Behaviour of High-Modulus Asphalt Concrete from the Perspective of Deformation Characteristics - Stiffness

Jan Valentin1, Adriana Kotoušová1, Majda Belhaj1, Liang He2

1Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7, 166 29 Prague, Czech Republic
2National and Local Joint Engineering Laboratory of Traffic Civil Engineering Materials, Chongqing Jiaotong University, Chongqing 400074, China

jan.valentin@fsv.cvut.cz

Abstract. High-modulus asphalt concrete is a specific type of asphalt mixture which is used for several decades in pavement engineering. It was originally invented as a solution which should help to minimize the effects of permanent deformation caused mainly by heavy traffic and mainly during the periods with elevated temperatures. These mixtures are used either in binder or base courses, whereas for base courses, it is important to combine reasonably the high stiffness with good fatigue life to avoid premature pavement failures not caused by rutting but by fatigue cracking. In this respect, various types of HMAC used and designed in the Czech Republic were tested first and foremost to determine stiffness. The stiffness modules were tested according to EN 12607-26, test method IT-CY, at selected temperatures representing cold, moderate and high service temperatures. The susceptibility to temperature change can be shown by thermal susceptibility for each mixture. In the parallel test, specimens were laboratory age to identify the changes in stiffness caused by thermo-oxidative ageing. This allows calculating a simple measure of the ageing index. Not presented in this paper but performed as a very last test was resistance to crack propagation.

1. Introduction

High-modulus asphalt concrete mixtures (specified in the Czech Republic under the abbreviation “VMT”) have been in use in the Czech Republic since 2001. Their initial introduction was promoted by an extensive research project commissioned by the Ministry of Transportation of the Czech Republic, known under the project title “New Generation of Asphalt Pavements” (AVNG) which was realized by a broad expert team 20 years ago. The starting point was a collection of practical findings and experience with the application of such type of mixture in France starting from the early 1990s where the mixtures were referred to as EME (Enrobés à Module Élevé). The initial development of the mixtures in France was followed by a number of studies and practical implementations in other countries, of which Great Britain should be mentioned where the mixtures gradually established themselves under the term HMAC (High Modulus Asphalt Concrete).

In the first stage, the original EME concept was based primarily on high stiffness values and excellent resistance to rutting while, at the time, the French approach distinguished several classes of mixtures: a higher stiffness modulus was required for base layers and a lower stiffness ($S_{\text{min}} = 11\,000$ MPa) applied to binder layers. It shall be pointed out that the French modulus characteristics have been and still are, in compliance with the EN 12697-26 test standard, most often determined by the 4-
point beam test or by direct tensile stress test. This, in itself, is a factor complicating a comparison of the original French limits to the limits introduced in the Czech Republic by technical specifications TP 151 (Technical Specifications of the Ministry of Transportation for High-Modulus Asphalt Mixtures).

However, it became obvious over time that too high stiffness might have its critical cons, demonstrated as e.g. fatigue or thermal induced (frost) cracking. Subsequent EME mix generations as developed in France necessitated partial reductions in the required limits and more significant consideration of the fatigue behaviour as another important aspect of asphalt pavement life-time. Similarly, more attention was paid to the asphalt behaviour in low temperature range as this issue was highlighted by one of the partial AVNG project reports focusing purely on High-Modulus Asphalt Mixtures. An extensive literature review was conducted almost 20 years ago in 2000 in relation to asphalt mix behaviour in low temperature range issues. Based on that, Annex 3 to the original Technical Specifications TP 151, defining principles for assessing cracking risk at low temperatures, was compiled, [1].

Of course, the incorporation of HMAC mixtures in TP 151 did not stop experts from collecting findings and pushing further partial developments in this area. The HMAC mixtures were paid attention within the national CIDEAS research project (2003-2010) involving key technical universities, as well as a number of construction companies involved in road construction. Additional development occurred in the CESTI virtual competence centre for effective and sustainable transport infrastructure which has been in operation in the Czech Republic as an important complex research project since 2013. Here, the objective was focusing on the possible development of second-generation HMAC mixtures and a gradual introduction of RBL (rich bottom layer) mixture which basically respond to the need to address the fatigue aspect in base layers to a larger degree. A number of findings concerning these issues can be found e.g. in [2, 3].

2. High-Modulus Asphalt Mixtures
As has been mentioned above, high modulus asphalt concretes (HMAC) are regulated by technical specifications TP 151. They are distinguished from common asphalt mixtures by a more restricted grading curve range, more stringent requirements for air voids content (3-5 % by mass), different requirements for the content of soluble bituminous binder and, first and foremost, by the required minimum stiffness determined at 15 °C; i.e. criterion $S_{\text{min}} = 9000 \text{ MPa}$. Generally, the stiffness modulus can be determined by one of the methods listed in EN 12697-26; the results delivered by the individual methods are believed to be inter-comparable, even if it is known from other international research studies that such assumption is at least problematic. However, to this day, no relationship for mutual comparison has been more deeply studied and even found that would provide a sufficient level of reliability, applying simple coefficients or clearly set parameters and stipulating that the stiffness of a mixture, determined at the relevant boundary conditions, delivers the same value with a different setup of boundary conditions of another method. In the Czech Republic, two methods have been admitted: the 2-point test using trapezoidal specimens (2PB-TR) and non-destructive repetitive tensile stress test on cylindrical test specimens (IT-CY). The laboratory results presented hereinafter use solely the latter method, which has been used more often during the last 15 years.

3. Scope of tested HMAC mixtures
A series of 21 HMAC mixtures which fulfilled technical requirements of Czech national specifications TP 151 was of VMT 22 type and was tested in the years 2016 and 2018 at the Czech Technical University in Prague (CTU Prague). The asphalt mixtures varied as to the type and content of bituminous binder and aggregate applied. Most of the mixtures were collected from mixing plants or from construction sites, so they have to be considered as asphalt mixtures paved on trunk roads or
motorways where high traffic load intensities are expected. In the majority of cases, the mixtures were produced by particular mixing plants. The binders used in the production of the HMAC mixtures were mostly polymer-modified (PMB 10/40-65, PMB 25/55-60), as well as paving-grade bitumen (30/45) and hard paving-grade bitumen 20/30 following existing European standards, see Table 1. The mixtures and used test specimens were always produced and compacted at mixing plants, the university received final cylindrical test specimens. The compaction is per TP 151 done by impact compactor applying 2x75 blows. In general, at least 6 test specimens are always needed and shall be prepared. Unfortunately, not all of the data necessary for a complex evaluation of the functional parameters measured have been received; this concerned primarily information on the maximum bulk density or bituminous binder content in the asphalt mixture.

| Asphalt mix identification | ID      | Used binder | Bitumen content (% mass) | Bulk density (g.cm\(^{-3}\)) | Maximum density (g.cm\(^{-3}\)) | Voids content (%- vol.) |
|---------------------------|---------|-------------|--------------------------|-------------------------------|-------------------------------|------------------------|
| VMT 22 – VD               | VD      | PMB 10/40-65| 4.8                      | 2.510                         | 2.667                         | 5.9                    |
| VMT 22 – JO_V.1           | VJ1     | PMB 25/55-60| 4.7                      | 2.409                         | 2.521                         | 4.4                    |
| VMT 22 – JO_V.2           | VJ2     | PMB 25/55-60| 4.8                      | 2.378                         | 2.467                         | 3.6                    |
| VMT 22 – TE               | VTe     | PMB 25/55-60| 4.6                      | 2.443                         | 2.546                         | 4.0                    |
| VMT 22 – SO               | VSo     | PMB 25/55-60| 4.7                      | 2.386                         | 2.479                         | 3.8                    |
| VMT 22 – TY               | T       | PMB 25/55-60| 4.7                      | 2.485                         | 2.593                         | 4.2                    |
| VMT 22 – PO               | VP      | PMB 25/55-60| 5.0                      | 2.389                         | 2.494                         | 4.2                    |
| VMT 22 – EU_01            | VE1     | PMB 10/40-65| 4.7                      | 2.573                         | 2.697                         | 4.6                    |
| VMT 22 – EU_02            | VE2     | PMB 25/55-60| 4.7                      | 2.582                         | 2.712                         | 4.8                    |
| VMT 22 – VI_V.1           | VIA1    | PMB 10/40-65| 4.9                      | 2.527                         | 2.636                         | 4.1                    |
| VMT 22 – VI_V.2           | VIA2    | PMB 25/55-60| 4.9                      | 2.633                         | 2.772                         | 5.0                    |
| VMT 22 – BY               | BY      | PMB 10/40-65| 4.9                      | 2.452                         | 2.537                         | 3.4                    |
| VMT 22 – VB               | VB      | PMB 25/55-60| 4.8                      | 2.343                         | 2.455                         | 4.6                    |
| VMT 22 – VC               | VC      | PMB 10/40-65| 4.8                      | 2.272                         | 2.422                         | 3.3                    |
| VMT 22 – TL               | VT      | PMB 25/55-60| 4.8                      | 2.357                         | -                             | -                      |
| VMT 22 – SK               | S       | 30/45       | 4.7                      | 2.414                         | -                             | -                      |
| VMT 22 – VA               | VA      | 30/45       | 4.9                      | 2.252                         | 2.446                         | 4.3                    |
| VMT 22 – T-JČO            | T-JČO   | TSA 20/30   | 4.8                      | 2.377                         | -                             | -                      |
| VMT 22 – T-PR             | T-PR    | TSA 20/30   | 4.9                      | 2.391                         | -                             | -                      |
| VMT22 30/45 – PON          | VOP     | 30/45       | 4.9                      | 2.521                         | -                             | -                      |
| VMT22 30/45 – V-PR         | V-PR    | 30/45       | 5.0                      | 2.342                         | 2.491                         | 6.0                    |

The following characteristics were tested and evaluated for the mixtures presented in Table 1:
- Bulk densities of the compacted Marshall test specimens according to EN 12697-6;
- Maximum bulk densities for some mixtures which allowed to determine the air voids content of some versions according to EN 12697-8;
- Stiffness determined according to EN 12697-26 on virgin and aged cylindrical test specimens by the IT-CY test method at four selected temperatures (0 °C, 15 °C, 27 °C, 40 °C);
Resistance to thermal induced crack propagation according to EN 12697-44 was also tested in both virgin and aged semi-cylindrical specimens of 100 mm diameter by the 3-point bending test in the non-linear visco-elastic range. The specimens were tested with a loading rate of 5.0 mm/min at 0 °C. A detailed recording of the course of the test was taken using a digital data logger that provides in-detail data for each test stage.

Since 6 test specimens were compacted for each variant, the decision was made to expose part of the specimens to the thermo-oxidative ageing process, once the stiffness has been measured at all test temperatures. The simulated long-term laboratory ageing process was applied to compacted test specimens conditioned in the tempering chamber with forced air circulation for 5 days at 85 °C. This ageing method complies with prEN 12697-52. The aged specimens were then tested for stiffness and the effect of ageing was assessed.

4. Results and discussion

4.1 Volumetric characteristics

The bulk density statistics of individual mixtures are summarised in Table 1. Bulk densities according to EN 12697-6 were obtained for all asphalt mixtures; unfortunately, there was a problem with the maximum densities of several mixtures (not provided by the producers). The value was ascertained for only 16 mixtures which allowed subsequent calculation of the respective void contents. Figure 1 depicts the values of bulk density for all tested HMAC mixtures. For the mix marked “VD”, a total of 12 test specimens were compacted and, therefore, groups of three specimens were exposed to thermal ageing for 5 days, 10 days and to long-term ageing based on the PAV test method. The last method is commonly used to simulate long-term ageing of bituminous binders. The test specimens were put in the PAV at 2.1 MPa for 20 hours at 85 °C. It should be pointed out that, prior to the ageing as such, the test specimens were wrapped in a steel mesh and tied by straps to prevent possible lateral deformation (Figure 2) based on prior experience at CTU Prague. Bulk density was rechecked after the PAV ageing due to possible changes which were expected (see Figure 1). The PAV ageing contributed towards reducing bulk density, thus increasing the voids content of the asphalt mixture. The voids content changed from 5.9 % to 10.26 %. This means an increase of almost 100 % in voids content value. This phenomenon was confirmed for other asphalt mixtures tested by CTU Prague in the previous years.

It begs the logical question of why bulk densities were not rechecked after the standard method of thermal ageing in a tempering chamber with forced air circulation. As was discovered earlier [4], thermal ageing has almost no impact on bulk density and, therefore, it was not retested for these asphalt mixtures.
4.2 Stiffness Modulus
As described above, stiffness was tested prior to and after the laboratory ageing process at either three
or four different temperatures.

| Mix ID | Ageing | Stiffness 0 °C (MPa) | 15 °C (MPa) | 27 °C (MPa) | 40 °C (MPa) | Thermal susceptibility S0/S0 | Ageing index 0 °C | 15 °C | 27 °C | 40 °C |
|--------|--------|----------------------|-------------|-------------|-------------|-----------------------------|-----------------|------|------|------|
|        | virgin | 23209                | 12769       | 4581        | 2376        | 9.80                        | -               | -    | -    | -    |
|        | 5d@85°C | 22686               | 13892       | 7478        | 2668        | 8.50                        | 0.98            | 1.09 | 1.63 | 1.12 |
|        | 10d@85°C | 24611              | 14167       | 7386        | 3017        | 8.16                        | 1.06            | 1.11 | 1.61 | 1.27 |
|        | PAV@85°C | 13791              | 7291        | 3153        | 914         | 15.09                       | 0.59            | 0.57 | 0.69 | 0.38 |
|        |        | virgin              | 18742       | 8652        | 3000        | 1124                       | 16.68           | -    | -    | -    |
|        | 5d@85°C | 19522               | 10453       | 4227        | 1547        | 12.62                       | 1.04            | 1.21 | 1.41 | 1.38 |
|        | 10d@85°C | 18898              | 8351        | 3000        | 926         | 20.41                       | -               | -    | -    | -    |
|        | PAV@85°C | 20464              | 9955        | 3979        | 1318        | 15.52                       | 1.08            | 1.19 | 1.33 | 1.42 |
|        |        | virgin              | 21194       | 13049       | 7519        | 3096                       | 6.85            | 1.02 | 1.25 | 1.25 | 1.22 |
|        | 5d@85°C | 20771               | 9298        | 3201        | 814         | 25.53                       | -               | -    | -    | -    |
|        | 10d@85°C | 21742              | 10373       | 3632        | 1078        | 20.18                       | 1.05            | 1.12 | 1.13 | 1.32 |
|        | PAV@85°C | 20637              | 7814        | 2876        | 937         | 22.03                       | -               | -    | -    | -    |
|        |        | virgin              | 20003       | 8285        | 3303        | 1266                       | 15.81           | 0.97 | 1.06 | 1.15 | 1.35 |
|        | 5d@85°C | 20019               | 8943        | 3858        | 1483        | 13.50                       | -               | -    | -    | -    |
|        | 10d@85°C | 18823              | 10569       | 4831        | 1792        | 10.50                       | 0.94            | 1.18 | 1.25 | 1.21 |
|        | PAV@85°C | 20512              | 8190        | 2510        | 787         | 26.07                       | -               | -    | -    | -    |
|        |        | virgin              | 21617       | 9159        | 3084        | 1161                       | 18.62           | 1.05 | 1.12 | 1.23 | 1.48 |
|        | 5d@85°C | 24740               | 12321       | 5074        | 1559        | 15.87                       | -               | -    | -    | -    |
|        | 10d@85°C | 25208              | 13096       | 5871        | 2425        | 10.39                       | 1.02            | 1.06 | 1.16 | 1.56 |
|        | PAV@85°C | 21406              | 10116       | 3610        | 1257        | 17.04                       | -               | -    | -    | -    |
|        |        | virgin              | 22756       | 12039       | 6345        | 1970                       | 11.55           | 1.06 | 1.19 | 1.76 | 1.57 |
|        | 5d@85°C | 28357               | 14058       | 6957        | 2418        | 11.73                       | -               | -    | -    | -    |
|        | 10d@85°C | 30643              | 17255       | 7231        | 2722        | 11.26                       | 1.08            | 1.23 | 1.04 | 1.13 |
|        | PAV@85°C | 23231              | 10427       | 5916        | 2349        | 9.51                        | -               | -    | -    | -    |
|        |        | virgin              | 23744       | 14446       | 7036        | 2734                       | 8.68            | 1.06 | 1.39 | 1.19 | 1.16 |
|        | 5d@85°C | 20805               | 9823        | 3754        | 991         | 20.98                       | -               | -    | -    | -    |
|        | 10d@85°C | 21323              | 10973       | 4180        | 2190        | 9.74                        | 1.02            | 1.12 | 1.11 | 2.21 |
|        | PAV@85°C | 17621              | 9422        | 4209        | 1426        | 12.36                       | -               | -    | -    | -    |
|        |        | virgin              | 19581       | 10630       | 4933        | 1915                       | 10.22           | 1.11 | 1.13 | 1.17 | 1.34 |
|        | 5d@85°C | 18032               | 7463        | 2843        | 1020        | 17.68                       | -               | -    | -    | -    |
|        | 10d@85°C | 18831              | 8826        | 3815        | 1436        | 13.12                       | 1.04            | 1.18 | 1.34 | 1.41 |
|        | PAV@85°C | 24719              | 14819       | 7310        | 3032        | 8.15                        | -               | -    | -    | -    |
The thermal susceptibility value for each mixture was calculated as a ratio of stiffness obtained at the lowest and at the highest test temperatures. The effect of ageing on HMAC mixtures was expressed by the ageing index as the ratio of values scored by aged test specimens to the values scored by virgin test specimens. The results are summarized in Table 2.

The results show that at the temperature crucial for pavement design calculation, 15 °C, ageing is most frequently associated with a 10-20 % stiffness increase. There are versions where ageing had virtually no effect on stiffness; contrastingly – primarily with options containing PMB – there have been several cases where the asphalt mix rated by its stiffness characteristic was more susceptible to ageing and the modulus characteristic rose by 20-40 %. Another generally applicable principle is that increasing test temperature makes the effect of ageing more noticeable; to a certain extent, this reflects the fact that as a composite material, asphalt mixtures are susceptible to temperature. This is then mirrored in the reduced thermal susceptibility of aged test specimens. This finding applies to all versions on test with no exceptions. It can be also noticed – following the VD version – that extended conditioning, the more distinctive the stiffness increase was. Unfortunately, this statement can only be verified in one of the cases herein; therefore, the conclusions may not be generalised in any way. Long ageing and PAV ageing which influenced the asphalt mixture stiffness differently when compared to the five-day ageing alone. It can be stated that the longer the test specimens were exposed to thermal conditioning, the more distinctive the stiffness increase was. Unfortunately, this statement can only be verified in one of the cases herein; therefore, the conclusions may not be generalised in any way. Long term ageing under elevated pressure had the opposite effect on stiffness: the PAV method made stiffness drop by up to 40 %. Mixture VIA2 (PMB 25/55-60) reached the highest stiffness modulus at 0 °C and, contrastingly, mixture VC (PMB 10/40-65) recorded the lowest stiffness modulus. At 15 °C, mixture S (paving grade bitumen 30/45) achieved the highest stiffness modulus while mixture VT (PMB 25/55-60) scored the lowest value. At the increased temperature of 27 °C, again, mixture S reached the highest stiffness modulus while, contrastingly, mixture VE1 (PMB 10/40-65) scored the lowest stiffness modulus. At 40 °C, mixture S had the highest stiffness modulus while VE1 demonstrated the lowest stiffness modulus value. Out of the full set of asphalt mixtures on the test, mixture S appears to be the stiffest; when HMACs are assessed from the point of view of bituminous binders, the mixtures comprising standard pavement-grade bitumen score higher stiffness modulus values when compared to a number of HMACs with polymer-modified bitumen. This applies
primarily to cases where PMB 25/55-60 (65) is used. That can basically be expected as the relevant type of PMB binder usually has a slightly higher penetration; however, the significant factor is the higher elasticity of the binder. Therefore, we cannot automatically conclude that the HMAC options with the relevant PMB binder are inferior from the quality and functionality perspective. This finding just illustrates a certain shortcoming of the current approach to HMACs in countries like the Czech Republic where stiffness is one of the determining factors along with resistance to permanent deformation.

Figure 3a and 3b. HMAC stiffness for tested variants at 0 °C and 15 °C

High stiffness is undoubtedly crucial if the mixtures in question are applied in the binding course of a pavement structure. They can then achieve the best possible resistance to repetitive traffic loading, from the perspective of permanent deformation even in the medium-temperature range (15 °C to 27 °C). Nonetheless, structural design very often applies the relevant mixtures in the base layer where the effect of tensile stress generated by repetitive loading must be taken into account in connection with resistance to material fatigue. Although the structural layer may deform due to the loading in the sense of permanent deformation; however, bending deformation occurs at the same time as the layer is placed on an elastic subbase, of considerably lower stiffness usually. If this layer is too stiff and has to transfer repetitive bending stiffness, it might crack upon the fatigue limit.

The results show that stiffness moduli tested by IT-CY method at the determining temperature of 15 °C range from 7,500 MPa to 15,000 MPa. The limit stipulated by TP 151 defines 9,000 MPa as the minimum threshold. From our perspective and in light of the above, the fact that Czech technical regulations do not define the top limit of the modulus characteristic might be risky to a point, as asphalt mixtures with stiffness exceeding e.g. 13,000 MPa at the relevant test temperature should be also assessed for fatigue characteristics, or the critical low temperature test (TSRST) should be carried out according to EN 12697-46 or alternatively bending tensile strength test and relaxation test according to the national specifications TP 151, to rule out any risk of weak points of the mixture: fatigue life or increased risk of frost cracking. Anyway, the approach restricting excess stiffness has been known from the latest HMAC mix generations as used in France.

It must also be emphasised that the selected bituminous binder type has a very important effect on the stiffness of the asphalt mixture; however, we may not omit the importance of the type of aggregate and the aggregate skeleton design for the asphalt mixture, as well as the possible effect of the additives which will influence the useful behaviour of the asphalt mixture as well. Similarly, the bituminous binder content and the resulting void content of the asphalt mixture have an influence that has been repeatedly demonstrated in the past (e.g. [5, 6]).
The charts in Figure 7 show a logical decrease in the stiffness modulus depending on increasing test temperature. It is obvious – and the trend has been repetitively verified – that this dependence is of an exponential nature and can be generally expressed by the formula:

\[ y = be^{-ax}. \]

In this equation, the simplified constant “b” indicates the stiffness modulus at 0 °C and “a” is the thermal susceptibility of the asphalt mixture. The lower the value is, the less thermally susceptible the mixture is. The dependent variable “y” determines the stiffness modulus, and independent variable “x” is used for the temperature at which the stiffness modulus is determined. Naturally, the level of suitability of such simplified formula for the dependence between stiffness modulus and temperature needs verification by a sufficiently robust statistical analysis.

Figure 4 shows that the asphalt mixtures assessed at 0 °C scored stiffness ranging from 14,000 to 32,000 MPa; at 27 °C, the interval was defined by 3,000 to 7,500 MPa and at 40 °C the values were 800 to 3,000 MPa. Six asphalt mixtures on the test, and just two mixtures exposed to simulated long-term ageing failed the minimum stiffness modulus condition as stipulated by TP 151 for 15 °C (S_{min} = 9,000 MPa).

![Figure 4. Temperature-Stiffness curves for assessed HMAC mixtures](image)

The Ageing Index depicted in the following figures 5a to 5d for the particular test temperatures indicates the increase or decrease in stiffness due to binder degradation. At 0 °C, stiffness increases by 0 % to 13 %. Any potential drop in the stiffness might be caused by the measurement circumstances – the low temperature might render the test specimen stiff per se, and any potential stiffness increase due to ageing is demonstrated to a much lesser extent. Therefore, the test specimen might appear unaged during the tests. At the same time, we have to take into account the permitted variance of IT-CY stiffness between -20 % and +10 % from the mean value. The extent of variance within the measurement as such depends on the positioning of linear shift sensors on the surface of the test specimen.

At 15 °C, stiffness increased due to thermal ageing as mentioned above. A 4 % to 76 % increase was recorded at 27 °C, and the stiffness increase at 40 °C amounted to 1 % to 121 %. Therefore, the results confirm that the higher the temperature, the bigger increase of ageing-related stiffness can be expected. This finding rather corresponds with the visco-elastic character of asphalt mix behaviour. If the ageing indices were compared from the perspective of the effect of the bituminous binder used, no correlation between the bituminous binder type and ageing index increase is found. To a certain extent, some asphalt mixtures comprising modified bituminous binders were more affected by simulated ageing when compared to mixtures comprising paving grade or hard bituminous binders.
Stiffness increases in the course of the ageing process. Right along with that, the brittleness of the mixture usually increases as well, and this should be kept in mind. The higher level of stiffness at a higher temperature is logical with respect to the rather high stiffness of the test specimens at or below 0 °C. The consequences of this finding are obvious also in the thermal susceptibility assessment; in the case of stiffness, it is always calculated as the ratio of stiffness measured at the lowest temperature (0 °C) to the value associated with the highest temperature (40 °C). The simulated ageing resulted in a 20 % drop in thermal susceptibility on average. The decrease in thermal susceptibility noted after the ageing process suggests an apparently superior resistance of the mixture to the temperature changes of the aged composite. This finding has been repeatedly verified by a number of tests in the past, and is also logical with respect to the dependence of stiffness changes on test temperature, as has been mentioned above. If the thermal susceptibility drop after the ageing process is larger, this might indicate more serious degradation of the binder. That might have a negative impact on the fatigue characteristic perspective.

Figure 5a, b. Ageing index of assessed HMAC variants for test temperatures 0 °C and 15 °C

Figure 5c, d. Ageing index of assessed HMAC variants for test temperatures 27 °C and 40 °C

The thermal susceptibility decrease will depend on time and temperature used for the ageing process (Figure 6). Test specimens of VD asphalt mixture which were exposed to thermal conditioning for 5 and 10 days can be used as an example. It is obvious that thermal susceptibility kept decreasing depending on the time of ageing, i.e. the bituminous binder kept degrading. With respect to the influence of ageing, the results with PAV ageing are irrelevant in relation to the test specimen deformations which occurred as a result of the combined effect of higher temperature and pressure.
5. Conclusion

All of the asphalt mixtures included in the assessment presented herein were designed in various laboratories for the purpose of application in real-life construction projects. Although the void content values were not available, the above gives a clear indication that in compliance with TP 151, the void contents of the individual options were in the 3-5 %-vol. range. Therefore, it can be stated that the influence of varying void contents on the stiffness characteristic is in this case very limited. The other aspect that might have a certain effect is the quantity of soluble binder which should range from 4.1 to 5.4 %-wt. according to TP 151. In this case, the stiffness could be affected more considerably.

Presented results show just one part of the analysis performed with HMAC mixtures carried out by CTU in Prague in 2016-2018. The other part consists of a similar handling of the resistance to crack propagation characteristic. With respect to the quantity of data and findings, the second part is not presented in this paper. At the same time, it shall be underlined that the data collection concerning HMACs continued into 2019.

The results as such suggest several more or less important conclusions:

- The stiffness achieved in HMACs using modified or unmodified bituminous binders varies, and is always likely to be slightly lower when standard PMB 25/55-60 is used than in the case of using harder pavement-grade bitumen. However, that does not mean that solutions with harder pavement-grade binders must be more advantageous. If HMAC, in the base layer, in particular, should meet the fatigue life requirement, the type of binder applied must definitely be paid due attention.

- The stiffness data collected for 15 °C suggests that in a number of cases, stiffness exceeds 11 or 12 GPa. The question, with no clear answer, is whether this is risky for the pavement structure or whether it poses a potential chance. Primarily, in case of application in the base layers, placed on an elastic subbase of a much lower stiffness, excess stiffness might introduce the risk of earlier loss of fatigue life under repetitive bending loads. If the objective is the longest possible life of the asphalt pavement, this aspect must be paid attention; it is necessary to consider stipulating the maximum degree of permissible stiffness along with the minimum threshold.

- The effect of ageing in asphalt mixtures, in general, is a self-evident phenomenon. We can manage it to a certain point although we are incapable of eliminating it. That urges us to pay more attention to it. This has not been done sufficiently so far in relation to asphalt mixtures (not to be confused with bituminous binders). From the perspective of the life cycle and durability of the asphalt mixture, this is undoubtedly a shortcoming in need of a practical solution.

- Last but not least, it should be emphasised that the measurements presented herein have been carried out exclusively according to EN 12697-26 applying method C. Technical specifications TP 151 indicate the option of determining stiffness either by this method or by method A (2-point test on specimens in the shape of the trapezoidal specimen). As has been repetitively proved, it has not been managed to verify that the stiffness determined under sinusoidal load on a
trapezoidal specimen is identical with the stiffness determined by repetitive indirect tensile stress for the mixture in question. This might have an impact on other conclusions presented herein as well; if the stiffness modules are to be determined by both methods – or even by the 4-point bending test – in the future, sufficient set of comparisons of these test methods is needed to allow verifying the stiffness limit values as a set and used in the long term.

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