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Crack Resistance of Asphalt Concrete Subjected to Environmental Factors

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Abstract

The paper presents an analysis of the influence of environmental factors on the cracking susceptibility of asphalt concrete resulting in a change in the durability of asphalt pavement. In order to assess the phenomenon, laboratory tests were carried out taking into account the destructive effects of moisture, freeze-thaw cycle and long-term ageing. The influence of both factors occurring simultaneously was also verified. Due to the different methods of assessing resistance to water and frost, the tests were carried out according to four variants of conditioning the samples: Polish Technical Requirements WT:2-2010 and WT:2-2014, AASTHO (American Association of State Highway and Transportation Officials) T 273, AASHTO TP 140 (MIST). Long-term aging was conducted according to AASHTO R 30 for 120 h and also in extended time to 216 h. Finally, ten variants of conditioning samples were tested. Asphalt concrete for wearing course was investigated. Parameters of mixtures with neat (50/70) and SBS-modified (45/80-55) binders were compared. The evaluation of changes in fracture toughness was carried out based on the results of testing SCB (Semicircular bending) specimens with a 10 mm notch depth at a temperature of +10 °C, at a loading rate of 1 mm/min. Fracture toughness, fracture energy and Flexibility Index were assessed. A group of 40 results for each of the mixtures was obtained, taking into account both the dispersion due to material heterogeneity (four samples for each of the conditioning variants) and variation in material properties caused by environmental factors (10 conditioning variants). The influence of water and frost action causes a decrease in fracture toughness and a reduction in fracture energy. Long-term ageing increases the stiffness of the mixture, thus increasing the fracture toughness. A significant increase in the brittleness of the material is observed, which reduces the deformation at fracture and thus the fracture energy. On the basis of the obtained results, it can be concluded that the destructive effect of environmental factors is clearly more visible in the case of a mixture with a neat binder. The comprehensive laboratory test results allowed for probabilistic analysis and reliability estimation related to the assessment of the durability of asphalt mixtures. It could be concluded that asphalt pavements made with the use of modified bitumen are characterized by significantly higher durability.

Keywords

Asphalt concrete, SCB test, Pavement durability, Monte Carlo simulations, Reliability

Introduction

Improving the quality of road construction is of great importance for driving safety while optimizing the costs of road infrastructure development. Designing asphalt mixtures is strictly related to laboratory research. Proper determination of the material parameters of mixtures based on the test results is difficult, as they are usually highly dispersed [1-4]. The mixture selection process should therefore be supplemented with probabilistic analyzes and reliability estimation.

The paper presents an analysis of the influence of environmental factors on the change of material parameters of asphalt mixtures [5,6]. In the Polish guidelines, the requirement to verify the resistance of mineral-asphalt mixtures to water was introduced in the PN-S-96025 standard, based on the adaptation of the AASHTO T 283 method. By replacing the PN-S series standards with PN-EN standards, the water resistance testing procedure was also changed presented in the requirements of WT-2:2008. This procedure was based on the PN-EN 12697-12 standard. Over the years, the procedure for conditioning samples, i.e., subjecting them to cycles of environmental factors such as water and frost, has changed with the introduction of new versions of the guidelines: WT:2-2010 and WT:2-2014. In order to determine the impact of the conditioning procedure on the sensitivity of mineral-asphalt mixtures to environmental factors, the tests were carried out according to Polish procedures and two selected AASHTO procedures. Laboratory tests were carried out on SCB samples, taking into account the damaging effects of water and frost as well as the long-term ageing processes of the mixtures. The influence of both factors occurring simultaneously was also verified. The analysis was limited to two types of asphalt concrete designed to wearing course, tested at a one specified temperature, and loading rate. The wearing course was chosen due to the greatest exposure to environmental factors during the service life of the pavement. Reducing the strength parameters of the wearing course affects the durability of the entire structure, hence it is necessary to optimally design the mixes to extend their service life, and thus reduce operating costs, even if more expensive materials should be used at the building stage.

The main scope of the research was to determine the impact of environmental factors on the reduction of mechanical parameters responsible for crack resistance together with the performance of a probabilistic analysis, which allows a broader look at the analyzed issue.

Experimentation

Materials

Laboratory tests were carried out on asphalt concrete samples for the wearing course AC 11 S. Two types of concretes designed according to EN 13108-1 were investigated: AC 11 S 50/70 with granite aggregate and neat bitumen 50/70 and AC 11 S PmB 45/80-55 with granite aggregate and SBS-polymer modified bitumen 45/80-55. Materials used were with nanoproperties.

The properties of bitumens used in this research are shown in table 1. The compositions of the mixtures and standard properties are presented in table 2.

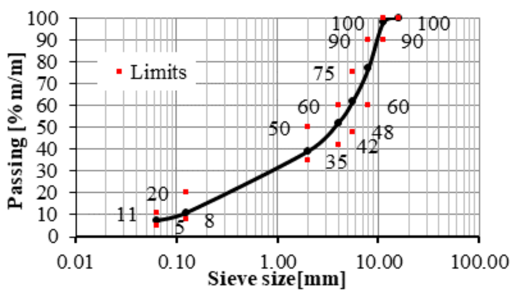
Asphalt mixture was prepared using a laboratory mixer according to EN 12697-35 and subjected to short-term aging (STOA) before specimen compaction according to the AASHTO R 30-2 procedure. Samples for SCB testing were

Table 1: Properties of bitumens.

Property		Type of bitumen 50/70	PmB 45/80-55
Penetration @ 25 °C, 0.1 mm, EN 1426	Original	54	60
	RTFO	40	40
Softening point, R&B Temperature, °C, EN 1427	Original	50.8	68.6
	RTFO	57.8	67.4
Performance Grade, AASHTO M 320		64-22	70-22

Table 2: Properties of asphalt concretes.

Property	Type of asphalt concrete AC 11 S 50/70 B	AC 11 S PmB 45/80-55
Bitumen type	50/70	PmB 45/80-55
Bitumen content, %, by mass	5.6	5.6
Fine and coarse aggregate type	granite	granite
Filler type	limestone	limestone
Air voids in Marshall samples, %	2.2 (2 x 75 blows)	2.3 (2 x 75 blows)
Sieve size, mm	Passing, %, by mass	
16	100	
11.2	98	
8	77	
5.6	62	
4	52	
2	39	
0.125	11	
0.063	7.2	



prepared using a gyratory compactor with a diameter of 150 mm and a height of 105 mm. Four SCB samples were cut out from a single gyratory specimen. The process was set to achieve two levels of target air voids. For evaluating comparative parameters of tested materials target air voids content in every SCB specimen was set to 3 ± 0.5%, which corresponded to a 99% degree of compaction (compared with Marshall samples). Samples intended for the study of environmental factors were compacted to 7 ± 0.5% air voids content.

Test method

The evaluation of changes in fracture parameters was carried out based on the results of testing 150 mm SCB specimens with a 10 mm notch depth at a temperature of +10 °C, at a loading rate of 1 mm/min. A standard universal testing machine with a thermal chamber was used. The testing scheme and the typical course of the F-d relationship are shown in figure 1.

The test was based on the procedure described in standard EN 12697-44. In this method, the asphalt mixture resistance to fracture K_{IC} is calculated using the equation (1) which takes into account the maximum force recorded during the three-point bending of the specimen.

$$\ddot{u}_{\ddot{u}} = \sigma_0 \quad \sqrt{\pi} \qquad (1)$$

Where: a - notch depth, σ_0 - test extreme stress, and Y_I - normalized stress intensity factor due to type I fracture.

The extreme bending stress in the specimen was calculated using the equation (2).

$$\sigma_0 = \ddot{u}/2 \qquad (2)$$

Where: F - maximum test force, r - specimen radius, and b - specimen thickness.

The normalized stress intensity factor was calculated by the equation (3).

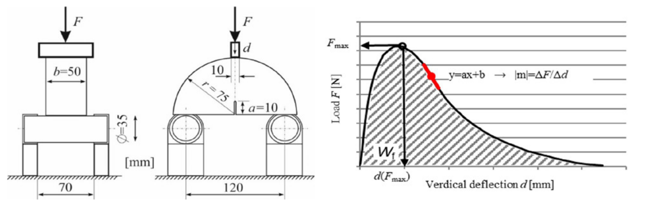


Figure 1: The testing scheme and the typical course of the F-d relationship.

$$YI = 4.782 - 1.1219(a/r) + 0.063\exp\left(7.045(a/r)\right) \qquad (3)$$

The load versus load-line displacement curve was also used for calculating the flexibility index (FI) according to the Illinois Flexibility Index Test (I-FIT) AASHTO T 393 using the equation (4).

$$FI = \frac{G_f}{|m|} \text{ x } 0.01 \qquad (4)$$

Where: G_f - fracture energy [J/m²], m - post-peak slope at the inflection point [kN/mm], 0.01- factor used for unit conversion and scaling.

Fracture energy is calculated from the work of fracture and ligament area, using the equation (5).

$$G_f = \frac{W_f}{A_{lig}} \text{ x } 10^6 \qquad (5)$$

Where: W_f - work of fracture [J], A_{lig} - the product of ligament length and sample thickness [mm²].

Simulation of environmental factors

Due to the different methods of assessing resistance to water and frost, the tests were carried out according to several selected variants of conditioning in the samples presented in table 3. In the case of comparative samples, 32 specimens were tested, in other cases four SCB samples were tested. The assessment of the influence of aging of the mixtures on the

Table 3: Water and frost action conditioning procedures.

Conditioning stage	Conditions according to the procedure			
	WT:2-2010	WT:2-2014	AASHTO T 283	AASHTO TP 140 (MiST)
Saturation of samples with water	Vacuum chamber; 20 ± 5 °C; pressure 6.7 ± 0.3 kPa	Vacuum chamber; 20 ± 5 °C; pressure 6.7 ± 0.3 kPa; required degree of saturation 55 - 80%	Vacuum chamber; pressure 13 - 67 kPa; required degree of saturation 70 - 80%	Lack of step
The action of water at increased temperature	Water bath; 40 ± 1 °C; 68 - 72 hours	Water bath; 40 ± 1 °C; 68 - 72 hours	Lack of step	Device chamber; 60 ± 1 °C; 20 hours; next 3 500 cycles of pressure changes to 40 PSI at 60 ± 1 °C
Freezing	Freezer; -18 ± 3 °C; minimum 16 hours	Freezer; -18 ± 3 °C; minimum 16 hours	Freezer; -18 ± 3 °C; minimum 16 hours	Lack of step
Thawing	Water bath; 60 ± 1 °C; 24 ± 1 hours	Water bath; 25 ± 2 °C; 24 ± 1 hours	Water bath; 60 ± 1 °C; 24 ± 1 hours	Lack of step
Conditioning prior to testing	Water bath; 10 ± 2 °C; minimum 4 hours	Water bath; 10 ± 2 °C; minimum 4 hours	Water bath; 10 ± 0.5 °C; 2 hours ± 10min	Water bath; 10 ± 1.5 °C; minimum 4 hours

Table 4: Summary of tested variants and number of tested samples.

Tested variants	Target air voids, %	STOA	LTOA 120 h	LTOA 216 h
Comparative samples	3 ± 0.5	X (32)		
No conditioning	7 ± 0.5	X (4)	X (4)	X (4)
WT:2-2010	7 ± 0.5	X (4)		
WT:2-2014	7 ± 0.5	X (4)	X (4)	
AASHTO T 283	7 ± 0.5	X (4)	X (4)	
AASHTO TP 140 (MiST)	7 ± 0.5	X (4)	X (4)	

fracture toughness was made based on long-term conditioning (LTOA) according to AASHTO R 30-02. The conditioning involves keeping samples in an airflow fan at the temperature of 85 °C for 120 h. The test simulates a ten-year service life of the pavement. Additionally, an extended long-term aging simulation process of 216 h was carried out, which simulates approximately twenty years of pavement operation [7, 8]. To evaluate the simultaneous influence of both factors, some samples subjected to the influence of water and frost were conditioned after long-term aging. A total of 11 variants were tested (Table 4).

Results and Discussion

Fracture parameters

The SCB test results are shown in figure 2, figure 3, figure 4, and figure 5. Mean values with standard deviations are shown. It should be emphasized that the comparative samples were compacted to a target void content of 3 ± 0.5%, while the rest of the samples compacted to 7 ± 0.5%.

In the case of the analysis of the test results of comparative samples, where the tests were performed on a group of 32 samples, it can be concluded that the same K_{IC} result was obtained for both asphalt concretes. In the strength criterion, no improvement can be seen after the use of modified bitumen. The improvement of anti-cracking properties is visible in the energy criterion. The fracture energy G_f is significantly higher in the case of a mixture with modified bitumen. A similar relationship can be seen in the case of post-peak slope |m| and *FI*.

Comparing the test results for samples compacted to 3 ± 0.5% of voids with samples compacted to 7 ± 0.5% (without conditioning), it can be concluded that the increase in voids content resulted in a decrease in K_{IC} for both mixtures. In the case of fracture energy G_f analysis, it can be concluded that the increase in the content of voids did not cause a significant change. Despite the lower strength of the samples, the post-peak cracking process was slower, which can be seen from the significantly lower post-peak slope value |m|. Hence, an inverse relationship was obtained for *FI*, for which mixtures with a higher content of voids are characterized by a higher value of *FI*.

Taking into account the influence of environmental factors, it can be stated that long-term aging deteriorates the fracture toughness of the tested asphalt concretes. Although there is an increase in K_{IC} due to the increase in asphalt stiffness, G_f decreases and the slope |m| increases significantly, leading to a decrease in *FI*. The increase in brittleness with

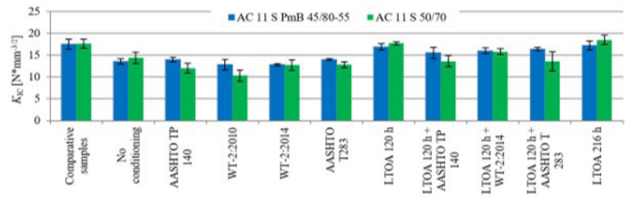


Figure 2: SCB test results - critical stress intensity factor K_{IC}, mean values, and standard deviations.

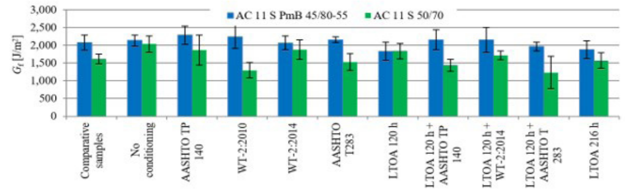


Figure 3: SCB test results - fracture energy G_f, mean values, and standard deviations.

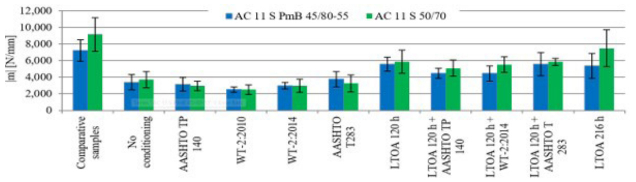


Figure 4: SCB test results - post-peak slope at the inflection point |m|, mean values, and standard deviations.

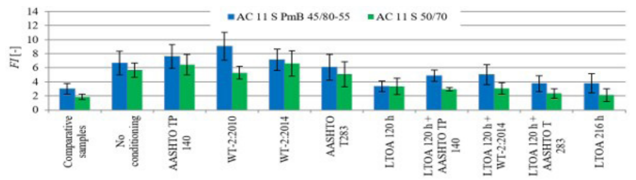


Figure 5: SCB test results - flexibility index *FI*, mean values, and standard deviations.

long-term aging is more significant in the case of a mixture with neat asphalt.

The action of water and frost in all conditioning schemes resulted in a decrease in K_{IC}, both for samples after short-term aging and for samples subjected to long-term aging before conditioning. In the case of G_f, it can be concluded that the conditioning process did not cause changes for the mixture with modified bitumen, while it decreased in the case of 50/70 bitumen. In the case of both mixtures, a decrease in the slope |m| is visible, which may indicate a more cohesive type of failure after the action of water and frost. Such a change in slope |m| increased the calculated *FI*. Comparing the results for different conditioning schemes, it can be concluded that the conditioning according to WT:2-2010 has the most destructive effect, which includes the most extensive scheme of water operation at elevated temperature and freezing, along with shock changes in the temperature of the sample.

As a summary of laboratory test results, it can be concluded that long-term aging has a greater impact on reducing the crack resistance of the tested mixtures than the action of water and frost. The mix with PmB 45/80-55 bitumen is characterized by better durability compared to the mix with 50/70 bitumen.

Probabilistic analysis and reliability estimation

The obtained results make it possible to describe the changes in the stress intensity factor K_{IC} depending on the assumed conditions for conditioning the mixtures. For this purpose, the probability p_f of not exceeding certain values K_{IC}^{K} can be determined. It will also determine the reliability R of the mixture $\left(R = 1 - p_f\right)$ with respect to this single parameter (K_{IC}). An important element of the analysis is the adoption of the reliability estimation method. As the tests were each time carried out for more than 30 samples, the Monte Carlo method was used in the calculations. The adoption of this method is also justified by the non-linear nature of the analysis [9].

Since there are no commonly used criteria for optimal K_{IC} values, several of its values, described as K_{IC}^{i} , have been assumed a priori. The analysis algorithm consists of several steps. First, all obtained results K_{IC}^{i} are arranged in ascending order, i.e., $K_{IC}^{1} \le K_{IC}^{2} \le .... \le K_{IC}^{i} \le K_{IC}^{n}$ where K_{IC}^{n} is the last highest K_{IC} value obtained. Then, for the assumed value K_{IC}^{i} , the following estimation of the probability p_f of occurrence of K_{IC}^{i} values lower than K_{IC}^{K} is performed

$$p_f \approx \frac{1}{n}\sum_{i=1}^{n} I\left[K_{IC}^{i} \le K_{IC}^{k}\right] \tag{6}$$

Where, $I\left[K_{IC}^{i} \le K_{IC}^{k}\right]$ is the function pointer equal to 1 when $K_{IC}^{i} > K_{IC}^{k}$ and 0 when $K_{IC}^{i} > K_{IC}^{k}$, and n is the total number of samples.

It is obvious that when $K_{IC}^{k} = K_{IC}^{n} \to p_f = 1$. Six values of K_{IC}^{k} (k = 6) were used in the calculations, and their results are presented in figure 6.

In addition, for the estimated p_f values, their approximation was carried out. The obtained correlation coefficients indicate a satisfactory approximation of the K_{IC} - p_f relation with a linear function. This allows to simplify the description of the K_{IC} relationships between the tested mixtures. Thus, the obtained graphs provide additional information about the parameters of asphalt mixtures. For example, a change in the angle of inclination of the approximating functions caused by the influence of environmental factors indicates the durability of the material. It can be concluded that the better the mixture, the smaller the change in the angle of inclination.

Based on the results presented in figure 6, it can be concluded that for the assumed minimum K_{IC} equal to 16 kN*mm$^{-3/2}$, the probability p_f of obtaining a lower value for

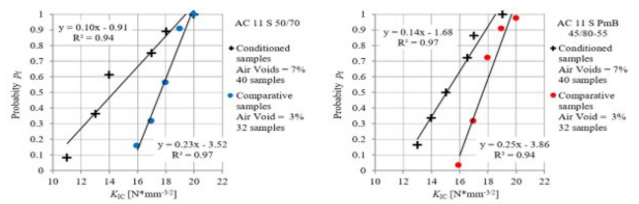


Figure 6: The probability p_f of not exceeding certain values of K_{IC}.

mixes with modified bitumen is about 0.05, while for mixes with neat bitumen it is three times higher and is about 0.15. In both cases, improper compaction of the pavement together with the impact of environmental factors during service life increases the probability to about 0.6.

The probabilistic analysis carried out allows the conclusion that mixtures made with SBS-modified bitumen will ensure greater durability of the pavement, thus reducing operating costs, extending the period between renovations. However, it should be emphasized that the analysis carried out is preliminary and shows directions for the possible use of probabilistic analysis of asphalt mix test results.

Conclusions

On the basis of performed research and analysis, the following conclusions can be stated:

- For the proper evaluation of the SCB test results, it is necessary to include the energy criterion, because the information on the critical stress intensity factor alone is insufficient.
- The mechanical parameters responsible for pavement cracking should be determined taking into account the impact of environmental factors, such as the action of water and frost and long-term aging, as this approach allows the behavior of mixtures to be assessed during the service life of the pavement.
- Mixtures with SBS-modified bitumen are characterized by higher resistance to cracking compared to mixtures with neat bitumen and their use can extend the service life of the pavement, thus reducing operating costs.
- The use of probabilistic methods enables the statistical evaluation of the tested mixtures and increases the possibility of predicting the durability of the pavement structure.

It should be noted that the tests were limited to one mixture for the wearing course. In order to generalize the conclusions, additional tests should be performed using different types of mixes (stone mastic asphalt, porous asphalt) and mixes with different aggregates.

Acknowledgments

None.

Conflict of Interest

None.

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