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Article

Calculation of model stresses from a motor vehicle wheel on the contact patch, depending on tire pressure

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Abstract. This article presents part of a model study on the abrasion resistance of an anti-icing agent impregnation composition, related to the calculation and modeling of stresses transmitted by a model wheel to a concrete road, taking into account actual indicators and scaling. The aim of the research was to assess the normal stresses arising from the impact of motor vehicles, taking into account the variability of the contact patch resulting from a decrease or increase in tire pressure. Calculations were performed for different types of vehicles, from bicycles to trucks, which were conditionally divided into categories A1-A5 (in ascending order of vehicle weight). The calculation results are presented as ranges of normal stresses on the road surface caused by the operation of motor vehicles, depending on their type and standard load capacity. The calculations were performed using the linear graph method of universal tire characteristics, taking into account normal deflection and variable potential pressure in the tire. The obtained calculation results will allow for more accurate development of calculation schemes in numerical or large-scale modeling of road situations.

Keywords: abrasion, contact patch, icing, modeling, road surface, tension, pressure.

Introduction.

Road construction plays a key role in the economic development of any country, ensuring territorial connectivity, mobility of the population, and the stable functioning of logistics systems. The quality and durability of road infrastructure directly affect transportation efficiency, safety indicators, and long-term maintenance costs. In modern road construction practice, particular attention is paid not only to structural strength but also to operational reliability under varying climatic conditions. The emphasis is on creating safe and comfortable traffic conditions while ensuring the long service life of pavement structures with minimal repair interventions. Technologies for constructing cement concrete and asphalt concrete pavements are widely used in the modern road industry [1]. The selection of pavement type depends on traffic intensity, climatic factors, economic considerations, and lifecycle performance requirements. Cement concrete roads possess a number of significant advantages compared to asphalt concrete pavements, including extended service life, high compressive strength, resistance to rutting, and improved performance under repeated freeze–thaw cycles [2]. Their structural rigidity allows for more uniform load distribution, which is especially important under heavy traffic conditions. In addition, cement concrete pavements demonstrate relatively stable mechanical characteristics at elevated summer temperatures, where asphalt pavements may experience softening and deformation. Despite these advantages, cement concrete pavements also have certain limitations. One of the most critical issues in cold regions is the formation of ice on the road surface at low temperatures, which significantly reduces skid resistance and poses a serious threat to traffic safety [3]. The relatively smooth surface texture of concrete and its hydrophilic nature contribute to water retention and subsequent icing under freeze–thaw conditions. In regions with prolonged winter periods, this problem becomes particularly acute. Although accident statistics during winter months do not always show a dramatic increase in the total number of road accidents compared to other seasons, the nature and causes of accidents differ substantially. In warmer periods, road accidents are typically associated with driver behavior, vehicle condition, or traffic density. In winter, however, an additional and often decisive risk factor emerges — icing of the pavement surface [4]. Even at minimum permissible speeds, vehicles may lose traction due to reduced adhesion between tires and the icy surface. Sudden skidding and loss of vehicle control can occur even under seemingly stable driving conditions. Therefore, preventive measures aimed at reducing ice formation and ice adhesion to the pavement are of considerable practical importance. Currently, the most widespread approach is the chemical method, which involves treating road surfaces with solid or liquid reagents that lower the freezing point of water and prevent ice formation. Combined methods, such as sand–salt mixtures, are also widely used. However, chemical reagents may accelerate pavement degradation, contribute to reinforcement corrosion, and negatively affect the environment [5]. The structural method focuses on modifying the surface layer of the pavement itself by introducing materials or coatings with inherent anti-icing properties. Although this approach can provide longer-term performance, it typically increases construction costs and requires careful technological implementation. Given these limitations, the development of effective and economically justified methods for protecting cement concrete pavements from icing remains a relevant research problem. A promising direction is the use of surface impregnations that do not require frequent reapplication and are capable of significantly reducing, or potentially eliminating, ice formation and adhesion [6]. In addition to technical performance, economic feasibility and ease of application are important criteria for practical implementation [7].

The ice-repellent impregnation composition proposed in this study is designed to reduce the adhesive resistance between ice and concrete surfaces. The bond strength between ice and concrete results from the combined action of two primary mechanisms: physicochemical adhesion at the material interface and mechanical interlocking of ice within the pore structure (micro- and macro-roughness) of the concrete surface. These mechanisms act synergistically, leading to a substantial increase in overall adhesive resistance. Therefore, reducing or eliminating one of the key components, namely interfacial adhesion, can significantly weaken the total bond strength of the ice crust. The proposed protective layer consists of an aqueous solution containing water-soluble polymer components. The use of a water-based system enables effective interaction with the hydrophilic surface of concrete. Due to capillary absorption, the solution penetrates into the near-surface pore structure, transporting the dissolved polymer components into the concrete matrix. As a result, the polymers migrate into the surface layer and partially coat the pore walls, forming a modified interfacial zone. This zone creates a stress-discontinuity layer that prevents ice and concrete from forming a rigid monolithic bond. Consequently, the ice layer can be detached under relatively small mechanical impact. However, the effectiveness of the impregnating composition depends on the depth and uniformity of polymer penetration into the concrete surface layer. These parameters are directly influenced by the concentration of components in the solution, viscosity, and absorption characteristics of the concrete. Therefore, determining the optimal concentration of the polymer components represents a key objective of the present study. The technological application process involves spraying the impregnating solution onto the pavement surface, forming a protective layer with ice-repellent properties.

Thus, the research is aimed at substantiating the effectiveness of a polymer-based impregnation capable of reducing ice adhesion to cement concrete pavements while maintaining practical applicability and economic feasibility.

The methodology

The methodology of the technological process for producing the anti-icing composition is shown in Figure 1. The polymer component is expected to be a colloidal dispersed polymer in combination with a keratin-containing component. Acrylic latex is proposed to be used as the colloidal polymer, and keratin-containing products will be manufactured from agricultural industry waste.

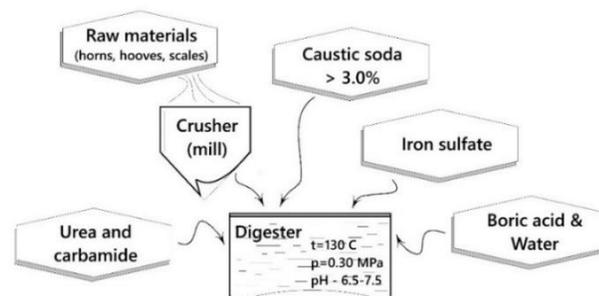


Figure 1. Technological diagram of additive production

The keratin-containing raw materials required for the production of ice-repellent coatings are of animal origin and include animal wool, hair, horns, hooves, and others. Before production begins, the keratin-containing components are prepared, precisely crushed and ground. Next, the raw materials are loaded into a boiling kettle with a weak concentration of boric acid in water (the ratio of water to raw materials is 1:3 by weight). At the same time, a mixture of urea in water is added (the water ratio is 2:3 by weight to the raw material). After the hydrolysis process at a temperature of 1300 °C for up to 10 hours, a pH acidity neutralizer, represented by iron sulfate, is added to the cooled mass.

To simulate the stresses transmitted by motor vehicles to cement concrete road surfaces, calculations were made for the wheel contact patch at its minimum and maximum standard loads. The stress calculations were necessary for subsequent large-scale tests based on the actual stress transmitted from the vehicle wheel to the concrete road surface. Motor vehicles were conditionally divided into five categories according to their load capacity, the characteristics of which are presented in Table 1, [10-14].

Table 1. Categories of motor vehicles

Category	GOST	Type of vehicle	Maximum permissible load, kN			
			single		double	
			Min	Max	Min	Max
A1	GOST 4750	bicycles	4.2	14.2	-	-
A2	GOST 5652	motorcycles, motor tricycles, motor scooters, and mopeds	2.6	5.7	-	-
A3	GOST 52900	passenger cars and trailers	0.98	3.29	-	-
A4	GOST 4754	light trucks and buses with particularly low capacity	0.29	0.85	-	-
A5	GOST 5513	trucks and buses	13.34	50.52	12.26	35.80

The contour area of the contact spot is calculated using the formula for the area of an ellipse, [13]:

$$F_{k_i} = \frac{\pi}{4} a_{k_i} b_{k_i} \quad (1)$$

where a_{k_i} and b_{k_i} — are the length and width of the contact patch of the tire tread with a flat, rigid surface, m.

The dimensions of the tire tread contact patch using universal tire characteristics parameters are proposed to be calculated using the following formulas:

$$a_{k_i} = \frac{20,5}{11,9 + \left| \frac{D}{B} - \frac{|n-9|}{2} - 3 \right|} \cdot \sqrt{D} \cdot f_{\text{ш}_i} - f_{\text{ш}_i}^2 \quad (2)$$

$$b_{k_i} = 2 \sqrt{2 \frac{B+H}{2.5} \cdot f_{\text{ш}_i} - f_{\text{ш}_i}^2} \quad (3)$$

where D — is the outer diameter of the tire;

B — tire profile width, m;

$H = (D - d)/2$ — tire profile height, m;

d — nominal rim diameter, m;

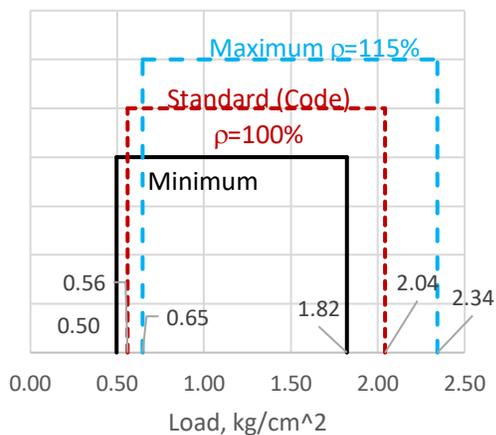
The dimensions of tires D , B , and the layer ratio n are given in table A.1 of GOST 7463 2003 [14], and the value $[f_{\text{ш}}]$ can be approximately determined using the known formula:

$$[f_{\text{ш}}] \approx D/2 - r_{\text{ст}} \quad (4)$$

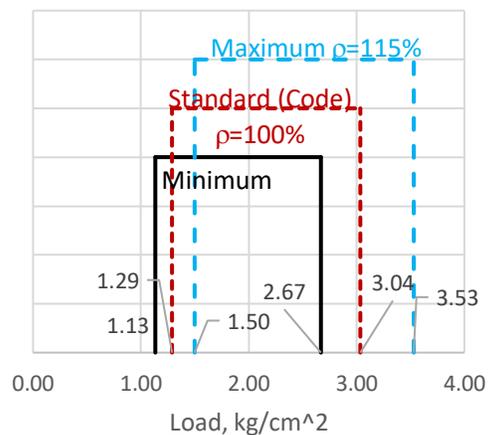
where $r_{\text{ст}}$ — static radius.

Findings/Discussion.

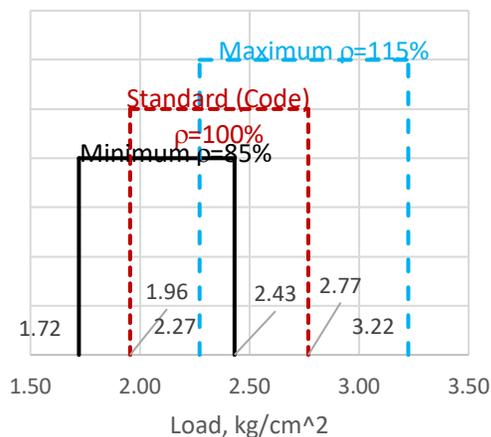
Figure 2 shows calculations of stresses transmitted from motor vehicles to the road depending on the wheel contact patch (more precisely, the range of stresses from minimum to maximum). Figures 2A–2E show the results of calculations by category, and Figure 2F shows a comparison of the stress ranges for all categories, depending on tire pressure. The variation in tire pressure was taken from a condition of $\pm 15\%$ of the standard, the permissible deviations of which vary in the range of $\pm 2.5\%$. When the pressure decreases, the static radius decreases and the static deflection increases, therefore the contact patch increases. Conversely, when the pressure increases, the contact patch will increase, and consequently, the stress transmitted by the wheel will also increase. The values of the maximum permissible loads, static radii, tire widths, outer diameters, and rim diameters were taken from GOST [9-13]. Thus, the wheel contact patch was determined from the conditions of standard ($\rho_{St} = 100\%$), minimum ($\rho_{min} = 85\%$) and maximum ($\rho_{max} = 115\%$) tire pressure. It is logical that when tire pressure is low, the contact patch increases, thereby reducing road stress. For bicycles, the minimum road pressure at the minimum permissible tire pressure is 0.50 kg/cm^2 (48.7 kN/m^2), and the maximum pressure at the maximum permissible tire pressure is 2.34 kg/cm^2 (229.8 kN/m^2). The same values, under similar conditions, for motorcycles are: minimum stress – 1.13 kg/cm^2 (111.2 kN/m^2); maximum stress – 3.53 kg/cm^2 (346.2 kN/m^2). For passenger cars, the minimum stress is 1.72 kg/cm^2 (168.8 kN/m^2) and the maximum stress is 3.22 kg/cm^2 (316.2 kN/m^2). For light commercial vehicles, the minimum stress is 2.62 kg/cm^2 (257.2 kN/m^2)



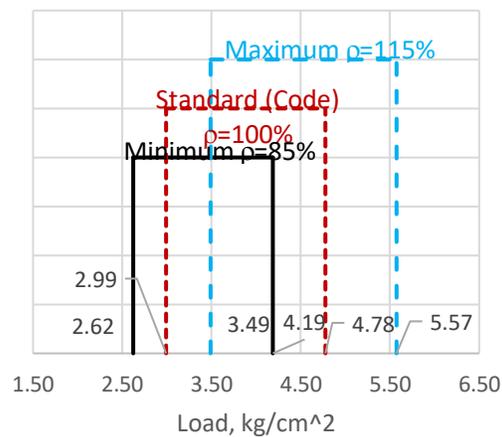
A - Category A1



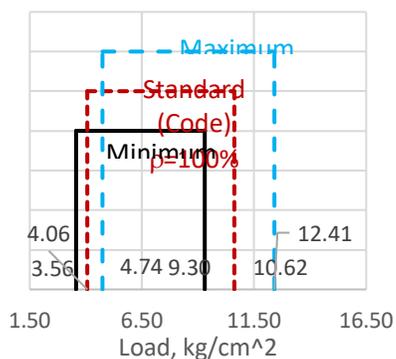
B - Category A2



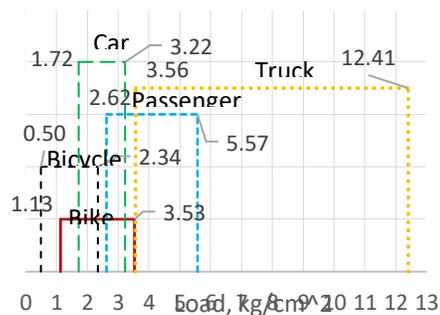
C - Category A3



D - Category A4



E - Category A5



F - Comparison

Figure 2. Wheel-to-road voltage ranges by category

For trucks, the minimum stress is 3.56 kg/cm² (349.4 kN/m²) and the maximum is 12.41 kg/cm² (1216.7 kN/m²). Thus, it is logical that trucks, due to their high weight relative to the size of their tires, transmit the greatest stress to the road. Moreover, given the degree of freedom of large trucks relative to the width of the lane, the degree of abrasion of the tread increases significantly. In other words, the width of the wheel's contact patch is smaller for large trucks than for small ones. Therefore, despite the relatively higher stress from a motorcycle (3.53 kg/cm² or 346.2 kN/m²) compared to a passenger car (3.22 kg/cm² or 316.2 kN/m²), the abrasion resistance of the impregnating compound for the latter will be higher.

Based on the data in Figure 2, a summary table of maximum permissible load limits by vehicle category was compiled (Table 2).

Table 2. Normal stress values from a motor vehicle wheel

Category		Spot area (S_t), cm ²			Stress on the road (σ_t)					
					ρ_{min}		ρ_{St}		ρ_{max}	
		ρ_{min}	ρ_{St}	ρ_{max}	kN/m ²	kg/cm ²	kN/m ²	kg/cm ²	kN/m ²	kg/cm ²
1	min	46.5	53.6	60.5	48.7	0.50	54.9	0.56	63.4	0.65
	max	25.6	29.4	32.9	178.7	1.82	200.2	2.04	229.8	2.34
2	min	85.2	99.1	112.7	111.4	1.13	126.7	1.29	147.4	1.50
	max	92.1	107.1	121.8	261.8	2.67	297.6	3.04	346.2	3.53
3	min	116.6	135.5	154.0	168.8	1.72	191.7	1.96	222.8	2.27
	max	173.7	202.3	230.3	238.5	2.43	271.5	2.77	316.2	3.22
4	min	146.6	171.0	194.9	259.0	2.62	295.3	3.01	344.5	3.51
	max	185.7	216.7	247.2	410.6	4.19	468.4	4.78	546.6	5.57
5	min	348.3	406.4	463.4	349.4	3.56	398.4	4.06	464.8	4.74
	max	362.9	423.9	484.1	912.1	9.30	1041.5	10.62	1216.7	12.41

Conclusion.

1) Calculations were made of the normal stress ranges from a motor vehicle wheel on the road surface, based on the standard characteristics of tires, permissible load values, and potential tire pressure.

2) For convenience, all motor vehicles were classified into categories based on their type,

purpose, and general characteristics reflecting their common properties: A1 – bicycles; A2 – motorcycles (mopeds); A3 – passenger cars; A4 – light trucks and buses with very low capacity; A5 – trucks and buses. For each category, stress ranges were calculated depending on the type of vehicle, the standard load capacity, and tire pressure.

3) For each category of motor vehicles, calculations of normal stresses on the road surface were performed: for category A1 the stress range is 48.7 kN/m² - 229.8 kN/m² (2.34 kg/cm²); for A2 111.4 kN/m² - 346.2 kN/m²; for A3 168.8 kN/m² - 316.2 kN/m²; for A4 259.0 kN/m² - 546.6 kN/m²; for A5 349.4 kN/m² - 1216.7 kN/m².

4) The results obtained will be useful for designing roadbeds and subgrade foundations, in particular for modeling vehicle loads in design schemes.

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The contribution of the authors:

L.T. Kabdyrova - data collection, editing

R.E. Lukpanov – concept, methodology, analysis, modeling

F.B. Abdushkurov – analysis, interpretation, visualization

M. Karacasu – editing.

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Шинаның қысымына байланысты жанасу нүктесі бойынша автокөлік дөңгелегінен модельдік кернеулерді есептеу

Аңдатпа. Бұл мақалада нақты көрсеткіштер мен масштабтауды ескере отырып, модельдік доңғалақпен бетон жолына берілетін кернеулерді есептеуге және модельдеуге байланысты мұздан тазартқыштың сіңдіру құрамының тозуына арналған модельдік зерттеудің бір бөлігі келтірілген. Зерттеудің мақсаты шиналар қысымының төмендеуіне немесе жоғарылауына байланысты жанасу нүктесінің өзгергіштігін ескере отырып, көлікке ұшыраған кезде пайда болатын қалыпты кернеулерді бағалау болды. Есептеулер велосипедтерден бастап жүк көліктеріне дейінгі әртүрлі көлік түрлеріне арналған, олар шартты түрде А1-А5 санаттарына бөлінеді (көлік құралының массасының өсу ретімен). Есептеу нәтижелері автокөлік құралдарының түріне және нормативтік жүк көтергіштігіне байланысты пайдаланудан туындаған жол төсеміне қалыпты кернеулер диапазонымен

ұсынылған. Есептеулер қалыпты ауытқуды және шинаның өзгермелі потенциалдық қысымын ескере отырып, шинаның әмбебап сипаттамасының сызықтық графигі әдісімен орындалады. Есептеудің алынған нәтижелері жол жағдайларын сандық немесе масштабты модельдеу кезінде есептеу схемаларын дұрыс жасауға мүмкіндік береді.

Түйін сөздер: абразия, жанасу нүктесі, мұздану, модельдеу, жол жамылғысы, кернеу, қысым.

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Расчет модельных напряжений от колеса автотранспорта по пятну контакта в зависимости от давления в шине

Аннотация. В настоящей статье представлена часть модельного исследования на истираемость пропиточного состава антиобледенителя, связанная с расчетом и моделированием напряжений, передаваемых модельным колесом на бетонную дорогу, с учетом фактических показателей и масштабирования. Целью исследования была оценка нормальных напряжений, возникающих при воздействии автотранспорта, с учетом изменчивости пятна контакта, обусловленной понижением или повышением давления в шинах. Расчеты выполнены для различных типов транспортных средств, от велосипедов до грузовых автомобилей, которые условно разделены на категории А1-А5 (в порядке возрастания массы транспортного средства). Результаты расчета представлены диапазонами нормальных напряжений на дорожное полотно, вызванных эксплуатацией автотранспортных средств, в зависимости от их типа и нормативной грузоподъемности. Расчеты выполнены методом линейного графика универсальной характеристики шины, с учетом нормального прогиба и вариативного потенциального давления в шине. Полученные результаты расчета позволят более корректно разрабатывать расчетные схемы при численном или масштабном моделировании дорожных ситуаций.

Ключевые слова: истирание, пятно контакта, обледенение, моделирование, дорожное покрытие, напряжение, давление.

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