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Healing process in Mineral asphalt mixtures

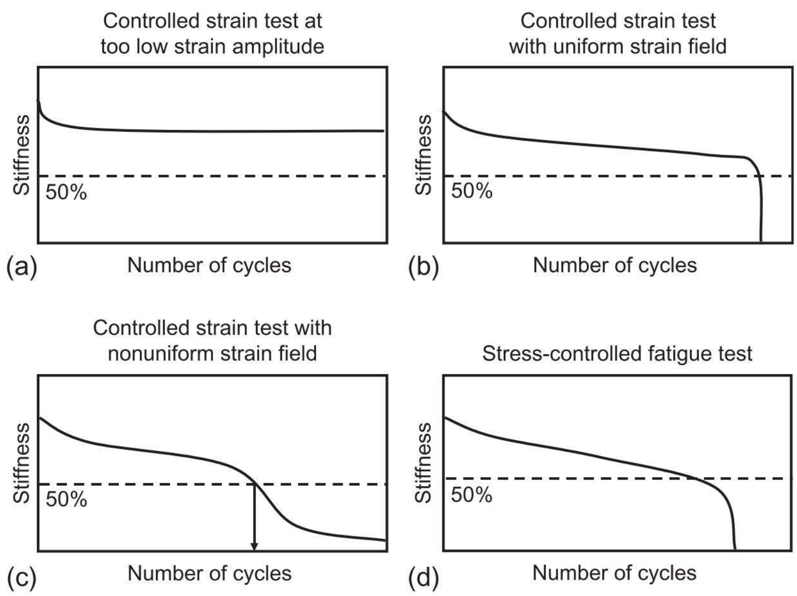
Abstract: The article presents an issue related to the phenomenon of regeneration occurring in mineral-asphalt mixtures. The introduction of the work discusses the problem of decreasing strength and fatigue life of asphalt mixtures expressed by changing the stiffness modulus. Attention is paid to the complexity of this phenomenon, which is associated with microstructural changes. The review of the state of knowledge discusses a phenomenon called "healing" referring directly to the regeneration of mineral-asphalt mixtures. Later on, based on fatigue tests of the four-point bending beam in the controlled deformation mode, this phenomenon was analyzed. Rest periods between load and heating of samples regenerating the tested mixture are taken into account. Based on the analysis of the test results, it was found that the heating process is a more effective factor leading to a greater regeneration gain not only the stiffness of the sample, but also its lifespan expressed in cycles compared to the rest period. At the end of the work, hysteresis changes were shown to analyze energy changes and the essence of regenerative processes in the context of extending the life of mineral asphalt mixes used in the pavement construction layers.

Keywords: Mineral asphalt mixes, healing, energy, structural damage, stiffness, amount of repetitive loading

Introduction

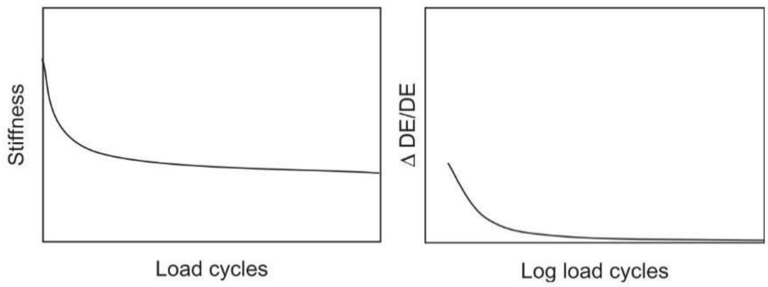
Newly constructed high technical class roads - highways and expressways, whose layers, eg top and binding, are composed of mineral-asphalt mixtures (referred as MMA), are exposed to many external factors that lead to their destruction. Among them are environmental conditions such as: temperature variability, humidity or aging processes caused by UV rays [2, 4, 6, 11]. However, the direct, important factor determining the durability of the surface is the load from the wheels of the vehicle. Due to the load in the surface layers, a complex state of stress arises causing compression, bending and shearing [12]. The load exceeding the load capacity of the surface causes immediate damage, e.g. in the form of cracks directly under the wheel of the vehicle and / or on the bottom of the layer. This is particularly noticeable at low temperatures at which the material exhibits high stiffness but also brittleness. The result of such damage is usually the destruction of the material - lack of its ability to carry loads. Destruction of the surface can also occur for extrusions that do not exceed the strength of MMA. There is then a long-lasting fatigue of the material. The measure of fatigue is the number of fixed forced cycles that the material is able to transfer before it is destroyed. The evaluation of the durability of MMA is carried out in fatigue tests in accordance with [15].

The standard test can be carried out in an attempt of controlled strain or stress by introducing in the pendulum an appropriate sinusoidal excitation for determined test conditions. There are many types of fatigue tests (eg tension-compresion, indirect tension, two-point bending), but the most common method is four-point bending (4-BP) [1, 2, 4, 11] due to good mapping of in-situ conditions and uniform stress distribution. The measure of durability in such tests is usually the number of cycles that a prismatic sample is able to transfer with an arbitrarily assumed criterion which is a decrease in the stiffness modulus to 50%. The result of cyclic loading in the sample is accumulation of defects causing structural changes and, in a further stage, cracking. Different cases of fatigue testing (controlled stress, strain) are shown in Fig.1.



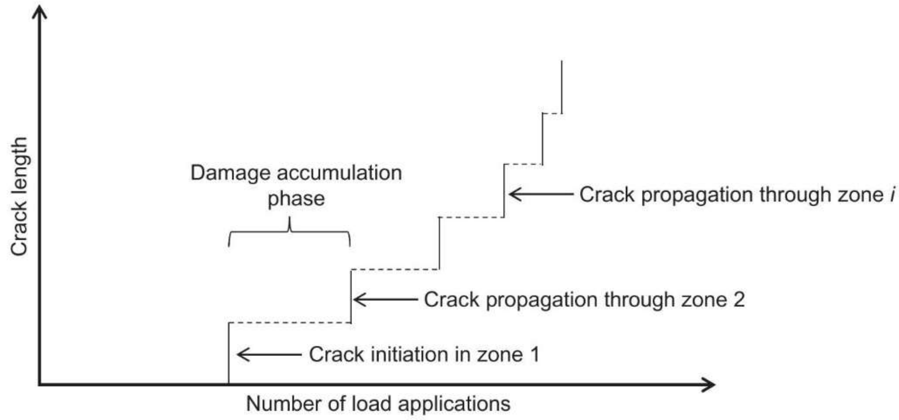
1. Cases of fatigue testing (controlled stress, strain)[4]

The commonly used methodology in the fatigue test is not sufficient to fully evaluate the phenomena occurring in the fatigue process, which is related to material degradation at the level of the microstructure. During each load cycle, energy changes in MMA occur. During the dissipation of energy, the properties of the material change (eg the value of the stiffness module decreases). This is shown by the diagram made by Carpenter et al. [4] (Fig.2.)



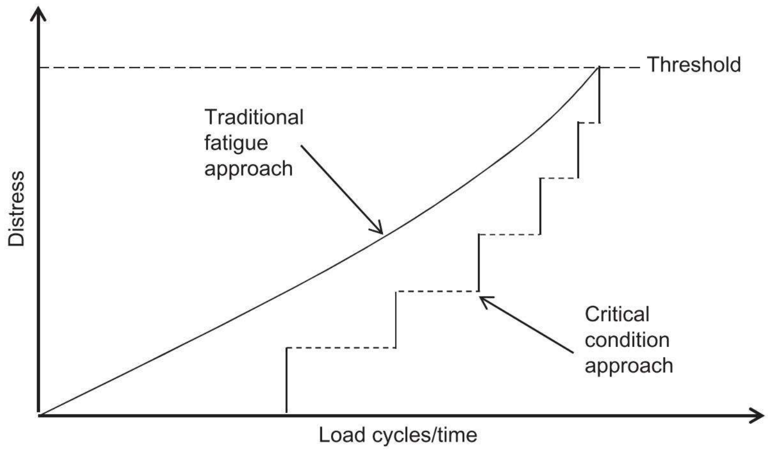
2. Decrease in stiffness and dissipated energy in fatigue tests [4]

Many studies have shown [1, 2, 4, 5, 7, 11, 14, 19, 20], that energy is dissipated in two ways. In the first case, thermal energy is released outside the system in the form of heat, while in the second case energy leads to structural changes in the material. Their effect may be, for example, the mobility of MMA components or / and the initiation and nucleation of microcracks. Each of the structural changes at a later stage leads to the creation of new microcracks and propagation of existing ones [2, 4, 8, 11, 14]. During the load micro-cracks are transformed into macro-cracks which in the further stage cause total destruction. A diagram made by Roque et al.[4] on Fig. 3 shows the rule of the crack length increment with the quantitative increase in applied extortion for the HMA-FM model used as the basic description of the MMA fracture mechanism [13].



3. Accumulation of cracks and crack growth for the HMA-FM model [4]

It is worth noting that the cracking process leading to destruction proceeds suddenly, unpredictably - mostly staggered. What is connected with energy changes. Huang et al. [4] they attempted a more detailed description of this phenomenon - Fig. 4. In the fatigue process, the stiffness module, the phase shift angle is easy to register, while the initiation, accumulation and propagation of cracks requires more complicated observations. During tests in the laboratory, the sample may suddenly burst despite an unused load capacity resulting from the fatigue criterion based on the stiffness module. An unambiguous assessment of MMA durability is therefore complicated and not always unambiguous. The problem of fatigue is further complicated by the variability of the load over time and the variability of material features when the load is not working.

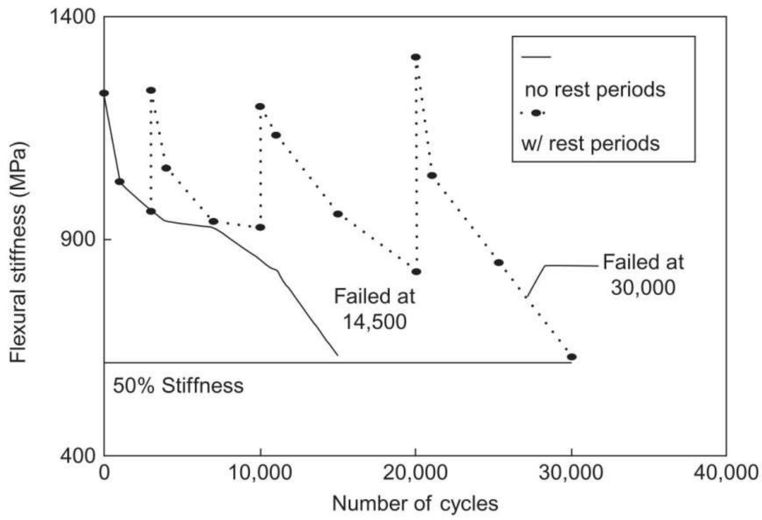


4. The difference between ordinary fatigue and the occurrence of cracks. [4]

The phenomenon of MMA regeneration has been analyzed for 30 years. The regeneration process called "healing" consists in recovering the material's capacity to carry loads. Many researchers [4, 7, 10, 13, 16–18] noted that the initiation of "healing" begins when the material is not loaded. It has been proven that the appropriate rest time and temperature have an effect on MMA regeneration leading to "recovery" of stiffness, increasing the number of cycles carried by the material. It was also observed that the regeneration process occurs in all layers of the surface and varies depending on their location in the surface.

In the first "healing" studies, the changes of the bitumen binder itself were analyzed. It has been proved that the regeneration process takes place at the level of bonds between atoms - the forces of adhesion and cohesion as well as surfaces in the vicinity of the crack [3, 9, 16]. It was only after several years that attention was focused on MMA.

An example of the dependence of changing the number of cycles from the stiffness modulus, including the rest period, is shown in Figure 5.



5. The effect of implementing rest periods for the tested samples of asphalt concrete at 20 ° C [4]

At work [4] it has been shown that with the use of appropriate rest times, up to twice the fatigue life can be achieved compared to a continuous load process.

Currently, the phenomenon of "healing" requires a quantitative and qualitative description of the MMA regeneration capability. Researchers like eg.[3, 4, 7, 10] they are trying to solve this problem, but the results of current work are not effective. It was found that the described process is dependent on temperature conditions, duration of rest and heating, type of material, level and load method.

The phenomenon of "healing" is extremely important, because it leads to increased fatigue life and "recovery" of stiffness - the two most important values used in the assessment of micro and macroscopic. It should be noted that in reality the road surface is variable over time (eg within a day or a year) to load phenomena. There are periods of "rest" and regeneration that affect the extension of the life of the planned surface. This is important for the higher classes of roads subjected to large, variable loads. In connection with the described issues, the author made preliminary attempts to analyze this phenomenon by conducting appropriate laboratory tests.

Test method

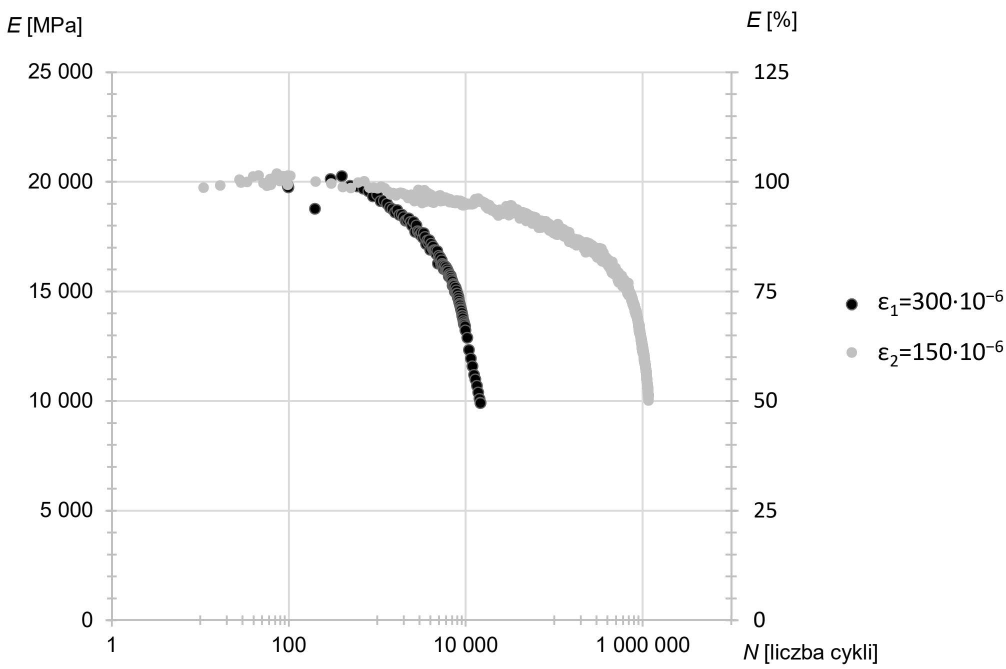
To assess the phenomenon of "healing", the author used the standard fatigue test [15]. The experiment was carried out in a controlled deformation test in the 4BP test. Prismatic samples with dimensions of 38 cm x 6 cm x 5 cm made of asphalt concrete mix with high stiffness modulus (AC WMS 16) were used for the test. 12 beams made from one "grit" with the content of asphalt in the mix at the level of 5.2% were prepared. The tests were carried out at a temperature of 5.0ºC. Prior to testing, the samples were conditioned as required. At these low temperatures, MMA exhibit a quasi-resilient nature of work and are more prone to brittle fracture. It should be noted that AC WMS is characterized by a relatively high rigidity modulus, which indicates an increased susceptibility to cracking. The load frequency used in the test was 15.0 Hz. The experiment was carried out for two constant levels of excitation with an amplitude equal to: ε1 = 300 · 10-6 and ε2 = 150 · 10-6. Such varied loads allowed to follow the regeneration process more closely. The arbitrary criterion for fatigue reduction of the module by 50%, compliant with the standard requirements, was adopted for making the determinations.

The study was conducted for three cases. The first case consisted in double-fatigue of the sample without rest time and heating process (hereinafter referred to as fatigue # 1-fatigue # 2). The second case involved 12.0 h of resting time at the temperature of the experiment (fatigue # 1 - rest time - fatigue # 2). The third one uses a three hour heating of the MMA bar in the dryer, using a temperature of 80.0ºC. Then for 12.0 h the sample was rested at the test temperature before it was subjected to another fatigue (fatigue # 1 - heating - fatigue # 2). For each load level and the analyzed case, a determination was made for two samples. The results were averaged and presented in the results of the study. To evaluate the regeneration of the test mixture, the variability of the stiffness modulus and the number of cycles were used. Fig.6 shows the selected sample on the test bench.

6. Sample on the test bench

Experiment results

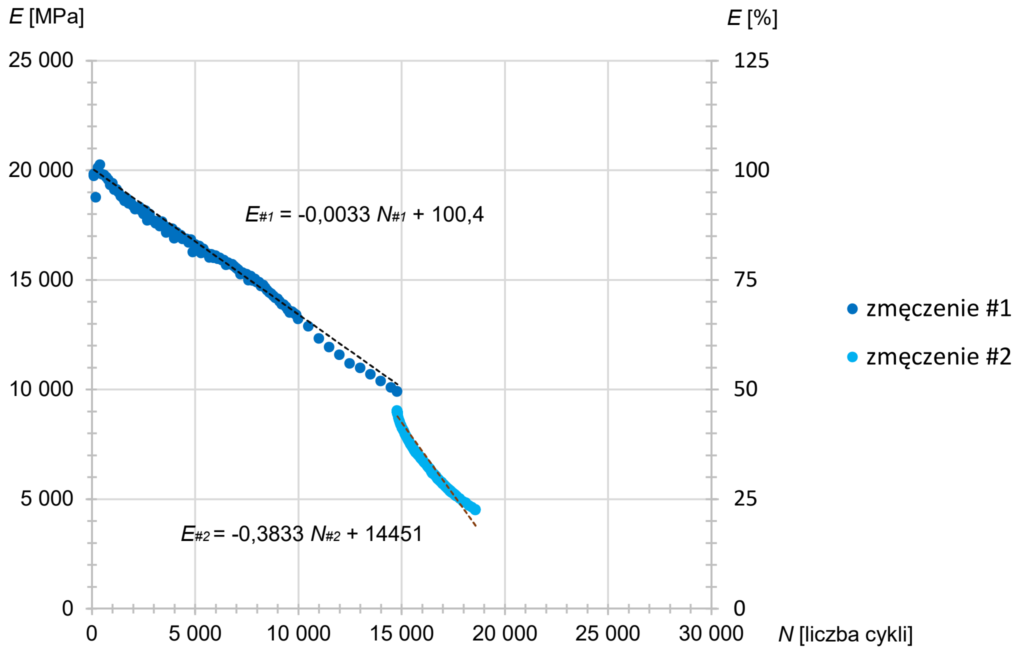
During the experiment for the assumed test conditions, the first parameter monitored was the stiffness modulus. For each analyzed sample, it amounted to approximately 20,000 ± 1,000 MPa. It was suggested that the differences in the stiffness module could have been caused by the aggregate arrangement in the mix and its heterogeneity typical of compaction technology. The results of the fatigue test for two levels of excitation (ε1 = 300 · 10-6 and ε2 = 150 · 10-6) of fatigue are shown in Figure 7. Due to significant differences in durability (100-fold difference) the test results in this case were presented on a logarithmic scale.



7. Changing the module value for the amplitude of 300 and 150 micro-distortions

The following figure 7 shows the variability of the stiffness modulus (from 100 cycles indicating the initial stiffness E0 to E50% expressing the assumed fatigue criterion) from the number of cycles at the assumed load level. The obtained graph is typical for the controlled deformation sample. It is worth paying attention to the characteristic changes in the stiffness value after about 100 cycles. A minor disorder may result from the sample being laid between clenched jaws during the test.

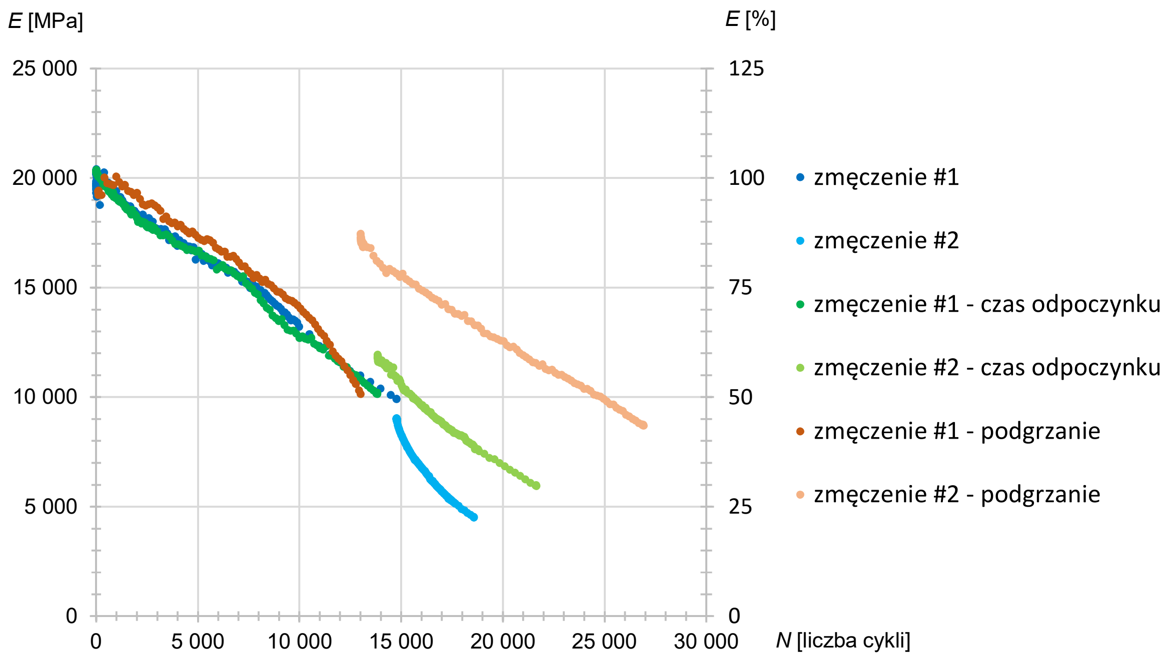
In a further stage of the research, the variability of the stiffness modulus under immediate and repeated loading was analyzed. The graph obtained for the first and second case (fatigue # 1 - fatigue # 2) for the load level of 300 micro-distortions is shown in Figure 8.



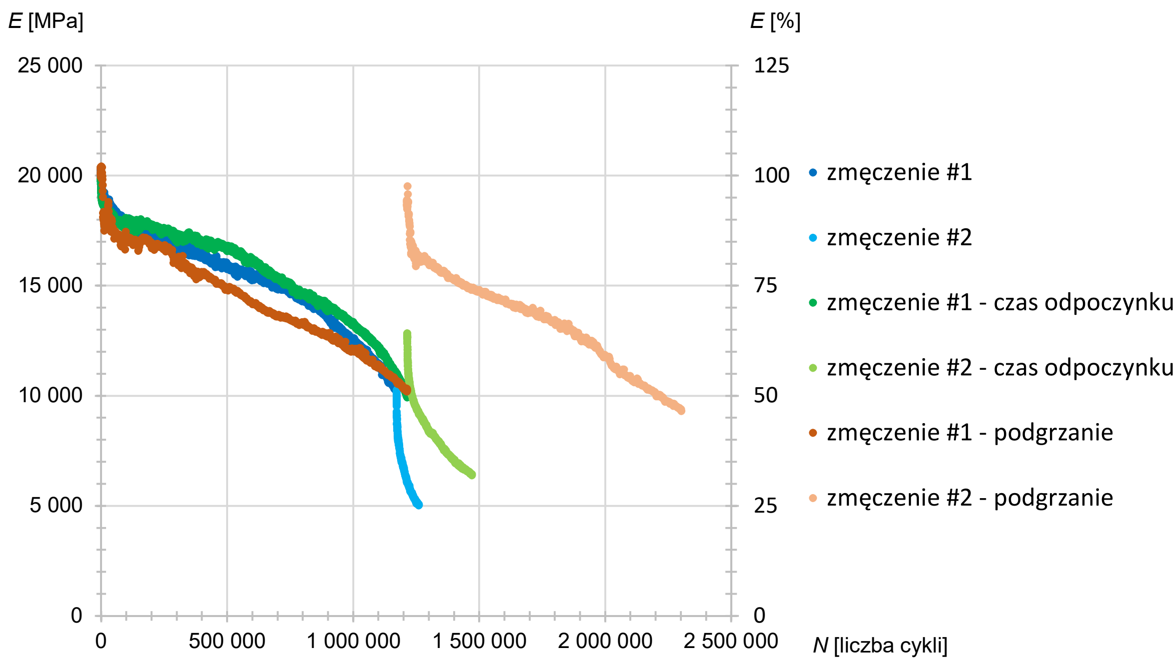
8. Module variability when repeating the fatigue test for the 300 micro-deformation load level

The graph shows a decrease in the stiffness modulus between successive fatigue tests. It can be noticed that for the second fatigue there is a clear change in the angle of inclination approximating the linear function. Probably these changes result from the exhaustion of the fatigue life of the material that is not able to carry more loads. The key observation in the second fatigue is to reduce the number of cycles carried by the material by about 70.0%. It is hypothesized that the observed changes in the graph are related to structural changes of the material, despite the fact that it is a very short relief time during the fatigue test.

In accordance with the assumptions described earlier, the remaining combinations of tests were carried out, taking into account a longer rest period and heating of the material. The obtained results for all three cases taking into account different load levels are presented in Fig. 9 and Fig. 10.

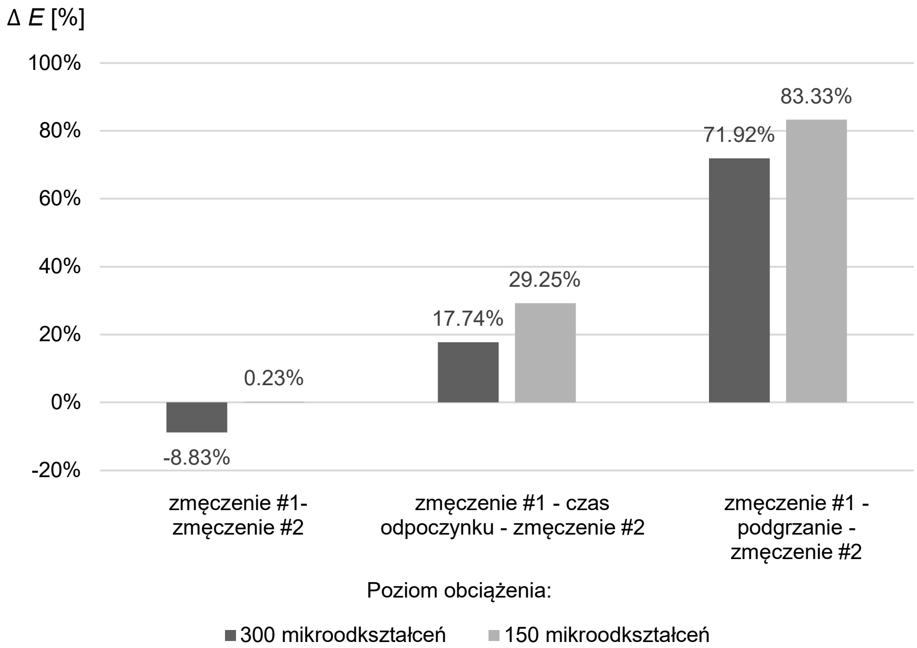


9. Variability of stiffness modulus and number of cycles for all test cases - load 300 micro-deformations



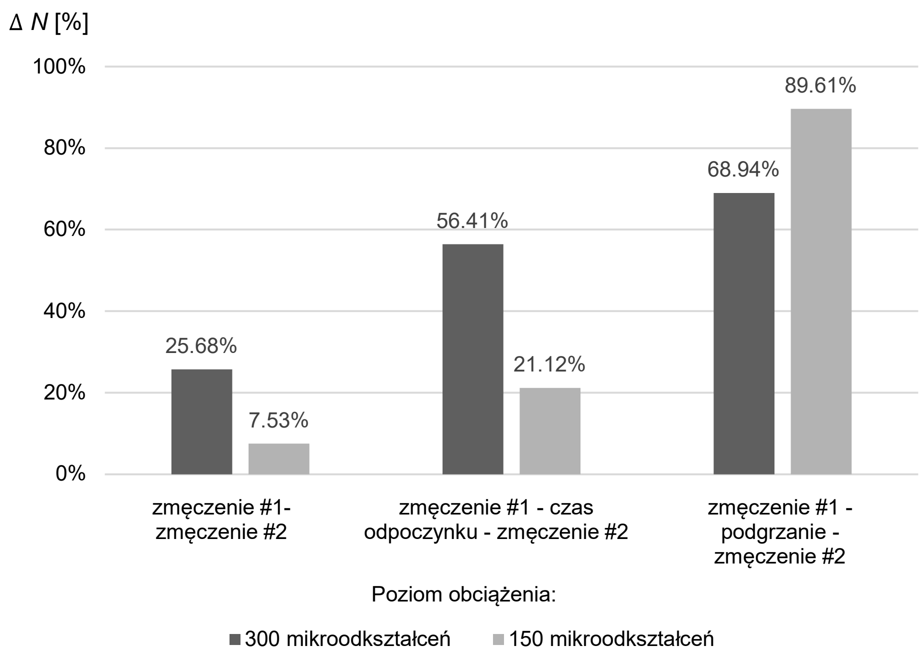
10. Variability of stiffness modulus and number of cycles for all test cases - load 150 micro-deformations

Both charts show the same level of initial stiffness. Significant changes occur during the first stage of fatigue. When comparing both drawings, the stiffness modulus varies with increasing number of load cycles. The shape of the charts is varied. It can be noticed that the applied higher load level, several dozen times faster, leads to exhaustion of durability in the mix. A double the load resulted in a 80-fold reduction in durability. Considering the stage of transition from one research scheme to another, one can notice the "jump" of the module's value. The lack of "healing" actions caused a sharp decrease in stiffness. On the other hand, the long rest periods applied caused an increase in the value of the module. This is particularly visible when using material heating. When using only rest time, the module decreases rapidly (in the second attempt of fatigue). The angle of inclination of the approximate linear function is greater. Heating led the test samples to virtually complete regeneration. The diagram of the change in the value of the module relative to the load cycles for the second sample in relation to the first is very similar. The angles of the curves on the graph are almost identical. This may suggest that at the structural level, MMA's "primary state" has been restored. Fig. 11 presents the percentage analysis of the variability of the module values between the tested cases for both load levels.



11. Percent variation in the stiffness modulus of all test cases

The drawing confirms previous observations. The level of regeneration of the blend module is greatest for the case of heating the sample to 80.0 ° C. The applied rest period (12.0 hours) has a relatively small impact on the change in the value of the module. A negative value in the diagram means that there was no increase in the stiffness modulus but only its decrease. The percentage change in the number of cycles during the secondary examination to the original one is given in Figure 12.



12. Percentage dependence of cycle variability for all test cases

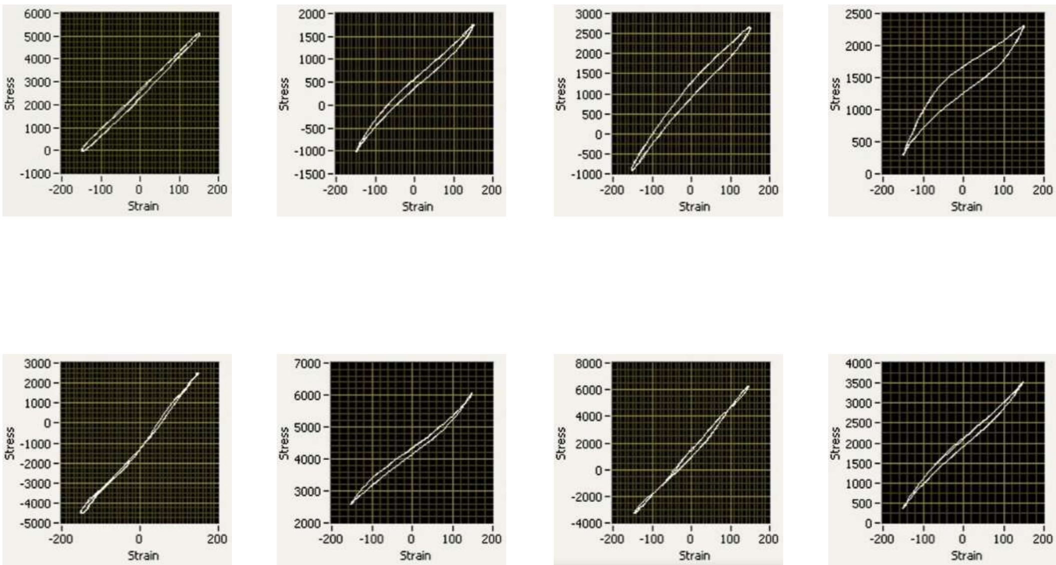
The graph also confirms previous observations. It can be concluded that for smaller load levels there are smaller structural changes in the material - e.g. microcracks, which MMA is able to regenerate. However, for higher load levels (ε1 = 300 x 10-6), MMA is not able to restore full fatigue life due to the irreversible damage accumulated in the material. The situation that arises for rest and load time at the level of 300 micro-deformations may result from the size of the applied load and the degree of accumulation of damage inside the material. The process of micro-cracking development is intense and causes irreversible damage, which to a greater extent is no able to regenerate the rest period with setting high temperatures.

The last point of observations was the analysis of variability of fatigue hysteresis. 4 control points were introduced during the test. Due to the fact that the hysteresis shapes were similar for the first and second case of the study, the graphs were shown for one case. The difference in the hysteresis geometry between the excitation levels used in the test is small - only the field area is variable. The shape remains analogous. Therefore, the graphs for the load level ε2 = 150x10^(-6) were used. A summary of the results obtained is presented in Figure 13.

The beginning of fatigue #1 | End of fatigue #1 | The beginning of fatigue #2 | End of fatigue #2

MMA subjected to fatigue without rest

MMA subjected to fatigue along with rest (12.0h) and heating at 80.0°C



13. Hysteresis variability in four stages of the study for different regenerative cases

From the visual assessment both for the case of fatigue without a rest period, hysteresis is transformed from an almost linear form to an ellipsoid one. This indicates irreversible energy changes inside the material. This is particularly evident in the second fatigue test. The energy is dissipated mostly in the form of heat, however, a large amount of it can be transformed into the initiation and propagation of microcracks. The material degrades, and its module quickly decreases its value. In the case of a hysteresis for the sample given heating, it can be noted that after supplying heat (energy) to the system that was previously dispersed, the hysteresis begins to return to the original shape. It is hypothesized that the supply of thermal energy to the system is the cause of the accelerated regeneration of MMA, which "removes" the resulting damage, eg sufficiently small microcracks causing favorable changes in the material structure.

Conclusion

The article introduces the issue of MMA regeneration. The complexity of the studied problem was demonstrated and an attempt was made to quantitatively and qualitatively assess changes in the "healing" properties of MMA. An effective 4-BP test method and appropriate levels of excitation (amplitude of 300 and 150 micro-deformations) were demonstrated to demonstrate the MMA regenerative potential. Although the classic fatigue criterion, expressed by the decrease in the value of the module by 50%, was used, it was possible to demonstrate the effectiveness of the rest period used and material heating. The study analyzed three cases of the study, which clearly indicated the possibility of MMA regeneration: the first - double fatigue of the sample without rest period, the second - two-time fatigue with the introduction of 12.0 hours rest period and the third - two-time fatigue of the sample using heat at 80ºC in 3 hours and using 12.0h conditioning. Based on the observation of fatigue hysteresis it was found that the decrease in the stiffness value may be the cause of energy changes, leading to degradation of the material and changes occurring at the structural level at the stage of microcracks development. Finally, the high MMA ability to regenerate after using the heating process was demonstrated. The process of rest time gives small results of a few to several dozen percent. On the basis of the diagrams it was found that the process of energy supply to the system in the form of heat causes recovery of approx. 84% of the stiffness module value and up to approx. 90% fatigue strength for forced $\varepsilon 2 = 150 \times 10^{(-6)}$ and 72% of the value module and 69% durability for $\varepsilon 1 = 300 \times 10^{(-6)}$. The results were compared to the observations of other researchers, confirming the impact of energy conversion on the destructive and regenerative processes in MMA. However, it should be borne in mind that when the structural level defects are too large, the sample is only healing up to a certain level. However, understanding this issue better requires performing structural studies for more and more diverse cases. This will be the subject of further research by the author. This article shows that the issue of "healing" when designing MMA is important and should be taken into account when designing road surfaces for heavy loads. It is also worth remembering that appropriate maintenance procedures may extend the lifetime of the pavements and reduce its cracking.

Source materials

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