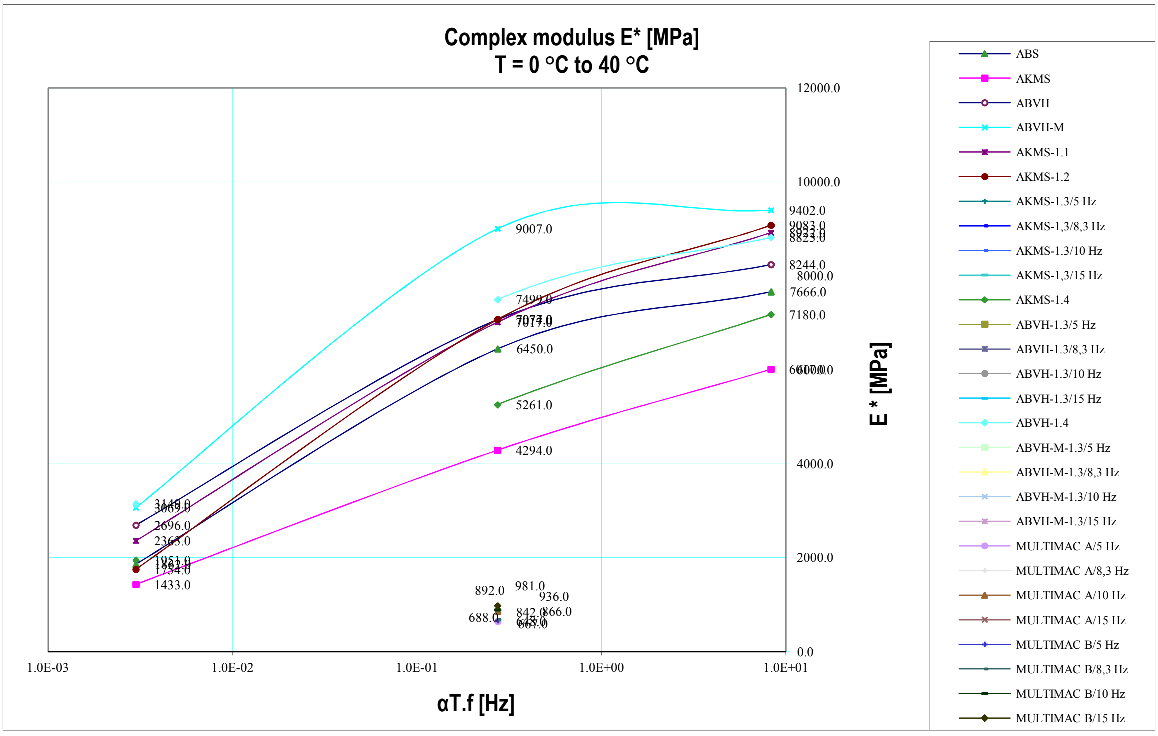


Figure 7 - Course of master curves of selected mixtures under consideration

At mixtures in the circular testing track was also monitored the impact of frequency of loading. The measured results show that:

- due to the impact of increasing the frequency of loading at the same temperature, the value of complex modulus E^*,real component E_1 and imaginary component E_2 is rising
- value of the phase angle (FI) is not significantly altered by the frequency impact, the impact of the frequency is irrelevant in terms of the design or calculated value of the complex modulus for the asphalt mixes design at this frequency range (6 to 25 Hz, which corresponds to the vehicle vibrations), because the value of E^* does not change significantly
- at measurements it is advantageous to use the frequency of excitation (harmonic) force of 10 Hz, as recommended by the European standard (EN 12697-24) and taking into account the recommended temperature for testing. Measurements should be carried out under conditions:
  - air and sample temperature + 15 ° C
  - excitation force frequency 10 Hz

- free end displacement $\varepsilon \leq 50.\ 10^{-6}$

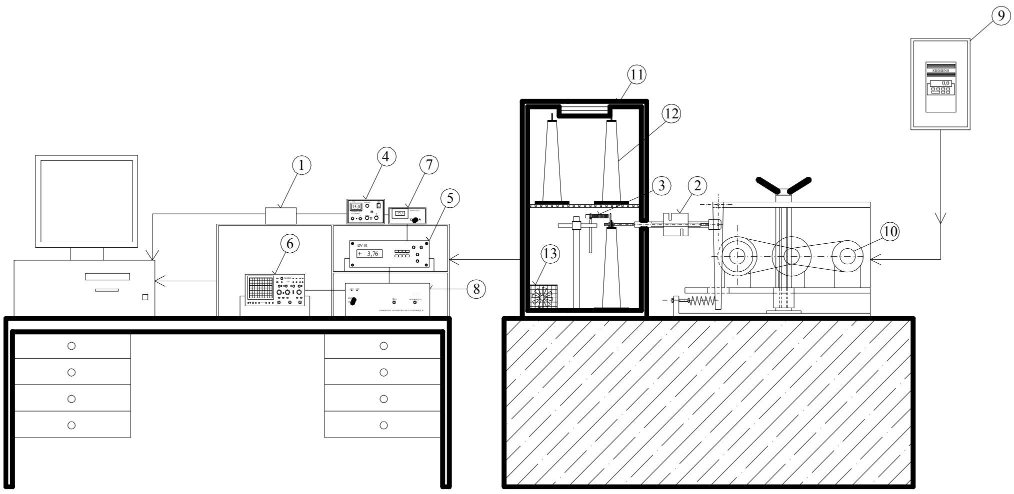
- by increasing the temperature the value of the complex modulus, the real and imaginary components decreases, while the value of the phase angle increases
- SMA 11 mixture has higher levels of E1, E2, E* when using modified binders compared to traditional binders in the mixture
- on assessed mixtures were obtained higher values of relative strain (ε_0) than when using traditional binders
- change of the angle φ (FI) expresses plastic properties of mixtures. Measurements showed greater accession in temperature difference from +11 °C to +27 °C compared with values obtained from measurements at the temperature difference from ±0°C to +11 °C. The largest accession was observed for the mixture SMA11.

The impact of cellulose fibres on the final parameter of the SMA mixture was also verified [1]. Verification results and deformation properties are listed in the Table. 3.

Tab. 3 - Results of experimental measurements

Mixture	Temperature [°C]	$E*$ [MPa]	$S_{i(t)}$ [MPa]	$y_{(t)}$ [mm]	φ [°]	σ_0 [10^{-2}MPa]	ε_0 [$1*10^{-6}$]
SMA	27	2884.5	30.78	0.4593	44.64	19.80	6.902
	11	6586.0	218.58	0.1585	30.24	44.35	6.773
	0	7644.5	716.70	0.1028	20.05	49.13	6.633
SMA+	27	3363.8	39.67	0.3727	44.80	22.53	6.706
	11	7658.0	337.78	0.1059	23.42	41.65	5.465
	0	9363.5	796.03	0.0885	14.86	43.85	5.945

Note: + SMA mixture with cellulose fibres



1-analog converter; 2-pressure transducer; 3-deformation transducer; 4-electric source of transducers; 5-voltohmmeter; 6-oscilloscope; 7-convereter and regulator of temperature; 8-converter of pressure and deformation; 9-frequency converter; 10-pressure exciter; 11-conditioning chamber; 12-specimens; 13-ventilator

Figure 8 - Scheme of the test equipment

Relative strain changes to a small extent. Acquired knowledge confirms the effect of temperature on the rheological properties of asphalt mixtures, where the impact of cellulose fibres additive (added to the standard basic binder) was verified. At the comparison of deformation characteristics of Stone Mastics Asphalt without stabilizer (SMA) and Stone Mastic Asphalt with cellulose fibres (SMA+) smaller static creep modulus and complex modulus of stiffness were found. Small differences in values of phase shift were found. SMA+ has at high temperatures higher stiffness and thus the mixture has better resistance against permanent deformations. At low temperatures it has higher modulus of creep and thus the resistance to cracking is increased.

The tests of the complex modulus and fatigue were carried out in the laboratory of Department of Construction Management (Figure 8). The equipment works with constant deviation. It is possible to change the frequency and temperature for the tests.

Overall assessment of deformation properties of mixtures on the circular test track found the largest variance of values of the complex modulus and static modulus almost at every evaluated mixture at +11 °C (according to current method of dimensioning in the Slovak Republic) or +10 °C (according to European standards). Therefore, mixtures with standard and modified asphalt binder were verified.

3.3. Fatigue.
According to the Slovak dimensioning method the fatigue is given by

$$S = a - b.\log N_i$$

where a, b - fatigue coefficients
N_i - number of load cycles.

Measurements determined the fatigue coefficients *(a, b)* of mixtures under the review. In dimensioning method are the computing values of the coefficient *a* smaller than 1.0. Fatigue coefficients *b* were obtained for mixtures at the coefficient *a* = 1.0 with standard (asphalt) and modified binder. Durability of asphalt mixtures, which corresponds to the value of coefficient *b* according to the type of pavement construction layer was found. The course of fatigue is shown (Figure 9) for SMA 11 (AKMS) mixtures. In the same way were carried out tests on recycled mixtures with composite binders. Utilised was the combination of residual asphalt in the mixture, asphalt emulsion, cement and water. Example of Wöhler fatigue line is shown in Figure 10.

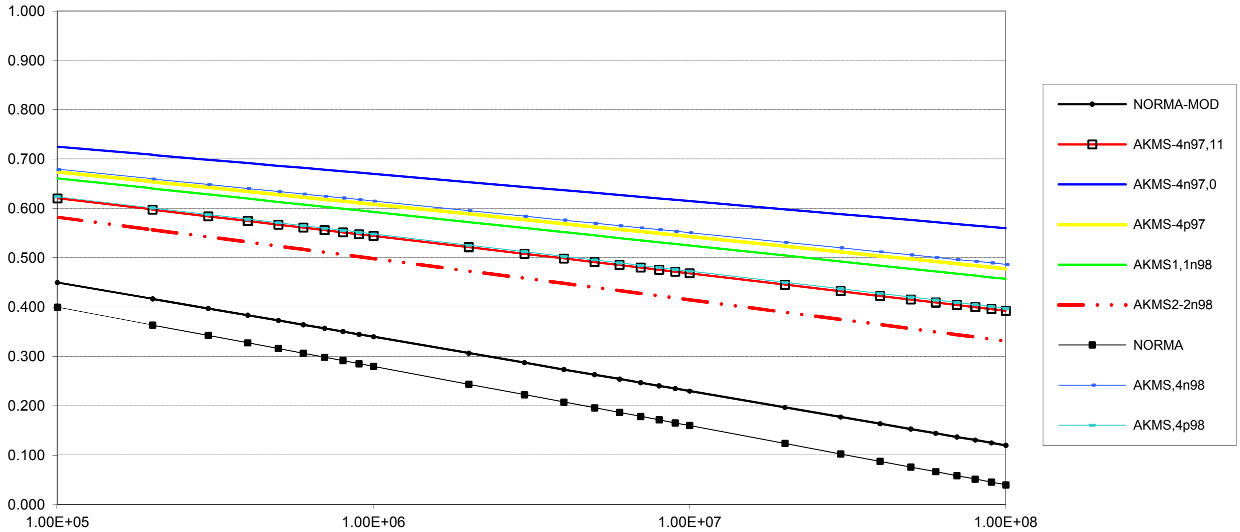


Figure 9 - The course of fatigue mixture SMA 11 (AKMS)

Evaluated mixtures have values of coefficient *b for:*

- asphalt concrete (AC 11 and 22)

• AC 11 S= 1 - 0.10 log N (*b*=0.10; range 0.078 to 0.129)

- AC 22 — S= 1 - 0.06 log N (*b*=0.06; range 0.038 to 0.125)
- AC 22 (PmB) — S= 1 - 0.07 log N (*b*=0.07; range 0.066 to 0.071)
- SMA 11 — S= 1 - 0.07 log N (*b*=0.07; range 0.055 to 0.083).

- asphalt concrete I (1st quality grade)

AC I (with standard binder) S= 1 - 0.090 log N
AC-M (with modified binder PmB) S= 1 - 0.075 log N

- Stone Mastic Asphalt

SMA: S= 1 - 0.080 log N.

For the recycled asphalt concrete mixtures on the basis of asphalt binder was found the durability (number of loads by the design axle) for mixtures:

- AC - mixture recycled in-situ $Ni = 1{,}02.10^6$
- AC - comparative mixture $Ni = 7{,}35.10^6$
- AC - new mixture $Ni = 5{,}61.10^6$

The measurements (Figure 8) show that the worst course - in terms of fatigue - has the mixture of AC 11 with the standard asphalt binder. Other mixtures (SMA 11) have a moderate decline and the durability of mixtures is higher than expected by the standard.

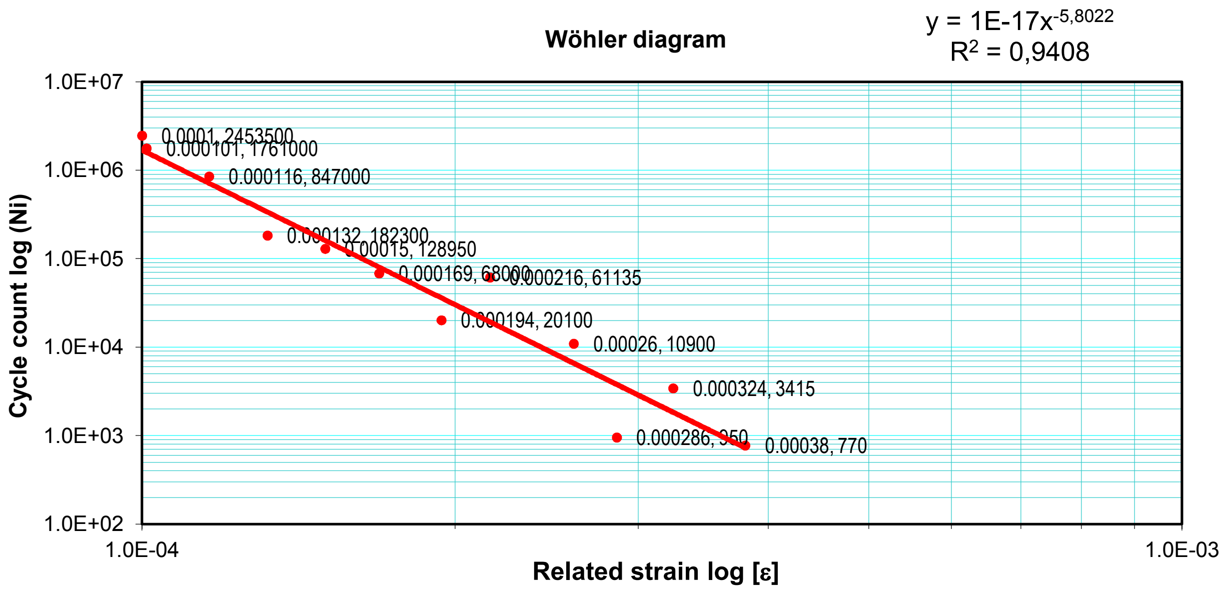


Figure 10 - Wöhler diagram chart of recycled material

The fatigue of mixtures with different binders was verified under the international cooperation.

Test specimens were tested according to the standard EN 12697– 24, Annex A (two point bending test method) [23], [24]. Ten samples from each mixture were tested at temperature of +10 °C and frequency of 20 Hz. The results of measurements were evaluated, fatigue parameters were defined and the fatigue line for each asphalt mixture was determined (Figure 11).

Value of proportional strain at 1 million cycles (ε_6) according to European standard [23] expresses the fatigue of the tested sample. Assumed is the load of the free end of trapezoid by harmonic force at three different displacements.

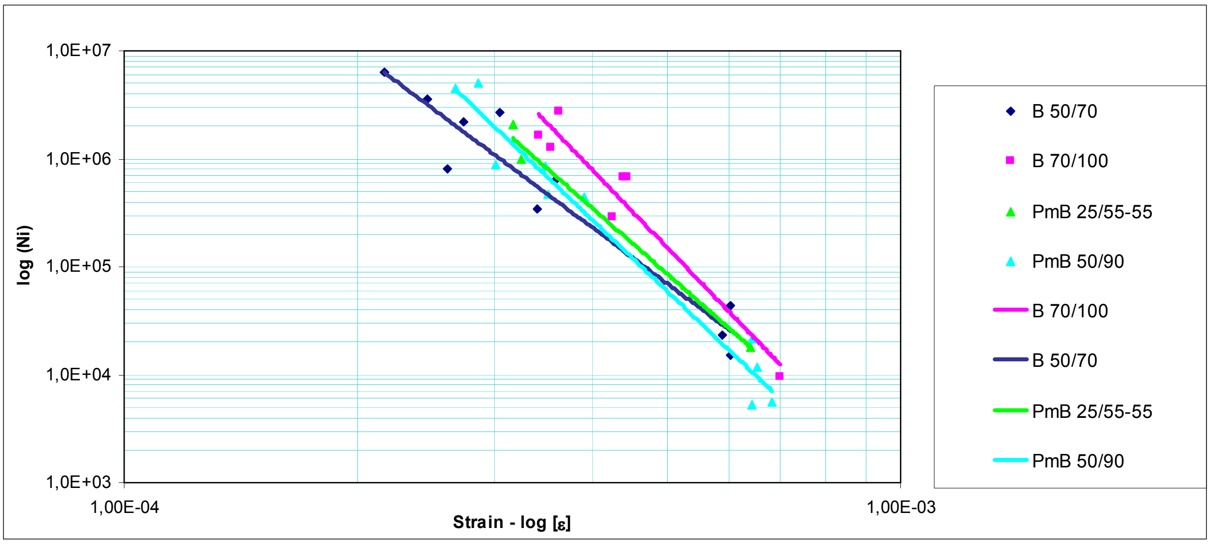


Figure 11 Fatigue of the SPENS-mixtures [17]

Important results [17] are the following:

- the best mixture was AC 11 with binder B 70/100 (non modified)
- the mixtures with polymer modified binders have similar resistance to fatigue
- the mixtures with polymer modified binders have slightly lower resistance to fatigue than AC 11 B 50/70, but are in the same category
- spacing of ε_6 value of B 70/100 from polymer modified binders is higher than the difference of ε_6 value between B 50/70 and polymer modified binders.

5. CONCLUSIONS

The dynamic tests of bituminous mixtures better represent the dynamic impacts of moving vehicles (6 – 25 Hz). The viscoelastic materials can be tested by using the complex modulus method.

The physical and mechanical characteristics express the character of bituminous reinforce materials. The rheology characters materials are tested with the complex modulus method. Deformation characteristics of asphalt mixtures were being found out during measurement. The comparative measurements on mixes loaded by the effect of transport were done; it was established, that with decline of temperature values of static modulus of deformation, complex modulus, maximum strength loading on the free end of trapezoid increase. The phase shift decreases with decline of temperature. Deflection of the free end of sample has almost the same value of static modulus of deformation at temperature + 27 °C for all compared mixtures. Obtained knowledge acknowledged influence of temperature on deformation properties of asphalt mixtures.

Deformation properties and fatigue of asphalt bound materials influences the use of modified asphalts and cellulose fibres. The values of deformation properties, complex modulus (stiffness) and fatigue (durability) increase. The use of recycled materials protects the environment, reduces the usage of traditional quality materials and allows more roads to be built or repaired. Deformation and mechanical properties of mixtures were verified on the circular test track and in the laboratory conditions. Recycled mixtures can be used for pavement sub-layers and if the required criteria are met, in some cases even for pavement wearing courses.

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