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ANALYSIS OF KEY TRENDS IN PAVEMENT CRACKING ON ROADS

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ABSTRACT: The formation and propagation of cracks in asphalt concrete pavements remain one of the critical challenges affecting the durability and safety of road infrastructure. This study presents the results of field observations conducted across various climatic regions of Kazakhstan to identify the correlation between climatic conditions and the intensity of transverse crack development. The collected data demonstrate that climatic conditions of the region influence the stress-strain behavior of asphalt concrete, promoting the emergence of temperature-induced cracking. Based on the analysis conducted, the study proposes a technological approach to pavement design that emphasizes the consideration of climatic factors in selecting asphalt concrete mixtures, particularly those incorporating polymer-modified bitumen binders. A key parameter recommended for inclusion in design calculations is the coefficient of thermal expansion and thermal conductivity, both of which significantly affect the distribution of thermal stress throughout the pavement system. The proposed approach enhances the crack resistance of road pavements by integrating thermophysical and mechanical characteristics of construction materials under unstable climate conditions. This facilitates the development of adaptive pavement structures capable of withstanding adverse thermal influences, thereby increasing the structural performance and long-term stability of the road network.

Keywords: Asphalt concrete, Transverse cracking, Climatic conditions, Thermal stress, Pavement durability

1. INTRODUCTION

During the construction and reconstruction of road embankments and the stabilization of subgrade layers, engineering problems often arise that require an understanding of moisture and temperature distribution in the soil mass [1]. The mechanical behavior of soils is closely related to their thermophysical properties, which significantly influence the formation of defects such as cracking [2]. An increase in soil moisture, especially in fine-grained soils, leads to the formation of thick water films around soil particles, separating microaggregates.

Under such conditions, interparticle adhesion is mainly determined by molecular and energy interactions, which depend on thermophysical characteristics such as thermal conductivity, heat capacity, and thermal expansion [3]. The formation of cracks in soils and road pavement materials is largely due to natural and climatic factors that alter the mechanical behavior of embankment structures [4]. Fluctuations in ambient temperature and changes in material moisture content have a noticeable effect on the development of cracks in various types of road pavements [5]. Researchers emphasize the significance of various factors influencing the intensity of crack formation in pavement structures. In many European countries, particular attention is given to the investigation of the rheological properties of road bitumen and polymer-bitumen binders [6]. Furthermore, field observation data on crack development during the service life of asphalt concrete pavements is regarded as highly important in modern pavement engineering practice [7].

It has been established that the occurrence of transverse cracks depends not only on climatic, traffic, and material-related factors, but also on structural characteristics of the pavement, including the friction coefficient between the asphalt layer and the underlying base. According to studies [8], the presence of cracks does not have a significant impact on traffic safety but does lead to increased maintenance costs and contributes to the development of other types of damage, such as raveling, potholes, and related forms of deterioration. Through these cracks, solar radiation and atmospheric oxygen penetrate the pavement structure, accelerating the aging processes of bitumen and mineral components. In one of the works [9], the effect of thermo-oxidative aging and test temperature on the cracking resistance of asphalt mixtures was investigated. Two types of asphalt mixtures were selected: Asphalt Concrete with a maximum aggregate size of 13 mm and Stone Mastic Asphalt with a maximum aggregate size of 13 mm. Mixtures were subjected to different aging levels and tested at various temperatures using the direct tension method.

A comprehensive Cracking Resistance Index was developed based on multiple mechanical indicators, applying the entropy weight method and TOPSIS. Results showed that short-term aging improves cracking resistance, while long-term aging decreases it. SMA-13 demonstrated superior performance compared to AC-13 under all test conditions.

Scientists [10] have noted the impact of climate change on fatigue cracking of asphalt pavements in seven provinces of China. The analysis considered temperature fluctuations and frozen zone migration, introducing the Fatigue Cracking Climate Index to assess this influence. Results showed that rising temperatures increase fatigue cracking, while frozen zone migration partially mitigates this effect. The study examined four long-term pavement sections in New York and California, covering flexible and composite pavements [11]. Analyses of thermal cracking and rutting under different traffic and climate conditions showed that additional asphalt layers reduced rutting, whereas chip seal layers demonstrated low resistance, particularly under heavy traffic and freezing conditions.

Thus, sharp diurnal and seasonal temperature fluctuations, along with the aggressive impact of climatic factors, rank among the key causes of cracking in road pavements. Kazakhstan's climate is sharply continental and arid: the mean annual temperature is +5.5 °C, daily temperature swings range from 0 to +25 °C or more, and annual precipitation over most of the territory falls between 100 and 500 mm [12].

In the northern and eastern regions, which lie within the West Siberian temperate climatic zone, mean annual precipitation reaches 350–650 mm, minimum temperatures can drop to –57.2 °C, and the winter season lasts up to six months, whereas summers are short and often hot (peaking at +42 °C).

Spring, lasting about one month from mid-April, is characterized by abrupt temperature changes; summer precipitation falls mainly as heavy showers (although some years see prolonged rains and cool summers), and frosts can occur even in June and August. Autumn is dry, with early nocturnal drops below 0 °C [13].

Despite extensive research, the issue of transverse cracking in road pavements under climatic fluctuations remains unresolved. Based on the results of field investigations, this study presents a technological approach to the design of road pavements.

2. RESEARCH SIGNIFICANCE

This study combines theoretical calculations and field tests to address the impact of daily temperature fluctuations on pavement cracking. A linear relationship is observed between the daily temperature range and the coefficient of thermal expansion of soils in subgrade layers. Field observations confirm that regions with the highest daily temperature variations have the most intense transverse crack development. Based on the research conducted, an approach to the design of asphalt concrete mixtures is proposed that considers the thermal characteristics of the materials, which will allow for improved resistance to temperature-induced cracking and enhance the overall durability and service life of pavements in regions with unstable climatic conditions.

3. MATERIALS AND METHODS

3.1 Theoretical Aspects of Factors and Causes of Crack Formation

Cracks in pavement structures manifest in various forms and configurations due to numerous factors acting at both microstructural and macro levels. The classification of cracks is based on their morphological characteristics, orientation, depth, and mechanisms of formation. The most common types of cracks include transverse, longitudinal, fatigue, radial, block, and reflective cracks [14]. Transverse cracks are predominantly oriented perpendicular to the direction of traffic flow and typically result from cyclic thermal stresses. Daily temperature fluctuations induce expansion and contraction of pavement materials, leading to the accumulation of internal strains and, ultimately, crack formation.

Thermal cracks usually initiate in the upper asphalt layers and reflect the thermal brittleness of the material. Longitudinal cracks run parallel to the direction of traffic and are associated with stresses caused by uneven subgrade settlement, mechanical vehicle loads, and dynamic forces, often indicating insufficient structural support or deviations from proper construction practices [15].

Fatigue cracking is characterized by interconnected small cracks resembling a reptile's skin pattern and signifies material aging, loss of elasticity, and fatigue damage due to repeated load cycles. Fatigue cracks deserve particular attention, as they originate as microcracks that gradually coalesce into larger fractures, significantly diminishing the pavement's load-bearing capacity.

Radial and block cracks often develop at stress concentration zones linked to deformations in the underlying pavement layers, which also contribute to the initiation and propagation of reflective cracking, as shown in Figure 1.

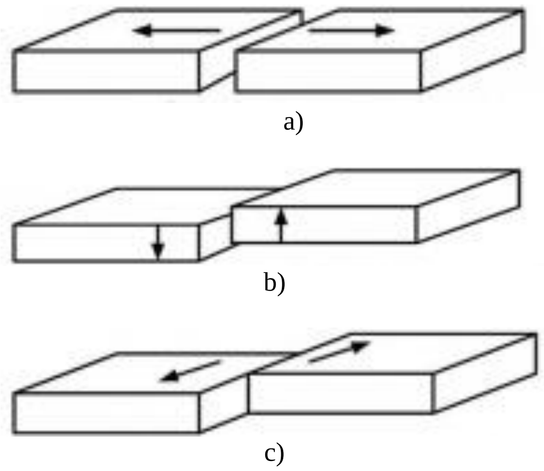

Fig. 1 Types of deformations in the underlying layer of the pavement: a) horizontal movement, b) vertical movement, c) parallel movement

Pavement damage and deterioration are influenced by several key factors [13]. Climatic conditions, including daily and seasonal temperature fluctuations, precipitation, and humidity, create thermal stresses that can lead to frost cracking and accelerated aging of the pavement. Terrain relief, characterized by slopes, landscape features, and drainage conditions, contributes to base shifts, uneven deformations, and crack formation.

Moisture conditions, such as water penetration and accumulation within the pavement layers, result in the loss of material adhesion, corrosion, and the development of microcracks. Traffic intensity, defined by the number of vehicles and their loads, leads to fatigue damage, microcrack propagation, and rutting. The composition of traffic also plays a role: heavy vehicles impose greater stresses compared to passenger cars, accelerating pavement deterioration [16].

Finally, the design and materials used, including the type, thickness, and structure of pavement layers, significantly affect the pavement's strength, thermal deformation resistance, and overall fatigue performance. Understanding these factors is crucial for improving pavement durability and maintenance strategies. Each crack type arises from the complex interplay of various factors, including climatic conditions, traffic loads, structural design, and material properties.

3.2 Impact of Thermophysical Characteristics on Pavement Performance

The thermal conductivity of soil is significantly influenced by its density, moisture content, and porosity [17]. As porosity decreases, soil density increases, particles are packed more tightly, and the thermal conductivity of the material decreases. Additionally, soils with the same mineral composition exhibit a higher specific heat capacity in a moist state compared to a dry state, due to the greater heat storage ability of water contained within the pore spaces [18]. These phenomena affect the degradation processes of the pavement foundation and contribute to the formation of cracks in the upper layers of the pavement structure.

The resistance of a material to the formation of various types of cracks is determined by a combination of its thermophysical (coefficient of linear thermal expansion), deformational (relaxation modulus at the design low temperature), strength-related (ultimate structural strength), and fatigue-related (level of accumulated damage) characteristics. Thermal expansion is taken into account when assessing the material's susceptibility to temperature-induced cracking [19]. The most commonly used parameter in such assessments is the coefficient of linear thermal expansion.

The studies conducted by A.M. Boguslavsky [19] demonstrated that the coefficient of linear thermal expansion of asphalt concrete mixtures varies depending on the type of mixture and the grade of binder used. Experimental results, obtained under constant cooling conditions (temperature gradient of 10 °C, cooling duration of 3600 seconds), revealed significant differences in the deformation characteristics of the materials.

The effect of cooling rate on relative strain underscores the need to consider thermal conditions in pavement design. A relationship was proposed to estimate conditional thermal strain, noting that relaxation mainly reduces thermal tensile stresses rather than deformations. As emphasized by B.I. Ladygin [20], selecting an appropriate crack resistance criterion—one that reflects the actual stress state of the asphalt concrete and the specific climatic conditions of the construction region—is essential for enhancing the durability and performance of asphalt concrete pavements.

The conditional thermal strain is determined by the equation:

$$\varepsilon=\frac{(\alpha_1-\alpha_0)\cdot(\theta_2-\theta_1)\cdot E\upsilon_1}{(1-\mu)\cdot\upsilon_0} \qquad (1)$$

where:

α_1, α_2 - coefficients of thermal expansion of asphalt concrete and the base layer at temperature;

Θ_2, Θ_1-final and initial cooling temperatures;

E -modulus of elasticity;

υ_1 - cooling rate from $\Theta_1 to\ \Theta_2$;

υ_0 - equilibrium cooling rate during internal stress relaxation;

μ - Poisson's ratio, depending on the types of pavement materials and bitumen.

In determining the coefficient of thermal expansion (ε) under temperature variations in the subgrade layer of the pavement structure, various soil types were considered with the corresponding Poisson's ratios: μ = 0.27 for coarse-fragmental soils, μ = 0.30 for sand and sandy loams, μ = 0.30 for loams, and μ = 0.42 for clay soils. The temperature difference in the base layers was assumed to range from 5 to 25 °C.

3.3 Field Investigation

During the roadway survey, the air temperature varied between +14-17°C. The sections under study included the following road segments and their respective regions:

- Almaty–Yekaterinburg Road, km 547–375 and 913–1100 (Kostanay and East Kazakhstan regions, temperature fluctuations up to 25–30°C), surveyed 5 sections;
- Omsk–Maikapshagai Road, km 191–324 (North Kazakhstan region, fluctuations around 20–25°C), surveyed 3 sections;
- Aktobe–Uralsk Road, km 193–526 (Aktobe region, fluctuations 15–20°C), surveyed 4 sections;
- Dossor–Kulsary–Beyneu–Sai Utes–Aktau Road, km 0–332 (Mangystau and Atyrau regions, fluctuations 10–15°C), surveyed 6 sections.

Section 1 of the «Omsk-Maikapshagai» road (km 310–324) passes through a highly water-saturated area. The roadside zone of this section runs through a permanently wet area, such as a river floodplain, locations where stagnant water accumulates due to insufficient surface drainage from the side ditches of the road embankment. The feature of this road is the application of high-strength materials in the base layers of the pavement structure (Fig.2).

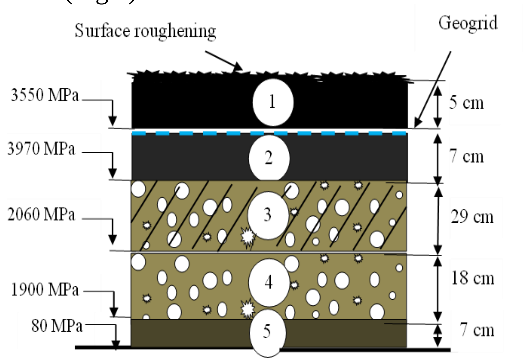

Fig.2 Road pavement structure: 1 – fine-grained asphalt concrete; 2 – coarse-grained asphalt concrete; 3 – crushed stone–sand mixture; 4 – reclaimed asphalt concrete; 5 – coarse-grained sand

The upper base layer (29 cm) consists of a crushed stone–sand mixture stabilized with 25% bauxite residue and 5% Portland cement, while the lower base layer (18 cm) is made of reclaimed asphalt concrete blended with 40–70 mm crushed stone and stabilized with 5% Portland cement (M-400). A 7 cm layer of coarse-grained sand is placed beneath the base layers.

Visual inspection of the pavements was carried out using a mobile laboratory installed on a Gazelle vehicle. The operating speed was 25-30 km/h, providing an optimal balance between the detail of visual inspection and the efficiency of data collection. During the survey, continuous video recording of the road surface was carried out with subsequent transcription of the recordings in camera conditions. The focus of the visual diagnosis was on fixing pavement cracks, particularly transverse and longitudinal cracks. Based on the measurements obtained, the average distance between transverse cracks was calculated, which was one of the key indicators of the current condition of the pavement. The calculation was performed by dividing the total length of the surveyed section by the number of registered cracks of the corresponding type.

4. RESULTS AND DISCUSSION

4.1 Survey Results of Pavement Cracks

As the calculation results present, an increase in the temperature gradient within the base layers of the pavement structure leads to a corresponding increase in the coefficient of thermal expansion.

For loams, sands, and sandy loams, the coefficient of thermal expansion (ε) shows a steady increase with rising temperature, reflecting the stable thermal behavior characteristic of soils with fine and medium grain sizes. The data indicated a clear linear relationship between temperature variation and thermal expansion across all examined soil types (Table 1).

Table 1. Coefficient of Thermal Expansion

Type of Soil	Coefficient of Thermal Expansion, ε				
	5°C	10°C	15°C	20°C	25°C
Loam, Sand, Sandy Loam	3.6×10^{-5}	7.1×10^{-5}	1.07×10^{-4}	1.43×10^{-4}	1.79×10^{-4}
coarse-grained soils	1.8×10^{-5}	6.8×10^{-5}	1.02×10^{-4}	1.37×10^{-4}	1.71×10^{-4}
Clay Soils	4.3×10^{-5}	8.6×10^{-5}	1.29×10^{-4}	1.72×10^{-4}	2.16×10^{-4}

Such uniform dynamics indicate a predictable response of these soils to thermal effects, which is crucial when using them as a base for road pavements. In contrast, coarse-grained soils exhibit lower ε values across the temperature range, indicating reduced susceptibility to thermal deformation due to their granular structure and weak cohesion, which limit internal stress accumulation during temperature fluctuations.

Clay soils show the most pronounced thermal expansion, with ε increasing sharply as temperature rises, reflecting high plasticity and moisture retention. These properties amplify volume changes under thermal influence, making clayey foundations particularly sensitive to temperature fluctuations and prone to thermal cracking and heaving.

This necessitates careful consideration when designing road structures in regions with unstable temperatures. The data highlights the key role of soil type in predicting and managing thermal behavior in geotechnical applications. The high thermal expansion and low porosity of clay soils significantly increase the risk of pavement defects under variable temperature conditions. Over 10 thousand cracks were identified along the entire length of the surveyed roads (Table 2).

Table 2. Distribution of cracks on the roads surveyed

Road	Surveyed sections	Number of cracks
Almaty-Yekaterinburg Road	1	2499
	2	1948
	3	352
	4	3244
	5	1998
Aktobe-Uralsk Road	1	145
	2	548
	3	188
	4	297
Dossor-Kulsary-Beyneu-Sai Utes-Aktau Road	1	480
	2	246
	3	356
	4	276
	5	264
	6	290
Omsk-Maikapshagai Road	1	93
	2	221
	3	179

Figures 3 and 4 illustrate the findings from the crack survey. Figure 3 shows the general appearance and typical pattern of the identified cracks, while Figure 4 presents the average distance between cracks across the surveyed road sections.

The average interval between cracks on different sections is different and varies from 4.52 m (km 289-291 of Omsk-Maikapshagai road) to 25.14 m (km 537-551 of Arkalyk-Petropavlovsk road). The average distance between cracks on the sections of the road «Aktobe-Uralsk» fluctuates within laver=5.7-20.6 m, there is a big difference between the sections.

Fig.3 Cracking in the pavement layers of Section of the Omsk-Maikapshagai road.

The distribution of cracks is presented in Table 3.

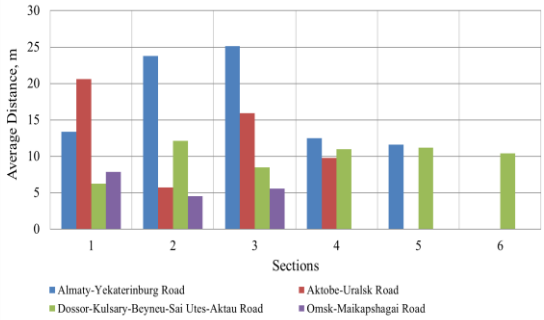

Fig.4 Average crack spacing along the surveyed road sections

On the road section «Omsk-Maikapshagai» on the surveyed sections, the frequency of transverse cracks formation is approximately the same laver 4.52-7.85 m.

The main reason for the difference in the frequency of transverse crack occurrence is primarily related to the service life of the roads after reconstruction. At low service life, the number of transverse cracks reaches its maximum, while on well-established roads, it is minimal.

In addition, the occurrence of cracks largely depends on daily temperature fluctuations and the dynamic impact of traffic loads. In Pavlodar Region, winter daily temperatures range from –12 to –27 °C, in Atyrau Region from –2 to –12 °C, and in Aktobe and West Kazakhstan regions from –4 to –12 °C. Thus, for the 'Aktobe–Uralsk' road, the average crack spacing decreases from 20.6 m to 5.7 m (a difference of 14.9 m); for the 'Dossor–Kulsary–Beyneu' road, from 12.1 m to 6.24 m (a difference of 5.86 m); and for the 'Omsk–Maikapshagai' road, from 7.85 m to 4.52 m (a difference of 3.33 m). Reflective cracks are shown in Figure 5.

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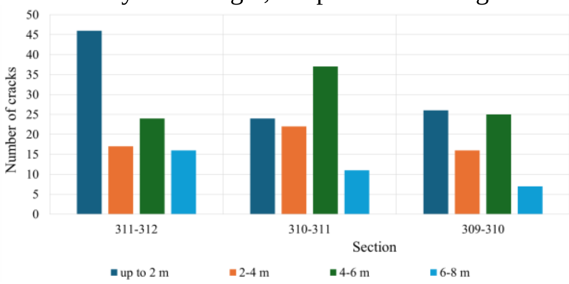
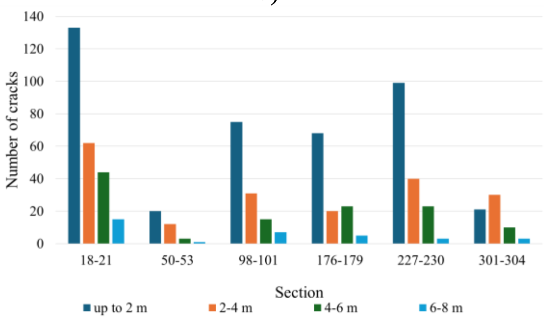
Fig.5 Reflective cracks in the Omsk–Maikapshagai road

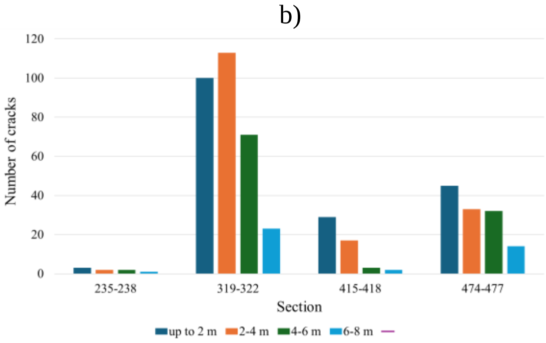
The results of the identified transverse cracks, classified by their length, are presented in Figure 6.



a)



b)



c)

Fig.6 Results of observing a) Omsk-Maikapshagai Road; b) Dossor-Kulsary-Beyneu-Sai Utes-Aktau Road c) Aktobe-Uralsk Road

Each surveyed section is 3 km in length. Sections 311-312 had the largest number of cracks up to 2 meters in length (46 cases), indicating significant damage to the surface layer of the pavement. At the same time, a significant number of cracks in other length ranges are also present, indicating the varied nature of the damage. The average spacing between cracks is 5.7 m, indicating about evenly distributed.

Sections 310-311 were characterized by relatively fewer short cracks (24 up to 2 m), but had the largest number of long cracks in the 4-6 m category (37 pieces), indicating deeper structural defects in the pavement. The average crack spacing was the smallest at 5.4 m, indicating a high density of damage.

At sections 309-310 (Fig.6a), the distribution of cracks is relatively balanced: short and medium-length cracks predominate. At the same time, despite the largest distance between cracks (5.7 m) and fewer long cracks, the total number of damages remains significant. This indicates the beginning of the fracture process.

The survey results revealed significant variations in the distribution and severity of transverse cracks across the investigated sections. The highest crack density was recorded at section 18-21 (Fig.6b), with 133 cracks up to 2 m long, 62 cracks between 2-4 m, and 44 cracks between 4-6 m, indicating progressive pavement deterioration. Sections 227-230 and 98-101 (Fig.6b) also showed elevated crack density in the up-to-2 m category (99 and 75 cracks, respectively) due to similar operating conditions.

In contrast, sections 50-53 and 301-304 of the Dossor-Kulsary-Beyneu-SaiUtes-Aktau Road exhibited fewer cracks (36 and 21 in the up-to-2 m category, respectively), reflecting lower levels of damage. The average crack spacing ranged from 6.24 m at sections 18-21 to 12.1 m at section 50-53, with higher values (10.4-11.2 m) at sections 176-179, 227-230, and 301-304, indicating moderate crack density. Sections 98-101 had a mean spacing of 8.5 m, linked to uneven crack distribution.

Sections 319-322 (Fig.6c) showed the most severe cracking, with 100 cracks up to 2 m, 113 cracks between 2-4 m (the highest among all sites), and 71 and 23 cracks in the 4-6 m and 6-8 m ranges. This pattern suggests active structural failure beyond the surface layer.

Conversely, sections 235-238 and 415-418 exhibited minimal cracking, with only 8 cracks in section 235-238. Sections 474-477 of the Aktobe-Uralsk Road demonstrated intermediate conditions, with 124 total cracks and signs of early structural failure. Crack spacing exceeded 21 m in sections 235-238 and 415-418, contrasting with the 12.8 m and 16.8 m spacing at sections 319-322 and 474-477, respectively.

Table 3 summarizes the number of transverse cracks across the width of the carriageway and the average distance between cracks for several surveyed sections on different road segments. This data provides insight into the frequency and distribution of transverse cracking along each section, which reflects the condition and structural performance of the pavement.

Table 3. Comparison of transverse cracking characteristics across different road segments

Section, km	Number of Transverse Cracks, pcs	Average Distance Between Cracks, m
Omsk-Maikapshagai Road		
311-312	73	13.7
310-311	9	11.2
309-310	101	10.6
Dossor-Kulsary-Beyneu-Sai Utes-Aktau Road		
18-21	226	13.3
50-53	210	14.2
98-101	228	13.3
176-179	160	19.0
227-230	99	29.8
301-304	226	13.3
Aktobe-Uralsk Road		
235-238	137	21.8
319-322	241	12.8
415-418	137	21.9
474-477	173	16.8

The data reveal noticeable variation in the frequency of transverse cracks across different road sections. For example, sections of Road «Omsk-Maikapshagai» exhibit a relatively low number of cracks (from 9 to 101), with average spacing ranging between 10.6 and 13.7 meters, indicating moderate pavement conditions.

4.2 Practical Recommendations

The results of field studies made it possible to identify the dependence of the dynamics of transverse crack growth on the climatic conditions. These findings confirm the need for preventive measures at the early stages of defect formation.

Based on the obtained results, it has been established that the optimal period for crack sealing is early spring, when the pavement temperature reaches +5…+15 °C, but the cracks have not yet closed. An effective solution is the use of hot-applied rubber-bitumen mastics, which have proven to be the most durable under the cold climate conditions of Kazakhstan and Central Asia. After cleaning, the cracks should be filled with sealant and then covered with a mixture of granite screenings and mineral powder to improve adhesion and protect the pavement surface [21].

In parallel with crack prevention measures, the design of asphalt concrete mixtures should consider both mechanical and thermal properties to enhance pavement durability. Key material characteristics include the strength, elasticity, and plasticity of polymer-bitumen binders, the particle size of fillers, and the thermal expansion and conductivity of pavement layers. Climatic factors such as temperature fluctuations and humidity must also be evaluated.

Mathematical modeling allows the asphalt mixture composition with its thermophysical properties, such as the thermal expansion coefficient (ε) and thermal conductivity (λ). By applying numerical optimization and simulating thermal deformations under local climate conditions, it is possible to determine the optimal component ratios that minimize thermal stresses. This integrated methodology ensures that thermal expansion and conductivity parameters are systematically accounted for in the design of asphalt concrete mixtures, thereby improving crack resistance and extending the service life of road pavements.

5. CONCLUSIONS

Field surveys of road pavements across different regions of Kazakhstan have shown significant variations in the density and spacing of transverse cracks, strongly influenced by climatic factors and the service life of road structures. Roads in regions with high daily temperature fluctuations and prolonged winters, such as northern and eastern Kazakhstan, demonstrate the highest crack density and the shortest spacing between cracks. The average distance between cracks varies widely, from 4.52 m on the Omsk-Maikapshagai road to 25.14 m on the Almaty-Yekaterinburg road, reflecting different levels of structural fatigue and surface wear.

Reflective cracking was identified as a particularly critical issue, as it develops much faster than cracking in newly built pavements. While it can take decades for cracks to appear in the underlying layers, reflective cracks may form in overlaid reinforcement layers within just 1–3 years, reducing the overall service life of rehabilitated pavements. The rapid widening of these cracks, from 0.5–1 mm to over 7 mm, underscores the importance of addressing this issue in maintenance planning.

The results of the study emphasize the necessity of integrating thermophysical parameters—such as thermal expansion and thermal conductivity—into asphalt mixture design and pavement maintenance strategies. This approach will enhance crack resistance, improve structural performance, and extend the lifespan of road pavements, especially under difficult climatic conditions.

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