What information can be provided by the asphalt crack propagation test done on semicylindric specimens?

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Abstract. For several years, the crack propagation test data of bituminous mixtures according to CSN EN 12697-44 have been collected and evaluated at CTU in Prague. Over the time the standardized test procedure was adapted to the conditions more suitable to be used mainly in the Czech Republic - in terms of compaction of test specimens, the availability of cutting discs, diameters of test specimens etc. Some of the other test conditions were adapted as well as the procedures of collecting and evaluating the test data. Step by step, it has also been identified that the strict European focus on the fracture toughness as a suitable qualitative parameter is probably not correct. The characteristics of the fracture energy have been introduced and further study is devoted to the use of the tangent direction of force-strain diagrams. Selected findings from the testing of HMAC 22 are summarized in the paper.

1. Introduction
Recently the semi-circular bending (SCB) test is gaining popularity to assess fracture properties of asphalt mixtures. The popularity of this test grows all over the globe. It is widely used in the US, but it starts to occur in Asian or European research studies and technical standards as well.

Cracking is one of the major failures that affect the long-term performance of asphalt pavement structures, [1], [2]. The cracking can be caused by traffic load repetitions (fatigue) or more often by low atmospheric temperatures (thermal induced cracks). At low temperatures, asphalt pavements often behave as a brittle material and so the risk of sudden fracture in the pavement increases, [3].

Low temperatures cause that asphalt layers are shrinking, which causes tensile stress increase. Tensile stress increases with decreasing temperature or when surface temperature changes suddenly. When the tensile strength reaches the critical value, a crack is formed on the top of the surface layer. Due to repeating thaw-freeze cycles and water immersion, the crack propagates to the rest of the pavement structure and widens (so called "top-down" cracking). This type of failure is often not perceived as critical, contrary to permanent deformation, although it may have similar negative impacts on the service life of a road, especially when it is not rehabilitated on time, [4, 5].

There are many different laboratory methods how to measure low temperature characteristic: two, three or four-point bending tests, disk-shaped compact tension test (DCT), indirect tension (IDT) test, semi-circular bending test (SCB) and others, [6, 7]. The SCB geometry is practically more conducive to testing laboratory and field specimens than traditional beams. Compared to traditional beam testing,
the SCB geometry has a short span, and the more complex geometry and loading pattern introduce problems with boundary conditions, [8]. However, repeatability and reproducibility data has demonstrated that the test has analytical value, and the relative ease of sample preparation from using cylinder specimens or cores rather than beams encourages further use of the SCB approach, [8], [6, 9-11].

Biligiri et al. [12] evaluated the results of SCB test parameters for laboratory blended asphalt mixes and actual field test section specimens (cores) using 3 different temperatures (-10 °C, 0 °C, +10 °C). The study showed that the procedure can act as a tool to estimate/forecast a lifespan of flexible pavement. Omranian et al. [10] presents all different SBC indicators used in different standards and countries. The paper implements some of the new indicators of SCB testing and evaluates them. Molenaar et al. [13] determined the tensile strength of asphalt mixtures by SCB test and indirect tensile test (ITT). It was found that the tensile strength in the different test methods was greatly different. The SCB test was found to be a suitable methodology for the determination of the fracture toughness and the tensile strength of the AC mix. The SCB is a simple, low cost test that easily can be performed on specimens prepared by means of a gyratory compactor or on cores drilled from the pavement. Nsengiyumva [14] compared different loading ranges (from 1 mm/min. to 5 mm/min.), different notch lengths (from 5 mm to 25 mm) and testing temperatures (from 15 °C to 40 °C). He also experimented with specimen thickness (from 40 mm to 60 mm) to find the most accurate method. Lui et al. [15] summarized from their results, that fracture toughness (Kc) is not that suitable for evaluating asphalt mixture as the fracture energy (Jc integral), which defines the asphalt mixture cracking performance better. In some research works this was confirmed and further developed by introducing additional parameters like e.g. flexibility index [16].

2. Semi-circular bending test (SCB test)

The behaviour of asphalt mixtures in the range of low temperature can be determined by a number of different experimental tests. These tests differ in the shape of used specimens, temperatures, required equipment, determined parameters, etc. In the Czech Republic, the only commonly used low temperature characteristic is flexural tensile strength (3 points bending test on beam specimens). The flexural tensile strength is required as a qualitative parameter for High Modulus Asphalt Concrete (HMAC) for initial type testing. Some other methods are used, but only in small scales, usually at universities as part of research studies (e.g. [17]).

This paper presents a modified method of semi-circular bending test (SCB test) as originally defined by the European standard EN 12697-44, [18]. The method was modified to meet the Czech technical environment, conditions and commonly used equipment available in the laboratories. The method has been used for many years at the Faculty of Civil Engineering, CTU in Prague. The test was used there to extend the knowledge of tested asphalt mixtures above the regular set of performance characteristics, which are considered for asphalt mix characterization.

2.1. Modification of SCB test procedure

The principle of SCB test is a three point bending of the semi-circular specimen with a defined notch on the bottom edge. The standard EN 12697-44 requires test specimen with 150 mm diameter compacted according to EN 12697-31 on the gyratory compactor. This requirement has been changed due to the character of test specimens used normally in the Czech Republic. The Marshall test specimens (compacted according to EN 12697-30 by impact compactor, [19]) with 100 mm diameter are commonly manufactured for determination of air voids content or stiffness (by IT-CY method). Compaction of specimens on gyratory compactor has no history in the Czech Republic and therefore it would be problematic to enforce such a procedure with respect to other parameters given by the standards for material specifications. Laboratories work with Marshall test specimens for initial testing, control tests, during research or optimization of advanced asphalt mix designs. The gyratory
compactor, which is able to compact the 150 mm diameter specimens is only one in the Czech Republic – theoretically, the test specimen preparation could be done according to the standard, practically this would be useless since in the near future laboratories would not accept such procedure.

Another requirement for the test specimens according to the standard EN 12697-44 is the width of the semi-circular specimen, which shall be 50 mm. The required width of 50 mm is achieved by cutting of specimens on laboratory saw. After narrowing the specimens are cut in half. Cutting work must be performed precisely, parallel and centrically. Any inaccuracies can negatively affect the test results, [20]. If the specimen has inaccuracies on the bottom edge, the weakest point can occur on a different spot than the notch and the test results can easily turn to unsatisfactory state – the force-displacement diagram has than illogical drops and uneven shape (Figure 1).

As it was stated above, on the bottom edge the defined notch is cut. The notch has a depth of 10 mm and a width 0.9 mm, which is another difference from the standardized method. The standard EN 12697-44 requires a notch width of 0.35 mm, but based on performed long-term monitoring, the width was increased mainly due to problems with purchasing suitable thin cutting blade in Europe and fast depreciation of such a blade. Cutting diamond blades able to provide a notch of 0.9 mm notch are produced in the Czech Republic and their lifetime is at least 3 times longer than the blades required by the standard.

| Table 1. Comparison of test methods |
|------------------------------------|
| **Standard EN 12697-44** | **Modified method** |
| Test specimens - compaction | gyratory compactor (EN 12697-31) | impact compactor (EN 12697-30) |
| - diameter | Ø 150 mm | Ø 100 mm |
| Notch - width | 10 mm | 10 mm |
| - depth | 0.35 mm | 0.9 mm |
| Loading rate | 5.0 mm/min | 2.5 mm/min |
| Test temperature | 0 °C | 0 °C; -10 °C; 15 °C; 25 °C |
| Test parameter for evaluation | fracture toughness | fracture toughness fracture energy up to F\(_{\text{max}}\) total fracture energy |

The last modification in comparison to the standardized method was lowering the loading rate (Table 1). The EN 12697-44 requires a loading rate of 5.0 mm/min. At the beginning of the implementation of this test method, the standardized rate was used. For later measurements, the
The loading rate was modified and decreased in sequential steps down to a level of 1 mm/min to finally stabilize at 2.5 mm/min in the last 4 years. The reason for decreasing the loading rate was an effort to obtain better correlations with results of flexural strength test (three points bending test on beam specimens) performed at the same temperature and with a loading rate of 1.25 mm/min (according to Czech specification for HMAC – TP 151, [21]). Another later reason was to obtain a sufficient dependence of measured test parameters on temperature since for temperatures higher than 5 °C it is possible to talk more likely about fatigue cracking than temperature induced cracking, which is typical for low temperatures. Here the lower loading rate is more important with perspective to getting as close as possible to the actual condition in the pavement construction, where there is always a relaxation period between particular loading cycles. However, it is true that even lowering of loading rate, does not allow for any dramatic relaxation of the specimen under load and does not represent test performance in the linear viscoelasticity range.

The loading rate of SCB test differs in dependence not only on geographical area (Europe, Asia, USA and others) but also on test temperature. The range of loading rate in different standard regulations is usually given from 0.5 mm/min (e.g. ASTM D8044-16) to 50 mm/min (e.g. AASHTO TP105-13, [22]) and is often dependent on standardized test temperature. Lower or higher loading rates are exceptionally used in research works or in combination with non-standardized test temperatures.

The loading rate of 2.5 mm/min appears to be optimal for the modified test conditions even at higher test temperatures in the range of 15-25 °C.

2.2. New test parameters

The result parameters according to EN 12697-44 are deformation at maximum force, maximum stress and fracture toughness, which is a parameter based on fracture mechanics. All these three parameters are related to the value of maximum force and deformation gained at this force, i.e. the moment of initiating the failure of the test specimen (crack initiation).

In addition to the standard procedure, the test course was recorded and a force-displacement diagram was drawn. The (mechanical) work from the F-D diagram is interesting from several points of view. The standardized procedure does not require it because it considers only maximum force and deformation, but it has been repeatedly proven during the ongoing research study, that evaluation of data only from point of view of maximum force (using only fracture toughness parameter) can be partially misleading. To some extent, this represents an analogy to previously performed ductility and later modification of the procedure to force ductility test.

The force-displacement diagram was used to calculate fracture work "W". Fracture work is calculated as the area under the force-displacement curve from starting point to complete crack propagation. Its units are joules [J]. Due to meaningful recording of data, the crack propagation logging was stopped by the force drop to 0.3 kN, respectively 0.5 kN for asphalt mixtures with aggregate size ≥ 16 mm. In the initial phase, this value was set more strictly at 0.1 kN, but the later established level was found to be fully satisfactory.

Fracture work was determined at two stages: (i) up to the value of maximum force (crack initiation) and (ii) up to the value of completed crack propagation. In many cases, these two fracture works are equal, because the specimens show a brittle fracture – a sudden drop of stress right after crack initiation.

Figure 2 shows an ideal force-displacement diagram with highlighted fracture works.
Further, the fracture work was recalculated to fracture energy [J/m²], by dividing fracture work by fracture area as it is defined e.g. in AASHTO TP 105, [23]:

$$G_f = \frac{W}{t \ast (w - a)}$$

where  
- $t$ is thickness of specimen (m);  
- $w$ width of specimen (m);  
- $a$ notch depth (m);  

Figure 3 shows how misleading it can be to evaluate asphalt mixtures only on one of those test parameters. The figure shows two sets of asphalt mixtures, which always reached the same value for one parameter, but have a significantly different value for the other one. The mixtures on left (AC binder and BBTM LA) reached the same value of fracture energy, but AC binder reached almost double fracture toughness. On the other hand, the asphalt mixtures in the right figure (HMAC and SMA) reached the same fracture toughness, but the fracture energy to $F_{\text{max}}$ differs by 40 % and the total fracture energy by more than 300 %.

Which of these assessed asphalt mixtures will have better performance, efficiency and durability under the traffic load in a pavement structure? Even such an answer depends on several boundary conditions. Nevertheless, the asphalt mixtures cannot be classified to have the same resistance to cracking.

Figure 3. Comparison of test parameters for different asphalt mixtures  

2.3. Evaluation of test results validity  
The force-displacement diagram can also be used to compare the correctness of loading of certain specimens (whether the load is constant and there is no unexpected drop). Figure 4 shows an example
of load diagrams of 6 test specimens of the same asphalt mix (standard test set). One of the test specimens (marked in black) shows a drop in the force value and then the follow-up increase. Such load performance is non-standard and results of such specimen should be excluded from the assessment (although it reaches the highest maximum value). Without the recording and drawing of F-D diagram, it is not possible to determine correct loading or eliminate some illogical courses.

Figure 4. Force – deformation diagram: example of an uneven test course

Such a drop and subsequent increase can be caused by many factors. Most often it is due to not enough precise cutting work. If there is an inaccuracy (even a very little one) on the bottom edge of the specimen, it determinates the weakest point and the first crack initiation occurs somewhere else than at the notch. After eventual fracture within this inaccuracy, the force (stress) increases again (Example in Figure 5, left picture).

Another influencing factor can be the distribution of aggregate particles within the test specimen. If such distribution is inhomogeneous or contains a higher ratio of coarse aggregate (22 mm), the particles can wedge to each other and cause an additional force (stress) increase. The distribution and rotation of coarse particles within the semi-circular specimen can also affect the test course. The aggregate with a maximum grain size of 22 mm can, due to the character of selected specimens (Ø 100 mm and width 50 mm), negatively influence the fracture properties (Example in Figure 5, right picture).

Figure 5. Example of invalid tested crack propagation on HMAC 22 mixtures with different aggregate granularity

According to EN 12697-44, the crack must be propagated in area of ± 10% of the diameter from the axis of symmetry in order for the test to be valid. If the crack is outside this defined area or starts somewhere else than on the notch, the data must be discarded and the measured values should not be taken into account for the calculation of the mixture average parameters (figure 6).
3. Experimental data

For the presented experimental study, 23 mixtures designed as high modulus asphalt concrete (HMAC) with maximum aggregate size 22 mm were chosen. The data were divided into two control groups – the first one covered 9 mixtures with polymer modified bitumen (PMB 10/40-65, PMB 25/55-60 or -65) and the second covered 14 mixtures with hard paving grade bitumen (15/25, 20/30, 30/45). The data are separate because the polymer modified bitumen behaves very differently from non-modified bituminous binders and it could misrepresent the data.

HMAC 22 included in this study were in most of the cases prepared in the laboratory as part of the initial type testing. The mixtures were prepared with aggregates from different locations, having different binder content and air voids content. All of the mixtures fulfilled the limits for HMAC mixtures given by the Czech technical specification, TP 151.

One of the required parameters for HMAC mixtures in the Czech Republic is the determination of stiffness modulus at the temperature of 15 °C. The HMAC mixture has to exceed the limit of 9.000 MPa to be called „high modulus“. After stiffness testing (EN 12697-26, IT-CY method), the specimens were cut in half, notched and tested at the temperature of 0 °C to assess the low temperature properties. So for every mixture, not only fracture parameters are known, but also the stiffness modules at the test temperature of 15 °C (Figure 7).

HMAC are specific for high stiffness values and so the mixtures are very hard-stiff. The harder/stiffer the mixture is, the higher is the risk of crack damage (temperature induced or fatigue). For very stiff mixtures, it is therefore important to observe the cracking properties.

For non-modified binders, it usually applies that the stiffer the mixture is, the lower the fracture toughness is – the stiffness-toughness relation has descending trend. This assumption was confirmed also with the presented data. The curve of “hard bitumen specimens” has a descending trend.
For polymer modified bituminous binders, this presumption cannot be made. The properties depend on the polymer source, polymer content, cross-linking method etc. It can be also observed from these data, that even mixtures with high stiffness modulus, can reach high fracture toughness.

The correlation (coefficient of determination) between stiffness and fracture toughness is very similar for both of the test sets.

![Figure 8. Comparison of stiffness modulus at 15 °C and fracture energy till F_{max}](image)

For fracture energy, there is no pre-assumption, how the mixtures should behave because there is not enough data yet. But the trend of the correlation curves is very similar to the previous figure 8. For “hard bitumen specimens” the fracture energy decreases with the increase of stiffness modulus. For “PMB specimens” the trend is again reverse.

The correlation (coefficient of determination) between stiffness and fracture energy is again very similar for both of the test sets, but it shows a higher value than in the previous case. It means that maybe this parameter can be more easily predicted from the stiffness modulus determination. But it is important to emphasize, that the comparison was made on quite a small set of specimens of one specific kind of mixture and the conclusion has to be verified on a much bigger set of test specimens characterized by different composition.

![Figure 9. Comparison of fracture toughness and fracture energy](image)

The last figure (Figure 9) shows the relation between determined fracture parameters. For “hard bitumen specimens” there is quite a strong trend between the parameters – coefficient of determination higher than 0.54, resp. 0.73. It means that for mixtures with non-modified binders, the fracture
properties can be evaluated either from point of view of fracture toughness or energy. The parameters show similar trends and the evaluation of only one point may not be misleading.

For “PMB specimens” the correlation of fracture parameters is quite small, which means that the evaluation of only one point could be misleading. As it was stated above, the properties of mixtures with PMB are dependent on many factors (polymer source, its content in bitumen, cross-linking etc.) and it is important to evaluate the properties from as many points of view as possible.

4. Conclusion
Over last 5 years, more than 1,000 asphalt mixtures have been tested at CTU in Prague to find the optimum test method for crack propagation test (either temperature induced or fatigue cracking), which could be easily applied in the Czech pavement material testing environment. The crack propagation test (SCB test), as described above, is performed on standard Marshall press, which can be found as standard equipment in every road laboratory, which performs indirect tensile strength test, respectively moisture susceptibility test (ITS ratio). The press requires only a special kit for attachment of semi-circular specimens and laboratory saw (for cutting specimens and notching). Therefore, the input costs for such qualitative test are not significant for a commonly equipped laboratory.

The Marshall specimens are produced regularly in the Czech Republic during the control tests on asphalt plants or during the research work and in many cases after determining of air voids content, they are disposed without further use. The temperature induced (or fatigue) crack resistance test which can be a relatively simple extension of the qualitative test to verify and ensure a sufficiently high quality of produced asphalt mixtures. In some cases, the results of the SCB test can be a quick indicative alternative to more accurate but much more time-consuming fatigue test.

The presented research showed the fracture properties of 23 HMAC 22 mixtures. The mixtures were separated into two groups according to the used bitumen – 9 mixtures with polymer modified bitumen and 14 mixtures with non-modified hard paving grade bitumen.

The results of “hard bitumen” specimens show quite a strong correlation between the fracture toughness and fracture energy. This set has also a logical descending trend between stiffness modulus and fracture properties. It means that the fracture properties can be partially predicted from the stiffness modulus determination and the individual fracture properties can be substituted from each other in the evaluation – using the only one of the test parameter (toughness or energy) should not end in misleading results.

The results of “PMB” specimens show different results. The correlation between the test parameters describing behaviour in the low temperature range (toughness and energy) is quite low. It means that even if the specimen reaches low fracture toughness, it can still reach high fracture energy. So, in this case, it is very important to always evaluate the data from as many points of view as possible. Evaluating only one parameter could be misleading and incorrect. Polymer modified bituminous binders because of their elasticity and ductility can strongly influence asphalt mixture properties.

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