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Application of X-ray tomography to assess fatigue structural changes in asphalt mixtures

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Abstract. The article presents an analysis of the change in air voids in asphalt mixtures subjected to fatigue tests at three temperatures of 0°C, 10°C and 25°C. The X-ray computerized tomography imaging method, XCT, was used to identify the air voids in the samples. The research allowed to determine changes in the content of air voids in subsequent fatigue cycles in the sample area. The relationship between air voids volume and the stiffness modulus value was also determined during fatigue for three temperatures. The largest changes were found in samples with notches at 0°C. The analysis of the change in the content of air voids showed that the micro-cracking nucleation processes develop with the number of fatigue cycles. Using the numerical model finite element method we determined the distribution and change in fatigue damage in the extreme areas of the sample during various stages of fatigue. We found clear relationship between the damage and the increased content of air voids.

Key words: fatigue, air voids, fatigue damage, notch, X-ray.

1. Introduction

The problem of fatigue and cracking asphalt mixtures is a widespread topic. It is connected with material and structural changes presented in a phenomenological way, as well as described with the use of fracture mechanics. At the base of the fatigue process lies the slip of particles. Under the influence of cyclic loads, successive dislocation movement occurs and causes local strain. At the level of 10 Å–1 μm a nucleation occurs. At the level of 10 μm–100 μm, microcracks develop, and above 1 mm, macrocracks propagate.

The main fatigue phenomena occurring in asphalt mixtures are associated with macro-crack propagation and constitute the final stage associated with cracking in the road surface. However, it should be taken into account that in the early phase of the fatigue process, microcracks will appear, which combine due to the accumulation and form the basis for the initiation and formation of macro-cracks.

During the fatigue process, there are structural changes in asphalt mixtures and the formation of microcracks [1]. They are closely related to energy changes during subsequent fatigue cycles. The first analyses of the dissipation energy change with respect to fatigue cycles were carried out at work [2]. It has been shown in it that the energy decreases with the increasing number of cycles under the conditions of controlled strain, while, under the controlled stress conditions, the energy increases. During a typical fatigue test, the sample is subjected to a cyclic (usually sinusoidal) loading at a given temperature and frequency. Typical fatigue tests of asphalt mixtures include: two-point bending (2PB) with trapezoidal and prismatic samples, three-point bending (3PB), four-point bending (4PB), rotary bending (RB, simple uniaxial compression-stretching (T/C, tension/compression), indirect stretching (ITT) and semi-circular bending (SCB). Apart from T/C, the mentioned tests belong to nonhomogeneous methods characterized by inhomogeneous stress distribution in the tested samples. It should be noted that the fatigue results are strongly dependent on the way in which the load is applied and attached, although the established values of tension or strain are applied.

Currently, the criterion of changing the basic material characteristic, i.e. the stiffness modulus, is used in the practical verification of asphalt mixtures composition in fatigue tests. Fatigue failure of the material is most commonly associated with the observed 50% decrease of its initial stiffness modulus. This approach is convenient in the field of laboratory tests, hence this criterion has been practically arbitrarily adopted [3–5]. Unfortunately, there is no certainty that such a change in the modulus corresponds to the structural changes responsible for initiating the microcracks.

Despite many proposals related also to energy analysis [6–9], no critical point has been explicitly determined at which an asphalt mixture reaches fatigue failure or is significantly changed in a microstructural manner, relating to a future initiation of macrocracks. So far, the nucleation mechanism has not been well recognized, also in the field of metallurgy. In the case of asphalt mixtures, the problem is more complex due to the variety of structure (aggregate, asphalt binder and air voids) and the variability of parameters, e.g. the number of cycles and temperature. In the vicinity of defects, which are air voids, local stress accumulation appears under the influence of the load. The stresses can then cause the development and propagation of cracks. Therefore, this publication focuses on direct changes in the internal structure of asphalt mixtures.

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The problem of the usage of the X-ray computerized tomography (XCT) imaging method for fatigue analysis in 4PB test of samples with notches was not considered so far. It allowed to determine changes in air voids content in subsequent fatigue load cycles.

2. XCT measurement system

Recently, X-ray technology has developed in science and industry. This method has been effectively associated with computerized imaging, i.e. X-ray computerized tomography (XCT). The development of the XCT technique made possible to obtain the visualization and reconstruction of three-dimensional internal microstructures of many materials.

The XCT system generally consists of an X-ray generator, a collimator and sensor assemblies. Samples are placed between the X-ray source and the detector. X-ray radiation passes through the sample and is absorbed to varying degrees depending on the density of sample internal structure. Intensity is recorded on the detector board located on the other side. Reconstruction allows to obtain a 3D model taking into account the density of individual components (Fig. 1).

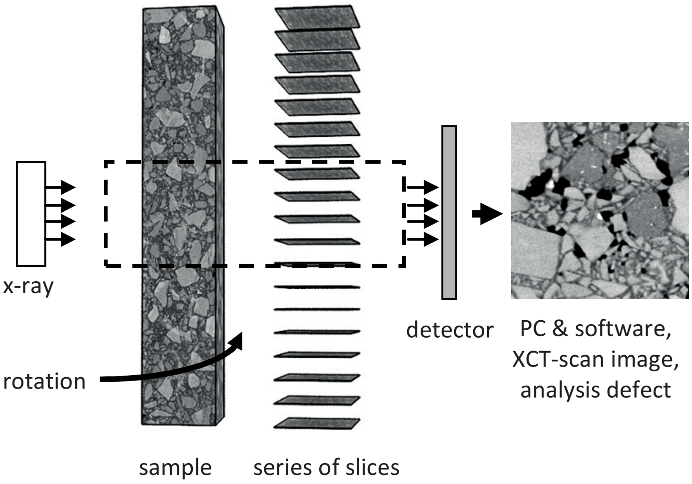


Fig. 1. X-ray study scheme

Most of the works related to the asphalt mixtures concern the analysis of aggregate and air voids distribution [10, 11], asphalt film thickness of the rubberized recycled hot mix asphalt [12] and arrangement in various compaction conditions [13–16] X-ray was also found to be an effective means of measuring the moisture distribution in the internal structure of asphalt mixtures [17]. The finite element method was also associated with the imaging technique to analyse stress distributions in a flat state in selected static studies [18, 19]. The more advanced work with three-dimensional analysis and damage assessment in relation to the changes of air voids was carried out by Wang [20–22]. An interesting application of tomographic measurements was made in [19] during the analysis of the orientation of steel fibres including destructive tests with fracture energy analysis. The effectiveness of the X-ray method was indicated in fibre orientation analysis.

Noteworthy are the observations of the initiation of nano- and microcracks in samples cut out of the surface using a scanning microscope [24, 25]. Interesting are also measurements using a fluorescent pigment applied also in aging analyses [26]. The full effectiveness of these methods was not unequivocally confirmed due to various technical problems. However, there are no papers that include the use of computed tomography for fatigue analysis in four-point bending (4PB) tests.

We carried out the X-ray tomographic measurements using the Nikon XT H 225 device (Figs 2 and 3) with the reflection source system and the motorized filament alignment system. The device had high parameters of X-ray 225 kV, 225 W.

Fig. 2. Device Nikon XT H 255

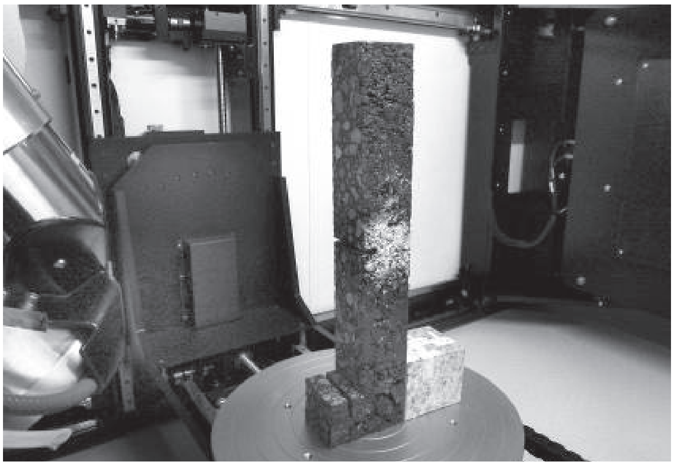


Fig. 3. A sample on the research table

The focal size (spots) X-ray was less than 3 μm. The device had a suitable Perkin Elmer 1620 panel detector characterized by observation and measurement field 400×400 mm and the number of pixels 2000×2000. Such resolution parameters are sufficient for analysing the diversified internal structure of asphalt mixtures.

The advantage of this device is the possibility of screening samples of large size and weight. Therefore, it was possible to observe samples directly from the tests without additional processing.

3. Four-point beam fatigue testing

Fatigue testing of rectangular asphalt mixture samples was performed using the four-point bending (4PB) setup under a sinusoidal, cyclic load. The adopted loading mode allows obtaining a constant value of the bending moment in the critical, central part of the beam. Examinations without variable temperature schemes were carried out using notches in samples. The role of the notches was to create predetermined stress concentrations, which simulated material discontinuities that occur in asphalt mixtures. The use of notches allows not only to accelerate the destruction process but also to control the location of the crack and determine the necessary coefficients to describe the propagation process and the energy needed to destroy a sample [27–30]. Figure 4 presents a diagram of the fatigue test with the use of notches in the samples.

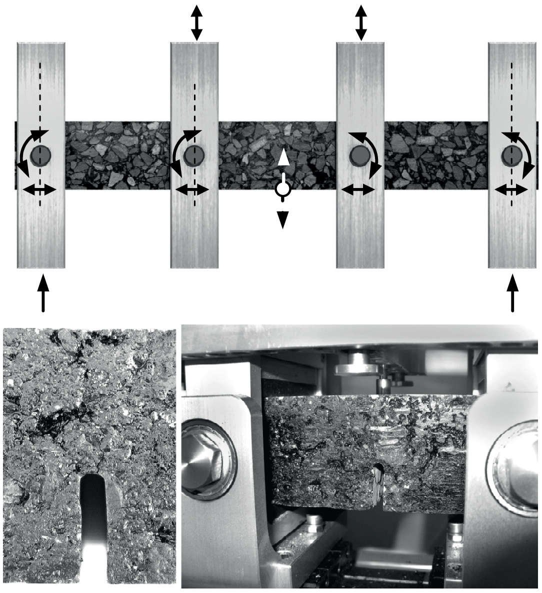


Fig. 4. Fatigue test diagram and a notched sample fixed in the device

In the field of fatigue tests, analysis of structural changes was carried out for samples with notches of 10 mm length, without notches and for three temperatures of 0°C, 10°C and 25°C. The samples were tested under controlled strain conditions $\Delta\varepsilon = 200\times10^{-6}$. We tested the AC 16 W asphalt mixtures used for a binding layer with 4.5% asphalt content and 3.8% air voids. During fatigue tests, a change in the stiffness modulus was also recorded. Its decrease was associated with the loss of fatigue life. Due to the fact that it was difficult to perform simultaneous screening and fatigue testing of large-size samples under isolated thermal conditions, the following scheme was proposed to ensure the continuity of fatigue measurement. For example, several samples were used for one research scheme. The continuity of the tests was carried out on one sample, while the remaining tests were terminated after a specified number of cycles N_i, and then examined in a tomography (Fig. 5).

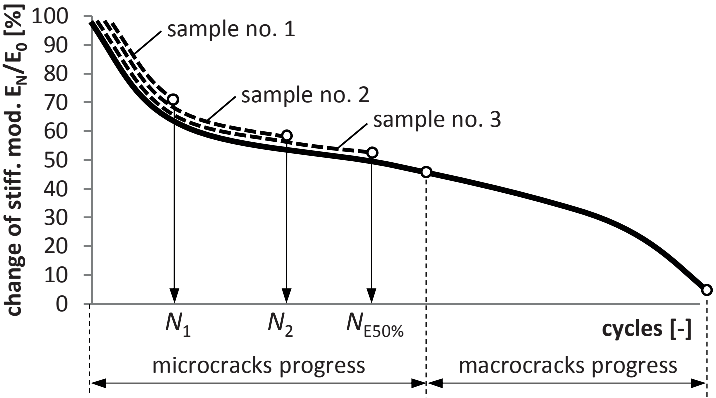


Fig. 5. Research scheme for several samples subjected to tomographic measurements

These samples were no longer re-used in this study. As a result, disturbances resulting from the "rest" of asphalt mixtures after the test were eliminated. The results were processed in the VG StudioMax 2.2 program (Fig. 6).

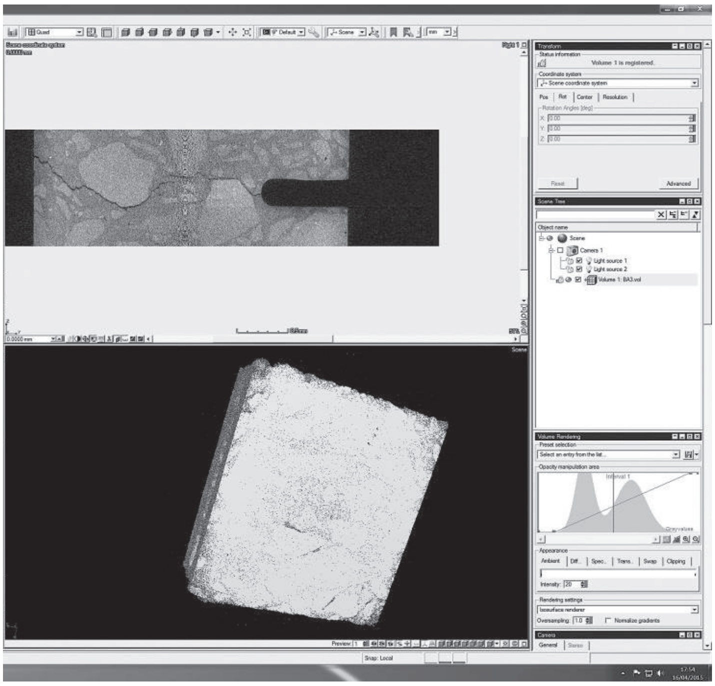
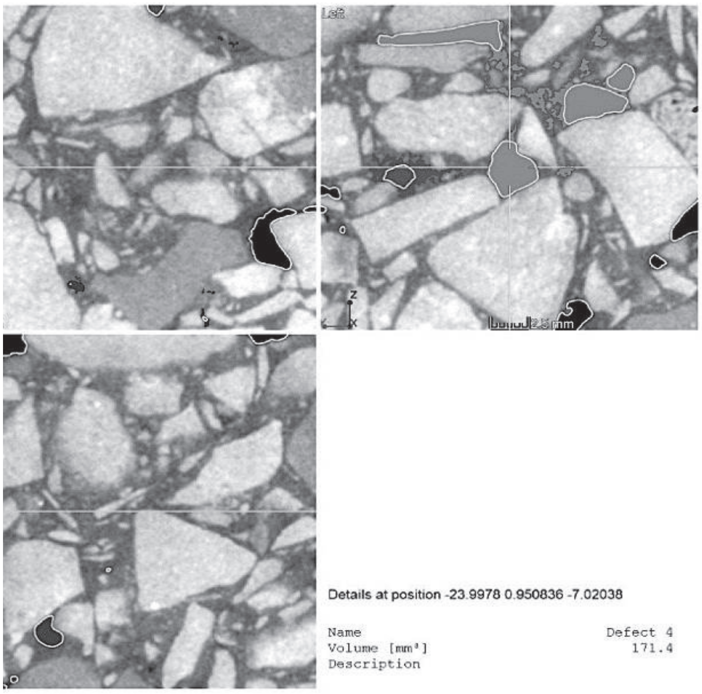


Fig. 6. Software for reconstruction VG StudioMax 2.2

4. Results of measurements

The central part of the beam section with the length of 10 cm was subjected to analysis. In subsequent cross-sections, the percentage of air voids was counted, and then the percent change was calculated relative to the sample before the test. An example of their identification was shown in Fig. 7.



Details at position -23.9978 0.950836 -7.02038

Name Defect 4
Volume [mm³] 171.4
Description

Fig. 7. An example of microstructure identification using tomography

In Fig. 8 (sample without notch) and 9 (notched sample), the results of measurements of the air voids distribution for the fatigue test carried out at 0°C were shown.

The results were summarized in the cross-section of the beam in relation to its height. The change in the content of air voids was also shown as the ratio of the number of air voids before the test to the number of air voids identified in a given fatigue cycle. It is visible that as the number of cycles increases, the distribution of air voids in the sample significantly changes.

We noted that the area in the upper part of the beam degraded to a lesser extent in notched samples compared to those without notches, with the changes occurring mainly in the area adjacent to the top face of the notch. For samples without notch, there were changes in the content of air voids in the extreme areas of the beam. The results were analysed for the next three stages of fatigue and different load cycles. The final cycle for which the results were analysed was that for which the stiffness modulus decreased to 50% of the initial value. Due to the accumulation of tensile strains in key places, i.e. in the upper and lower part of the beam and in the vicinity of the notches, there was a significant change compared to the situation before the test. Similar shapes of the graphs were obtained for testing at 10°C and 25°C temperatures.

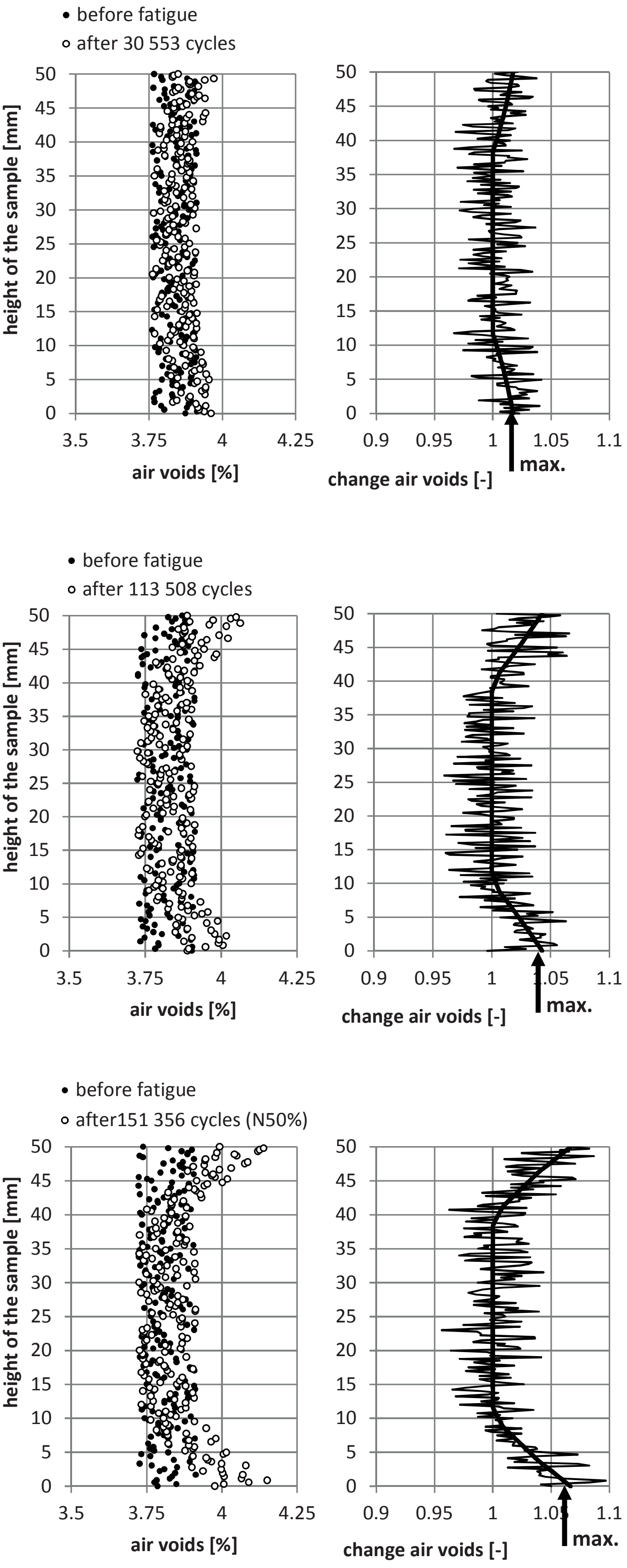


Fig. 8. Distribution of air voids in beam section for individual fatigue stages (sample without notch, fatigue test at 0°C)

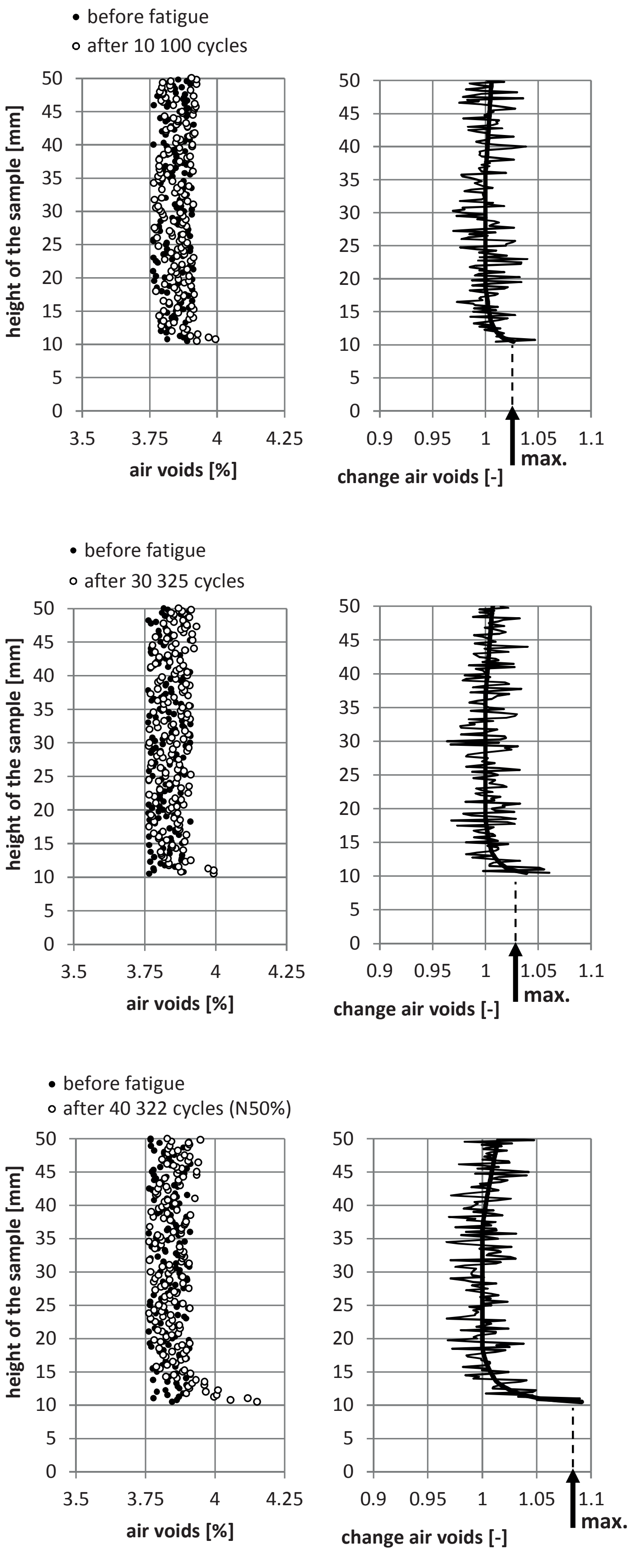


Fig. 9. The distribution of air voids in the cross-section of the beam for individual stages of fatigue (10 mm notch, fatigue test at 0°C)

Taking into account the test results for all three temperature values, the changes in air voids relative to the number of cycles were shown in Fig. 10 for samples without notches, and in Fig. 11 for samples with notches. The biggest changes registered after the fatigue failure (50% reduction in stiffness modulus) in notched samples on the edges of areas under tension were as follows: 1.0913 at 0°C, 1.0799 at 10°C, while 1.0579 at 25°C. The samples without notches were characterized by smaller changes: 1.0665 at 0°C, 1.0631 at 10°C and 1.0109 at 25°C.

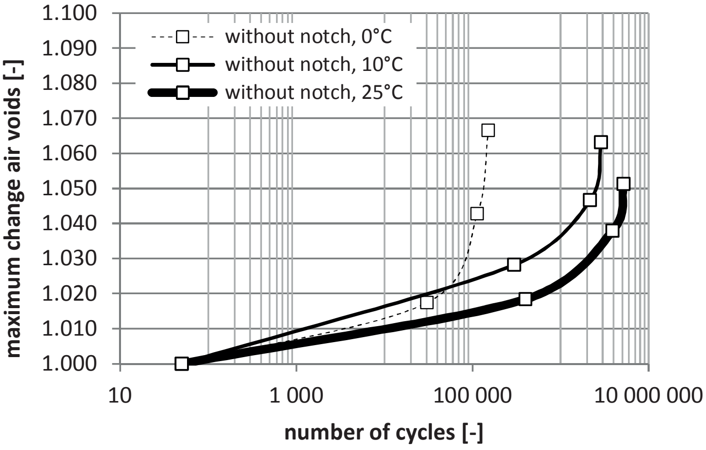


Fig. 10. The maximum change in air voids in cross-section of the beam for different load cycles (samples without notches)

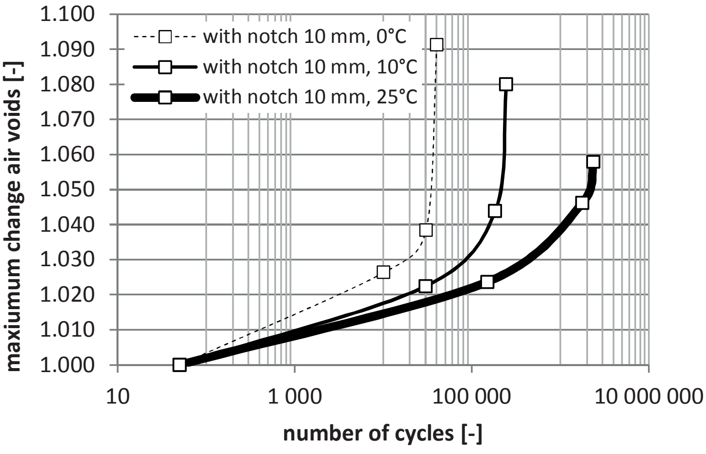


Fig. 11. The maximum change in air voids in cross-section of the beam for different load cycles (sample with notches)

It can be seen that at the time when the modulus reached about 50% in the final stage of the test, the largest change in air voids in the sample occurred at any temperature. For a notched specimen, faster changes in air voids were observed, which may correspond to higher microcracks propagation rates. The speed of changing air voids relative to the cycles was also evaluated. For the notched sample, the change rate for the initial stage of fatigue was: 0.0026 at 0°C and 1000 cycles, 0.00074 at 10°C and 1000 cycles, 0.00016 at 25°C and 1000 cycles. For a sample without notches, the increase in air voids was on average five times smaller. It should be noted that in the conditions of lower temperature (0°C) the air voids formation speed was from 6 to 20 times higher than at 10°C, and compared to 25°C, i.e. from 12 to 60 times higher.

The number of air voids was also observed depending on their volume. Figures 12 and 13 show these relationships for notches and notched samples, respectively.

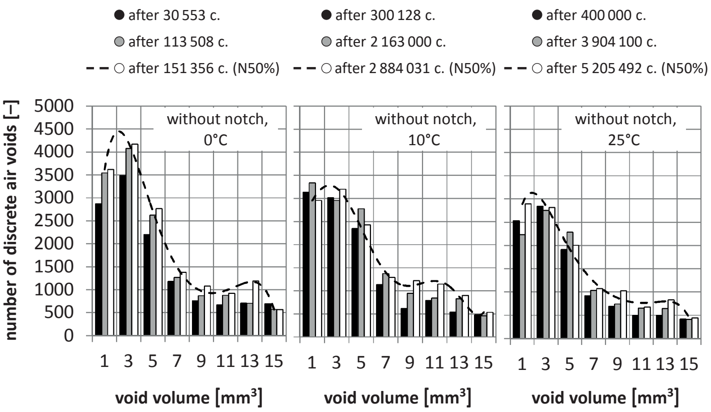


Fig. 12. The number of air voids depending on their volume for subsequent cycles (sample without notches)

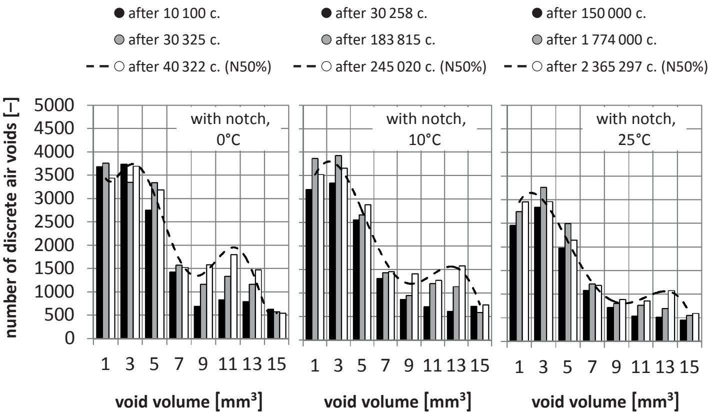


Fig. 13. The number of air voids depending on their volume for subsequent cycles (notched sample)

It is observed that as the number of load cycles increased, the overall number of air voids increased, however, in a differentiated way for different volumes. This was particularly visible for notched specimens. For cycles corresponding to the change of the modulus to 50%, there was no significant change in air voids with a small volume (from 0.5 mm^3 to 5.0 mm^3) and the number of air voids with a larger volume increases (above 9.0 mm^3). This situation occurred for all temperatures with a higher intensity at the lowest temperature. It can be concluded that after a certain number of cycles, there may be no initiation of new microcracks, which correspond to the formation of additional air voids with small volumes but already existing larger microcracks are growing or merging, which is illustrated by the increase of air voids with larger volumes (above 9.0 mm^3). A similar situation, but with lower intensity, was visible for samples without notches. We found that along with the number of voids, the distribution of their size changes very profoundly, producing a bimodal distribution. The changes were more pronounced for samples with notches in the range from 10.0 mm^3 to 14 mm^3. On the basis of changes in the volume of air voids, the dependence on the change in the stiffness modulus obtained in fatigue tests was also analysed. Generally, the stiffness modulus was considered to correspond to structural changes occurring in the sample subjected to the fatigue tests. The results of the percentage change of the modulus were related to the change in the volume of air voids from the analysed area of the sample without the notch (Fig. 14) and with the notch (Fig. 15).

It has been found that in the range of temperatures used (0°C, 10°C, 25°C) there was a correlation between the volume change of air voids and the change in stiffness modulus. The obtained determination coefficients were very high form 0.86

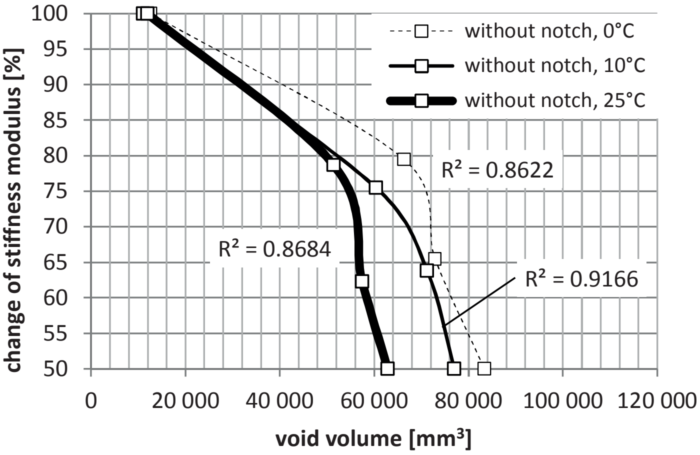


Fig. 14. Change in the volume of air voids in the cross-section of the beam without the notch relative to the change in stiffness modulus

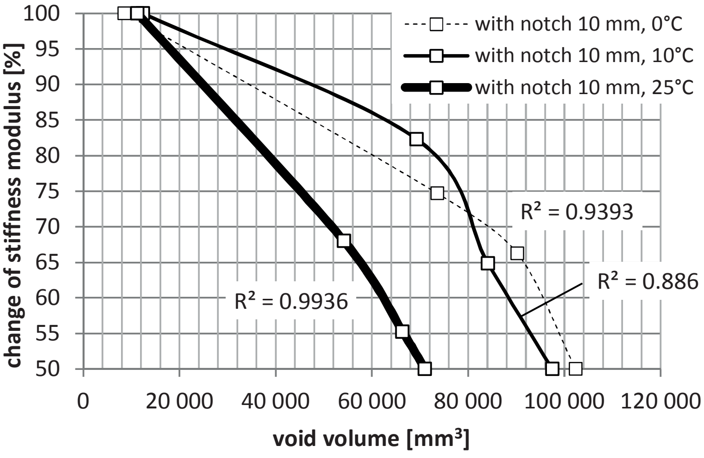


Fig. 15. Change in the volume of air voids in the notched beam section relative to the change in stiffness modulus

to 0.99 (Fig. 14 and 15) for individual data sets. Using a comparison with the average content of air voids, there was a significant variation in this relationship for the modulus in the range of 75% to 60% (inflection of the dependency curves). This may be related to the heating effects of the sample during fatigue. More regular changes in this respect were found mainly for notched specimens. During the fatigue process, the volume of air voids increased around 1400 mm^3 for every 1% drop in the stiffness modulus value. At lower temperatures, there were major changes in the volume values of air voids. Based on the observations, it can be concluded that the change in the stiffness modulus, in the proposed temperature range, reflects the structural changes occurring in asphalt mixtures subjected to the fatigue test.

5. Conclusions from tomographic measurements

The carried out tomographic measurements showed that during the fatigue test there was a change in the structure of asphalt mixtures. The increase in the number of air voids relative to cycles corresponded to the development of microcracks in subsequent cycles. This can be useful in assessing the propagation speed of microcracks and determining threshold values for initiating cracking conditions. It was found that at the temperature of 0°C, the structural changes associated with microcracking were faster compared to higher temperatures. The tomographic measurements were effective in identifying structural changes, however, due to the small sample size, additional tests should be carried out over a larger temperature range and the modulus variability in extreme temperatures should be verified.

6. Numerical analysis of FEM

At the later stage of the work, the fatigue damage change was verified in terms of the change in air voids obtained in the tomographic study. Using the developed beam model corresponding to the fatigue test (Fig. 16), numerical calculations were made using FEM. The numerical model was built in the Cartesian three-dimensional system xyz using the SOLIDWORKS Simulation, COSMOS/M application 31.

The calculations used load conditions corresponding to individual situations during the tomographic examination characterized by the following parameters: temperature 0°C, 10°C and 25°C, a variable stiffness modulus obtained from the test identification and the value of loading force corresponding to the peak-to-peak strain $\Delta\varepsilon = 200\times10^{-6}$. Next, the typical fatigue characteristics (a criterion for modifying the stiffness modulus to 50%) obtained for the four-point fatigue test was introduced into the FATIGUE COSMOS/M modulus. The fatigue characteristics and related laboratory tests, due to the large scope, will be the subject of a separate publication. The conditions of internal forces in the beam were determined for a single cycle, and in the subsequent stage, the unit damage for a single cycle was calculated using fatigue characteristics. Using the algorithm for adding the fatigue damage based on the Miner hypothesis, the cumulative damage values were calculated for subsequent cycles. For the declared criterion, a value of one was assumed for the cycle in which the last tomographic measurements were made and the modulus dropped to 50%. The purpose of the calculations was to verify variations of air voids obtained for various temperatures in tomographic tests in relation to the fatigue damage determined numerically. Figures 17–19 show changes in fatigue damage in the area of the beam, 10 cm wide, corresponding to the tested samples. Based on the analysis of the fatigue damage distribution, it can be stated that in the case of notches there is a rapid concentration of damage in the initial cycles. As the number of loads increases, the area of damage increases.

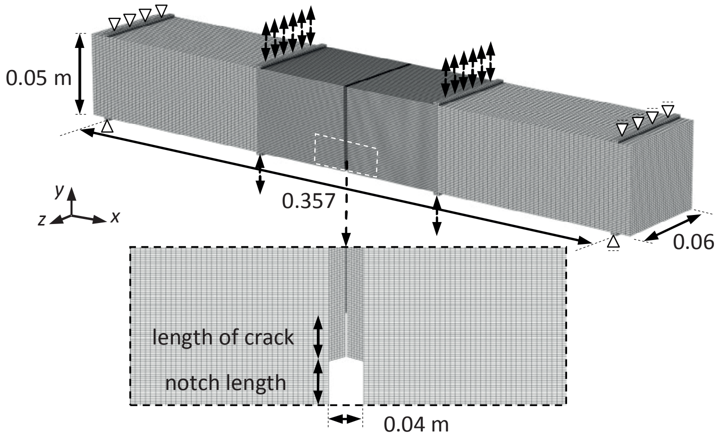


Fig. 16. The FEM beam model used to simulate the fatigue test

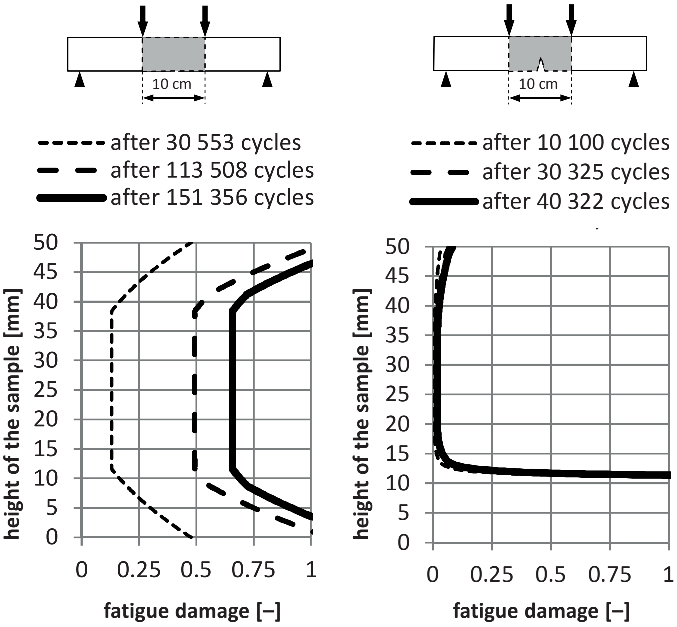


Fig. 17. Change in the damage distribution to the number of cycles (temperature 0°C)

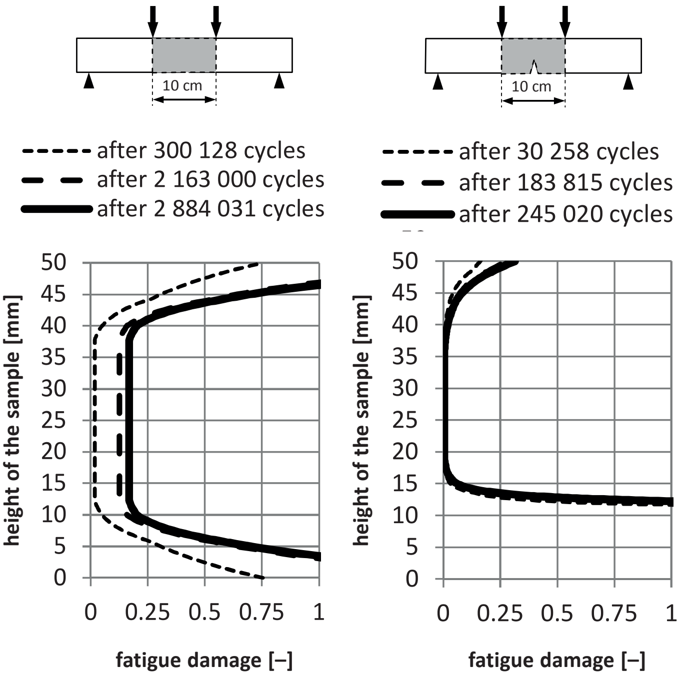


Fig. 18. Change in the damage distribution to the number of cycles (temperature 10°C)

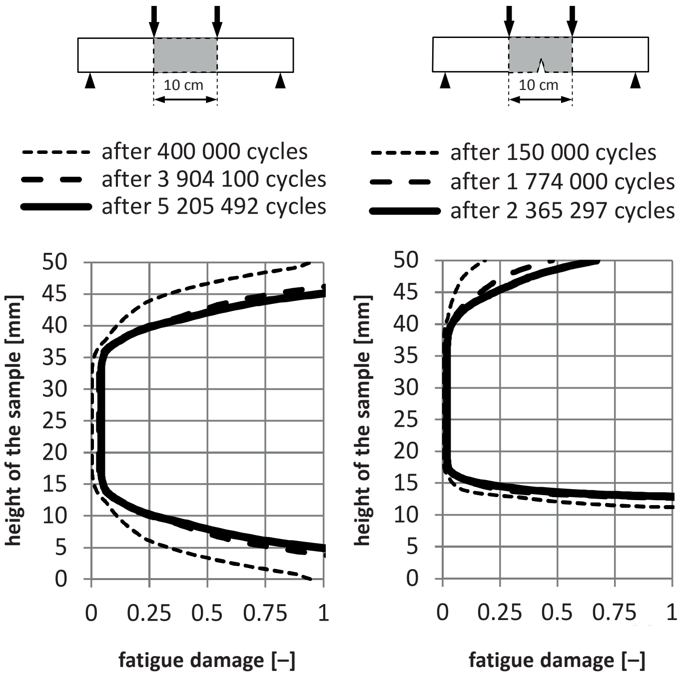


Fig. 19. Change in the damage distribution to the number of cycles (temperature 25°C)

In the example of the analysis of the sample without the notch, it can be seen that at higher temperatures, the outer parts of the sample were mainly damaged, while the central part got damage below 20%. At the temperature of 0°C, the damage inside the sample reached the value of around 65%. This was also confirmed by the observations of the distributions of air voids in the samples. It should be noted that damage cumulated at the top of samples with notches already in the initial cycles. With a further fatigue load, the fatigue zone moved slightly into the interior of sample from the notch side, and at higher temperatures, the destruction processes started on the other side of the sample.

It was noted that the damage distributions in the sample cross section correspond to the distributions of air voids determined in the tomographic studies. The air voids method is effective in the assessment of microcracks. Analyses indicate that changes in the stiffness modulus value and fatigue damage in the sample correlate with the change in air voids in asphalt mixtures. The increasing air voids are potential stress concentrators and support the accumulation and development of microcracks. With the increase in the average air voids content, the fatigue damage in individual beam locations increases.

7. Summary

On the basis of the presented measurement procedure using a computerized tomography, a significant effect of structural changes occurring in asphalt mixtures in the fatigue process was demonstrated. On the example of fatigue tests at three temperatures, the development of microcracks was characterized and related to the increase in air voids content and the decrease in stiffness modulus.

At the edges of the stretched areas, the maximum changes of air voids were registered the highest at the temperature of 0°C, while the smallest at 25°C. The samples without notches were characterized by smaller changes than those with notches. The analysis of the air voids number depending on their volume indicates that small microcracks were formed to a certain stage. Next, the microcracks connected and developed. This was visible even before the stiffness modulus reaches 50%. This was mainly observed in the notched specimens. In the initial stage, air voids with a small volume were changed (from 0.5 mm^3 to 5.0 mm^3). In the next stage, which corresponds to a change in the modulus about 65%, the content of air voids with a volume above 6.0 mm^3 was increased. A similar situation occurred at the analysed temperatures, except to 25°C, at which the number of air voids was the smallest.

It was also found that there was a correlation between the volume of air voids and the change in stiffness modulus. It can be assumed that the change in the stiffness modulus in the range reflects the structural changes in asphalt mixtures during the fatigue test. It can also be concluded that computerized tomography scans are effective in monitoring structural changes resulting from the fatigue and should be developed at other temperatures.

Using the numerical model and considering the variability of the stiffness modulus, we showed the correlation between the change in fatigue loss and the number of cycles. The study also indicated the areas associated with the change and development of microcracks, which were located in the extreme areas of the beam, and at their top in the case of samples with notches. The sites of accumulation of damage were associated with an increased number of air voids, which means the formation and nucleation of microcracks. In the temperate climate. in which Poland is located, most of the cracks occur in the winter, when the stiffness of the surface is the highest. In the summer, the number of cracks is reduced. Analysis of changes in air voids in asphalt mixtures with the use of tomography examinations may allow to assess the degree of fatigue of exploited asphalt surfaces, which will be the subject of further work of the authors.

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