Chapter 4

Fatigue Destruction of Asphalt Concrete Pavement: Self-Organization and Mechanical Interpretation

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.75536

Abstract

This chapter analyzes the fatigue failure of the asphalt concrete pavement of the highway on a macroscopic level. Based on the actual data, obtained on the sections of the real highways, the principle was formulated for the staged fatigue failure of the asphalt concrete pavement. During the analysis of the existing classifications of the fatigue cracks, it was determined that in Kazakhstan, the stage behavior of the fatigue cracks was not considered, and in the USA, the relation between stages of failure was not established. Similarly to the known phenomena of self-organization in thermodynamics of irreversible processes and dynamics of nonlinear systems (synergetics)—Benar's effects and division of biological cell, it was proposed to consider the parts of the asphalt concrete pavement as the specific dissipative structures, occurring in critical conditions, and a new regularity of fatigue failure was formulated. The formulated regularity of the staged fatigue failure of the asphalt concrete pavement was explained based on the new proposed scheme of bifurcation with the use of the results of experimental determination of the occasional, cyclic, long-term and residual strength.

Keywords: asphalt concrete pavement, staged fatigue failure, consequential change of deformation types, asphalt concrete strength, self-organization, dissipative structures, bifurcation

1. Introduction

Fatigue is one of the main types of failure for the asphalt concrete pavement of a highway. As it determines, in association with other types of failure (rutting, low-temperature cracking), the service life of pavement in accordance with the requirements of standard document [1], all pavement structures of the highways of capital and lightweight types on the design stage should be calculated for strength under the criterion of tensile bending strength of the cast-in-situ (asphalt concrete) layers.

It is considered that the fatigue cracking on the asphalt concrete pavement of highways occurs at frequently repeated load impact of the vehicles' wheels [2].

Hveem F.N. of the far abroad country has been one of the first researchers, who mentioned the phenomenon of fatigue in the asphalt concrete pavement of a highway [3]. The first investigations of the fatigue properties for the asphalt concretes in laboratory conditions were performed by Sall R.N.J., Pell P.S., Taylor I.F. in the UK [4, 5] and Monismith C.L. in the USA [6].

The study of the fatigue of the asphalt concretes in the former Soviet Union was started by the works of Sall A.O. (Leningrad), Radovskiy B.S. (Kiev), Zolotaryov V.A. (Kharkov), Rudenskiy A.V. and Kalashnikova T.N. (Moscow) [7–11].

It was found out that the phenomenon of fatigue failure for the asphalt concrete pavement of a highway was a complex one. In spite of the fact that the specialists of many countries of the world have been studying the phenomenon to the present day, the issue of the fatigue life for the asphalt concretes and asphalt concrete pavement remains actual.

2. Field observation

Figure 1 represents the photos showing fatigue failure of the asphalt concrete pavement of Karagandy-Shakhtinsk highway. These photos show clearly that the fatigue failure occurs by stage: first, parallel quasi-straight line longitudinal cracks occur on the patch line, between which quasi-straight line asphalt concrete strips have been formed, and then these quasi-straight line asphalt concrete strips are divided into cells of small sizes due to the occurrence of quasi-transversal cracks. Thus, in the considered case, the formation of a grid of alligator

a) b) c)

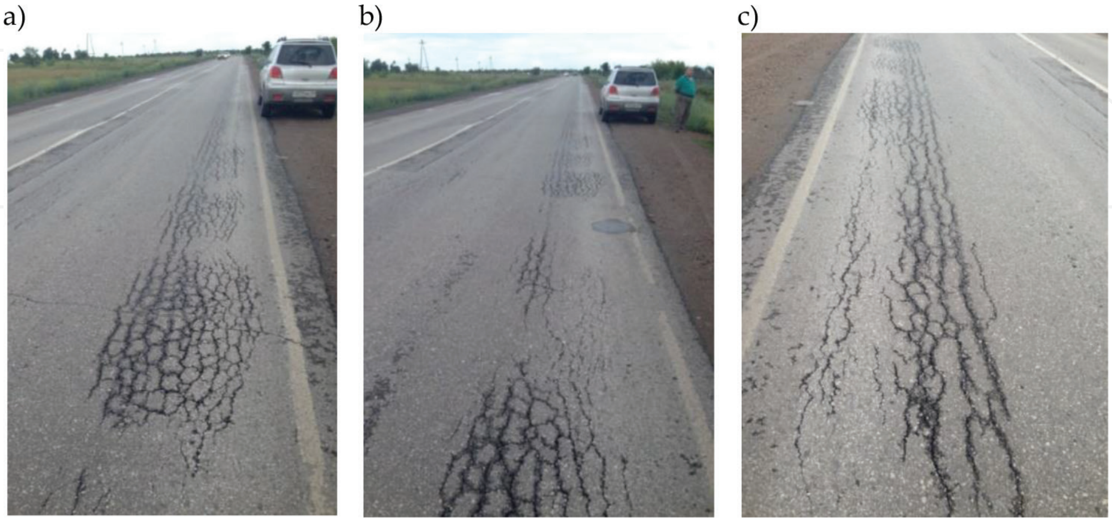

Figure 1. Fatigue failure of asphalt concrete pavement (860 km) of Karagandy-Shakhtinsk highway (Kazakhstan, Karagandy oblast, July, 2016).

cracks on the asphalt concrete pavement represents by itself a two-staged process, each of which has been realized during less or more prolonged period.

The fragments of another sequence for crack occurrence in the staged process of fatigue failure of alligator type on the asphalt concrete pavement are shown in **Figures 2** and **3**. As it is seen from **Figure 2**, there are only specific (separated from each other) quasi-parallel transverse cracks on the asphalt concrete pavement within the patch line. At first sight, they are similar to the low-temperature cracks. But that is not the case. The considered highway is located in Sharjah city (United Arab Emirates), where there is actually no winter. But, **Figure 3** shows the patterns of fatigue cracks of alligator type, which are formed at the further occurring of longitudinal cracks, connecting the existing transverse ones. During the period of observation, it has been determined that a large number of multiaxle heavy vehicles run along the highway, and it suggests that this type of staged fatigue failure has been connected with dense traffic of multiaxle heavy vehicles. Based on the abovementioned types of the staged failure for asphalt concrete pavements of the highways, we can formulate the following principle: "The process of fatigue failure for the asphalt concrete pavements of the highways occurs stage by stage and according to various types of stages. Type 1: stage I—quasi-linear parallel longitudinal cracks occur on the patch lines, between which quasi-straight line asphalt concrete strips are formed; stage II—formation of patterns of fatigue cracks of the alligator type by division of quasi-straight line strips of the asphalt concrete into the cells with small sizes by quasi-transverse cracks. Type 2: stage I—occurrence of insulated quasi-parallel transverse cracks; stage II—formation of alligator type cracks with relatively large dimensions of cells due to the occurrence of longitudinal cracks, connecting the existing transverse ones; stage III—decrease of dimensions for the cells of crack patterns due to the sequential occurrence of transverse and longitudinal cracks within each cell".

We suppose that the staged progressing of the fatigue failure is mechanically and thermodynamically "of benefit" to the system—to the asphalt concrete pavement, and which type of the stage is progressed—"the system will choose itself" depending on specific conditions: volume and type of traffic, regime and speed of traffic, weather and climatic conditions, design features, properties of the materials, including asphalt concretes, and so on.

a) b)

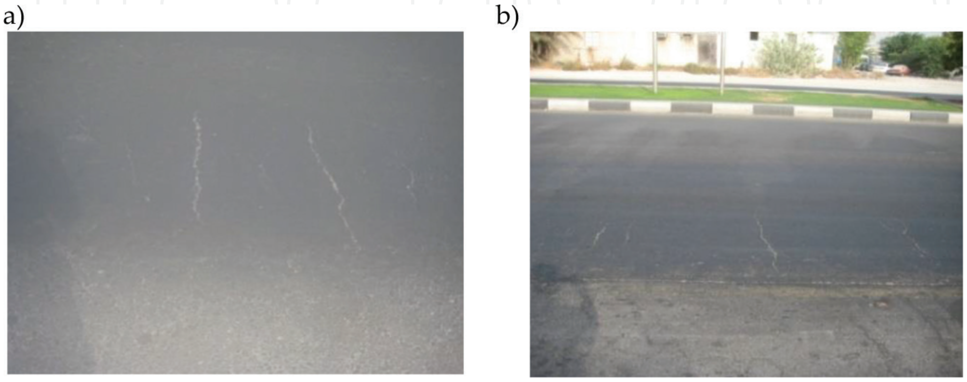

Figure 2. Fatigue failure of asphalt concrete pavement: transverse fatigue cracks (Sharjah city, United Arab Emirates, August, 2010).

a) b)

Figure 3. Fatigue failure of asphalt concrete pavement: alligator cracks (Sharjah city, United Arab Emirates, August, 2010).

3. Fatigue cracks classification

In Kazakhstan, the fatigue and other types of cracks on an asphalt concrete pavement for diagnostics and evaluation of road condition are considered in the standard [12], in which all defects on the pavements are divided into two groups: the defects, certifying inadequate strength and the defects, which do not certify inadequate strength in explicit form. Analysis of these defects shows that:

- in spite of the fact that they have different causes for their occurrence and progress character, cracks of various types (fatigue, thermal, reflected, sagging) are not identified separately;
- the staged development nature is not reflected for fatigue cracks;
- the maximum allowable measures are not contained for the cracks, including the fatigue ones.

The largest and wide scale program on investigation of performance for road structures (highway pavements) was started within the so-called Strategic Highway Research Program (SHRP) in the USA in 1987. The road agencies of the American States and 15 other countries have been collecting the data for 20 years for state of repair of pavements, climate, volume and density of traffic on more than 1000 experimental sections of the highways.

A special guide has been developed to perform data collection under the unique method, which was published three more times in the following years [13]. This Guide gives the following definition for the fatigue cracks in asphalt concrete pavement: “They occur in the areas subjected to repeated traffic loadings (wheel paths). They can be a series of interconnected cracks in early stages of development. They develop into many-sided, sharp-angled pieces, usually less than 0.3 m on the longest side, characteristically with a chicken wire/alligator pattern, in later stages. The fatigue cracks are divided into three levels. Low level: an area of cracks with no or only a few connecting cracks; cracks are not spalled or sealed; pumping is not evident. Moderate level: an area of interconnected cracks forming a complete pattern; cracks may be slightly spalled; cracks may be sealed; pumping is not evident. High level: an area of moderately or severely spalled interconnected cracks forming a complete pattern; pieces may move when subjected to traffic; cracks may be sealed; pumping may be evident.”

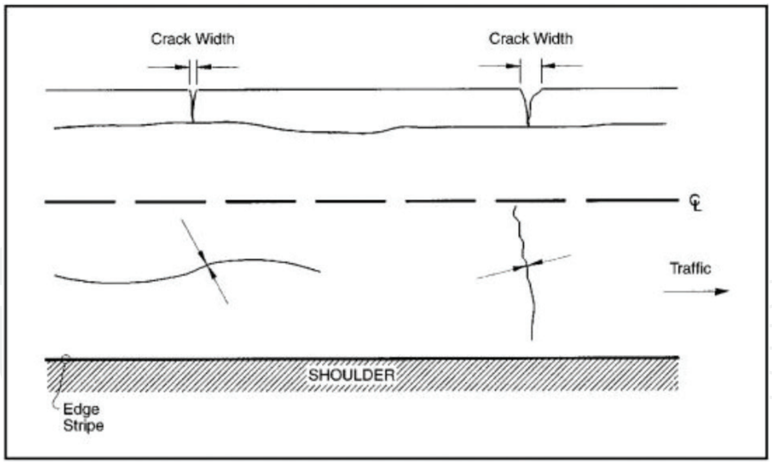

Figure 4. All levels of fatigue failure of asphalt concrete pavement for the highway according to the Guide [13].

a) b) c)

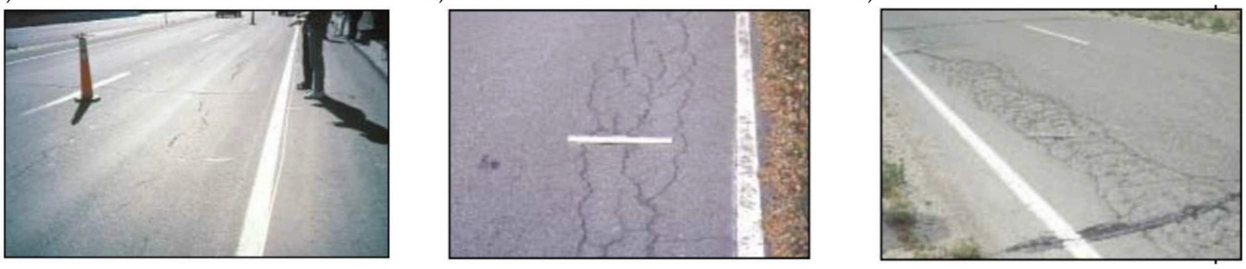

Figure 5. Fatigue failure of asphalt concrete pavement for the highway according to the Guide [13]: (a) low level; (b) middle level and (c) high level.

Figures 4 and **5** show the photos from the Guide [13], which demonstrate visually the levels of the fatigue failure for the asphalt concrete pavement under the adopted classification.

As it is seen, contrary to the Kazakhstan Guide, the American Guide identifies the fatigue cracks separately from other types of cracks and three levels have been established for their development. Another American standard document [14] subdivides the fatigue cracks into two types: surface-down fatigue cracking and bottom-up fatigue cracking; admissible limit values have been shown for these types of cracks for surface-down—1000 ft./mile = 190 m/km and for bottom-up—25–50% of the lane area.

4. Self-organization

The works [15–17] based on provisions of thermodynamics of irreversible processes and non-linear dynamics (synergetics) show that the asphalt concrete pavement with low-temperature cracks is a specific dissipative structure, which is the form of adaptation for a thermodynamic system to the external conditions and each time, when air temperature reaches the critical temperature of pavement, the crack occurs. This is regularity, determined by collective behavior (self-organization) of structural elements of the asphalt concrete pavement in critical conditions.

In thermodynamics [18, 19], the systems, which exchange their energy and mass with the environment, are considered as open ones, and they are structurally complex. Due to the complexity of open systems, the various forms of structure occur in them in critical conditions. Energy dissipation plays the constructive role in the formation of these structures. To emphasize that I. Prigozhin introduced the term "dissipative structures" [20–23], and H. Haken introduced the term "synergetics" to stress the role of collective behavior for substructural elements in formation of dissipative structures [24, 25].

Prigozhin I. showed that the entropy variation ds for open thermodynamics system can be considered as the sum of two summands [19–21]:

$$ds = ds_e + ds_i, \tag{1}$$

where ds_e is entropy variation, connected with its inflow or outflow; ds_i is an amount of entropy, produced inside a system.

For short, ds_i is simply called "entropy production."

Component ds_e can have as positive sign, as well as negative one depending on the fact if the system receives or give energy as the result of interaction with environment. According to the second law of thermodynamics, entropy production ds_i is positive or equal to zero:

$$ds_i \geq 0, \tag{2}$$

Equal-zero entropy production, that is, $ds_i = 0$ will occur only under condition of balance.

4.1. Benar's effect

It is known that Benar's effect [26–28] is one of the famous examples for formation of dissipative structures in an open thermodynamic system. It occurs at critical difference of temperatures ΔT_{cr} of bottom and upper surfaces of the thin layer of the viscous liquid (for example, in silicon oil) in a dish, heated from below. When reaching T_{cr}, the behavior of the liquid varies dramatically—convection occurs, and the liquid is divided into hexagonal cells (**Figure 6**). The new structure is created by joint cooperative molecular motion of the liquid. As it is seen from **Figure 7**, the sharp break occurs for a dependence of heat transport rate dQ/dt on temperature difference ΔT at ΔT_{cr} and formation of a new structure occurs. The outflow (export) of entropy is precisely compensated by entropy production inside the liquid up to ΔT_{cr}, and when reaching ΔT_{cr}, the heat transport rate increases due to the convective mechanism of the heat exchange.

4.2. Cell separation

The work of M.V. Volkenstein [26] showed one more example of the formation for the dissipative structure in the open thermodynamics system. This is a cell separation of the living organism.

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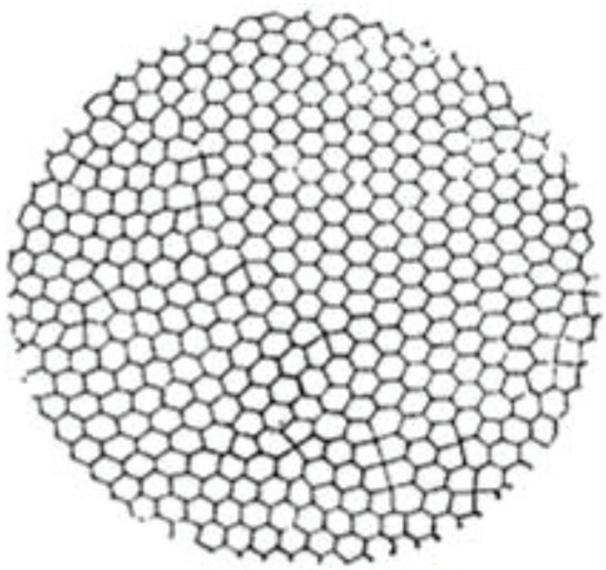

Figure 6. Benar's effect.

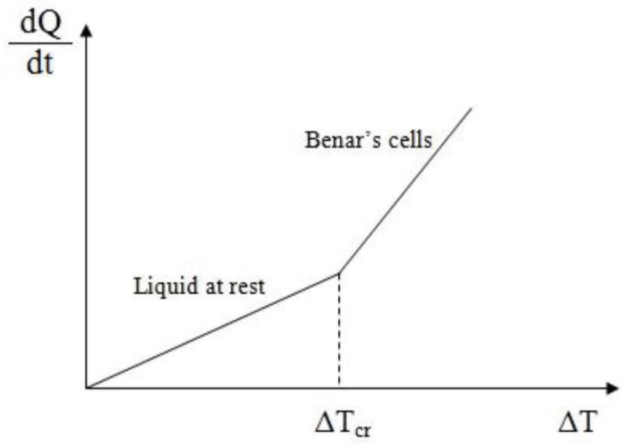

Figure 7. Dependence of heat transport rate on temperature difference.

For the simplicity, the cell is considered as a sphere with radius R. Entropy production inside the cell ds_i is proportional to its volume $V = \frac{4}{3}\pi R^3$, and entropy outflow from the cell ds_e is proportional to the area of its surface $S_{пов.} = 4\pi R^2$. Then, according to the expression (Eq. (1)), we have:

$$ds = A \cdot \frac{4}{3}\pi R^3 - B \cdot 4\pi R^2, \tag{3}$$

where A and B are the parameters of proportionality, which have appropriate dimensions.

The cell grows with the growth of the organism, and radius of the sphere R increases. The cell under the mechanism of self-organization tries to remove the excess of the accumulated entropy. As the entropy production ds_i increases proportionally to the cube of the radius R, that is, R^3, and the entropy outflow increases proportionally to the square of the radius R, that is, R^2, then the gradual accumulation of entropy occurs under the expression (Eq. (3)).

Stationary state is achieved at $R = \frac{3B}{A}$, that is, $ds = 0$. And at $R > \frac{3B}{A}$, that is, $ds > 0$, therefore, at $R_{cr} > \frac{3B}{A}$ (R_{cr}: critical size of the cell) the cell should be separated, otherwise, it will die. The volumes of the mother cell and two daughter cells are similar, and the total area of the surfaces of new cells is bigger.

The abovementioned examples for self-organization in thermodynamics systems—Benar's cells and cell separation can be used further for the explanation of the fatigue failure phenomenon for the asphalt concrete pavement.

Fatigue failure of the asphalt concrete pavement, of course, has been directly connected with the asphalt concrete strength.

5. Asphalt concrete strength

5.1. Bitumen

Bitumen of grade BND 100/130, produced by Pavlodar Petrochemical Plant (PPCP), was used for the preparation of fine-grained dense asphalt concrete in laboratory conditions in this work. Bitumen complies with the requirements of Kazakhstan standard ST RK 1373-2013 [29]. Standard indicators for bitumen are represented in **Table 1**. Content of bitumen in the asphalt concrete was 4.8% by the mass of the dry filler.

5.2. Asphalt concrete

Hot dense fine-grained asphalt concrete of Type B was adopted for test, which satisfies the requirements of the Kazakhstan standard ST RK 1225-2013 [30], and it was prepared with the use of aggregate of fractions 5–10 mm (20%), 10–15 mm (13%), 15–20 mm (10%) from Novo-Alekseevsk rock pit (Almaty oblast), sand fraction 0–5 mm (50%) from the plant "Asphaltconcrete-1" (Almaty city) and mineral powder (7%) from Kordai rock pit (Zhambyl oblast). The main standard indicators for asphalt concrete are represented in **Table 2**. The grading curve of mineral part of hot mix asphalt concrete is shown in **Figure 8**.

5.3. Test methods

In this study, asphalt sample tests have been performed according to the following methods:

1. Determination of asphalt concrete strength at direct tension at various temperatures has been performed in thermal chamber of TRAVIS, manufactured by Infratest GmbH (Germany). Sample tests have been performed at deformation with constant rate 1 mm/min in accordance with European standard pr EN 12697-46 [31]. Samples had dimensions of 5 × 5 × 16 cm.

2. Cyclic (fatigue) asphalt concrete strength at various temperatures has been determined by sample testing with dimensions 5 × 5 × 38 cm in thermal chamber of four-point bending device under European standard EN 12697-24 [32]. Loading frequency was f = 10 Hz. The stress, equal to σ = 1400 kPa, was kept as constant prior to the sample failure.

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3. Asphalt concrete samples in the form of beam with dimensions 4 × 4 × 16 cm have been tested at various temperatures on mechanical press with the use of special device under transverse bending scheme according to standard ST RK 1218-2003 [33]. The deformation rate was 3 mm/min.

4. Asphalt concrete sample strength of various shapes (cylindrical and rectangular), various dimensions and at various temperatures at direct compression has been determined by their testing on the mechanical press under standard ST RK 1218-2003 [33]. The deformation rate was 3 mm/min.

Indicators	Unit	Requirement of ST RK 1373-2013	Value of indicators
Depth of needle penetration			
25°C	0.1 mm	101–130	110
0°C		30	37
Penetration index	—	−1.0… + 1.0	−0.82
Ductility			
25°C	cm	≥90	135
0°C		≥4.0	6.6
Softening point	°C	≥43	44.0
Fraas point	°C	≤−22	−30.2
Dynamic viscosity, 60°C	Pa·s	≥120	121.0
Kinematic viscosity, 135°C	mm^2/s	≥180	329.0

Table 1. Main standard indicators for bitumen.

Indicators	Unit	Requirements of ST RK 1225-2013	Value of indicators
Average density	g/cm^3	—	2.38
Water saturation	%	1.5–4.0	3.4
Air voids of mineral filler	%	≤19	15.1
Air voids of asphalt concrete	%	2.5–5.0	3.8
Compression strength			
0°C	MPa	≤13	7.4
20°C		≥2.5	3.5
50°C		≥1.3	1.38
Water resistance	—	≥0.83	0.80
Shear resistance	MPa	≥0.38	0.39
Crack resistance	MPa	4.0–6.5	4.5

Table 2. Main standard indicators for asphalt concrete.

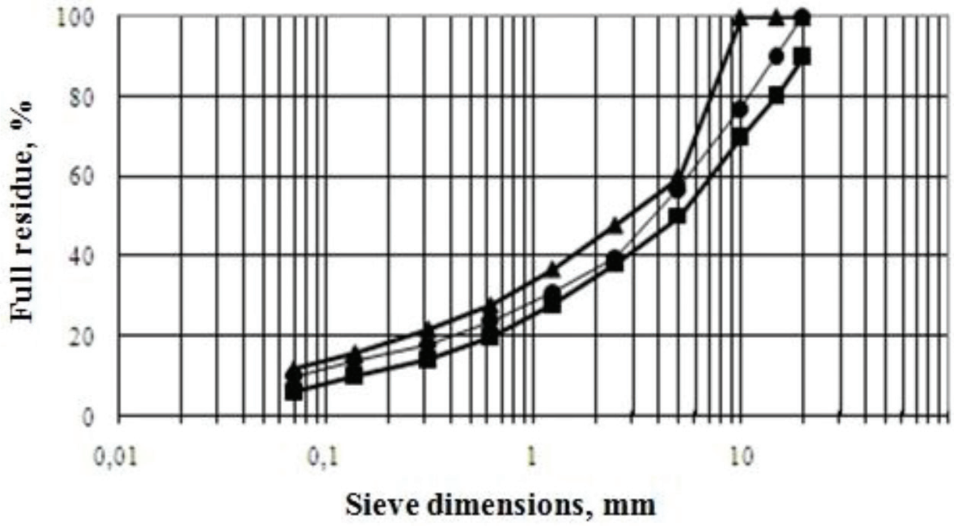

Figure 8. Asphalt mixture grading curve.

5.4. Sample preparation

Asphalt concrete samples of cylindrical shape, designed for direct compression, were prepared under Kazakhstan standard ST RK 1218-2003 [33] by compaction of the asphalt concrete mix in special mold. The samples of rectangular shape and in the shape of beam of various dimensions were prepared in the following way. First, the asphalt concrete samples in the shape of square slab with dimensions 5 × 30.5 × 30.5 cm were prepared by roller compactor (model CRT-RC2S, company Cooper, UK) in accordance with European standard EN 12697-33 [34]. Then, the samples with the shape of rectangular prism of various dimensions were obtained from square slabs.

5.5. Single loading, cyclic and long-term strength of asphalt concrete

Figure 9 represents the graphs, showing the dependence of the asphalt concrete strength at various types of loading—tension, compression and bending. As it is seen, in the considered temperature interval (0–50°C), the asphalt concrete has the least tensile strength, and the largest—at compression. Bending strength occupies the intermediate location between tension and compression. Meanwhile, compression and bending strength of the asphalt concrete with the temperature increase decreases nearly with the similar rate within the whole temperature interval considered, and at tension, the rate of decrease is higher than two times compared with compression and bending strength. It is also seen that the difference between temperature curves of bending strength and compression strength is kept as constant in the whole temperature interval considered and it is equal to, at average, 1.0 MPa. The maximum difference between temperature curves of tensile strength and bending (compression) strength occurs at low temperatures (0–10°C), which is equal to 2.5 MPa (3.5 MPa) and decreases with the temperature increase; these differences at temperature 50°C are equal to 0.8 and 1.6 MPa, respectively.

It is generally accepted that the fatigue cracks occur due to the repeated impact of the tensile stress in the bottom surface of the asphalt concrete pavement [2, 35–39], the more the value of

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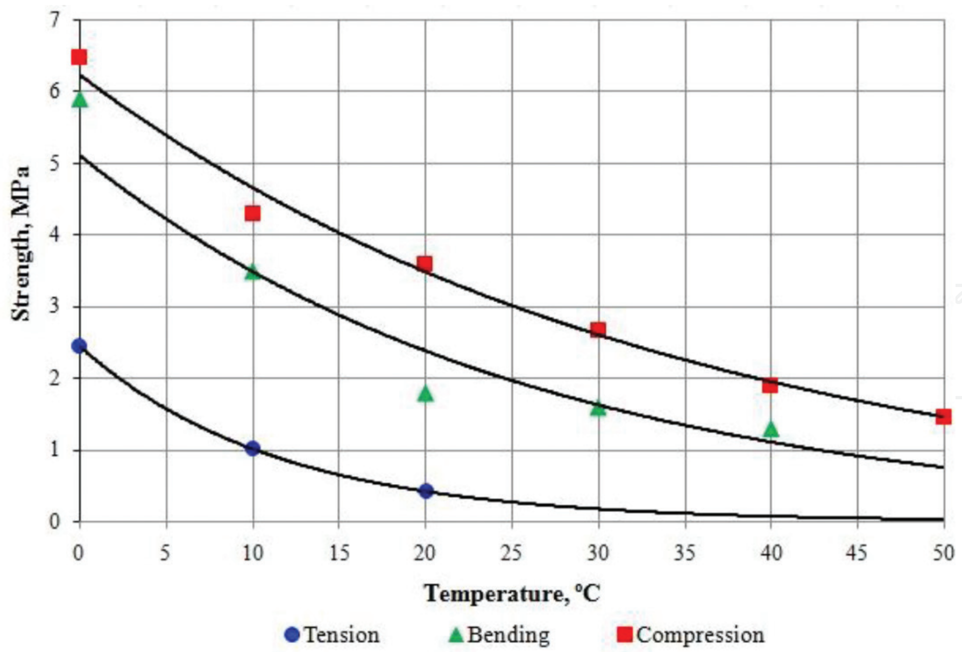

Figure 9. Strength of fine-grained asphalt concrete (BND 100/130, PPCP) at various types of stressed condition.

which at any other equal conditions, the more is the ratio of elasticity modulus of the asphalt concrete layers to the elasticity modulus of the under layers of the pavement base and subgrade soil [10, 40]. It is considered that the abovementioned ratio of elasticity moduli in pavement structure is the biggest one in the spring season, when the upper part of subgrade has been defrosted and loosened, and the asphalt concrete pavement has a big stiffness due to the relatively low air temperature, which is within 0 and +10°C [2, 41–43].

As it is seen from **Figure 10**, namely within the temperature interval 0 and +10°C, the difference in the asphalt concrete tensile strength and bending strength (compression) is the biggest one!

Figure 10 shows the graphs of cyclic strength for fine-grained dense asphalt concretes at bending and tension at the temperature of 20°C. The upper graph has been constructed at testing of asphalt concrete samples under scheme of bending on the four-point bending device in Kazakhstan Highway Research Institute, and the bottom one has been constructed according to the experimental data, obtained in the University of North Carolina State (USA) at direct tension [44]. It is clearly seen that the cyclic strength of the asphalt concrete at bending is considerably higher than at tension. Similar regularity can be seen on the curves of the long-term strength of the asphalt concrete, as shown in **Figure 11** [45, 46].

Thus, single loading, cyclic and long-term strength of the asphalt concretes at tension is considerably less, than at bending and compression.

To answer the question: "Does the asphalt concrete strength depend on the tested sample dimensions at compression?", the test of samples for the fine-grained dense asphalt concrete of type B (BND 100/130) has been performed for direct compression. The thickness of all the samples was similar and equal to 5 cm, and the length and the width of the samples had the values

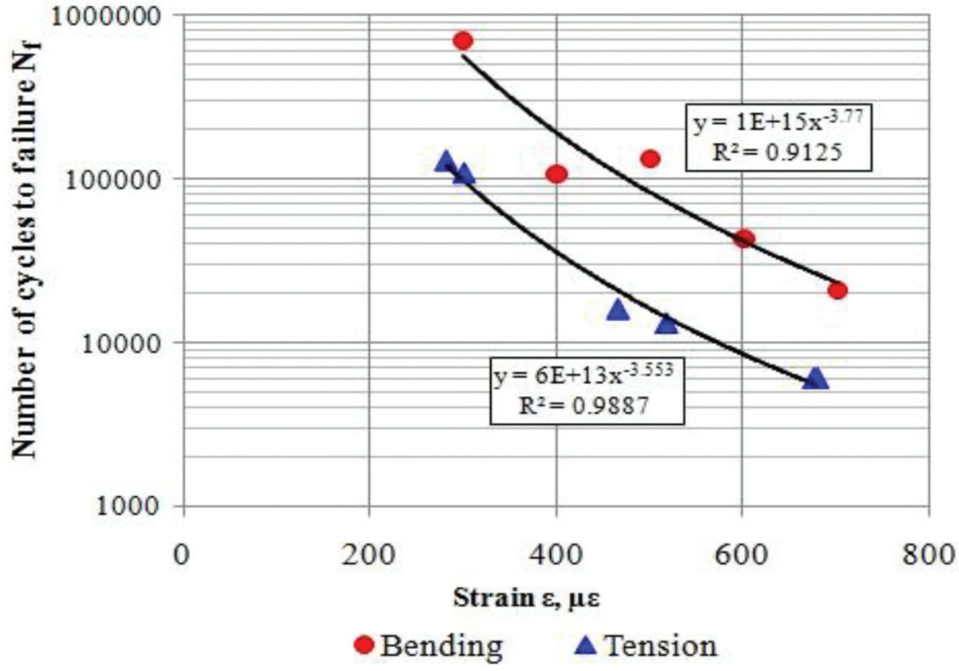

Figure 10. Cyclic strength of the asphalt concrete at bending and direct tension at the temperature of 20°C.

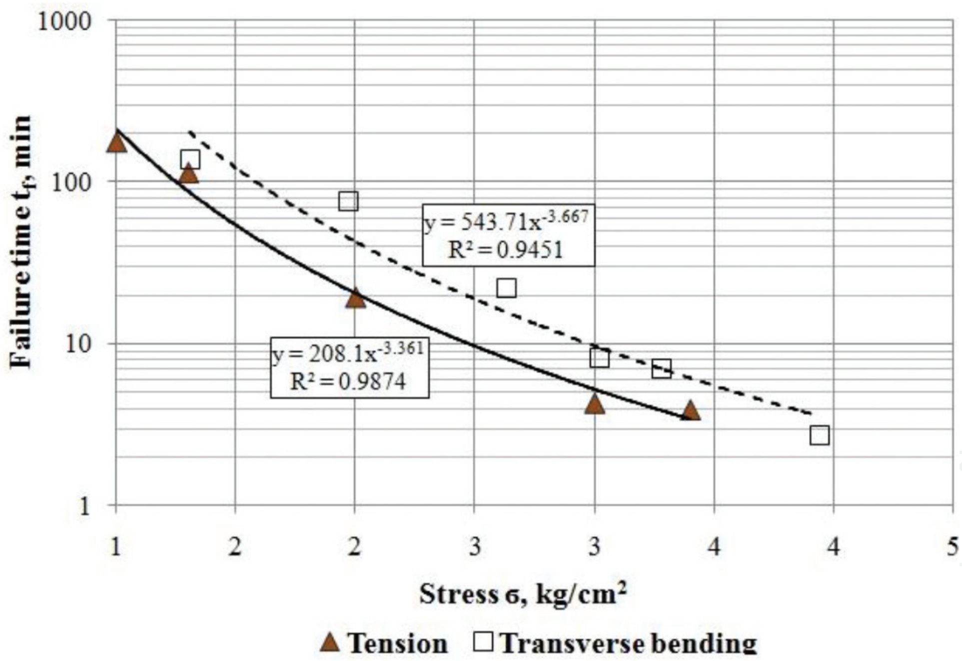

Figure 11. Long-term strength of the fine-grained asphalt concrete of type B (BND 60/90) at transverse bending and direct tension.

equal to 2, 5, 7, 10, 12 and 15 cm. The test has been performed at the temperatures of 0, 10 and 20°C. Three parallel tests have been performed at each temperature and dimensions of samples.

As it is seen from **Figure 12**, the asphalt concrete strength at compression depends considerably on sample dimensions. The biggest strength occurs at the temperatures of 10 and 20°C

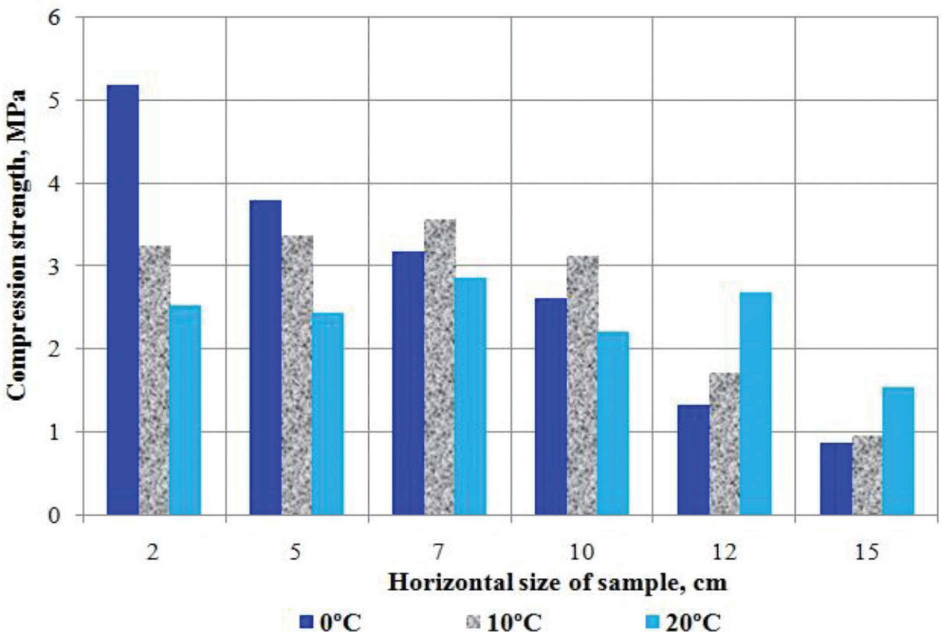

Figure 12. Compression strength of the fine-grained asphalt concrete samples of type B (BND 100/130, PPCP) of various dimensions at different temperatures.

with the length of sample side equal to 7 cm, and the strength increases almost linearly at the temperature of 0°C with the decrease of sample dimensions.

These results serve as the reliable explanation for gradual decrease of the horizontal dimensions of the asphalt concrete pavement cells with progressing of its fatigue failure.

5.6. Residual strength of asphalt concrete

The fatigue crack on the asphalt concrete pavement occurs when it almost completely lost its tensile strength (tension at bending). Let us raise the question: can such asphalt concrete have residual compression strength? To clarify the issue, we have carried out a special experiment. The same fine-grained dense asphalt concrete of type B (bitumen grade BND 100/130) has been adopted. First, the asphalt concrete samples with dimensions 5 × 5 × 38 cm have been tested on the four-point bending device for bending fatigue to failure (stiffness reduction to 10% of the initial one) at the temperatures of 10, 20 and 30°C. Then, the samples with dimensions

T, °C	Number of cycles to failure N_f			
	Parallel 1	Parallel 2	Parallel 3	Average
+10	5187	4965	10,180	6777
+20	568	512	534	538
+30	565	219	222	335

Table 3. Test results of the fine-grained dense asphalt concrete of type B (BND 100/130, PPCP, f = 10 Hz, σ = 1400 kPa) at fatigue on the four-point bending device.

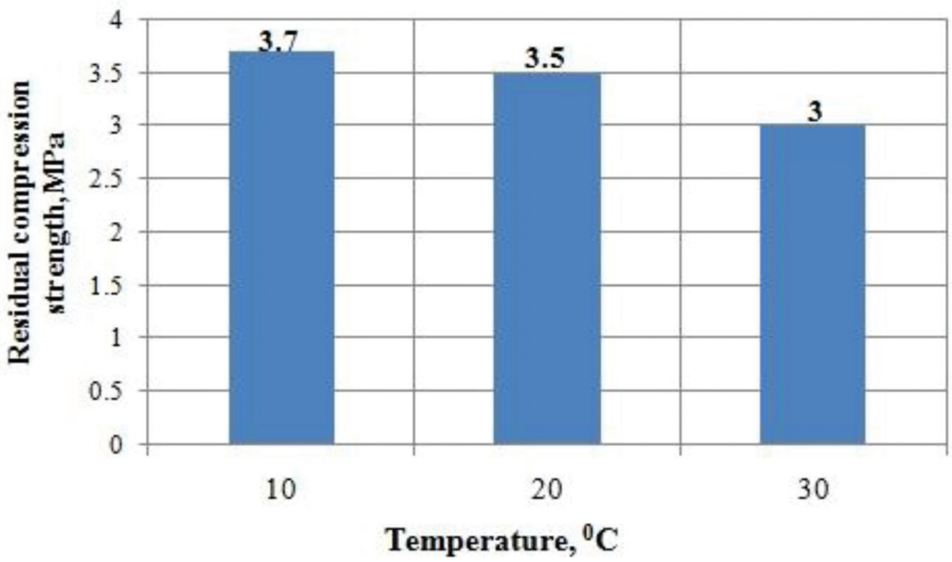

Figure 13. Residual strength of the asphalt concrete at compression after cyclic bending at various temperatures.

5 × 5 × 5 cm have been prepared from these samples, and they have been tested for direct compression at the same temperatures. Three asphalt concrete samples have been tested at each temperature. The results of the initial tests of the asphalt concrete samples at cyclic bending have been represented in **Table 3**, and their further test at direct compression—in **Figure 13**. As it is seen, the asphalt concrete has a high residual compression strength after the cyclic bending to failure, comparable with the strength of a new asphalt concrete (**Figures 9** and **12**).

6. Principle of consequential change of deformation types

As it is known, the self-organization phenomenon occurs in complicated open thermodynamics systems and new structures occur in them in critical conditions such as Benar's cells, separated cells of living organisms, laser ray, and so on. Occurrence of specific dissipative structures in critical low-temperature conditions on the asphalt concrete pavement has been shown in the works [15–17, 47]. The provided above staging of the fatigue failure for the asphalt concrete pavement, possibility in principle for occurrence of dissipative structures in it at critical conditions as a result of self-organization of its structural elements, significant dependence of single loading, cyclic and long-term strength of the asphalt concrete on deformation type (stressed condition) and existence of residual strength at another deformation type after failure allow formulating of a new regularity for the fatigue failure:

Fatigue failure of an asphalt concrete pavement under repeated load impact is realized according to the consequently changing stages in every of which pavement parts function as specific dissipative structures with characteristic deformation type, which interchange in the sequence of: tension-bending-compression.

7. Bifurcation

The principle of consequential change of deformation types at fatigue failure for an asphalt concrete pavement formulated earlier can be explained on the basis of provisions for thermodynamics of irreversible processes and nonlinear dynamics (synergetics).

In short description of the examples for dissipative structure occurrence—Benar's cells and cell separation, it has been mentioned earlier that the action of systems in critical conditions in both cases is a benefit for them: liquid flow along the hexagonal cells allows including additional convective mechanism of heat exchange with environment; separation of the cell into two saves it from "death."

We also consider that the realization of the fatigue failure according to the consequent stages, changing deformation type from "tension" into "bending" and from "bending" into "compression" at the continuous mechanical impact is a benefit to the asphalt concrete pavement, as:

1. The asphalt concrete strength at bending is bigger than at tension, and at compression, it is bigger than at bending.
2. Residual strength of asphalt concrete at compression is relevant after its failure at deformation under the scheme of bending (tension).

Such staged failure with consequential change of deformation type prolongs the existence time ("life cycle") of separate parts of the asphalt concrete pavement.

The formulated principle can be visually demonstrated by the bifurcation scheme proposed (**Figure 14**).

In thermodynamics and synergetics, it is accepted to consider that the system away from the equilibrium condition acquires new properties. The system in the strong nonequilibrium condition becomes more active and all substructural elements of the system work jointly, consistently, fluctuations are synergized and new structures occur at the critical moment [18–26, 48]. In addition, the system has a choice in critical conditions—what scenario of evolution to follow further.

In accordance with the proposed bifurcation scheme, the asphalt concrete pavement works as continuous medium under scheme of volumetric stressed-deformed condition since the moment of starting of operation to the moment of losing of the tension resistance (0–1). At the time moment of the complete losing of the tension resistance (point 1), the thermodynamics system (substructural elements of the asphalt concrete pavement) has a choice—which thermodynamics branch (branch A and branch B)—to function further. If the system in point of bifurcation chooses the thermodynamics branch A, the parallel cracks occur on the patch lines in point 1, and the asphalt concrete strips work as a long beam between points 1 and 2, and they are deformed under the scheme of bending. The transverse cracks occur in point 2, long asphalt concrete strips are divided into more short parts, each of the obtained parts for the period of

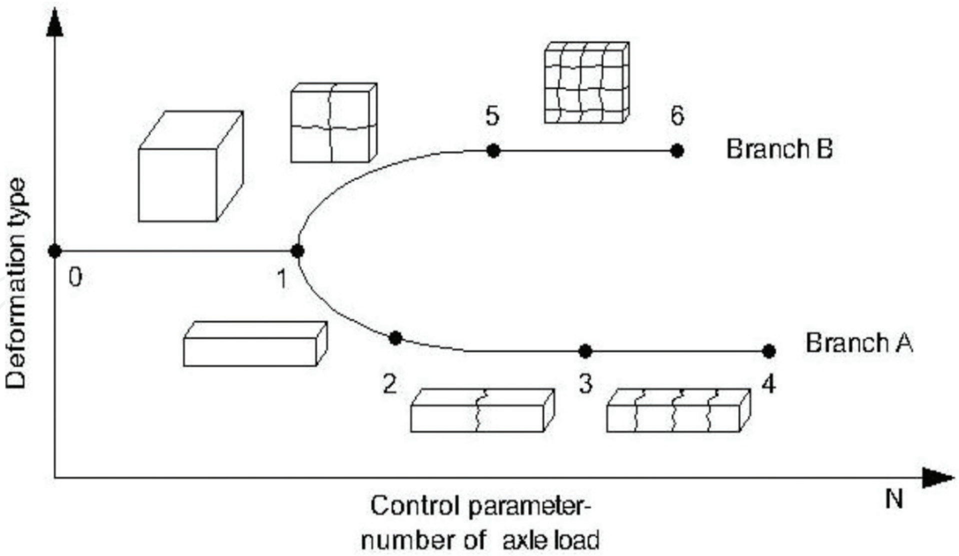

Figure 14. Bifurcation scheme at fatigue failure of an asphalt concrete pavement.

2–3, work as a short beam, and it is also deformed under the scheme of bending. In point 3, the number of the occurred cracks increases and for the period of 3–4, separate failure fragments of pavement work under scheme of direct compression. Complete failure of the asphalt concrete pavement occurs at the time moment 4. The road section of the highway "Karagandy-Shakhtinsk," described earlier can serve as an example of the practical realization for the fatigue failure of the asphalt concrete pavement according to the thermodynamics branch A.

If the system in point of bifurcation 1 chooses the thermodynamics branch B, then, first, the transverse cracks occur on pavement, then longitudinal fatigue cracks occur between them, and for the period of time 1–5, separate pavement blocks function as big and short slabs, and they are deformed under scheme of bending. Additional transverse and longitudinal cracks occur in point 5, grids of cracks become more intensive until each of the pavement fragments is not deformed under scheme of direct compression (time period 5–6). Complete failure of the asphalt concrete pavement occurs in time moment 6. The road section of the highway located in Sharjah city (UAE) can serve as an example of the practical realization for the fatigue failure of the asphalt concrete pavement under the thermodynamics branch B.

8. Conclusion

The results of this study allow drawing the following conclusions for the fatigue failure of the asphalt concrete pavement of a highway:

1. In Kazakhstan, the cracks of various types on the asphalt concrete pavements (fatigue, thermal, reflected and sagging) are not identified separately. The staged character of the fatigue failure was not considered. Maximum allowable characteristics, including the fatigue ones, were not determined as well. In the USA, the fatigue cracks are identified separately

http://dx.doi.org/10.5772/intechopen.75536

from other types of cracks, three levels for their development have been determined, but the relation is not considered between these levels.

2. Fatigue failure of the asphalt concrete pavement is realized stage by stage. Change of stages for failure occurs under mechanism of self-organization for the substructural elements of the pavement material—asphalt concrete in critical conditions. Similar to the known phenomena of self-organization—Benar's effect and biological cell separation, it is proposed to consider the parts of the asphalt concrete pavement as specific dissipative structures. They work as specific dissipative structures on each stage of the fatigue failure.

3. Comparison of the results for the performed and known tests of the asphalt concretes for determination of single loading, cyclic, long-term and residual strength for tension, bending and compression has shown that the strength at bending is always more than at tension; and it is more at compression than at bending.

4. The determined staged character of the fatigue failure for the asphalt concrete pavement, possibility in principle for occurrence of dissipative structures in it, dependence of asphalt concrete strength on deformation type (stressed condition), moreover, its increase in the sequence of "tension-bending-compression," and also the existence of residual strength for the asphalt concrete at compression after failure at tension have served as a basis for formulating of a new regularity for the fatigue failure: *fatigue failure of an asphalt concrete pavement under repeated load impact is realized according to the consequently changing stages in every of which pavement parts function as specific dissipative structures with characteristic deformation type, which interchange in the sequence of tension-bending-compression.*

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