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Performance of a Semi-Rigid Pavement: A North Kazakhstan Case Study

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Abstract

This paper presents instrumental assessment of the pavement condition of the section (length: 43 km) of "Ekaterinburg-Almaty" highway located in the Kostanay region (northern Kazakhstan). The pavement condition indicators (roughness, rut depth, total length of longitudinal and transverse cracks, areas of asphalt concrete pavement with block cracks, pavement surface modulus) were evaluated using a mobile diagnostic laboratory (Dynatest, Denmark). It has been established that: due to high moisture in the upper part of the subgrade during the spring thawing period, significant accumulation of plastic strains is possible; longitudinal and transverse cracks are the main type of destruction of the asphalt concrete pavement.

Keywords: Pavement; Rigid base layer; Temperature; Mobile diagnostic laboratory; Pavement condition indicators.
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1. Introduction

A pavement and subgrade are the main structural elements of a road, which must be durable until the end of the design life.[1-3] Modern pavement are designed as multilayer, and the layers are made of different materials (asphalt concretes, crushed stone, gravel, sand, mixtures of stone materials, sand in different proportions; they can be treated with organic, inorganic and complex binders; also soils treated with various binders).

It is clear that the higher the road category and the more heavy vehicles in the traffic flow, the higher the strength of the road pavement. High strength-type pavements may consist of four, five, six, and in some cases even seven layers.[4,5] At the same time, in order to reduce the number of layers of a pavement with a simultaneous increase its strength, usually arranged base layers of treated stone materials. It is known that stone materials treated with cement have the greatest strength in comparison with others.

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When designing the pavement and particularly the subbase, the previous regulatory documents[6,7] recommended to use the stone materials treated with cement, if necessary, but it was not mandatory. However, now in Kazakhstan it is recommended to meet the new design axle load of 130 kN, and the regulatory document[8] requires that a pavement structure, calculated for the specified load, must have at least a two-layer base, the top layer of which must be treated; regardless of results of a calculation, the thickness of this layer should be at least 12 cm if treated with organic binders and at least 20 cm if treated with inorganic binders. In the active regulatory documents,[4,5] these requirements remain valid.

Thus, in Kazakhstan there are tens of thousands of kilometers of roads with a semi-rigid pavement structure with rigid base layer (made of stone materials treated with a cement). But their operational behavior and the defects that arise in them have practically not been studied. A diagnostic (an instrumental survey) of their condition with identification of defects and their quantitative description are important for accumulating the data of the operational behavior of the roads with the specified type of pavement. The data collected helps optimizing the maintenance and addressing the future design activities.

It should be noted here that currently in Kazakhstan, the standards for financing the current repair and maintenance of highways[9] do not take into account the types and volumes of characteristic defects of semi-rigid pavement structures. Therefore, in 2017, Kazakhstan started assessing behavior (condition) of semi-rigid pavement structures. The first was the “Yekaterinburg-Almaty” highway (Fig. 1S).

This highway has both local (republican) and international importance: firstly, it connects the north (Kostanay, Akmola), central (Karaganda), south (Zhambyl) and southeast (Almaty) regions of the republic, including a large city - Almaty; secondly, it is a part of the Transport Corridor 1 of the Central Asia Regional Economic Cooperation (CAREC),[10] which includes the following 11 developing countries: Afghanistan, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Mongolia, Pakistan, China, Tajikistan, Turkmenistan and Uzbekistan.

This paper presents instrumental assessment of a pavement condition of a section (length: 43 km) of the highway. The pavement condition indicators (roughness, rut depth, total length of longitudinal and transverse cracks, areas of asphalt concrete pavement with block cracks, pavement surface modulus) were evaluated using a mobile diagnostic laboratory (Dynatest, Denmark). The instrumental assessment results established that the longitudinal and transverse cracks are the main type of destruction in the semi-rigid pavement structure in these climatic conditions. Cracks of this type, both in asphalt concrete layers and in the rigid base layer, occur at low temperatures during cold periods of the year. Therefore, it is also important to study the temperature regime in the region.

2. Highway section

2.1 Short description

The surveyed 43 km section, is a part of “Yekaterinburg-Almaty” highway (km 428-470). The road category is III.[11] The number of traffic lanes is 2. The width of the carriageway is 7.0 (2×3.5 m). The width of the shoulder is 2×2.50 m. The highway section is 74 km from Kostanay (northern Kazakhstan) and goes towards Yekaterinburg (Russia). The section was reconstructed in 2004. A periodic repair was carried out in 2014;[12] the top layer of the pavement was replaced with two asphalt concrete layers: the first layer is a hot fine-grained dense asphalt concrete - 4 cm; the second layer is a hot coarse-grained porous asphalt concrete - 6 cm.

2.2 Pavement structure

The semi-rigid pavement structure of the considered highway section consists the following layers:

1) Hot dense fine-grained asphalt concrete, 4 cm;
2) Hot porous coarse-grained asphalt concrete, 6 cm;
3) Hot porous coarse-grained asphalt concrete, 10 cm;
4) A mixture of crushed stone and sand, treated with Portland cement (6-7%), 15 cm;
5) A mixture of sand and gravel, 20 cm.

The total thickness of the pavement structure is 55 cm. Subgrade soil: heavy sandy loam.

3. Methods

3.1 Mobile diagnostic laboratory

In 2015, by order of the Kazakhstan Highway Research Institute, The Dynatest Company (Denmark) manufactured a mobile diagnostic laboratory (Fig. 2S), which is equipped with laser and electronic systems for measuring and processing roughness, rut depth and defects (cracks) of a road pavement surface.[13]

The laboratory is equipped with the Laser Crack Measurement System (LCMS) (Pavemetrics Co., Quebec, Canada), which automatically scans defects (cracks) on a pavement surface at moving, and processes the received data using the Dynatest Explorer software, classifies the cracks (they are divided into longitudinal and transverse cracks, block cracks) and determines their quantitative characteristics. This system scans up to 28,000 lines per second both during the daytime and at night-time while driving at speeds of up to 120 km/h, and identifies cracks up to 1 mm wide.

A Road Surface profiler fitted with five laser sensors is installed on the lab front bumper, which measures the longitudinal and transverse profiles of a pavement surface. The software Dynatest Explorer uses the collected information to calculate the International Roughness Index (IRI) and rut depth.

This mobile laboratory also includes a falling weight deflectometer (FWD) to assess a pavement layers stiffness (Fig. 3S). The FWD is an equipment that performs non-destructive measurements of pavement structures capacity (surface modulus) with high productivity (at 60-70 points on the pavement surface per working day). It also has the following advantages: wide load limit (up to 120 kN), number of sensors - 9; loading time - 0.2-0.3 s; There are air and surface temperature sensors. It is clear that the FWD produces a dynamic impulse load that simulates a moving wheel load. The survey results are analyzed and the surface modulus of the pavement structure is calculated using the software “Elmod”.

The following indicators were determined by the laboratory: rut depth, roughness, cracking and surface modulus of the road section. Roughness of the road section surface is characterized by the International Roughness Index (IRI, m/km).[14] Cracks on the pavement surface are estimated by two indicators: the pavement surface, which is occupied by block cracks S_{cr} (m^2), and the total length of longitudinal and transverse cracks l_{cr} (m).

The bearing capacity of a pavement structure is characterized by the surface modulus[15] E_o (MPa), calculated by the formula (1):

$$E_o = \frac{qD(1-\nu^2)}{l}, \quad (1)$$

where q is a specific load on a pavement surface, MPa;
D is a diameter of a loading plate, mm;
ν is an average value of the Poisson's ratio of the pavement structure, equal to 0.3;
l is a maximum deflection of the pavement surface, mm.
Deflection of the pavement surface of the asphalt concrete was measured with FWD and in accordance with effective standards.[16-18]

3.2 Traffic volume and composition

The MetroCount 5600 vehicle classifier system equipped with two rubber pneumatic tubes (two pneumatic tubes)[19] was used to determine the annual average daily traffic (AADT) and classification of traffic flow on the highway section. This system defines all vehicles passing on the selected section of the road and divides them into 12 classes. The obtained data about the axles of passing vehicles can be exported to MS Excel, which increases the speed and reliability of its processing. The system with a time resolution better than 1 ms provides extremely high reliability and serviceability, powered by an easily replaceable alkaline battery packs allow continuous surveys of around 290 days.

3.3 Characteristics of soils

Standard characteristics were determined for two types of soils. The first is a mixture of sand and gravel from which was constructed the lower base layer of the pavement structure; the second is a heavy sandy loam which is the subgrade soil.
The granulometric compositions of soils determined by the sieve method according to the standard.[20]

Moisture and density of the heavy sandy loam determined by the cutting ring method and the thermostatic-weight method.[21]

Moisture and density of the sand and the gravel mixture determined by the method of holes and the thermostatic-weight method.[21]

The maximum densities and optimal moisture of the soils determined from the "density-moisture" dependences established in laboratory conditions.[22] The content of organic substances in the soil is determined according to the standard.[23]

3.4. Temperature measurement

Since the mechanical behavior of asphalt concretes, cement-treated materials and soils is highly dependent on temperature,[24-27] it would be desirable to have information on temperature values in the pavement structure and subgrade.

In July 2021, the Kazakhstan Highway Research Institute installed an automated system for monitoring of temperature and moisture at the points of the pavement structure and subgrade on the 1st km of the "Kostanay-Yekaterinburg" highway (Fig. 4S). The system consists of an above-ground and a underground parts. The above-ground part is a vertical mast, equipped electronic units for storing and transmitting measured values of temperature and moisture, two solar panels and a battery; the underground part of the measuring system includes temperature and moisture sensors, cables for transmitting measured temperature and moisture values to the electronic storage and transmission units.[28-31] The temperature sensors are operated in accordance with the thermal resistance principle; The moisture sensors are based on changes in the diamagnetic permeability. Temperature and moisture values at points on the pavement structure and subgrade are hourly measured by the sensors, stored and transmitted to the database for the data accumulation. This data can be processed using various software, such as MS Excel.

The pavement structure in this section consists of the following layers:
1) hot dense fine-grained asphalt concrete, 5 cm;
2) hot porous coarse-grained asphalt concrete, 13 cm;
3) hot highly porous coarse-grained asphalt concrete, 9 cm;
4) mixture of crushed stone, gravel and sand (maximum grain size - 80 mm), 35 cm.

Subgrade soils: 1) sand - 90 cm; 2) black soil 148 cm.
Temperature and moisture sensors are pleased at the following points of the pavement, subgrade and soil base: 3 cm, 11 cm, 22 cm, 45 cm, 78 cm, 111 cm, 145 cm, 180 cm, 240 cm and 300 cm.

The information collected by the sensors was used to describe the temperature conditions in which the analyzed highway section operates.

4. Results and discussion

4.1 Traffic volume and composition

On the considered highway section, the AADT and composition of traffic measured in 2015, 2016, 2017 and 2019 (Fig. 5S). The AADT in 2015 and 2016 was almost the same and approximately equal to 2900 veh/day, while in 2017 and 2019 it increased slightly and amounted to 3019 veh/day (+5%) and 3252 veh/day (+13%) respectively. At the same time (Table 1), light vehicles (motorcycles, cars and minibuses) predominate (more than 64%) in the traffic; medium-heavy buses account for only 0.5%; single trucks with axle loads up to 10 tons - 12.5%, trucks with trailers and tractors with semi-trailers - 22.8%.

Thus, it can be considered that the pavement structure on the section is under average mechanical loading conditions.

Table 1. Traffic composition in 2019.

Type of vehicle		AADT veh/day	AADT %
Motorcycles		10	0,3
Light vehicles and minibuses		2078	63,9
Medium-heavy buses		16	0,5
Single trucs	< 2 т	280	8,6
	5-10 т	127	3,9
Trucks with trailers and tractors with semi-trailers		741	22,8
Total		3252	100

4.2 Characteristics of soils

The granulometric compositions of the sand and the gravel mixture, heavy sandy loam are presented in Tables 2 and 3.

According to Table 2, in the material of the lowest (fifth) layer of the pavement, the content of sand and gravel is 41% and 59%, respectively. At the same time, almost 40% (in fact 39,6%) of the gravel has a size in the range of 5-40 mm, and almost 20% (in fact 19,4%) is represented by grains with dimensions exceed 40 mm.

Table 3 shows that almost all particles of subgrade soil (heavy sandy loam) are less than 2 mm in size; 76.2% of the soil particles are in the range of 0.05-2 mm and 23.8% of the particles are smaller than 0.05 mm.

Characteristics of the soils of the pavement and subgrade are given in Table 4.

Analysis of the data in this table shows that the physical and mechanical characteristics of the sand and gravel mixture are close to their “favorable” values: the actual moisture content (8.2%) practically coincides with the optimal one (8.0%); the actual density differs very little (4.59%) from the maximum one (1.96%).

The actual density of the subgrade soil is slightly (9.4%) different from the maximum one; the actual moisture has a value (25.5%) practically equal to the liquid limit (25.1%). It means that at the specified actual moisture content, the soil is in a plastic condition, *i.e.* in the upper part of the subgrade, when driving heavy trucks with large axial loads, plastic strains can be accumulated. The sampling from the pavement structure was carried out in July of 2017, *i.e.* during the summer period, when the subgrade, as a rule, has the lowest moisture value (the highest stiffness). The highest moisture usually occurs in the spring, *i.e.* during the thawing period of the subgrade. Given this fact, it can be assumed that subgrade of the considered highway section can accumulate a significant plastic strain during the spring thawing.

The higher the moisture, the more the physical and mechanical characteristics of soils change when they freeze in winter and during spring thawing. In addition, the physical and mechanical characteristics of clay soils are highly dependent on moisture content. A significant decrease in soil density compared to its maximum value will lead to a decrease in its strength and stability. All this affects the mechanical behavior (destruction) of the subgrade and the pavement structure.

4.3 Cracks

The asphalt concrete pavement degradation in the form of cracks was characterized by the following two indicators: 1) the area of the asphalt concrete pavement, on which there are block cracks S_{cr} (m^2), and 2) the total length of longitudinal and transverse cracks l_{cr} (m).

There are several methods for measuring cracks on the surface of asphalt concrete pavements.[32] In recent years, Mobile Laser Scanning (MLS) systems have become widely used for rapid and high-precision determination of the characteristics of low-temperature cracks on asphalt concrete pavements of highways.[33,34] As stated in subsection 3.1 of the work, the characteristics of cracks (S_{cr}, l_{cr}) in the asphalt concrete pavement on the considered highway section were determined using a laser scanning method, which ensures high reliability of the data presented in Figs. 1 and 3.

4.3.1 Block cracks

The areas of the asphalt concrete pavement with block cracks (Fig. 6S) at different kilometers of the highway section are shown in Fig. 1, which shows that the values of block cracks areas a very widely range: from 1 m^2 (431 and 468 km) to 310 m^2 (457 km). At the same time, half of all pavement areas with block cracks (50%) has a value of up to 40 m^2 (Fig. 2); 69%

Table 2. Granulometric composition of the sand and gravel mixture.

Sieve size, mm	80	40	20	10	5	2,5	0,63	0,16	0,05
Full remainder, %	6,0	19,4	35,7	47,7	59,0	73,2	87,1	95,0	98,8

Table 3. Granulometric composition of heavy sandy loam.

Sieve size, mm	2	1	0,5	0,25	0,1	0,05
Full remainder, %	0,31	17,6	23,2	50,3	71,8	76,2

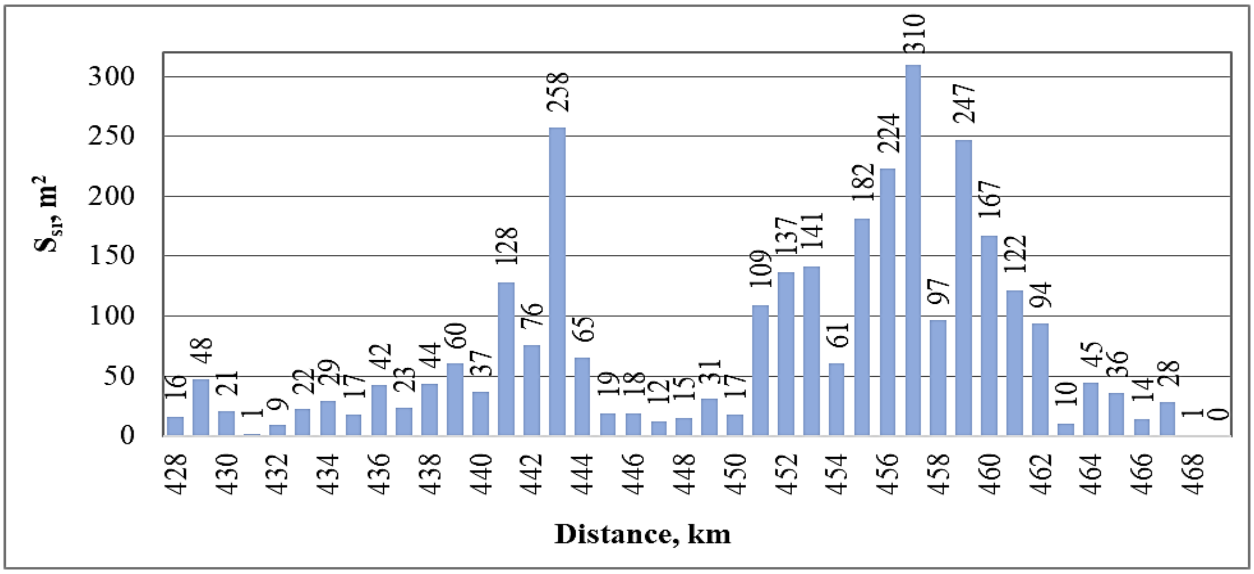

Fig. 1 Block cracks area vs distance.

Table 4. Characteristics of the soils of the pavement and subgrade.

Characteristic	Soil	
	Mixture of sand and gravel	heavy sandy loam
Moisture, %	8,2	25,5
Optimal moisture,%	8,0	12,6
Density, g/cm^3	1,87	1,63
Maximum density, g/cm^3	1,96	1,80
Compaction coefficient	0,95	0,91
Content of organic substances,%	-	2,97
Liquid limit, %	-	36,5
Plastic limit,%	-	25,1
Plasticity index	-	11,4

of all areas with block cracks are in the range from 1 m^2 to 80 m^2.

The traffic lane is 3.5 m. The total area of 1 km one-lane pavement is: S_{crkm}=3.5 m·1000 m=3500 m^2.

Then, the following formula (2) calculates the indicator which quantitatively characterizes the relative defectiveness of the pavement (%):

$$D_{crnet} = \frac{S_{cr}}{S_{srkm}} \cdot 100\%. \quad (2)$$

Calculations by the formula (2) shows that the above characteristic values of the pavement areas with block cracks equal to 1 m^2, 40 m^2, 80 m^2 and 310 m^2 correspond to the following values of the relative defectivity (D_{crnet}): 0.03%, 1.1%, 2.3% and 8 .9% respectively.

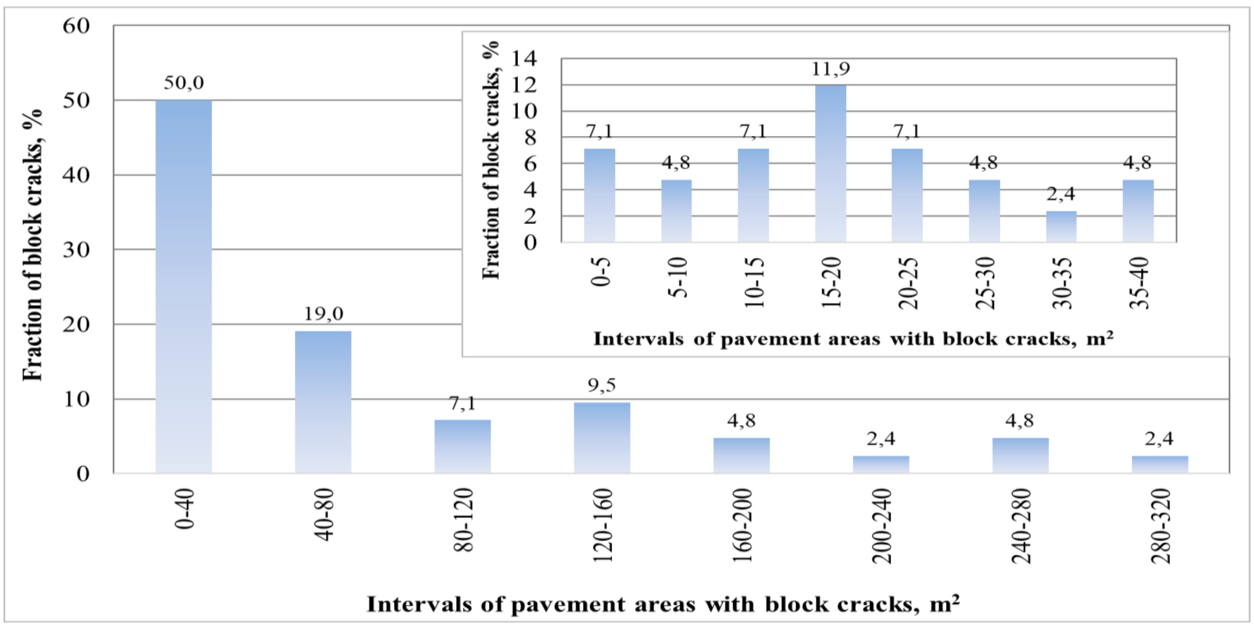

Fig. 2 Distribution of block cracks.

The average values of the two most “cracked” area intervals, equal to 19 m^2 and 50 m^2, correspond to the values of the D_{crnet} indicator, equal to 0.6% and 1.4%, respectively. Let us determine the weighted average value of the relative defectiveness D_{crnet} in the two most “cracked” intervals:

$$\frac{0{,}6\% \cdot 50\% + 1{,}4\% \cdot 19\%}{50\% + 19\%} = 0{,}82\%.$$

The average weighted defectiveness which calculated in a similarly manner, is of 2.1%.

The above results show that block cracks on the asphalt concrete surface of the surveyed highway section is available on small areas. Therefore, block cracks as a type of destruction of an asphalt concrete pavement on the surveyed section of the highway is not the main one.

4.3.2 Longitudinal and transverse cracks

The values of the total lengths of longitudinal and transverse cracks (Fig. 7S) on the asphalt concrete pavement l_{cr} are shown in Fig. 3.

This figure shows that the lengths of cracks at different kilometers of the highway section are not uniformly distributed, they have large range: from 264 m (a minimum value) to 2872 m (a maximum value). At the same time, almost half (in fact 47.6%) of the cracks lengths are from 590 m to 1250 m (Fig. 4). In this interval, the average length of cracks is 920 m.

To improve the visual representation of the distribution of longitudinal and transverse cracks, we assume that all identified cracks are only transverse, and each quasi-transverse crack has a length equal to the width of the traffic lane, *i.e.* we will further deal with “full quasi-transverse” cracks.

The total length of the quasi-transverse cracks in one traffic lane with length of 1 km is determined by the formula (3):

$$l_{cr} = l_{cr}^{long} + l_{cr}^{transv}, \tag{3}$$

где l_{cr}^{long} , l_{cr}^{transv} are total lengths of longitudinal and transverse cracks in a traffic lane with length of 1 km, respectively.

The number of the quasi-transverse cracks in one kilometer of the road is calculated by the formula (4):

$$n_{cr} = \frac{l_{cr}}{b}, \tag{4}$$

where b is the traffic lane width equal to 3.5 m.

Average distance between the quasi-transverse cracks d_{cr} (m) is calculated by the formula (5):

$$d_{cr} = \frac{1000}{n_{cr}}, \tag{5}$$

Indicators calculated by expressions (3), (4) and (5) determine the density of quasi-transverse cracks on an asphalt concrete pavement, provide information about the degree of damage of the asphalt concrete pavement by single (transverse and longitudinal) cracks. To calculate them, the data obtained using LCMS is sufficient.

Using formulas (3), (4) and (5), for the most (km 457) and least (km 469) "cracked" kilometers we find: n_{cr}=821 cracks, d_{cr}=1.2 m and n_{cr}=75 cracks, d_{cr} =13.3 m, respectively.

For the length intervals with the biggest number of the quasi-transverse cracks from 590 m to 920 m (an average crack length - 755 m) and from 920 m to 1250 m (an average crack length - 1085 m) we have: n_{cr}=216 cracks, d_{cr}=4.6 m and n_{cr}=310 cracks, d_{cr}=3.2 m, respectively.

The characteristics of the above quasi-transverse cracks show that the surveyed pavement is excessively cracked. Therefore, longitudinal and transverse cracks as types of destruction of an asphalt concrete pavement on the surveyed highway section, apparently, are the main ones.

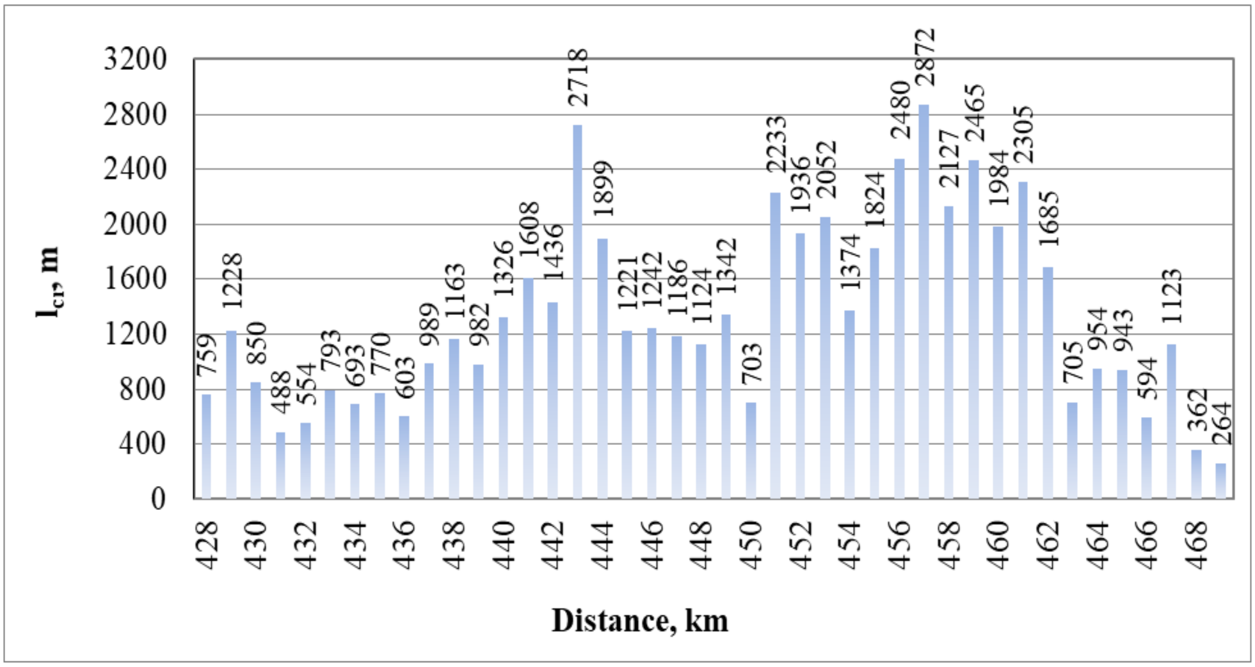

Fig. 3 Total lengths of longitudinal and transverse cracks vs distance.

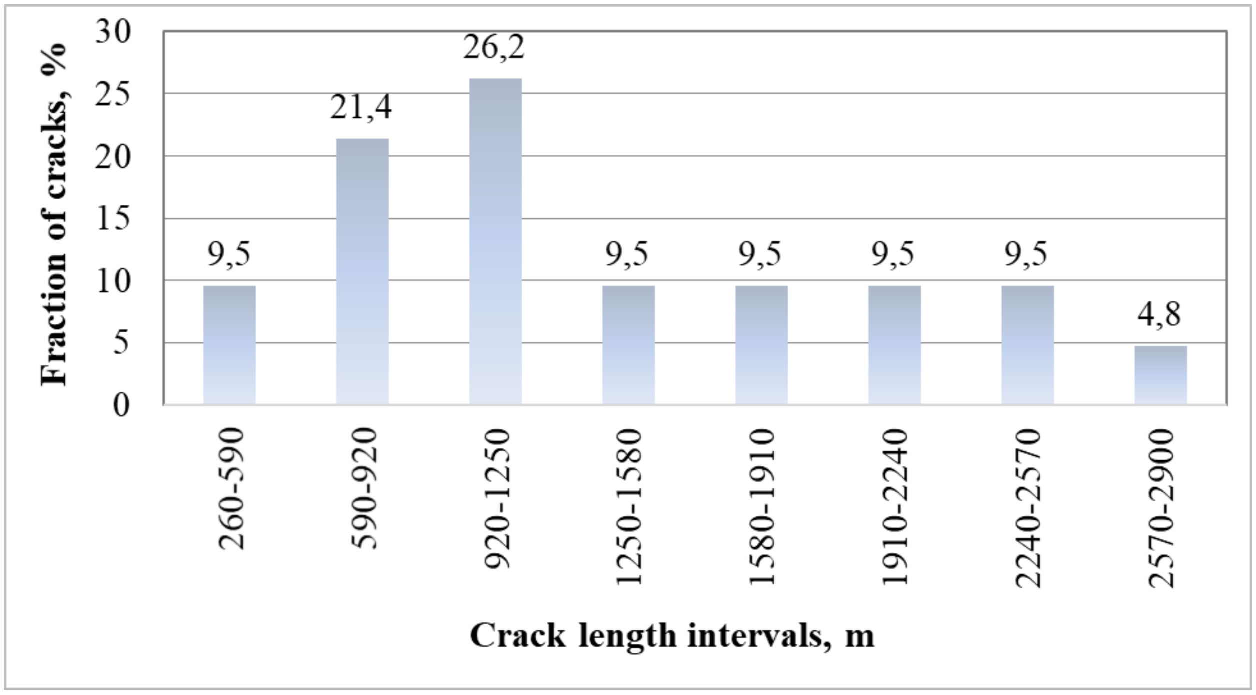

Fig. 4 Distribution of lengths of longitudinal and transverse cracks.

In Kazakhstan and in many countries of the world there are no standards for low-temperature cracks. In the US, it is believed that thermal cracks in an asphalt pavement allow water to enter underlying layers, causing structural failure of the pavement; temperature cracks also directly cause loss of roughness; therefore in US there is a limit their maximum number: 190 m/km.[35] Figure 3 shows that not a single kilometer of the surveyed highway section meets the current American requirement. The total length of cracks exceeds the specified norm from 1.5 to 15 times.

During the operation of a road, in order to ensure the design service life, cracks in asphalt concrete pavements should be repaired in a timely manner. Sealing cracks is a type of poorly mechanized road work that requires a lot of time and material costs. Untimely and poor-quality repair of cracks will lead to decrease in the quality of a pavement during operation.

The work[36] cites the fact of premature excessive (every 9-15 m) cracking of an asphalt concrete pavement with a base layer treated with cement. Based on the results of a comprehensive (laboratory and field) investigation performed using both destructive (trenching and coring) and non-destructive (FWD and ground penetrating radar) methods, it was concluded that the cause of this premature excessive cracking of the pavement was the cement-treated rigid base. The two reasons given are: excessive volume of cement and high moisture content during compaction.

Premature excessive cracking of asphalt concrete pavements has also occurred in pavement structures with very stiff (surface modulus above 20.7 GPa) lime-treated bases.[37] The cracks we observed and those mentioned above by other authors are “reflected” from cracks in the treated rigid base layers. Their appearance and frequency are influenced by a number of factors: characteristics of materials, features of the construction process, traffic load, resistant imposed on the base by the subgrade and design decisions.[38] Apparently, by optimizing the controllable factors listed above, it will be possible to reduce the degree of cracking in a pavement laid on rigid base layers.

The number of longitudinal and transverse cracks on asphalt concrete pavements on untreated base layers is significantly less.

4.4 Rutting

The rutting depth and roughness are also main indicators of road performance. When rutting and roughness are rising, the pavement condition and safety drastically decrease. Therefore, their maximum values are governed by the regulatory documents.[14,39]

It is clearly seen (Fig. 5) that both in the direct and reverse directions the rut depth on puts lines of the asphalt concrete pavement along the length of the section is distributed significantly not uniformly. The minimum and maximum rut depths in the direct direction are 2.6 mm and 18.7 mm, respectively, and in the reverse direction: 2.5 mm and 16.8 mm, respectively. It should be noted that nowhere on the consideration highway section the rut depth does not exceed the permissible maximum value of 20 mm.[39] The high reliability of these results is ensured, firstly, by the fact that they were measured with a laser profiler[40,41] and secondly, by

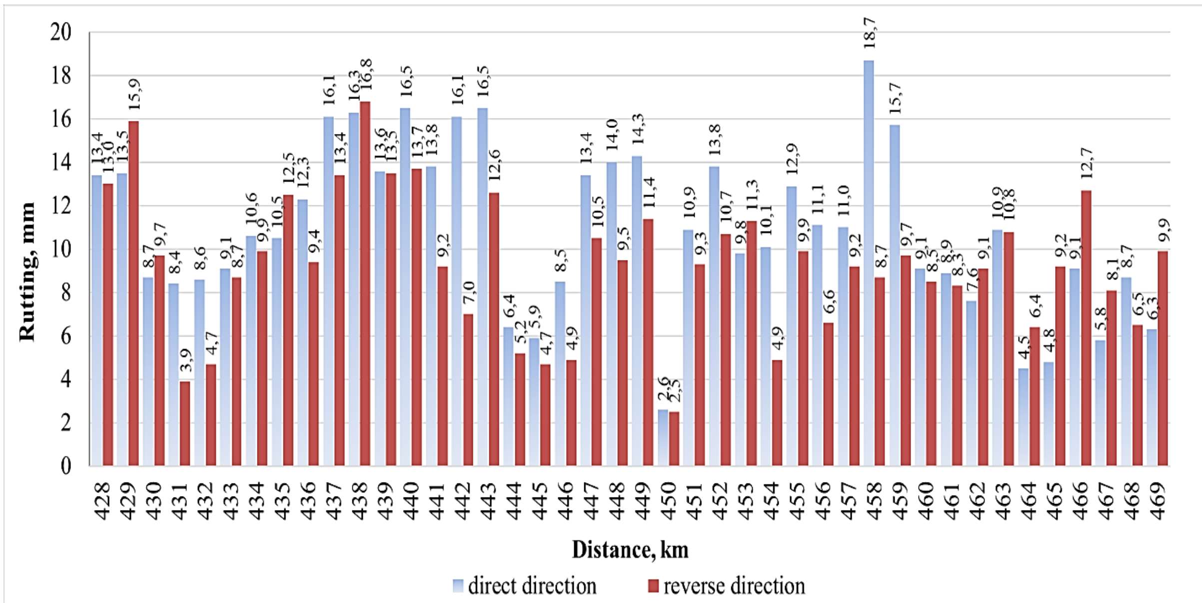

Fig. 5 Rut depth vs distance.

the comparable results of other researchers.[42,43]

The histogram in Fig. 6 clearly shows that in both directions, the greatest rut depths are in a narrow range with a width of only 3 mm from 8 mm to 11 mm: in the direct and reverse directions, respectively, 38.1% and 47.6%. More than 60% (in fact 61.9%) in the forward direction and exactly 70% in the reverse direction of all measured rut depths fall between 8 mm and 14 mm. It can be noted that during the three years of operation after the mid repair in 2014 until the time of the measurement in the summer of 2017, the average rate of increase in the rut depth for two thirds (66%) of the length of the highway section was 3.7 mm/year.

4.5 Roughness

From Fig. 7 it can be seen that the IRI value in the direct and reverse directions has an approximately the same distribution over the highway section. Here we note that the values of the roughness index (IRI) and the nature of their distribution along the length of the highway section are close to similar data from other authors.[44] Minimum and maximum IRI values in the direct direction is equal to 2.2 m/km and 4.2 m/km, respectively, and in the reverse direction - 1.7 m/km and 4.2 m/km, respectively, *i.e.*, we can say that the pavement of the reverse direction is a little smoother than in the direct direction. It can be seen from Fig. 8, in the direct direction, more than 90% (in fact 90.6%) of IRI values are in the range from 2.1 to

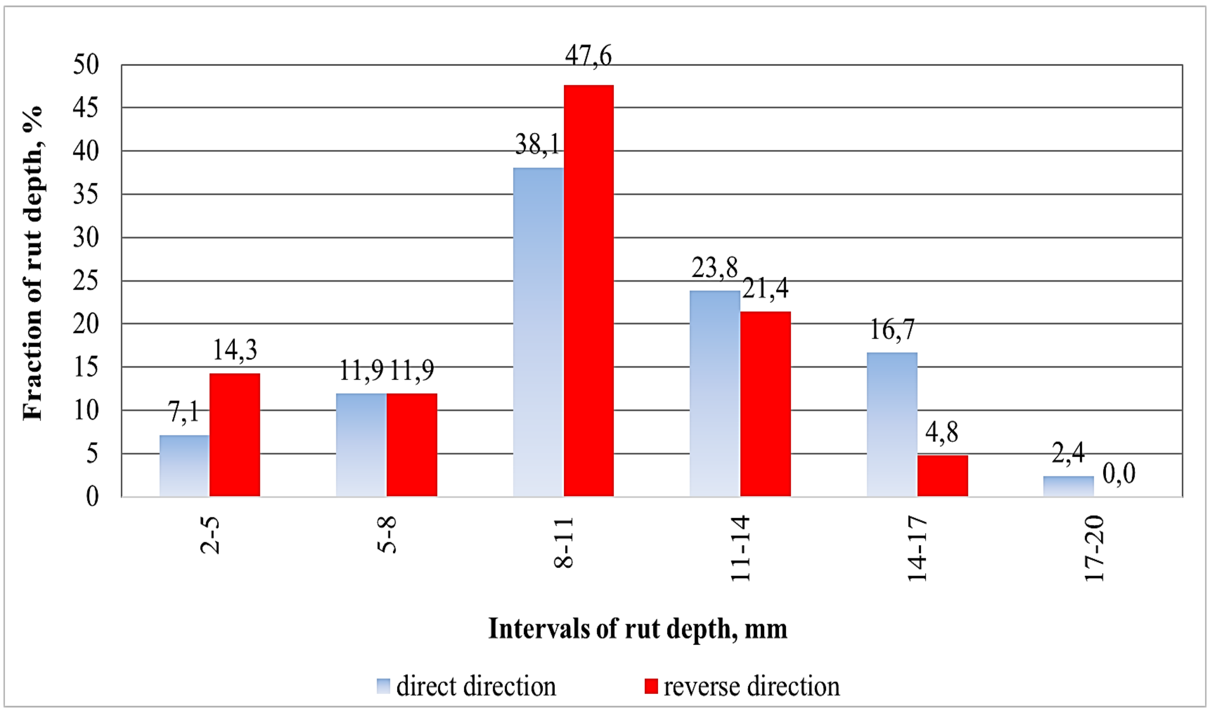

Fig. 6 Distribution of rut depth.

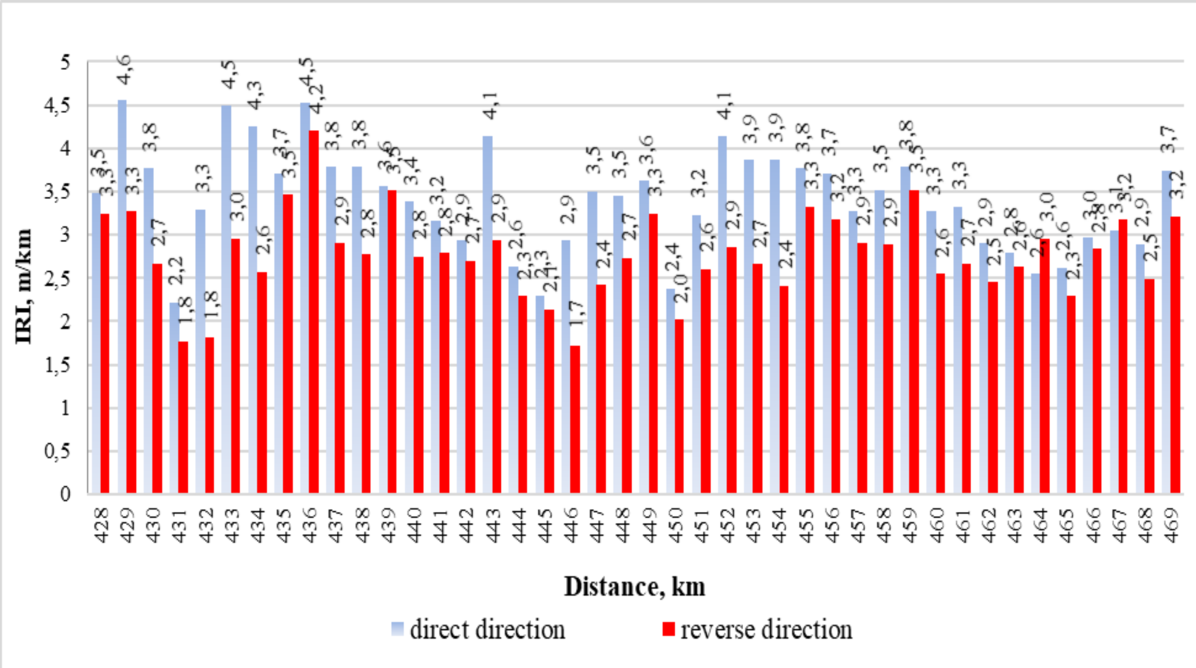

Fig. 7 Roughness vs distance.

4.1 m/km and almost 60% (in fact 59.6%) fall into a narrow interval: from 3.1 to 4.1 m/km; in the reverse direction almost all IRI values (in fact 97.6%) and almost 40% (in fact 38.1%) are in the range from 1.6 to 3.6 m/km and from 2.6 to 3.1 m/km, respectively.

According to the pavement surface roughness standard in Kazakhstan,[12] at AADT from 3000 to 4500 veh/day, highway sections with IRI up to 3.1 m/km are rated as “excellent” and ones with IRI value from 3.1 to 3.6 m/km are rated as "good". Similar norms are found in other works.[45,46] According to Fig. 8, we determine that 31% and 73.8% of the section in the direct and reverse directions, respectively, have an “excellent” rating in roughness, and 62% and 97.6%, respectively, have a “good” score. Thus, it can be concluded that the highway section at the time of the survey had good condition.

4.6 Surface modulus

Surface modulus indicates the overall pavement stiffness (indirectly the overall capacity). It is believed that the higher the surface modulus, the stronger the pavement. During the road operation, the surface modulus of the road pavement gradually decreases and at the end of its service life reaches the permissible minimum value. Therefore, the surface modulus is assigned when the pavement design[4,5] and is periodically evaluated instrumentally during its operation.[39] Currently, measuring road surface deflection using a non-

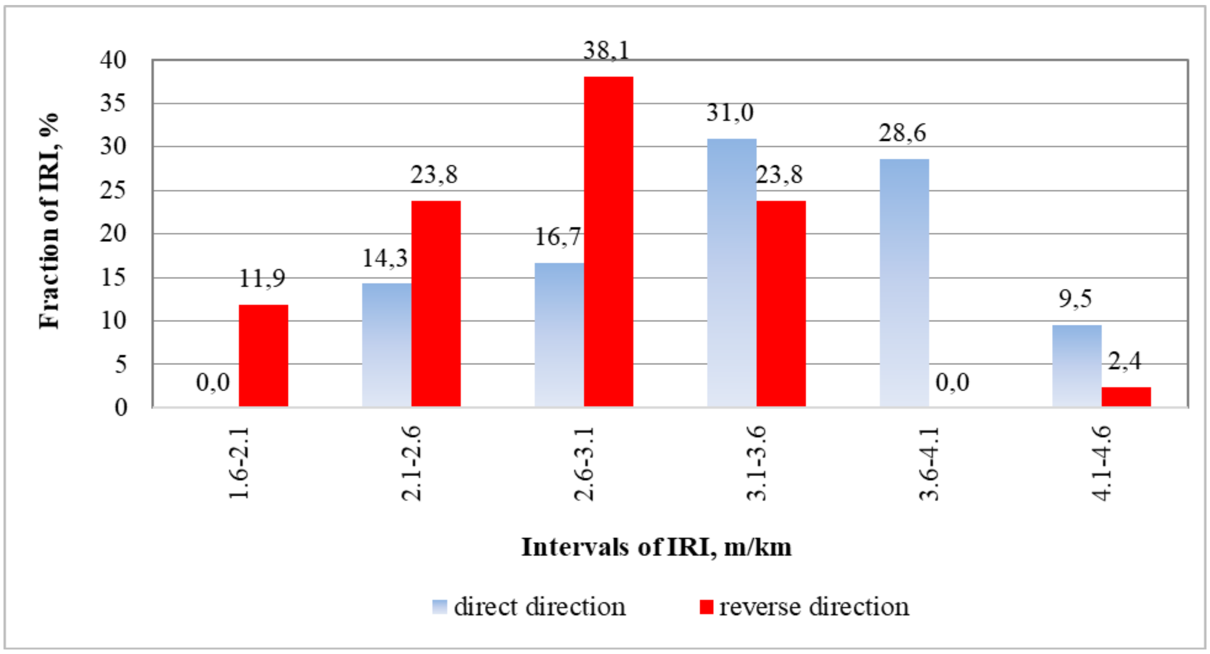

Fig. 8 Distribution of IRI values by intervals.

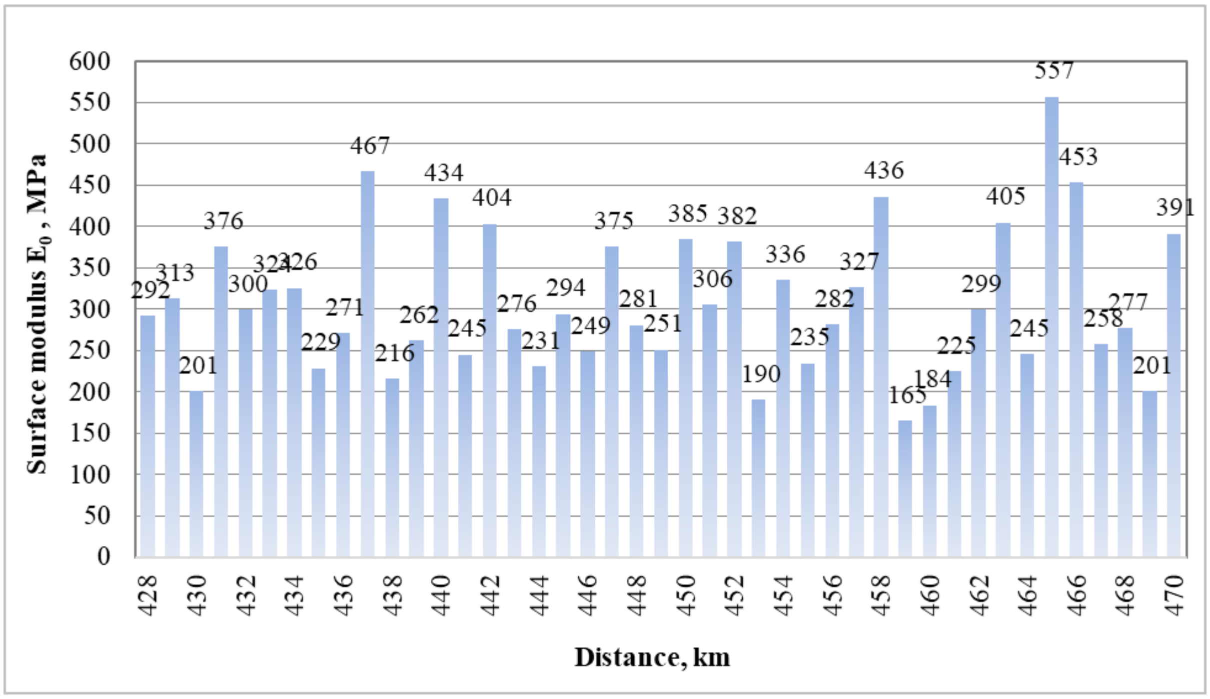

Fig. 9 Pavement surface modulus vs distance.

destructive FWD method is generally accepted as highly accurate and reliable.[47,48]

The surface modulus of the pavement was measured only in direct (Kostanay-Yekaterinburg) direction. The values of the surface modulus are shown in Fig. 9. Noted that the modulus values have large range: E_o^{min}=165 MPa (459 km), E_o^{max}=557 MPa (465 km); the maximum value of the modulus is 3.5 times greater than its minimum value. At the same time, exactly half (50%) of the modulus values are in the range of 210-310 MPa (Fig. 10). The intervals 160-210 MPa, 310-360 MPa and 360-410 MPa include 12%, 12% and 14% of the modulus values, respectively.

A comparison of air and pavement surface temperatures (Fig. 8S) measured during surface modulus assessment using FWD showed that the values of the air and the pavement surface temperatures at different kilometers of the highway section are highly homogeneous. This fact shown that the high inhomogeneity of the surface modulus values is not due to the temperature impact. Then it can be assumed that such a high inhomogeneity of the modulus values indicates a significant inhomogeneity of the mechanical characteristics of the pavement layers and subgrade. So, we can conclude: a surface modulus (a deflection of the pavement) is very sensitive to mechanical inhomogeneities in structural elements of the

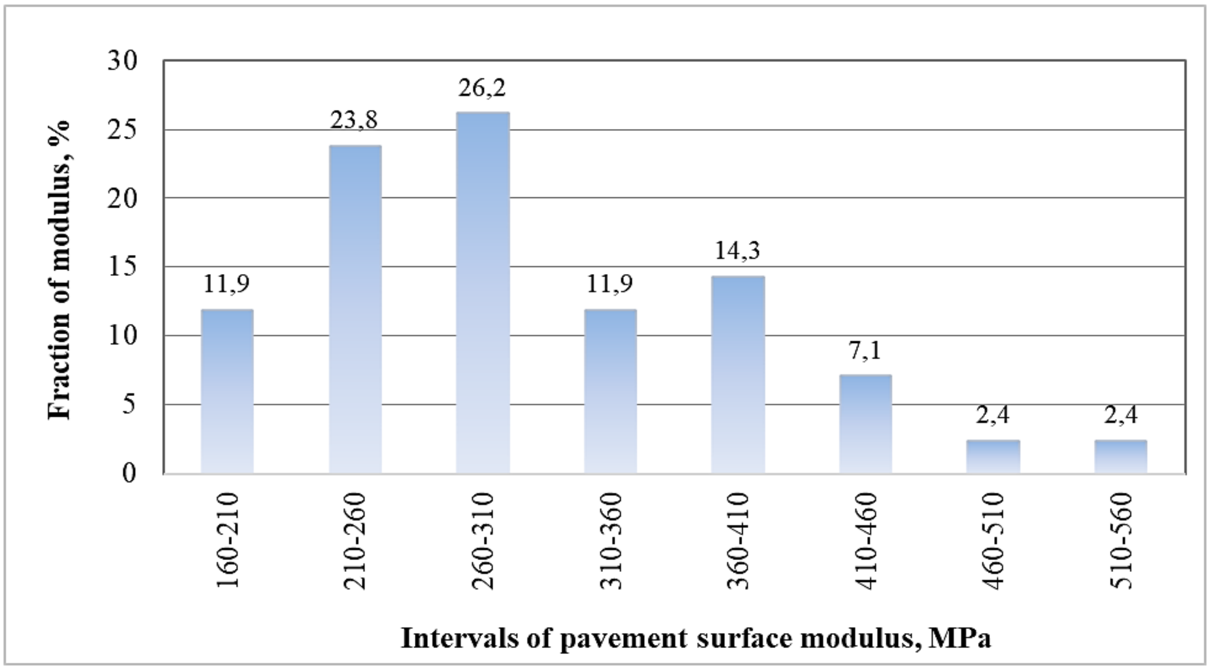

Fig. 10 Distribution of surface modulus.

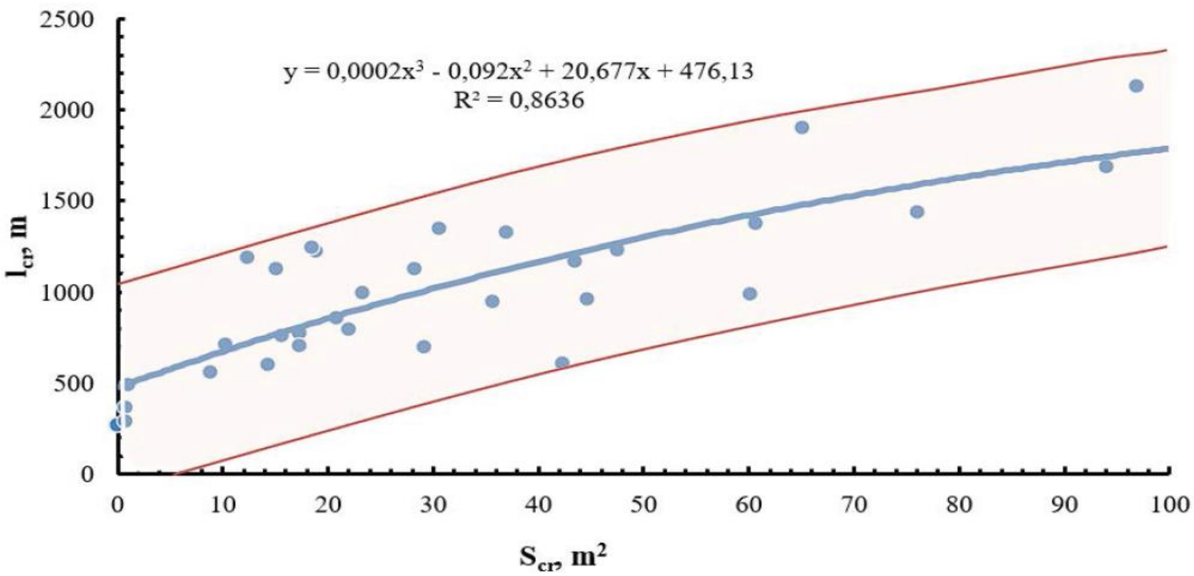

Fig. 11 Correlation between S_{cr} and l_{cr}.

pavement and subgrade.

4.7 Correlation dependences

Figure 11 shows that there is a good correlation between the values of the total lengths of longitudinal and transverse cracks and the areas of block cracks: with an increase in the area of block cracks, the total length of longitudinal and transverse cracks also increases.

Figure 12 shows that there is the following correlation between the roughness of the pavement surface and the rut depth in the considered highway section: if the rut depth is up to 9 mm, the roughness of the pavement (IRI) is directly proportional to it; a further increase in the rut depth does not affect the roughness. The nonlinear correlation dependence we established is in good agreement with the results of similar studies presented in the work,[49] which concluded that there is a positive correlation dependence between roughness (IRI) and rut depth, but it is nonlinear.

It turned out that the block cracks on the pavement surface does not practically affect the roughness of the pavement surface (Fig. 9S).

4.8 Temperature

Figure 13 shows that in 2021, the hottest weather occurred on July 21-22 and August 21-23. The air temperature was 36-37 °C. In 2022, the hottest days were on June 22-23 and July 14-15. The air temperature reached 35 °C. On those days, the temperature of the upper part (depth 3 cm) of the asphalt concrete pavement reached 46-48 °C. As it is known, the pavement surface temperature will be higher. The upper part

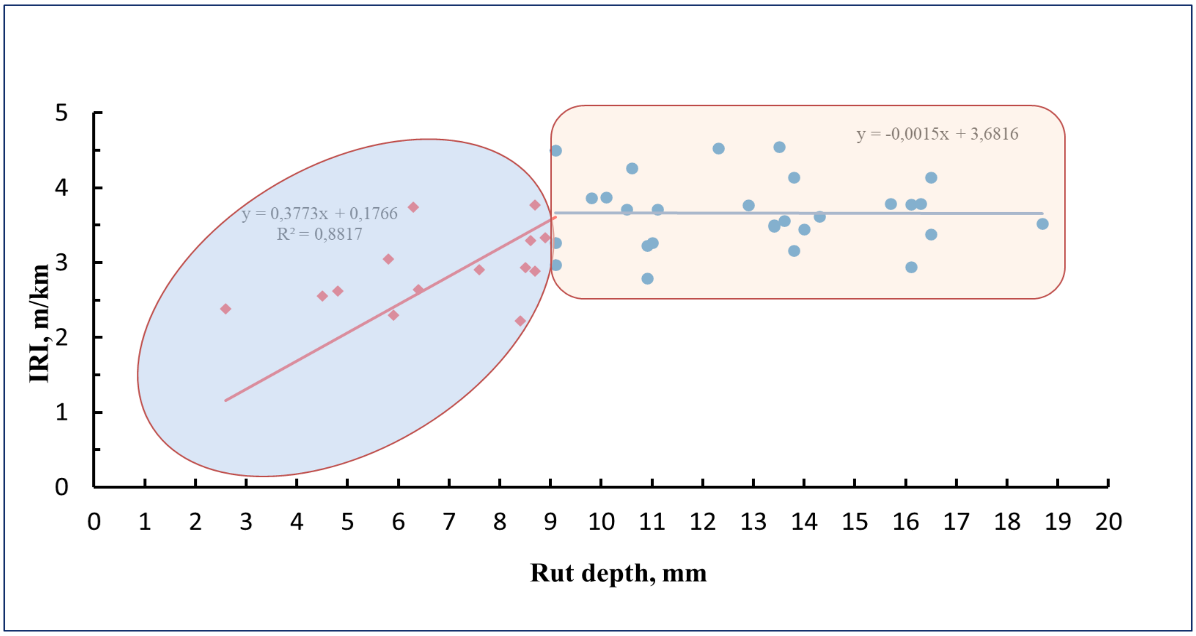

Fig. 12 Correlation between roughness (IRI) and rut depth.

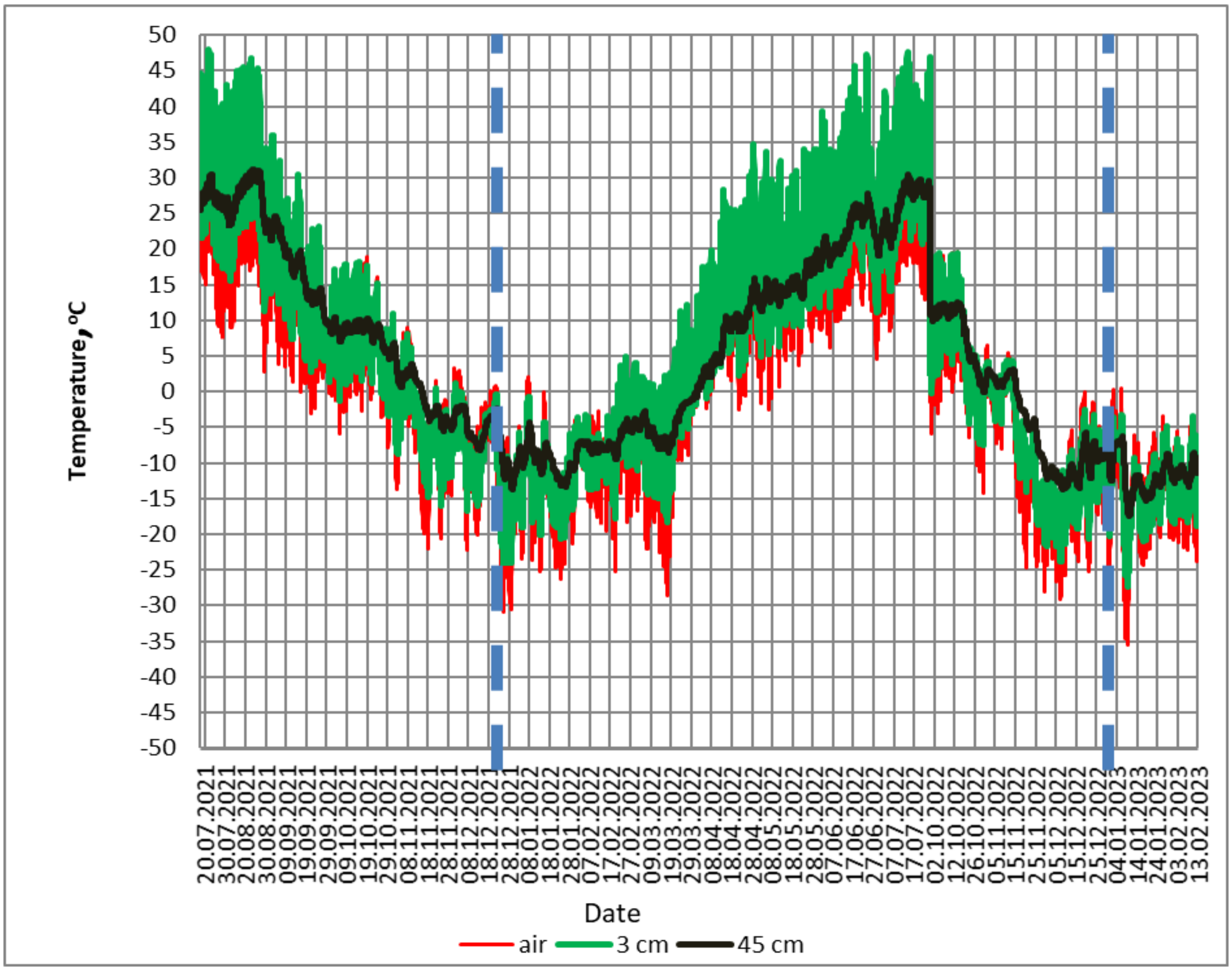

Fig. 13 Air temperature, temperatures in the upper part (depth 3 cm) of the asphalt concrete pavement and in the rigid base layer (45 cm).

(depth 2 cm) of the layer of crushed stone and sand mixture treated with cement heated up to 36-37 °C.

In the third decade of December, 2021 and at the end of the first decade of January 2023, the air temperature dropped to -32 °C and -36 °C, respectively. In the upper part (depth 3 cm) of the pavement on those days of winter in 2021-2022 and 2022-2023, the lowest temperatures were -24 °C and -28 °C, respectively; the temperature of the upper part (depth of 2 cm) of the layer of crushed stone and sand mixture treated with cement dropped to -18 °C and -25 °C, respectively.

The above data show that the annual fluctuations in air temperature, temperatures of the upper part (depth 3 cm) of the pavement and the upper part (depth 2 cm) of the layer of crushed stone and sand mixture treated with cement reached 73 °C, 76 °C and 62 °C, respectively.

During the winter there are several dozen sharp and prolonged temperature drops in the asphalt concrete layers and in the layer of crushed stone and sand mixture treated with cement (Fig. 10S), reaching significant negative temperatures: in the pavement from -14 °C (November 3, 2021) down to -36 °C (January 1, 2023); in the layer of crushed stone and sand mixture treated with cement: from -12 °C (December 13, 2021) to -25 °C (January 10, 2023).

At the end of September, the upper part of the pavement begins starts freezing. The maximum freezing depth (Fig. 11S) is almost 3 m (approximately May 5, 2022). The thawing of the upper part of the pavement begins at the end of the second decade of February (February 20, 2022). In early April (approximately April 2-4, 2022), the thaw reaches the subgrade surface (55 cm from the pavement surface). Complete thawing of the active layer (150 cm from the pavement surface) occurs around April 23-25.

5. Conclusions

Due to the high moisture during the spring thawing significant accumulation of plastic strains is possible in the upper part of the subgrade. Block cracks as a type of distress of the asphalt concrete pavement are not the main one on this highway section. Longitudinal and transverse cracks as a type of destruction of the asphalt concrete pavement is, apparently, the main one on this highway section. In this severe climatic conditions some of these cracks appeared in the asphalt concrete pavement, and their predominant part appeared due to thermal shrinkage from the layer of crushed stone and sand mixture treated with cement. The average rate of increase in the rut depth for the two thirds (66%) of the length of the section was 3.7 mm/year. The surface modulus (deflection) of the pavement is a "sensitive" indicator to mechanical inhomogeneous in structural elements of the pavement and subgrade. There are correlation dependences between the total lengths of (single) longitudinal and transverse cracks and areas with block cracks, roughness (IRI) and rut depth: 1) the greater the total length of single cracks, the larger the pavement surface area with block cracks; 2) the roughness of the pavement surface is directly proportional to the rut depth up to 9 mm, and a deeper rut does not affect the roughness.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Applicable.

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