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Relative hysteresis as an indicator of structural condition of pavements

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Abstract. The paper is devoted to the experimental study of dynamic hysteresis under impact loading on the surface of flexible pavements. The relevance of the study is associated with the lack of informative indicators of the condition of pavements, which would allow for the assessment of their structural condition taking into account the mechanisms of viscoelastic deformation. A FWD PRIMAX 1500 falling weight deflectometer was used as the measuring equipment, which allows for the registration of dynamic hysteresis loops on the pavement surface under impact loading. Based on the recorded hysteresis loops, the values of dissipated energy, potential energy of deformation and relative hysteresis were determined. For the first time, the quantitative values of relative hysteresis characterizing energy absorption in different pavement layers have been determined. The regularities of change in the relative hysteresis value with increasing load transmitted by the impact loading unit have been established. It is shown that the curve of relative hysteresis change as the load increases contains two sections. A flat section, where its value is close to constant, and a section with a monotonic increase in the value of relative hysteresis, which suggests that the loads causing this monotonic increase are critical, forming a 'dangerous' fracture energy in the pavement. This result can be used in the preparation of short ultimate axial loads, as well as in the development of projects for the transport of heavy loads on public roads.

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1. *Introduction*

Road pavements are an important structural element of a motorway, directly determining its durability and operational condition. The control of their condition during operation is carried out by various indicators, among which structural indicators play a special role. In the practice of the Russian Federation, the main such indicator characterising the structural properties of a motorway is the general modulus of elasticity, or the moduli of elasticity of materials of individual layers, established during non-destructive tests using FWD impact loading units [1–3].

However, it is known that pavements are characterised by a complex set of properties determined by their constituent materials that make them up. Evaluating these properties solely from the point of view of elastic characteristics, which should include both modulus of elasticity and the elastic deflection, from which the modulus of elasticity is directly derived, can lead to errors and distortion of information. Work on the development of new structural indices is being carried out continuously by different groups of scientists [4–6].

In a number of studies, the deflection bowl parameters, linking different deflection bowl zones with the structural condition of the corresponding structural elements, are used as the main indicators characterising road properties. Such parameters include surface curvature index (SCI), base curvature index (BCI), and others [7–9]. This approach is an empirical one, and its undoubted advantage is the possibility of assessing the structural condition of the pavement without any prior history of the pavement, i.e. without information on the materials of its structural layers, design characteristics, and previous repairs carried out.

Another well-known approach to determining the condition of a pavement is the ‘backcalculation’ method, which allows for estimating its individual structural parameters from the deflection bowl measured in the field, based on the solution of the inverse coefficient problem. These problems are described in detail with reference to static pavements in the following works [10–13], and in a dynamic formulation in the works [14–17].

At the same time, modern dynamic loading facilities allow, in addition to discrete characteristics of deformation of pavements, which are certainly deflection bowls, for the recording of continuous characteristics such as amplitude-time characteristic of displacements and the hysteresis loop in the coordinates ‘displacement – load’. The hysteresis loop has a direct physical meaning, which is that its area is equivalent to the energy dissipated in the studied object. In terms of research of energy characteristics of deformation of road pavements determined in full-scale conditions, in domestic and foreign practice, there are separate works concerning changes in the shape and size of dynamic hysteresis loops in different periods of the year, as well as their application in relation to user parameters characterising the road condition. However, up to the present moment the issue of connection between energy characteristics of deformation and the structural condition of the pavement and its individual elements remains poorly studied [18–21].

In the laboratory practice of testing construction materials, studies concerning the energy parameters of deformation are much more widespread. A well-established approach is the study of strain energy dissipation in fatigue testing of asphalt concrete specimens in four-point loading and indirect tension facilities. The California Non-Rigid Pavement Design Method directly uses strain energy parameters determined on dynamic creep units to design new structures. Nevertheless, despite all the results associated with testing materials in laboratory conditions, it should be noted that the most reliable way to establish the design characteristics of the materials under study is to test them under in-situ conditions [22–24].

It should also be noted that studies related to the energy picture of deformation of various objects are widespread in many related fields. These are studies of dynamic instability of soils carried out by the scientific school of Prof. E.A. Voznesensky. Studies of reinforced concrete fracture based on full diagrams of its deformation, carried out under the guidance of Prof. V.M. Bondarenko. A significant body of research of fracture energy was carried out in the study of fatigue life of metals. In their fatigue tests, various hypotheses have been developed to establish the proportions of ‘dangerous’ and ‘non-dangerous’ deformation energy. Methods have been developed for predicting the fatigue life of various structural materials on the basis of the total dissipated strain energy [25–28].

All this together suggests that a gradual transition to the study of the energy picture of pavement deformation is an important and urgent task. The deformation energy expressed in the form of quantitative indicators allows for a comprehensive assessment of all structural processes that have occurred with the pavement and its individual layers during the period of operation. A quantitative assessment can be expressed by different indicators, in particular, the area of hysteresis loop, relative hysteresis (absorption coefficient) and potential deformation energy. The effective application of these indicators may allow for significant development both in the methods of non-destructive testing of road pavements and in creating prerequisites for the improvement of road pavement design methods.

Thus, the aim of this work is to investigate the quantitative parameters of the deformation energy, in particular the relative hysteresis recorded during in-situ measurements on the pavement surface, and to establish a qualitative relationship between the relative hysteresis value and the operational condition of the pavement.

2. Methods

Within the framework of this work, experimental studies were carried out using the FWD PRIMAX 1500 impact loading rig. This unit is a semi-trailer with a shock loading mechanism mounted on it and a beam with geophone sensors for recording the vertical component of displacements Fig. 1. The impact loading mechanism allows for reproducing impulse loading $F(t)$ with contact interaction time equal to 0.03 s. The shape of the loading impulse is close to sinusoidal Fig. 2. The range of possible loads is 10–

130 kN. The load value variation is done by changing the height of the load discharge. The sensors-geophones (D1–D10) allow for recording of vertical displacements in the time range – $u_i(t)$. The form of the amplitude-time characteristic is shown in Fig. 3.

Superimposition of the amplitude-time characteristic of displacements $u_i(t)$ on the time characteristic of the loading impulse allows for constructing a dynamic hysteresis loop Fig. 4. The area of the hysteresis loop characterises the energy irreversibly dissipated in the pavement structure under dynamic loading.

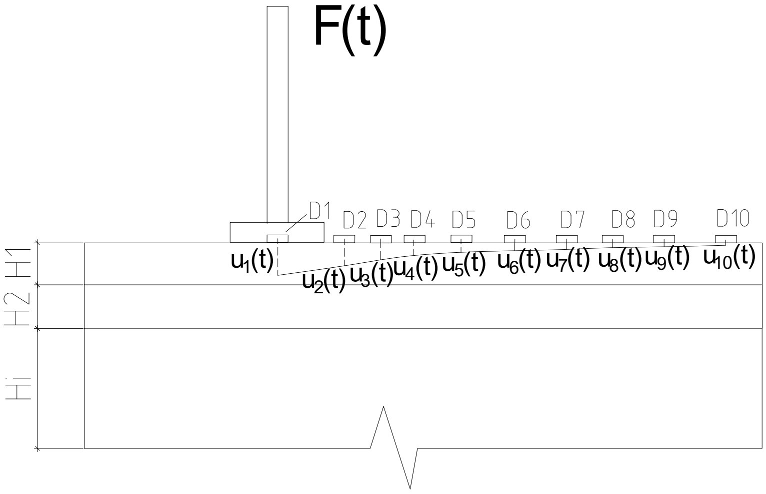


Figure 1. Registration of dynamic response on pavement surface by FWD unit.

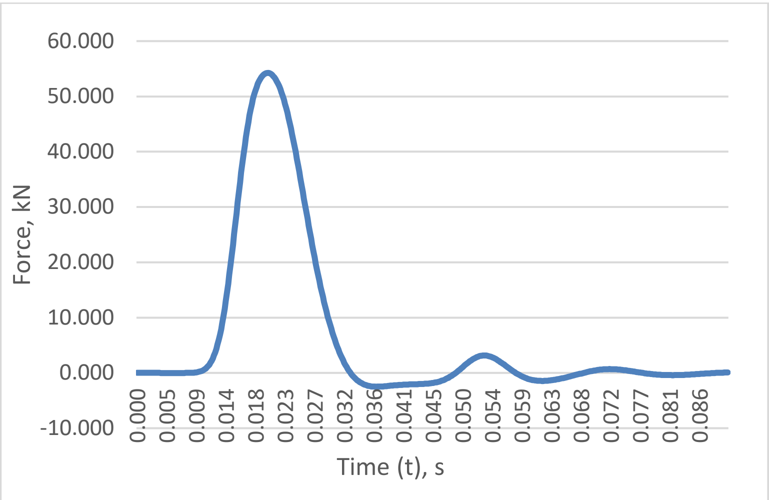


Figure 2. Pulse shape reproduced by the falling weight deflectometer.

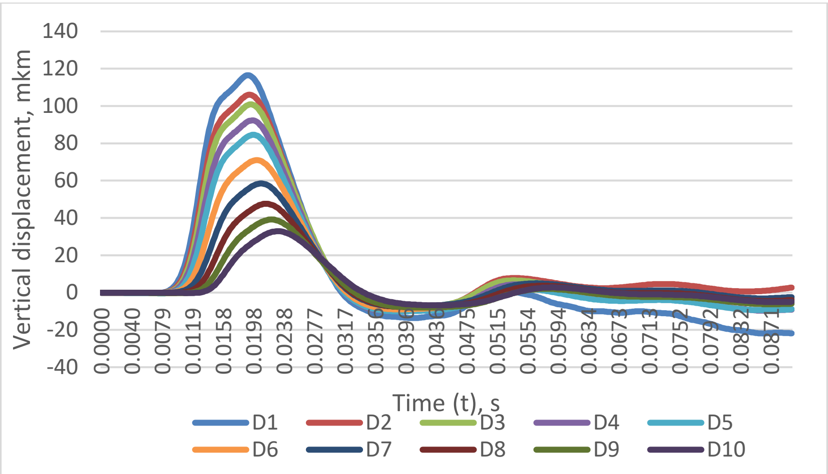


Figure 3. Shape of amplitude-time characteristic of displacements.

$$W = \int_0^t u_i(t) F(t) dt, \quad (1)$$

where $u(t)$ is the dependence of vertical displacements on time, $F(t)$ is time-dependent force impulse.

Taking into account that during field tests the amplitude-time characteristics of displacement and the impulse of impact loading are arrays of values, representing, in fact, the coordinates of the dynamic hysteresis loop this integral can be determined in accordance with the Gauss formula for the area of a polygon.

The potential energy of deformation is determined by the formula:

$$\Pi = \frac{1}{2} u^{\max} F, \quad (2)$$

where $u^{\max}$ is maximum value of vertical displacement on the surface of the medium under study, F is corresponding load value.

Relative hysteresis (absorption coefficient) η in this case is defined as:

$$\eta = \frac{W}{\Pi}. \quad (3)$$

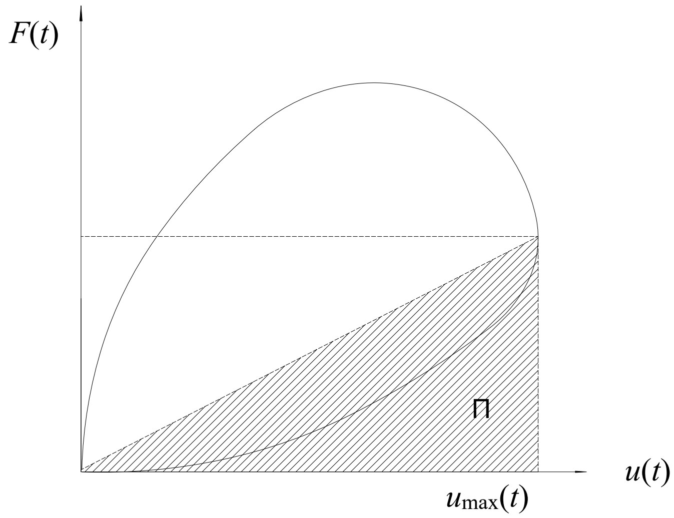


Figure 4. Dynamic hysteresis loop.

Experimental studies of deformation of pavements were carried out on different sections of motorways. In the first section, layer-by-layer tests were carried out as the pavement was constructed, starting from the crushed stone base layer and ending with the surface of the structure. The other three sections recorded dynamic hysteresis loops on the surface of the pavement to quantify energy dissipation, potential strain energy, and relative hysteresis. At the same time, the surveyed sections were in different transport-operational condition, which should allow for evaluating qualitative changes in the calculated parameters. The design of the test section where the layer-by-layer control was carried out is given in Table 1. The design of the operational sections where measurements on the pavement surface were carried out is given in Table 2, and the general view of their operational condition is given in Fig. 5.

Table 1. Pavement on monitoring station.

Layer no.		Layer name	Thickness, cm
Asphalt surface	1	SMA-16	5
	2	A32Lh (Lower layer of asphalt concrete pavement)	8
	3	A32Bh (Asphalt concrete base course)	12
Base	4	Stabilized base layer made of organomineral mixture HO 32 EM	22
	5	Crushed stone M800 crushed stone of 31.5–63 mm	36
Subbase		Medium coarse sand with a filter coefficient of more than 1 m/day,	20
Soil	6	Heavy dusty loam	–

Table 2. Structures of road pavements on maintained road sections.

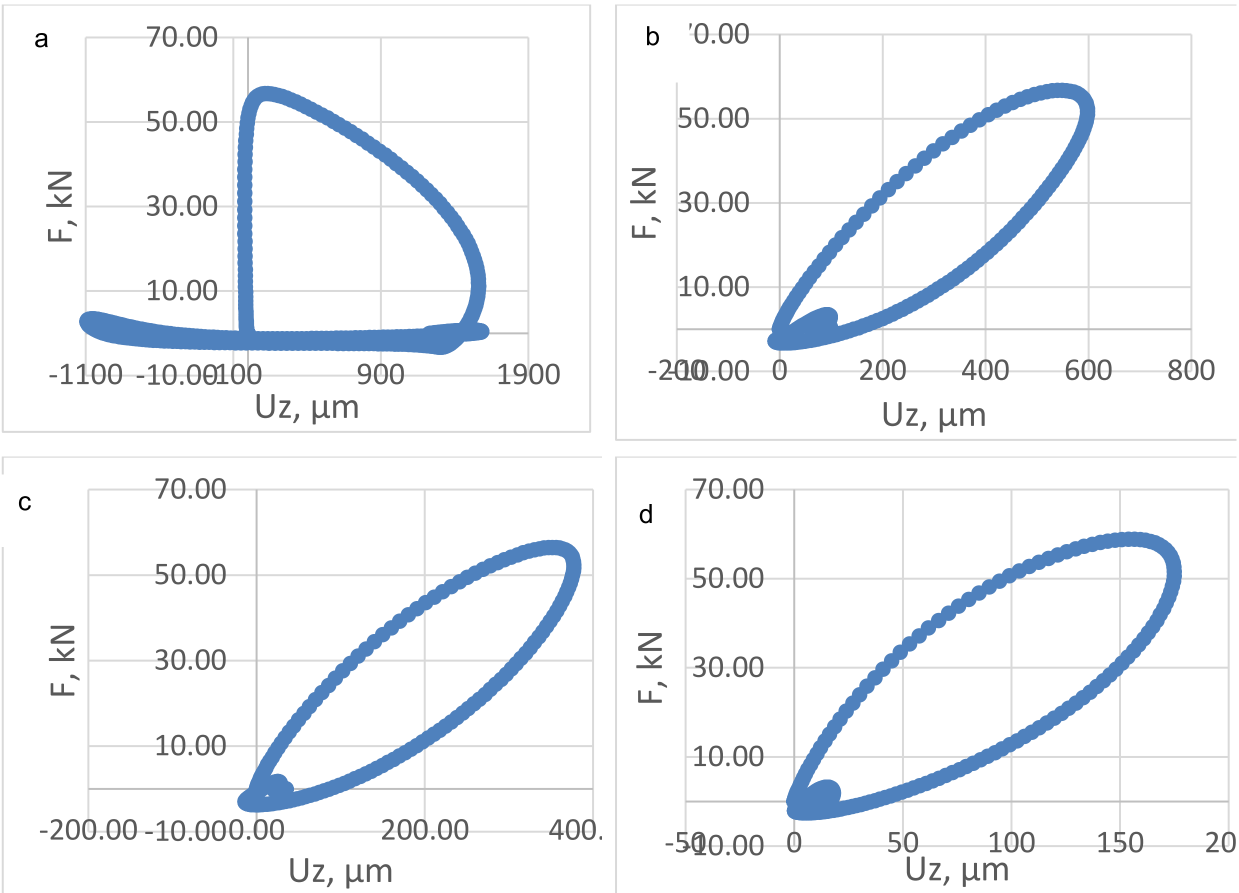
Section 1		Section 2		Section 3	
Layer name	**Thickness, cm**	**Layer name**	**Thickness, cm**	**Layer name**	**Thickness, cm**
SMA-15	4	SMA-15	4	SMA-15	4
A32Lh (Lower layer of asphalt concrete pavement)	7	A32Lh (Lower layer of asphalt concrete pavement)	7	A32Lh (Lower layer of asphalt concrete pavement)	7
A32Bh (Asphalt concrete base course)	7	A32Bh (Asphalt concrete base course)	8	A32Bh (Asphalt concrete base course)	14
Crushed stone M800	41	crushed stone-gravel-sand mixture	18	crushed stone-gravel-sand mixture	16
Gravel-sand mixture	66	Gravel-sand mixture	41	Gravel-sand mixture	32
Heavy dusty loam	–	Heavy dusty loam		Heavy dusty loam	

Figure 5. Visual condition of the monitoring sections.

During the tests, 4 impacts were performed on each measuring point. The first impact was a test impact and the remaining impacts were measuring impacts. The specificity of the FWD dynamic loading unit operation implies constant hardware control of the measurement accuracy. In case the vertical displacement values for each measurement impact differ by more than 5 %, the measurement is rejected and repeated. After a successful series of measurements, the data for the three measuring strokes shall be averaged. The observation time, during which the amplitude-time characteristics of displacements and loading impulse are recorded, is 0.1 s. During this time, there is almost complete decay of deformation characteristics and the experimental loop of dynamic hysteresis corresponds to the curve shown in Fig. 4.

3. Results and Discussion

The general view of the dynamic hysteresis loops recorded at the test section on the surface of different structural pavement layers is shown in Fig. 6.



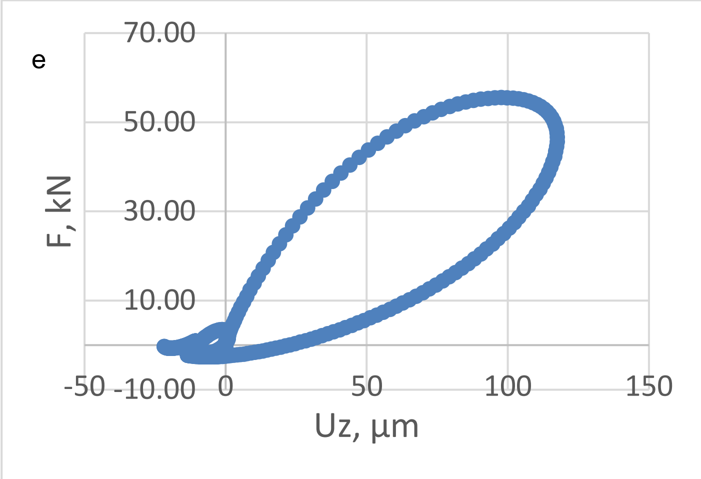


Figure 6. Hysteresis loop on surface pavement layers: a – on top layer no. 5, b – on top layer no. 4, c – on top layer no. 3, d – on top layer no. 2, e – on top layer no. 1.

The analysis of the results of experimental registration of dynamic hysteresis loops on the surface of each of the newly constructed pavements allows for drawing the following conclusions. On the surface of all layers, even under the condition of short-pulse loading of 0.03 s, the picture of dynamic deformation of each layer is highly non-linear. Thus, for example, on the surface of the crushed stone layer the loading curve increases sharply, while the value of vertical displacement practically does not increase. The maximum level of vertical displacement on the crushed stone base layer is reached at the moment when the load is about 24 % of the test loading value of 57.5 kN. On the surface of the other layers, the hysteresis loop tends to the classical ellipse shape, while also being slightly different. Thus, it can be seen that in all cases, the peak of loading does not coincide with the peak of vertical displacements and the width of the loop changes, which indicates a different magnitude of strain energy dissipation. Quantitative estimates of the dissipated energy, potential strain energy, and relative hysteresis are given in Table 3.

Table 3. Results of recording dynamic hysteresis loops on the pavement surface at the test section.

Layer no.		Layer name	Dissipated energy on surface layer – W, J/m³	Potential energy on surface layer – П, J/m³	Relative hysteresis, η
Asphalt surface	1	SMA-16	3.54	2.74	1.29
	2	А32Нт (Lower layer of asphalt concrete pavement)	4.63	4.51	1.03
	3	А32От (Upper layer of asphalt concrete pavement)	9.26	9.88	0.94
Base	4	Stabilized base layer made of organomineral mixture НО 32 ЕМ	15.14	15.47	0.98
	5	Crushed stone M800 crushed stone of 31.5–63 mm	72.2	9.5	7.6

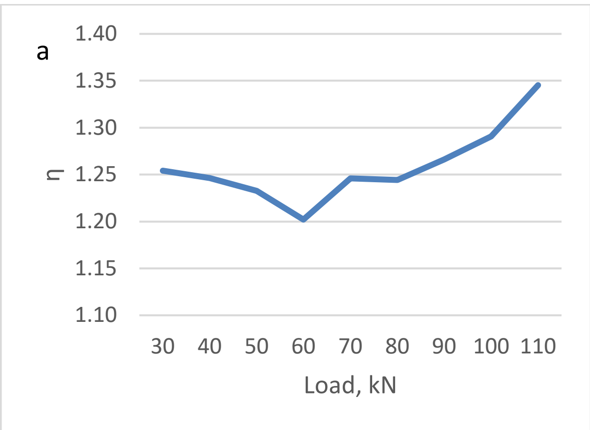
Thus, it can be seen that the value of strain energy dissipation during the construction of the pavement structure changed approximately 7 times, from 72.2 J/m³ characteristic of the unbound crushed stone base layer to 3.54 J/m³ registered on the surface of the crushed stone-mastic asphalt concrete layer. The picture of the relative hysteresis variation is somewhat different. Taking the maximum value on the surface of the unbound crushed stone base layer, as more rigid frame layers of asphalt-granulose concrete and asphalt concrete of the upper base layer are arranged, it decreases to 0.94–0.98, after which, as more viscous asphalt concrete layers of the lower pavement layer and the upper pavement layer are arranged, it increases again to 1.29.

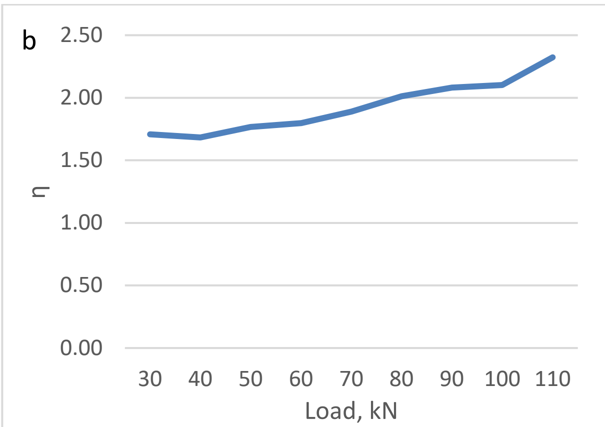
Given the obvious relationship of relative hysteresis to the structural properties of the structural layer materials, it is of some interest to study this index as the test loading increases. For this purpose, an experiment was carried out on three sections of motorways with pavement structures listed in Table 2, which are in different operational condition, in order to study the change in relative hysteresis as the load increases from 30 to 110 kN.

On each of the above sections, tests were carried out using FWD impact loading rig and the dissipated energy, potential strain energy and relative hysteresis were determined. The calculation results are summarised in Table 4. The variation of the relative hysteresis index as a function of the applied load is shown in Fig. 7.

Table 4. Results of registration of energy parameters of deformation at the operated sections.

Load, kN	Section 1			Section 2			Section 3		
	Dissipated energy, J/m^3	Potential energy, J/m^3	Relative hysteresis	Dissipated energy, J/m^3	Potential energy, J/m^3	Relative hysteresis	Dissipated energy, J/m^3	Potential energy, J/m^3	Relative hysteresis
30	2.50	2.00	1.25	3.78	2.21	1.71	3.41	2.30	1.48
40	4.57	3.67	1.25	7.07	4.20	1.68	5.67	3.98	1.42
50	7.58	6.15	1.23	11.75	6.66	1.77	8.44	5.99	1.41
60	10.37	8.63	1.20	17.21	9.58	1.80	12.19	8.57	1.42
70	14.20	11.40	1.25	22.93	12.13	1.89	15.56	11.12	1.40
80	17.86	14.35	1.24	29.19	14.51	2.01	19.84	13.99	1.42
90	22.71	17.94	1.27	36.60	17.58	2.08	24.37	16.79	1.45
100	27.04	20.95	1.29	45.14	21.46	2.10	30.49	20.33	1.50
110	32.71	24.31	1.35	53.78	23.15	2.32	36.46	22.94	1.59





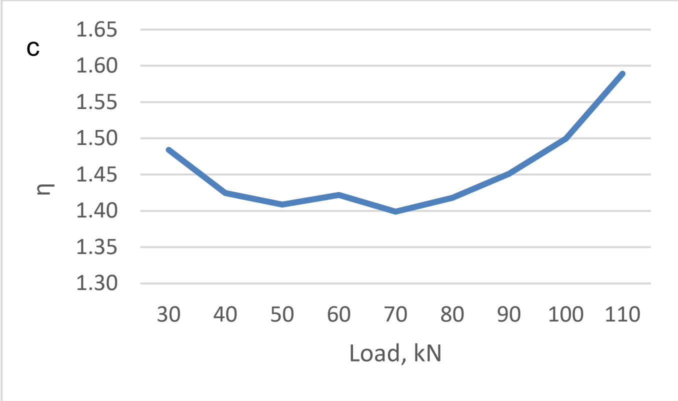


Figure 7. Variation of relative hysteresis with increasing test load:
a – section 1, b – section 2, c – section 3.

As can be seen in the presented graphs, all of them have a similar tendency of change. At the beginning, with a gradual increase in load, the relative hysteresis varies non-monotonically, increasing or decreasing by some value. This can be seen in section 1 in the range from 30 to 80 kN, section 2 from 30 to 40 kN, and section 3 in the zone of 30 to 70 kN. After that, the magnitude of relative hysteresis starts to increase steadily with increasing load magnitude. This character of change allows for making an assumption that the load value, after which the relative hysteresis starts to grow steadily, is critical, and its further increase leads to an increase in the ‘dangerous’ fracture energy in the pavement, which is used for the development of defects in its structure. Based on this example, it can be noted that the values of the permissible load on the half of the vehicle axle of 80, 40, 70 kN proposed on the basis of the graphs generally correlate well with the current condition of the survey sections shown in Fig. 5.

Further development of this approach will allow for approaching a relatively simple express methodology for assigning ultimate axial loads, or critical loads from large vehicles travelling with excessive loads.

As a comparison with the presented approach can be considered the work [29], in which the ultimate load from the traffic flow is calculated based on the operational condition of the motorway according to the criterion of fatigue damage accumulation, and the depth of rutting. However, it is clear that this approach requires much more information and is generally much more labour intensive compared to the in situ test results presented in this study. There is also a domestic document ODM 218.6.002-2010 ‘Methodical Recommendations for Determining Allowable Axle Loads of Motor Vehicles in the Spring Period Based on the Results of Diagnostics of Public Roads of Federal Significance’, which establishes the correspondence between the strength coefficient of the pavement and the maximum axle load. However, this approach also requires documented design information on the minimum required design total modulus of elasticity. In addition, the modulus of elasticity, being an elastic material characteristic, does not generally reflect the processes associated with the dissipation of deformation energy and the intensification of micro-destruction in the structure of pavement materials.

4. Conclusion

1. Experimental registration of dynamic hysteresis loops on the surface of pavement layers during its construction was carried out. The total energy dissipation, potential energy of deformation, and relative hysteresis on the surface of each layer were calculated.

2. It was found that the value of strain energy dissipation during the construction of the pavement structure changed approximately 7 times, from 72.2 J/m^3 characteristic of the unbound crushed stone base layer to 3.54 J/m^3 registered on the surface of the crushed stone-mastic asphalt concrete layer. It should also be noted that as the stiffer stabilized base layer frame layers and the asphalt concrete of the upper base course are placed, the relative hysteresis decreases to 0.94–0.98, after which it increases again to 1.29 J/m^3 as the more viscous asphalt concrete layers of the lower pavement and the upper pavement are placed.

3. Experimental studies of the relative hysteresis change, as the test load increases, have been carried out. It was found that with a gradual increase in the load, the relative hysteresis indicator changes non-monotonically, increasing or conversely decreasing by some value. Then the value of relative hysteresis begins to grow steadily with increasing load value. Such a character of change allows for making an assumption that the load value, after which the relative hysteresis began to grow steadily, was critical, and its further increase leads to an increase in the ‘dangerous’ fracture energy in the pavement, which was used for the development of defects in its structure.

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