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*Research Article*

# Deformation Properties and Fatigue of Bituminous Mixtures

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Deformation properties and fatigue performance are important characteristics of asphalt bound materials which are used for construction of pavement layers. Viscoelastic asphalt mixtures are better characterized via dynamic tests. This type of tests allows us to collate materials with regard to axle vibrations which lie usually in the range of 6 Hz–25 Hz for standard conditions. Asphalt modified for heat sensitivity in the range from −20°C to +60°C has significant impact on the overall characteristics of the mixture. Deformation properties are used as inputs for empirical mixture design, and fatigue performance of asphalt mixtures reflects the parameters of functional tests. Master curves convey properties of asphalt mixtures for various conditions and allow us to evaluate them without the need of time expensive testing.

## 1. Asphalt Binders and Asphalt Mixtures

Deformation properties, resistance to deformation, and fatigue performance of asphalt mixtures have a significant influence on operational performance of asphalt pavements. Within the pavement construction, the asphalt serves as a binder for mineral aggregate of surfacing layer. Asphalt is a bituminous material obtained as a residue of vacuum distillation process during the refining of crude oil [1]. Mechanical properties of asphalt mixture are mostly affected by the properties of applied asphalt binder. In regard to mixing process, asphalt binder must be fluid enough at high temperatures—about 160°C—to create homogenous coating of the aggregate. Local climate plays a role as the binder has to maintain prescribed stiffness at the highest summer temperature to resist rutting deformation, yet it has to remain flexible enough at low temperatures during the winter season [2].

The assessment of deformation properties is performed by means of dynamic impact test and fatigue life of particular asphalt mixture. Evaluation of fatigue life is based on resistance decrease or deformation increase in different binders and mixtures. Concurrently, the evaluation itself is performed in accordance with standard for measurement of complex modulus [3] and fatigue [4] of asphalt reinforced materials, that is, mixtures; these regulations represent realistic traffic-car axle during normal operation at the frequency from 6 to 25 Hz.

*1.1. Asphalt Binder Laboratory Tests.* Asphalt binders are thermoplastic liquids which behave as viscoelastic materials [5]. Their deformation behaviour can be determined by their rheological parameters. The changes in both viscous and elastic properties related to temperature and time are measured as response of the material to deformation induced by periodic forces-vibration or small-amplitude oscillatory stress. Phases of induced stress and responding deformation do not match exactly; the strain phase lags behind the stress by a certain phase angle. If the oscillatory deformation is sinusoidal, shear stress $\tau$ is expressed as [6, 7]

$$\tau(t) = \tau_0 \cdot e^{i\omega t} = \tau_0 (\cos \omega t + i \cdot \sin \omega t), \quad (1)$$

where $\tau_0$ is the stress amplitude, $\omega$ is the angular frequency, $t$ is the time, and $i = \sqrt{-1}$.

Table 1: Basic properties of tested bituminous binders.

| Type of binder | Unmodified binders | |
|---|---|---|
| | B 50/70 | B 70/100 (Q8) |
| Softening point (°C); STN EN 1427 | 46–54 | 43–51 |
| Penetration at 25°C (0,1 mm); STN EN 1426 | 50–70 | 70–100 |

The complex dynamic modulus $G^*$ [Pa] is defined as [6, 7]

$$G^* = \frac{\tau(t)}{\gamma(t)}. \tag{2}$$

Equation (2) can be divided into two parts:

$$G^* = G' + i \cdot G'' = \frac{\tau_0}{\gamma_0}(\cos\delta + i \cdot \sin\delta). \tag{3}$$

The first $G'$ is in phase with strain, and the second $G''$ is out of phase with strain with angle $\delta$. Therefore, two dynamic modules are defined [6, 7]:

$$G' = \frac{\tau_0}{\gamma_0}\cos\delta, \tag{4}$$

$$G'' = \frac{\tau_0}{\gamma_0}\sin\delta. \tag{5}$$

$G'$ is called storage modulus and its value is strain energy stored by the sample during the shear process. Thus, it represents the elastic behaviour. The value of loss modulus $G''$ is measured as strain energy used up by the sample during the shear process; therefore, they represent the viscous behaviour of the material. A part of this energy heats the sample and is released as heat to the environment. Sample with high loss modulus exhibits irreversible deformation [6, 7].

The complex dynamic viscosity $\eta^*$ [Pa·s] is defined by

$$\eta^* = \frac{\tau(t)}{\gamma(t)}, \tag{6}$$

where $\gamma$ [s$^{-1}$] represents the shear rate [6, 7].

## 2. Performed Testing

The comparison of rheological parameters $\eta^*$, $G'$, and $G''$ was performed for selected unmodified and polymer modified asphalt binders at the temperatures of 46°C–60°C (80°C). Rheological properties were determined and compared for unmodified bituminous binders B 50/70 and B 70/100 (Q8). Basic properties of tested materials are in Table 1. The composition of aggregate is equal for both mixtures, it is shown in Table 2.

Measurements were performed on the oscillatory Physica Rheometer MCR301 with convection heating device CTD 450. The applied method was the frequency sweep test (FS). FS method uses parallel plate system—PP system: lower plate is stationary; upper plate performs oscillatory motion and thus creates a shear in the sample. The distance between the plates—shearing interval—is well defined (Figure 1).

Table 2: Tested mix designs for AC 11 pavement layer.

| Mixture | Mixture 1 (A1) % B 70/100 (Q8) | Mixture 2 (A2) % PmB 70/100-83 |
|---|---|---|
| Filer | 7,1% | |
| 0/2 mm | 29,3% | |
| 2/4 mm | 15,6% | |
| 4/8 mm | 22,6% | |
| 8/11 mm | 19,8% | |
| Binder | 5,6% | |
| Sum | 100,00% | |

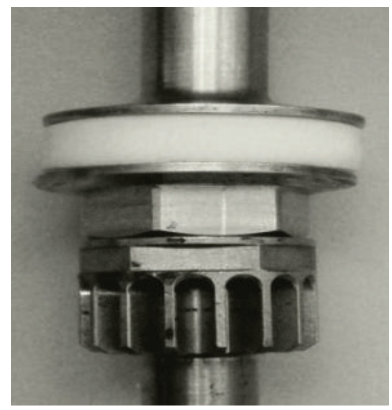

Figure 1: PP system, Physica Rheometer MCR301.

FS test is performed at a constant temperature. This measurement method enables simultaneous monitoring of rheological parameters $G'$, $G''$, and $\eta^*$ in the selected interval of angular frequencies [6]. Each test sample was placed between the two parallel plates with a diameter of 25 mm (PP25 system), with 1 mm distance from each other—shearing interval = 1 mm.

The trend of monitored rheological parameters $G'$, $G''$, and $\eta^*$ in dependence on angular frequency is linear except for storage modulus $G'$ at angular frequencies 400–600 s$^{-1}$at 60°C (Figure 2). Except for the above mentioned case, the $G'$ and $G''$ curves are nearly parallel. Ratio between viscous and elastic properties remains the same; this means that degradation which would be shown by changes in molecular weight—networking or macromolecular chains breaking—is not probable [6].

In addition, the modified binders were also tested. The chart curves expressing storage modulus $G'$ are losing their linearity at angular frequencies of 400–600 s$^{-1}$. The sharp decrease of $G'$ denotes higher ratio between loss modulus $G''$ and storage modulus $G'$, that is, damping factor. This points to degradation related to the loss of elasticity.

Knowledge ascertained from measurements is as follows:

(i) polymer-modified binder achieves the highest values of evaluated rheological parameters $G'$, $G''$, and $\eta^*$ in the considered interval of angular frequencies at the temperature of 60°C. The lowest values of rheological parameters were measured for unmodified binder Q8 70/100;

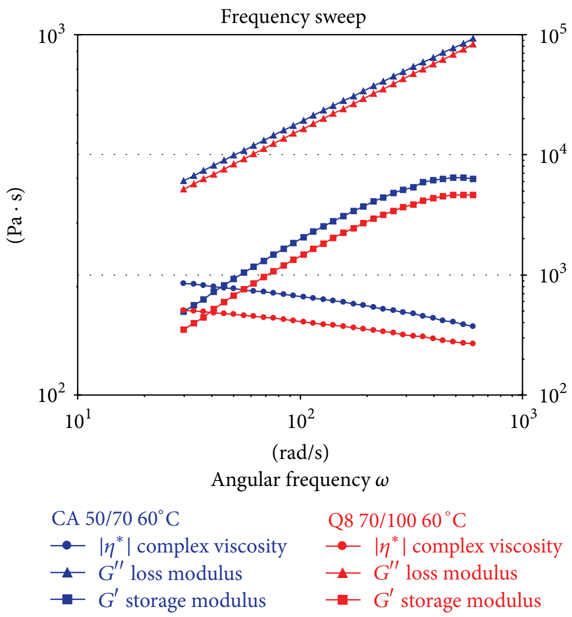


FIGURE 2: Comparison of rheological parameters of unmodified binders at 60°C.

(ii) modified binders show more significant reduction in complex viscosity with the increase of angular frequency in comparison to unmodified binders;

(iii) according to the obtained results, from the set of tested binders, the modified binders are most suitable for heavy duty pavements in climate with strong temperature fluctuations.

In order to obtain required properties, asphalt binders are not used exclusively in the form of pure asphalt, that is, unmodified asphalt binders; instead, they can be modified by synthetic polymers. Polymer modified bitumen (PMB) has higher softening point and lower breaking point than unmodified ones. Therefore, it is recommended for construction of heavy duty pavements in climates with large temperature fluctuations [3–5].

*2.1. Laboratory Tests of Asphalt Mixtures.* Complex modulus ($E^*$) is a ratio of strain and deformation at steady, harmonically variable oscillation in consideration of their mutual time shift [8]:

$$E^* = \frac{\sigma_0}{\varepsilon_0} = \left(E_1^2 + E_2^2\right)^{1/2}. \tag{7}$$

Complex modulus is measured on samples exposed to short-term alternating harmonic load. It conveys the proportion of maximum amplitude of excitation tension ($\sigma_0$), maximum amplitude of induced deformation ($\varepsilon_0$), and phase shift of their amplitudes ($\varphi$). The stress, that is, load, which varies sinusoidally in time, is applied to the element of linear viscoelastic material. The strain varies in time with the same frequency as the stress, but it lags behind by the phase. The measured values for particular mixtures are graphically presented in chart shown in Figure 3. Graphical representation

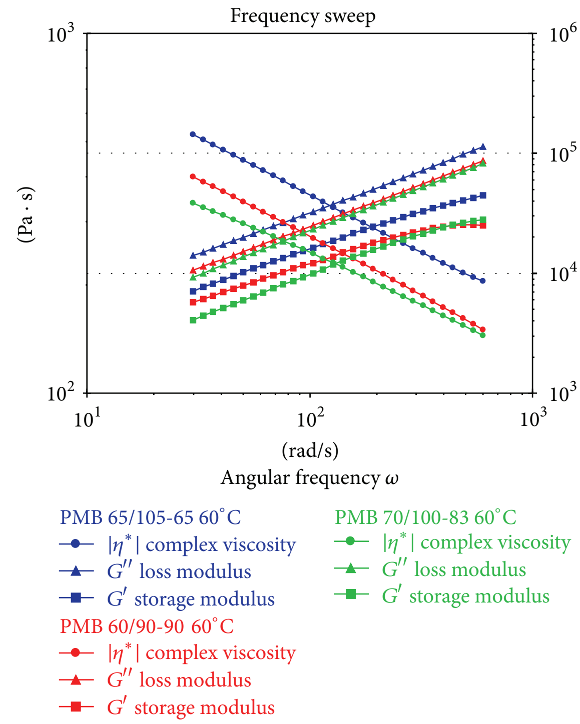


FIGURE 3: Comparison of rheological parameters of 3 modified binders at 60°C.

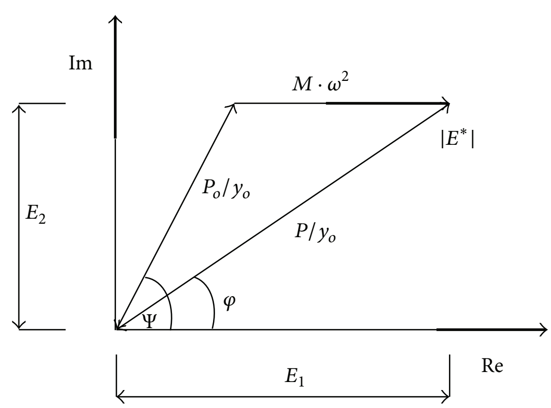


FIGURE 4: Scheme of complex modulus.

of measurement and complex modulus evaluation is shown in Figures 4 and 5.

An accurate assessment of the fatigue life of asphalt mixtures depends on the criteria used in the fatigue analysis [9].

Fatigue is reduction of strength of a material under repeated loading when compared to the strength under a single load [10]. The value $\varepsilon_6 = 1 \cdot 10^6$ cycles (in m/m) is the strain corresponding to $10^6$ cycles [10].

According to the Slovak dimensioning method, the fatigue is given by

$$S = a - b \cdot \log N_i, \tag{8}$$

where $a, b$ are the fatigue coefficients and $N_i$ is the number of load cycles.

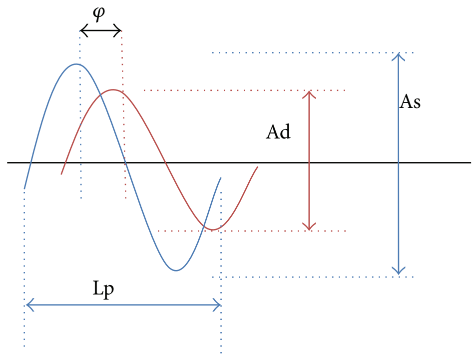


Figure 5: Measurement of complex modulus: Lp: length of period, $\varphi$: phase-shift, As: amplitude forces, and Ad: amplitude deformations.

Figure 6: Two-point trapezoidal bending beam machine used at the University of Zilina.

The tests of the complex modulus and fatigue performance were carried out in the laboratory of the Department of Construction Management of the University of Zilina (Figure 6). The equipment works with constant deviation. It is possible to change the frequency from 0.1 to 30 Hz and temperature for the tests from −20°C to +30°C.

Bending tests are used to ascertain the complex modulus and fatigue resistance of asphalt pavement surfacing materials. The two-point bending test on trapezoidal sample is arguably the most repeatable and reproducible bending test method detailed in the relevant EN 12697 directives [8, 10]. The samples were carefully stored on a flat surface protected from the sun at a temperature of <30°C to prevent distortion. The samples were measured with an accuracy of 0.1 mm.

In this test, the bottom of the sample is fixed and the free top is moved sinusoidally with constant displacement amplitude. The trapezoidal samples are tested simultaneously; they are subjected to constant strain amplitude at a selected frequency and temperature until the stiffness modulus decreases. Fatigue life of a sample is the number of cycles $N_{i,j,k}$ corresponding to the conventional failure criterion at the set of test conditions $k$-temperature, frequency, and loading mode, for example, constant deflection level, or constant force level, and or any other constant loading condition. It is a number of load applications, $Nf/50$, during which the complex modulus decreases to half of its initial value [10].

## 3. Tested Mix Designs and Measurements Results

Complex modulus and fatigue performance were tested for two mix designs. The aggregate content and ratios stay the same for both mixtures. However, the 1st mixture (A1) contains generic asphalt binder B 70/100 (Q8) compared to the 2nd mixture (A2) which contains polymer modified bitumen PmB 70/100-83. Both mixtures can be applied for the AC 11 pavement layer. In general, pavement performance properties are affected by the bitumen binder properties; it is known that the conventional bitumen has a limited range of rheological properties and durability that are not sufficient enough to resist pavement distresses [11]. Therefore, the testing was aimed to show us the magnitude of impacts on mixture properties attained through binder modification.

*3.1. Results: Complex Modulus.* Both samples were tested at temperatures ranging from −10°C to +27°C. The frequency varied from 1 Hz to 20 Hz. The measured results of complex modulus of mixture A1 are listed in Table 3 and Figure 7. The complex modulus ($E^*$) is different for temperatures of +10°C and +15°C during the same frequency (10 Hz):

$$E^*_{T=10^\circ\mathrm{C};\,F=10\,\mathrm{Hz}} = 8364{,}7\ \mathrm{MPa},$$
$$E^*_{T=15^\circ\mathrm{C};\,F=10\,\mathrm{Hz}} = 5938{,}0\ \mathrm{MPa}.$$

With identical approach, the same types of results were measured for mixture A2:

$$E^*_{T=10^\circ\mathrm{C};\,F=10\,\mathrm{Hz}} = 5844\ \mathrm{MPa},$$
$$E^*_{T=15^\circ\mathrm{C};\,F=10\,\mathrm{Hz}} = 4032\ \mathrm{MPa}.$$

In addition, deformation properties were verified for a third mix design A3rec, which is prepared from mixture A2 with 40% of the aggregate made of asphalt recycled material—recycle aggregate. For the A3rec mix design, less favourable deformational properties were ascertained. These were probably the consequence of brittleness of old asphalt in the new mixture and altered grain distribution curve as a result of added recycled material.

Complex modulus was measured by $\varepsilon < 50 \cdot 10^{-6}$ (microstrains). The reason to introduce this mix design to the test was that as natural aggregate sources are becoming depleted due to high demand in road construction and as the amount of disposed waste material keeps increasing, researchers are exploring the use of alternative materials which could preserve natural sources and save the environment [12].

*3.2. Results: Fatigue Performance.* Fatigue life was measured on samples, which were loaded at +10°C with frequency of 25 Hz. The fatigue line is estimated in a bilogarithmic system

Table 3: Complex modulus of mixture A1 in MPa.

| Temperature (°C) | Complex modulus $E^*$ (MPa) Frequency (Hz) 1 | 5 | 10 | 15 | 20 |
|---|---|---|---|---|---|
| −10 | 14158 | 16769 | 17744 | 17700 | 18503 |
| −10 | 14351 | 17063 | 18073 | 18219 | 18970 |
| 0 | 10727 | 13551 | 14698 | 15062 | 15538 |
| 0 | 10874 | 13723 | 14927 | 15407 | 15943 |
| 10 | 4991 | 7827 | 8923 | 9586 | 10009 |
| 10 | 4494 | 7098 | 8122 | 8778 | 9233 |
| 10 | 4832 | 7844 | 9138 | 9818 | 10260 |
| 10 | 3786 | 6256 | 7276 | 7873 | 8272 |
| 15 | 3021 | 5749 | 7055 | 7773 | 8366 |
| 15 | 2151 | 4284 | 5315 | 5958 | 6451 |
| 15 | 2339 | 4759 | 5867 | 6506 | 7014 |
| 15 | 2216 | 4436 | 5515 | 6173 | 6660 |
| 27 | 695 | 1798 | 2487 | 2915 | 3275 |
| 27 | 713 | 1755 | 2460 | 2922 | 3327 |

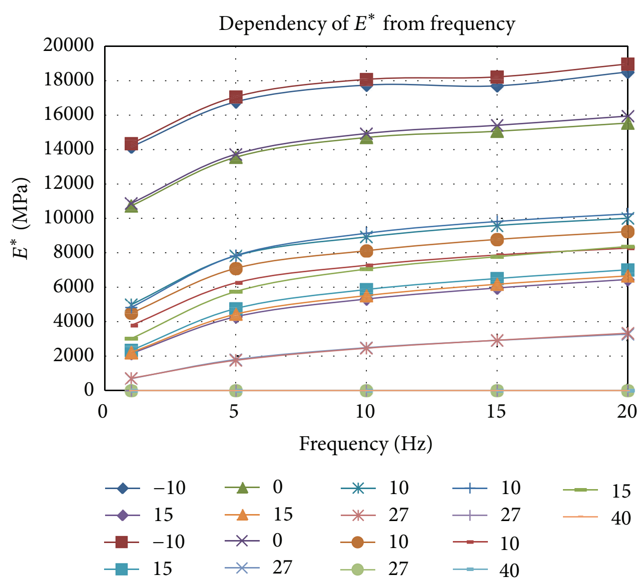


Figure 7: Dependency of complex modulus ($E^*$) from frequency ($F$) for mixture A1 for temperatures ranging from −10°C to +27°C.

as a linear regression of fatigue life versus amplitude levels. Using these results, the strain corresponds to an average of $10^6$ cycles ($\varepsilon_6$) and the slope of the fatigue line $1/b$. The parameters are

(a) $\varepsilon_6$,

(b) $\Delta\varepsilon_6$,

(c) slope $l/b$,

(d) estimated residual standard deviation $s_N$,

(e) correlation coefficient $r^2$.

The evaluation was performed in accordance with

$$\lg(N) = a + \left(\frac{1}{b}\right) \times \lg(\varepsilon). \tag{9}$$

For $n$ results, the following were calculated:

(i) the estimation of the strain at $10^6$ cycles (10),

(ii) the estimation of the residual standard deviation $s_N$ (11),

(iii) the quality index $\Delta\varepsilon_6$ (12),

$$\varepsilon_6 = 10^{b\times(6-a)}, \tag{10}$$

$$S_N = S_{\lg(N)} \times \sqrt{\frac{\left(1-r_2^2\right)\times(n-1)}{n-2}}, \tag{11}$$

$$\Delta\varepsilon_6 = 0.5\varepsilon_6 \times \left(10^{-2b\times S_0} - 10^{2b\times S_0}\right), \tag{12}$$

where

$$S_0 = S_N \times \sqrt{\left[\frac{1}{n} + \frac{\left(\lg(\varepsilon_6) - \lg(\varepsilon)\right)^2}{(n-1)\times S_{\lg(\varepsilon)}^2}\right]}. \tag{13}$$

The samples were subject to fatigue testing for three deformation values of the trapezoid's unfastened end, whereby the testing ended when the complex modulus decreased by half of its initial value. The fatigue is expressed as a value of $\varepsilon_6$, which is ascertained from linear regression for measurement on 18 testing samples. For mixtures A1, A2, and A3rec, ascertained values are presented in Table 4. The graphical representation of measured results is shown in Wöhler's diagram (Figure 8).

## 4. Evaluation: Master Curves

All three mixtures were subject to evaluation of maser curves. The evaluation was performed by means of master curves—after introducing the gas constant—at the frequency from 3

Table 4: Fatigue of mix designs A1 and A2.

| Mix. | Temp. (°C) | Freq. (Hz) | $\varepsilon_6 \cdot 10^6$ (microstrain) | $N_i$ (cycles) | $b$ (—) | $r^2$ (—) | $s_N$ | $\Delta\varepsilon_6$ | Category |
|---|---|---|---|---|---|---|---|---|---|
| A1 | +10 | 25 | 87,44 | 10908–2156738 | −0,2060 | 0,9554 | 0,1437 | 4,61$E$ − 10 | $\varepsilon_{6\text{-}80}$ |
| A2 | +10 | 25 | 193,10 | 40500–2382028 | −0,1310 | 0,5726 | 0,4481 | 4,41$E$ − 09 | $\varepsilon_{6\text{-}190}$ |
| A3rec | + 10 | 25 | 166,38 | 300–2369414 | −0,0397 | 0,8039 | 0,6119 | 1,24$E$ − 09 | $\varepsilon_{6\text{-}60}$ |

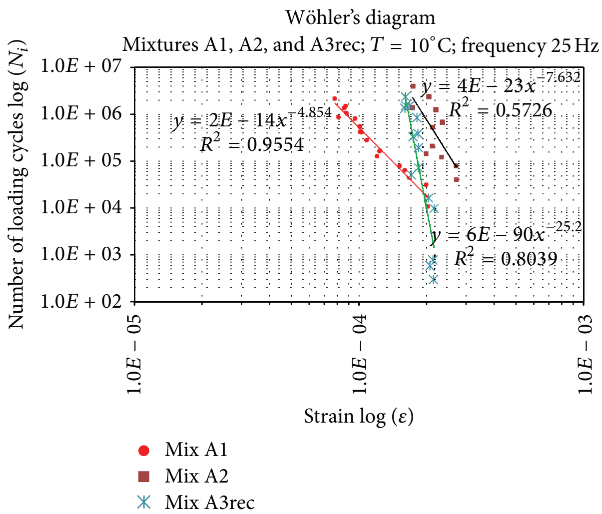


Figure 8: Fatigue life of mixtures with asphalt B 70/100 (A1), PmB 70/100-83 (A2), and 40% of recycling material (A3rec).

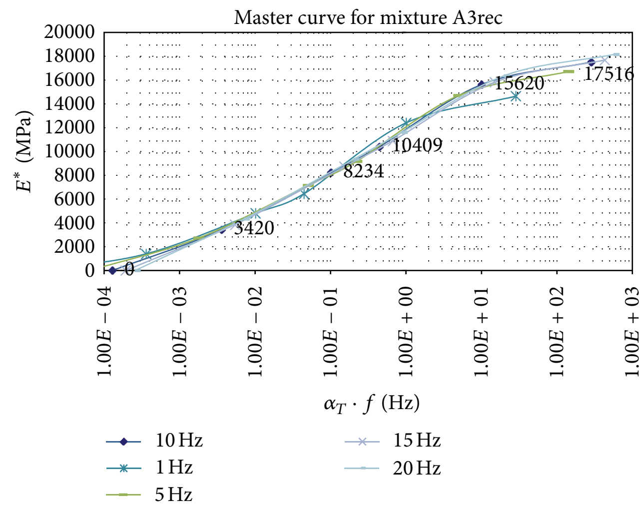


Figure 9: Master curve for mixture A3rec in MPa for temperature ranging from −10°C to +27°C and frequency ranging from 1 Hz to 20 Hz.

to 97 Hz. The values are computed according to the following [8]:

$$\alpha_T = \exp \frac{\Delta H}{R}\left(\frac{1}{T} - \frac{1}{Ts}\right), \tag{14}$$

where $\Delta H$ is the apparent energy activation ($2{*}10^5$ Jmol$^{-1}$), $R$ is the universal gas constant (8.31434 Jmol$^{-1\circ}$K$^{-1}$), and $T$, $Ts$ are the temperatures expressed in °K ($Ts$ is the reference temperature).

The advantage of master curves is that they allow the evaluation of properties of asphalt mixtures for different temperatures and frequencies with lower number of tests—recomputed values that express deformation properties of asphalt mixtures. The master curves convey the changes of complex modulus induced by temperatures affecting the pavement during its life span.

Figure 9 shows the master curves for mixture A3rec. We can observe the changes of complex modulus at different temperatures and the frequencies of excitation force—continuous lines. Discrete values in Figure 9 show the change in complex modulus at a constant temperature but at various frequencies of the excitation force.

## 5. Conclusions

According to the performed measurements, we ascertained that the mixture A1 with unmodified binder has superior deformation properties ($E^*$), while the modified binder mixture A2 has superior fatigue life parameter ($\varepsilon_6$). Asphalt, from the viewpoint of fatigue parameters, has a paramount influence on asphalt mixtures used for construction of pavement surface layers. Deformation characteristics and fatigue of asphalt binder influence normatively prescribed characteristics of pavement layers. Evaluated asphalts have varying complex modulus values in dependence on temperature. In spite of the fact that modified asphalt has higher values of shear modulus, the deformation properties are inferior, whereas fatigue life is superior. This knowledge was confirmed by measurements of other mixtures. The empirical mixture design methods usually use deformation properties; fatigue life characteristics are pivotal for functional testing. All three mixtures are satisfactory from the viewpoint of physicomechanical properties. Design of asphalt bound materials for pavement layers is empirical and utilizes deformation properties like complex modulus. However, for functional tests, fatigue life characteristic ($\varepsilon_6$) is more important. For different values of deformation properties and fatigue life, it is pivotal that the designed mixture is evaluated for required bearing capacity and resiliency against climate conditions.

Measurements show that superior modified asphalt mixture is defined by auspicious fatigue parameters. Deformation properties and fatigue life were validated also on mixture A3rec. The recycled aggregate was a milled-out pavement surfacing material. The A3rec mixture has lower fatigue life parameter, the angle of regression line is more acute, and the value of proportional deformation for one million cycles ($\varepsilon_6$) is lower. Despite this, the mixture is applicable for pavement construction layers and can be utilized for subbase layers.

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