High temperature impact on fatigue life of asphalt mixture in Slovakia

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Abstract. Temperature dependence of materials bonded with bitumen is a well-known fact. The impact of temperature changes the behaviour of asphalt mixtures from elastic to viscous state, and it also influences the complex modulus, phase angle and other properties of asphalt mixtures. This study observed the summer temperature influence on fatigue behaviour of an asphalt mixture for the surface course of roads in conditions of Slovakia. Measurements were made using the four-point bending method on the asphalt mixture with maximum grain size of 11 mm bonded with polymer modified bitumen. Summer conditions were represented by environmental temperature of 27 °C according to the Slovakian pavement design method. Ordinary temperatures for fatigue measurements are 10 °C, 15 °C and 20 °C according to European standards for asphalt mixture testing. Structural changes in the material were observed by dissipation energy calculations for each loading cycle. The aim of the study was to find out if the influence of high environmental temperature is positive or negative for the lifespan of asphalt mixtures.

1. Introduction

Asphalt mixtures consist of the optimum combination of two basic ingredients, the aggregate (various fractions) and asphalt binder (bitumen), and other optional additives. The term bituminous materials is generally used to denote substances in which bitumen is present or from which it can be derived. Bitumen is defined as an amorphous, black or dark-colored, (solid, semi-solid, or viscous) substance, composed principally of high molecular weight hydrocarbons, and soluble in carbon disulfide [1]. In road surfaces the combination is designed to meet diverse and often conflicting performance parameters, for example resistance to fatigue, deformation, cracking and moisture damage, durability, skid resistance, workability and economy. The mix designer generally manipulates three variables, namely type of aggregates, asphalt binder, and the ratio of asphalt binder to aggregates, and thus seeks to achieve the above-mentioned performance requirements. The components of an asphalt mixture play an important role in the mixture's behavior during the service period, so from the beginning of the design process it is very important to know their influence. Nowadays we face important changes in the way bitumen and aggregates are tested, and the development of new evaluation techniques for asphalt mixture components is essential for improving our understanding of the chemical composition and behavior of different binders and aggregates in order to develop performance-based specifications.

The asphalt mixture as the basic construction material in roads is described with specific deformation parameters. These are negatively influenced by temperature, and this is one of the
problems which causes short pavement lifespan. Increasing temperature affects the behavior of bitumen-bonded materials from elastic to viscous state. Due to this the asphalt mixture is considered as a visco-elastic material. When a visco-elastic asphalt mixture is subjected to sinusoidal varying stress, a steady state will eventually be reached in which the resulting strain is also sinusoidal, having the same angular frequency but retarded in phase by an angle (\(\phi\)). This is analogous to the delayed strain observed in creep experiments [2], and it means that the material structure is linear only in specific temperature and loading conditions. The influence of high temperatures on bitumen-bonded materials is a current research topic, and plenty of quality publications have focused on this problem. For example the study by Tao Ma [3] focused on the relation between air void content and high temperature creep behavior, using discrete element modeling. Other studies have focused on the temperature influence on permanent deformation of asphalt layers [4,5] and a few of them have also observed the high temperature fatigue performance of these materials [6]. The measurements applied in this study represent the fatigue behavior of a specific asphalt mixture and its structural changes at an environmental temperature of 27 °C, which is considered as a non-standard temperature because ordinary temperatures for fatigue measurements are 10 °C, 15 °C and 20 °C according to European standards for asphalt mixture testing.

2. Conditions of measurement
The material chosen for the study was an asphalt mixture which is one of the most frequently-used road construction materials for surface and binder courses of roads in Slovakia. Asphalt concrete (AC 11) with continuous gradation curve with maximum grain size of 11 mm was used, and the chosen binder was polymer-modified bitumen with penetration grade 25/55 - 65 with adhesive additive Wetfix BE. The mixture and binder were also tested for empirical properties according to the type testing standards. The results of the measurements can be seen in Table 1.

| Parameter                              | Unit       | Value | Limit   |
|----------------------------------------|------------|-------|---------|
| Penetration                            | mm/10      | 25    | 25~55   |
| Softening point                        | °C         | 67.7  | 65 >    |
| Binder content                         | %          | 5.8   | 5.4 >   |
| Air void content                       | %          | 3.4   | 2.5 ~ 4 |
| Void content filled by bitumen         | %          | 80.1  | 70 >    |
| Indirect tensile strength ratio        | %          | 98    | 80 >    |
| Wheel tracking slope                   | mm/10\(^1\)cycles | 0.04  | < 0.07  |
| Proportional rut depth                 | %          | 3.7   | < 5.0   |

The results show that this mixture is good enough for use in pavement construction and on heavy-loaded road sections as well. Negative influence of moisture on this asphalt mixture was also observed, because it can cause structural damage to the mixture [7], which was measured in this study using the indirect tensile strength ratio. Differences between the results and the limit values were minimal. These results support the assumption that the fatigue parameters of the mixture should reach appropriate values also at unconventional temperatures.

In the study the four-point bending method with a prismatic beam specimen was used for measurement of fatigue according to the European standards. The specimen dimensions were 400 x 50 x 50 mm and the loading scheme of the equipment was a beam supported at four points with outer
clamps free to rotate. The beam was loaded at the two inner points and it was fixed at the two outer 
points in a vertical direction. Load was applied with sinusoidal shape using the inner clamps. 
Observation of the asphalt mix fatigue lifespan was done at constant frequency 10 Hz. In this study the 
fatigue parameters of the asphalt mixture were observed at high temperature as a simulation of 
summer temperature conditions in Slovakia. The chosen temperature 27 °C is a typical summer 
environmental temperature in Slovak region, and at this temperature the asphalt mixture behavior 
should tend to viscous state. The four-point bending apparatus used can be seen in Figure 1.

Figure 1. Four-point bending apparatus for fatigue measurement in a climatic chamber.

3. Dissipated energy and asphalt mixture testing
Asphalt mixture dissipates energy through mechanical work (loading and relaxation). Usually in an 
elastic material the energy is stored in the system when the load is applied. All the energy is recovered 
when the load is removed, in this case the unloading and the loading curves coincide. Visco-elastic 
materials are characterized by a hysteresis loop because the unloaded material traces a different path to 
that when it is loaded (phase lag is recorded between the applied stress and the measured strain), in 
this case the energy is dissipated in the form of mechanical work, heat generation, or damage. The area 
of the hysteresis loop represents the dissipated energy in the load cycle, and the following equation 
can be used to calculate its value in visco-elastic material [8].

\[ w_i = \pi \sigma_i \varepsilon_i \sin(\phi_i) \]  

Where: \( w_i \) is the dissipated energy for \( i \)-th cycle (kJ/m³); \( \pi \) is the mathematical constant; \( \sigma_i \) is the 
applied stress (MPa); \( \varepsilon_i \) is the strain level (μm/m); \( \phi \) is the phase leg (degrees).

Figure 2. Dissipated energy of initial (gray) and final (black) cycle for each strain level.

Three different strain levels are illustrated in Figure 2. Each strain level shows the dissipated 
energy loops for the initial and final loading cycles. The value of dissipated energy in constant strain
mode decreasing during test duration and also the value of initial dissipated energy are directly proportional to the strain level. The progress of dissipated energy and cumulative dissipated energy at constant temperature 27 °C have different shapes (logarithmic and linear) and can be seen in Figure 3.

![Figure 3. Progress of dissipated energy (black) and cumulative dissipated energy (gray).](image)

According to the classical analysis, fatigue life is conventionally defined as the number of cycles at which the stiffness modulus has decreased to half of its initial value. However, dissipated energy methods also started being considered in order to determine the number of cycles to failure. The energy ratio (ER$_{HP}$) method considered here was introduced by Hopman and Pronk in 1989. Failure point according to the energy ratio concept is the cycle number where cracks are considered to initiate. Failure point is defined as the point at which the slope of the energy ratio versus the number of cycles deviates from a linear line.[8] The Hopman and Pronk method was chosen for this study because of its simplicity and its clearly noticeable failure point. The energy ratio calculation is shown below (2).

$$ER_{HP} = n \left( \frac{w_0}{w_i} \right)$$

(2)

Where: $w_0$ is the initial dissipated energy (MJ/m$^3$); $w_i$ is the $i$-th cycle dissipated energy (MJ/m$^3$); $n$ is the load cycle value.

![Figure 4. Progress of the energy ratio according to Hopman and Pronk during long-term dynamic testing, and fatigue failure point according to this method (conditions: 10 °C and 10 Hz).](image)
4. Results and evaluation of fatigue measurements

The durability of the asphalt mixture was measured by means of fatigue testing. During the testing the phase angle, complex modulus and the dissipated energy were calculated for every loading cycle. The presented results were obtained at constant temperature 27 °C and three different constant strain levels 260 µm/m, 300 µm/m and 340 µm/m. Frequency of loading 10 Hz in line with the standards, and the shape of dynamic loading was sinusoidal. The fatigue failure criterion was set in the control software to the standard AASHTO criteria where the test is stopped when the complex modulus goes down below 50 % of the initial complex modulus. The dissipated energy failure criterion was calculated after the measurements.

Before fatigue measurements were made stiffness modulus measurements for scale of temperatures (0 °C; 11 °C; 20 °C and 27 °C) because of creation of master curve for studied mixture which can be seen in Figure 5. For calculation of main curve was chosen polynomial function and applied was Arrhenius equation.

![Figure 5. Master curve of studied mixture (Arrhenius equation).](image)

The progress of the complex modulus during fatigue testing of the asphalt mixture should have a characteristic curve which can be seen in Figure 6. This progress has three specific phases: during the first the reduction of the complex modulus is steeper until the second phase, during which the complex modulus value is almost constant, or its reduction is much slower. In the final third phase the complex modulus reduction is again steeper until the fatigue failure point [9].

![Figure 6. Progress of the complex modulus (stiffness) during the fatigue testing of asphalt mixture with standard temperature and frequency conditions [9].](image)
The studied temperature influenced the shape of the complex modulus progress during testing, an example of which is shown in Figure 7. As can be seen, the third phase in this case was missing, and phase one was approx. 10% of the total lifespan of the sample. In this phase the complex modulus was reduced to approx. 65% of its initial value. Phase two represented 90% of the lifespan of the sample, and the reduction of the complex modulus was much slower than in phase one. Progress of the complex modulus in these conditions can be described with a semi-logarithmic mathematical function.

![Figure 7. Progress of the complex modulus (gray), strain level 260 µm/m.](image)

The shape of the complex modulus reduction was the same for each tested sample, and the proportion of the phases was also similar. Figures 3 and 7 show the same trend in the complex modulus and the dissipated energy, and this observation falsely suggests that the failure point should be the same for both methods. Evaluation of the fatigue measurements clearly shows that this prediction was not confirmed. An example of the energy ratio progress according to the dissipated energy method and the phase angle can be seen in Figure 8. In the plot of the energy ratio and number of cycles there is no deviation from the straight line, which means that there was no structural damage according to the Hopman and Pronk method. The failure point according to the dissipated energy method was not reached in every tested sample for each of the strain levels.

![Figure 8. Progress of the energy ratio (black) and the phase angle (gray) during the fatigue testing, strain level 300 µm/m.](image)

An interesting fact is that the progress of the phase angle was similar to the complex modulus progress, but in the opposite direction. The phase angle too achieved an almost constant value after the first third of the sample's lifespan. After a few tested samples there was an attempt to set a lower percentage for the fatigue failure point according to the AASHTO method, but then there were unwanted problems with the control software used. Because of these facts the evaluation of the fatigue
testing measurements was finally based only on the AASTHTO criteria. The Wöhler curve and correlation coefficients can be seen in Figure 9.

![Fatigue curve](image)

**Figure 9.** Fatigue curve according to current European standards (black) and estimation of polynomial function (gray).

Evaluation of the results shows that the bi-logarithmic relation between strain level and number of cycles until sample failure is not quite linear. The standard correlation coefficient should be within the interval of 0.9 - 1.0. As can be seen in Figure 8, the correlation coefficient of the polynomial function is higher, which means that the studied relation is closer to the polynomial than the linear function. Based on this curve it might be presumed that by reducing the strain level, the lifespan of the sample could become endless [10].

5. Conclusion
This study observed the summer temperature influence on fatigue behavior of an asphalt mixture for the surface course of roads in conditions of Slovakia. For fatigue evaluation were applied standard AASHTO method and Hopman and Pronk method.

Based on these results, the fatigue failure point according to the Hopman and Pronk method was not significantly clear for each of the strain levels. Energy ratio progress according to Hopman and Pronk was applied as main indicator of structural changes but results indicate that there were no structural changes such as micro-cracks, during environmental temperature 27 °C. Observation of the dissipated energy proved that the behavior of the material was more viscous than elastic, which is also documented by the phase angle observation.

Only the AASHTO method based on complex modulus reduction was utilized for this temperature. The lifespan of the sample did not have the third final phase, so the failure point was at the end of the second phase. Despite the fact that 50 % of the initial complex modulus was reached at the end of second phase, during the first phase there was reduction of the initial complex modulus to 65 %, which is also significant. From the failure point of view the fatigue lifespan of the asphalt mixture was positively influenced by increasing temperature. On the other hand, if we consider the fact that only 10 % of the sample lifespan had the complex modulus higher than 65 % of its initial value, the temperature influence appears more negative than positive.

In summary, the failure criteria used for fatigue testing measurements at higher temperatures should be based on the complex modulus, and moreover the reduction in bearing capacity of material during the first phase of the sample lifespan has to be considered for the better design of pavement structure.
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