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RESEARCH OF POROUS ASPHALT CONCRETE APPLICATION ON HIGHWAY SECTIONS WITH THE INCREASED AQUAPLANING DANGER LEVEL

OLEKSANDR RIEZNIK[1*], SHILIN YANG[2], ANDRII BIELIATYNSKYI[1], MEIYU SHAO[2*], MINGYANG TA[1]

[1]*School of Civil Engineering, North Minzu University, Yinchuan, China*

[2]*Department of Computer Technologies of Construction and Reconstruction of Airports, National Aviation University, Kyiv, Ukraine*

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Abstract. Statistics of road accidents show that even in the summer the number of accidents directly depends on weather conditions, and one such reason is aquaplaning in some parts of the road. Therefore, solving the issue of improving the road structure in such areas, while maintaining the regulatory strength, equality and coefficient of adhesion are relevant in road construction. The research allowed developing an improved mixture of porous asphalt mixture taking into account the physical-mechanical and operational properties. The construction of the road surface was also improved with the separation of the pavement layers, where porous asphalt mixture was used as the top layer, and the basalt canvas (impregnated) between the used construction levels was used. The mathematical calculation of the road was improved taking into account the physical phenomena occurring between the car and the road surface in the

* Corresponding authors. E-mail: reznik.oleksandr@gmail.com; shaomy1994@163.com

Oleksandr RIEZNIK (ORCID ID 0000-0002-5607-0898)
Shilin YANG (ORCID ID 0000-0001-9599-6960)
Andrii BIELIATYNSKYI (ORCID ID 0000-0002-2158-512X)
Meiyu SHAO (ORCID ID 0000-0001-5743-3630)
Mingyang TA (ORCID ID 0000-0003-4283-6554)

presence of water. The speed limits were calculated, and the thickness of the fluid layer was taken into account as well. The authors of the article also paid attention to the influence of road roughness on the speed limit.

Keywords: asphalt pavement, aquaplaning, porous asphalt mixture, properties of pavement, road surface.

Introduction

Ukraine is implementing a program for the development of urban transport infrastructure, which includes the construction and repair of public roads and urban roads that require the use of a significant number of quality road construction materials, including rubble, gravel and mixtures with their use – fine-grained and porous concrete mixtures which correspond to the law of Ukraine as of 11 June 2001 No. 2623-III "About priority directions of development of science and technology", e.g., No. 6 "Latest technologies and resource-saving technologies in energy, industry and agro-industrial complex" with the direction of optimizing the consumption of materials and, accordingly, saving energy resources in their production and directly saving energy consumption in the production of valuable finite product. In order to reduce accidents, one of the implementation areas of this program is to reduce the sections of the road where the car aquaplaning will take place. Since most of the roads in Ukraine are currently being repaired, the replacement of these sections (its parts without the use of drainage with collectors on porous material with improved performance) is a very important issue. A large proportion of road accidents occur due to the loss of contact between the tire and the road. As a rule, this happens when there is precipitation (snow, rain) and the phenomenon of aquaplaning occurs. The essence of the aquaplaning process is simple. At the moment when the car enters a large puddle at speed, a layer of water appears between the road and the wheel. There is a sliding effect on the water's surface. The tire loses contact with the road. The vehicle becomes completely uncontrollable. Water does not have time to be displaced from the contact spot on special grooves on the tread, and the car seems to float on the surface of the puddle. If the car drove into a puddle at too high a speed or if the puddle was too deep, the water simply could not get out from under the wheel fast enough. This effect becomes especially obvious when tires wear out. The old rubber grooves, which drain the water, become smaller. They themselves lose their depth. Consequently, water is displaced from under the tire more slowly. A car with worn rubber can experience the effect of aquaplaning and lose control even at not very high speeds. The area of traction of the wheel is shown in Figure 1.

In order to achieve our goal, namely to reduce the phenomenon of higher aquaplaning, it was necessary to take into account not only the factors of tire adhesion to the road, but also classify the factors that directly affect the adhesion plane and its coefficient. The coefficient of adhesion shows in numerical form the limiting phenomenon and with its help the limit after which aquaplaning begins is also shown in Figure 2.

a) the length of the wheel with the road in dry weather

b) the length of the wheel with the road during moderate rainfall

c) the length of the coupling of the wheel with the road during heavy rainfall (rain)

Figure 1. Wheel grip area

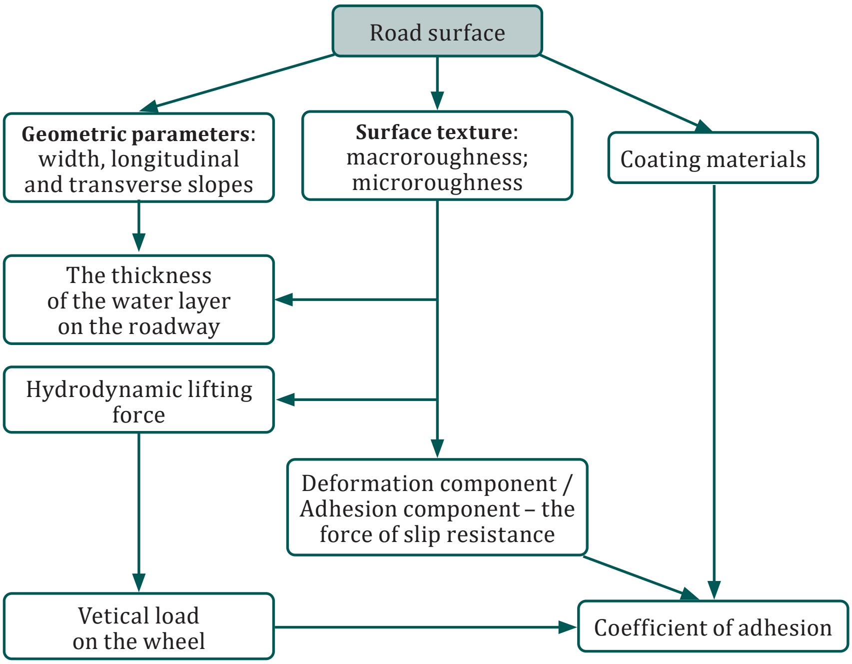


Figure 2. Schematic representation of the factors influencing the normative coefficients of adhesion

The scheme shows that the provision of the required adhesion to the coating can be achieved by adjusting the value of the adhesion coefficient and preventing the emergence of aquaplaning. This becomes possible due to: providing transport and operational indicators in accordance with the defined technical category of the road; regulation of vehicle traffic modes; use of hydrophobic construction of pavements on roads sections with the increased level of aquaplaning danger, arrangement of collectors and drains. Table 1 provides the types of surfaces that contribute to the emergence of aquaplaning.

The most effective way to reduce vehicle aquaplaning on the road is to design a surface that will provide maximum traction with a variety of tire types and conditions. First, the surfaces most conducive to aquaplaning were considered.

The support-coupling passability is determined not only by the design parameters, but also by the driving conditions, the condition of the pavement and the subjective factor – the driver's qualification. The size and weight of the car are undoubtedly factors that affect the passability. Thus, the coefficient of adhesion is the ratio of the adhesion force between the tires of the vehicle and the road surface to the weight of the vehicle (Danchuk et al., 2021). At first glance, it turns out that the greater the weight of the car, the higher the passability. However, the weight distribution of the car on the axles may be different, depending on the wheel formula, the number of axles and the number of drive axles. The power of the engine has a significant effect on the passability of the vehicle, as this characteristic depends on the torque on the wheel, which creates a circumferential force that is the driving force.

The interaction of the wheeled machine with the bearing surface is characterized by the ratio of the following forces: the tangential force of traction, which depends on the torque on the engine; the force of resistance of movement caused by energy consumption on deformation of the tire and road surface; traction force, which characterizes the adhesion of the tire to the support surface (Spitzhüttl et al., 2020). On paved roads, the coefficient of adhesion is determined by the friction

Table 1. Types of surfaces conducive to aquaplaning

Support surface	
Deforming soil	Hard ground
Drained	Drained
Dewy	Dewy
Snowed up	Icy

between the tire and the road. On deformed roads, the coefficient of adhesion depends on the resistance of the soil cut, and hence on the internal friction in the soil. The drive wheel sinks into the ground, deforms and compacts it, increasing the shear resistance, but then the destruction of this compacted soil begins, and the coefficient of adhesion decreases.

When wetting the hard surface, the coefficient of adhesion decreases sharply. However, this slippery film is washed away by heavy and prolonged rain, and the amount of adhesion on such a wet road is close to the values typical of a dry surface. As the vehicle speed increases and, consequently, the angular velocity of the wheel and the linear velocity of the peripheral points of the tire, the coefficient of adhesion usually decreases. The tread pattern has a great influence on the adhesion coefficient. When the tread protrusions are erased, the traction of the tire deteriorates. The traction of the tire on the road depends on other factors, such as the quality of the suspension, tire pressure, etc. (Vaitkus et al., 2021; Krayushkina, 2013).

As shown above, the coefficient of tire adhesion to the road is influenced by the type of surfaces to be joined. A good example is that the grip of a tire with asphalt is much better than with snow, even compacted, and even more so with ice. At the same time, the characteristics of the tire and tread will have a great influence on the coefficient of adhesion. This can be felt by every motorist – on winter tires the car better "holds" the road, better "sticks" to it than in the summer. The main difference between winter and summer tires is the composition of the rubber and tread pattern. There are soft and hard tires, which are determined by the recipe and technology of rubber; many tread patterns are known.

The speed and dynamics of the car, as well as its trajectory have a significant impact on the value of the adhesion coefficient. The weight of the car is unevenly distributed between the tires due to the different location and mass characteristics of the car units. When the speed and trajectory of the car changes, the weight distribution changes: some tires are loaded, some are unloaded.

In addition, the redistribution of weight is influenced by such a subjective factor as driving style, which largely determines the dynamics of the car. With careful driving, when the driver avoids sudden accelerations and braking, turns and adjustments, the coefficient of adhesion to the road is maximum, i.e., the tires are quite far from the transition to a state of complete slipping or slipping. In addition, the movement of the accelerator and brake pedals, as well as the steering wheel can be done in different ways: sharply and quickly or gradually, increasing. A sharp pressure on the pedal and turning the steering wheel will lead to a redistribution of weight on the tires and change the coefficients of adhesion of these tires (Elwardany et al., 2020).

The value of the adhesion coefficient, and hence the passability of the car is influenced by a large number of factors. Based on experimental studies, data have been obtained that the coefficient of adhesion depends even on the temperature of the road surface. There are also data on the change in the coefficient of adhesion when driving on "clean" and "dirty" asphalt (Onishchenko et al., 2021). However, as experience shows, a static factor in preventing aquaplaning is the installation of proper pavement with asphalt pavement, the composition of which will absorb excess water from the surface of the pavement, while the strength of the pavement should remain standard and not destroy the lower layers of the road structure. Accordingly, the aim of the research was formulated: to prevent the phenomenon of aquaplaning by modeling the road structure in the relevant areas.

To achieve the aim, it is necessary to solve the following tasks:

- To mathematically identify the critical height of the water layer and its dependence on the speed of the car;
- To theoretically and empirically investigate road construction;
- To empirically check the transport and operational performance of the developed pavement.

1. Materials and methods

The materials used for the carriageway, curb, and pavement structure directly affect the traction between the wheel and the road. These materials play a crucial role in determining the road technical and operational performance. Moreover, they contribute to showcasing the overall operational charm and appeal of the road.

Technical and operational indicators assess the road capacity to meet the required technical standards, ensuring road safety and accident prevention during its operation. Roughness – one of the types of TEP – shows the traction qualities of the road according to the adhesion coefficient. This indicator combines indicators of a covering unevenness which at the cyclic roughnesses do not cause fluctuations of motor transport and do not influence its work. Roughness exists of two types: macroroughness and microroughness. Macrohair has a volume of 2–3 mm, microhair from 0 to 2 mm. This indicator forms the main unevenness of the road surface and forms the much-needed traction. Figure 3 shows a diagram of the coupling of irregularities with the wheel (DSTU ISO 13473-1, 2020).

Studies (Poulikakos, et al., 2013; Bieliatynskyi et al., 2022a; Bieliatynskyi et al., 2022b) have shown that the moving elements contact the machine clings differently. There is a contour and actual contact (area) with the road surface.

The contour contact area (S_k) does not depend on the roughness of the coating, but is determined only by the design of the tire, the air pressure in the tire, as well as the usual load on the axle.

$$S_k = \frac{2b}{1}\left[\left\{2\text{ch}\frac{1}{3}\text{acrch}\left(\frac{3}{4}\frac{G_k r_0^2}{P_0 b a_0} - 1\right) - 1\right\}\right], \tag{1}$$

where b – tread width of the tire, cm;

G_k – normal wheel load, kgf;

r_0 – half the angle of girth, °;

a_0 – the average radius of curvature of the cord thread in the sidewall of the tire in the undeformed layer, cm;

P_0 – tire pressure, kgf/cm^2 (Grosch, 1974).

The actual contact area (S_f) directly depends on the roughness of the coating. Due to the macroroughness protrusions of the tire tread within the contour contact area does not always touch the coating material and, therefore, the actual contact area is smaller than the contour, and, to a greater extent, the higher the unevenness of the macroroughness. The value of the actual contact area is determined by the geometric parameters of the macroroughness protrusions – height, pitch, angle at the top. The dependence of the actual contact area (S_f, cm^2) on the contour (S_k, cm^2) is determined by the equation (Khomiak & Skorchenko, 1983):

$$\frac{S_f}{S_k} = 32.88 R_{av}^{-0.8}. \tag{2}$$

The degree of roughness affects the resistance to slipping of car tires, and resistance to aquaplaning of cars on the road (Liu et al., 2022; Bieliatynskyi et al., 2022c).The roughness of the coating affects the energy consumption of the car moving on the following actions: 1) friction and deformation of the tire tread, i.e., the value of the adhesive

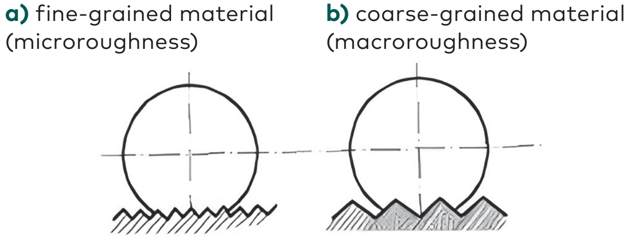


Figure 3. The scheme of coupling of roughnesses with a wheel

and deformation components of the sliding resistance; 2) resistance to the emergence of car aquaplaning; 3) the probability of rupture of the water film formed on the carriageway during rain or melting snow; 4) the formation of the thermal regime in the area of the tire contact with the road surface, which depends on the smoothness of the car, the level of traffic noise, the possibility of blinding drivers with reflected light from the headlights of oncoming cars.

The degree of the coating roughness significantly affects or reduces the level of aquaplaning car danger during rain or melting snow in winter. It should be borne in mind that the improvement of the coupling properties of the coating due to the increase in roughness is accompanied with an increase in traffic noise and increased vibration of the car (Sun et al., 2020). These phenomena are active and are regulated by the current State Building Standards of Ukraine (hereinafter – DBN) developed by the order of UKRAVTODOR (DBN V.2.3-4:2015; DBN V.2.3-5:2018; DBN V.2.3-6:2009; DBN V.2.3-14:2006; DBN V.1.2-15:2009; DBN V.2.3-22:2009; DBN V.2.3-26:2010; DSTU 2587:2021; DSTU 3587-97; DSTU 4036:2021).

The coefficient of adhesion is calculated and measured according to DSTU B B.2.3-2-2000, DSTU B B.2.3-8-2003. Normative speed and maximum speed are calculated according to the requirements of DSTU 3587-97.

The tire tread itself, which reacts with the road surface, also plays an important role in preventing aquaplaning. Tire tread less than 1.6 mm does not prevent slipping on the road and even more so aquaplaning. Aquaplaning at this tread height begins at a water depth of 5 mm and a speed of more than 75 km/h (AutoPortal, 2020). The results of the Nokian (Finland) research were systematized by the authors in Figure 4.

Thus, when detecting the effect of a water layer on the coating in the accident, you must simultaneously take into account a number of indicators: surface roughness, thickness of the water layer, condition of the vehicle wheels and speed of movement. When the thickness of the water layer is more than 0.5 mm for tires with maximum tread wear, the coefficient of adhesion at a speed of 100 km/h or more is close to zero, which corresponds to the beginning of the phenomenon of aquaplaning.

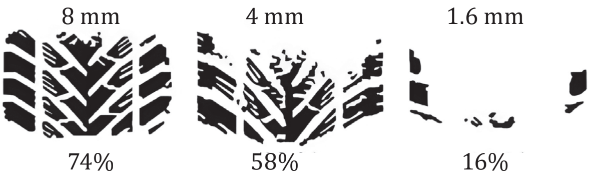


Figure 4. Dependence of the contact zone on the tread height

With a water layer thickness of 3–4 mm, aquaplaning can begin at a speed that usually does not exceed 50 km/h (AutoPortal, 2020).

Studies by well-known scientists (Yang et al., 2022) have shown that when bitumen combines with the mineral components of gravel and sand, there is an interaction between these components with the course of complex physicochemical intermolecular phenomena, which are found not only in the preparation of the mixture, but also in the operation of the coating. These phenomena allow dense asphalt concrete to withstand the effects of precipitation, rain, snow during melting, evaporation, to store a layer of water on the surface, not allowing it to seep into the lower layers of pavement. As a result of water resistance of dense asphalt concrete, on road sections with inappropriate geometrical parameters, difficult terrain conditions and a significant amount of precipitation, road transport is subject to aquaplaning. This leads to failure to ensure the safety and comfort of traffic, the occurrence of accidents with complex consequences and general interruption of traffic. On road sections with a high level of aquaplaning danger with a porous (draining) asphalt concrete, geosynthetic materials are used for drainage to the sloping part of surface water from the carriageway through the pavement layer, thus ensuring its purification from excess water and traffic safety. At the same time, such a layer performs the function of reinforcement (strengthening) of pavement. Reinforced pavement is a composite structure that combines the characteristic positive properties of two different materials of asphalt concrete and geosynthetic material.

When separating layers, reinforcement with simultaneous improvement of drainage conditions should improve operating conditions, reduce the appearance of ruts, potholes, slow down the process of appearance and cracks development and at the same time reduce the water column on the road, thus preventing aquaplaning.

2. Results

The beginning of the aquaplaning process can be shown by the Equation (3):

$$R_{\mathrm{A}} = \frac{n_{\mathrm{v}}}{N_{\mathrm{v}}}, \tag{3}$$

where R_{A} – critical importance of aquaplaning;

n_{v} – the number of cars that are taken into account when calculating aquaplaning, pcs;

N_{v} – the number of vehicles moving on the road at a critical speed, pcs.

The density of the fluid layer depth distribution in areas with unsecured drainage f(h_i) depends in direct proportion on the density of the distribution of the critical depths of the fluid layer f(h_{kp}), at which the front wheels of the car are positioned. Figure 5 shows the average and critical depth of the layer at risk of aquaplaning.

The interaction of the wheel with the liquid on the road is shown in Figure 6.

The rolling surface of the wheel in aquaplaning P_k can be shown by the equation:

$$P_k = \frac{\pi(r_k)\cdot\beta}{180}; \tag{4}$$

$$\beta = \frac{180\cdot L}{\pi r_k}, \tag{5}$$

where r_k – wheel radius under pressure, r_k = (0.93–0.935) for cars, r_k = (0.945–0.95) for trucks (r_k – nondimensional coefficient).

The equality of the roadway also determines the allowable criteria for the speed of the car. The appearance of aquaplaning at different speeds and thickness of the water layer is shown in Figure 7.

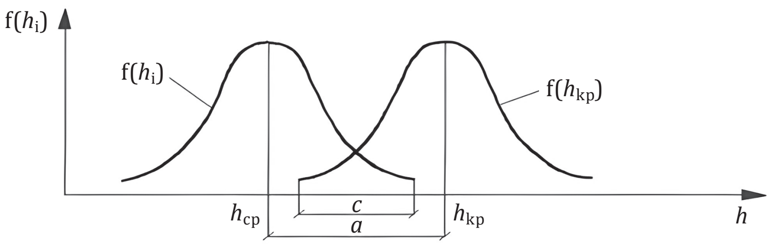
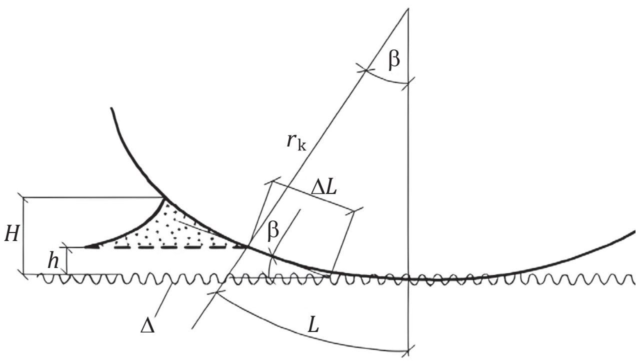


Figure 5. Average and critical depth of the layer at the risk of aquaplaning



β – is the average angle of inclination of the treadmill of the tire within the wetted surface, °;
ΔL, L – the length of the wetted surface of the tire at different speeds of the car, cm;
H – water head height on the wheel, cm;
h – the depth of the water layer on the coating, cm;
r_k – the radius of free movement of the wheel, cm;
Δ – protrusions of a covering roughness.

Figure 6. Interaction of a wheel with liquid at aquaplaning

The amount of water directly depends on the evenness and roughness of the pavement. The calculation of the optimal composition of pavement was carried out taking into account aquaplaning and operational needs. The technical and operational properties of porous asphalt concrete and basalt solid canvas, which served as a water barrier in the structure, were determined. The optimal composition of porous asphalt concrete was also calculated and its lifetime in the climate chamber was studied. The study was conducted in accordance with DSTU B B.2.7-119. Table 2 shows physico-mechanical properties of the optimized design of pavement (with the addition of basalt fiber to the top layer of the structure).

Table 2. Physico-mechanical properties of porous asphalt concrete

Name of indicators	Porous asphalt concrete	
	The data obtained	Requirements of DSTU B B.2.7-119
Mineral skeleton porosity, % by volume	22.8	23.0
Residual porosity, % by volume	9.6	10.0
Water saturation, % by volume	4.2	-
Compressive strength, MPa for temperatures, °C		
0, no more	11.5	12.0
20, not less	2.2	2.5
50, not less	1.1	1.2
Coefficient of long-term water resistance	0.85	0.85–0.75

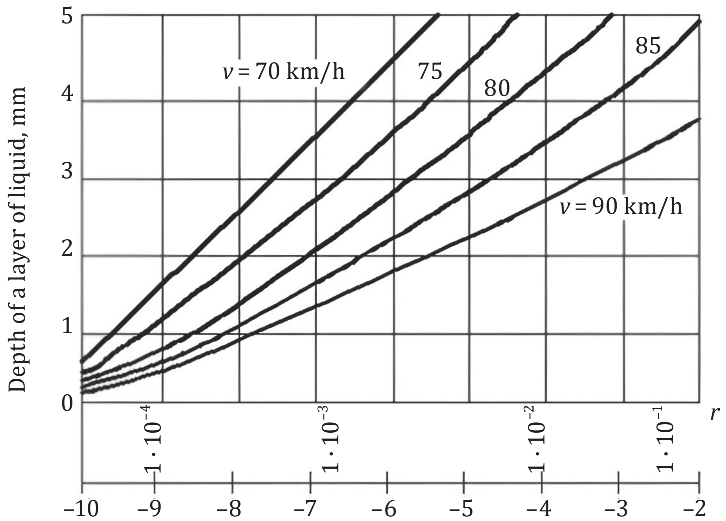


Figure 7. Dependence on the liquid layer of aquaplaning risk and speed

Granite crushed stone 5–20 mm was used as a filler, and in addition a fraction of 20–40 mm as well as granvids was used. Bitumen oil BND 60/90. The composition of porous asphalt concrete is provided in Table 3.

Physico-mechanical properties of the basalt sheet are shown in Table 4. The authors of this article conducted studies in the laboratory in accordance with the DBN and DSTU requirements.

Laying of a drainage cloth is brought between two layers of asphalt concrete and carries out function of water drainage on a slope. More pores allow absorbing water throughout the layer, and water drainage is done over the area of the canvas. Thus, water does not accumulate and there is no aquaplaning effect. At the same time, porous asphalt concrete eventually improves strength.

Experimental determination of the road surface adhesion coefficient of the experimental area made of porous asphalt concrete and the

Table 3. The composition of porous asphalt concrete in % by weight

No	Material	%
1	Granite rubble; Fr 20–40 mm	15
2	Granite rubble; Fr 5–20 mm	50
3	Crushing elimination	30.5
4	Bitumen oil BND 60/90	4.5

Table 4. Physico-mechanical properties of basalt canvas

Name of indicators	Unit of measurement	The data obtained	Requirements GBN B.2.3-37641918-544
Appearance	-	The solid canvas is impregnated with brown color	-
Surface density	r/cm^2	185.0	135–2000
Thickness	mm	0.8	0.25–0.75
Mechanical properties			
Tensile strength (for reinforcement)	kN/m	130.0	30–1200
Fatigue strength (endurance)	Number of cycles	Withstands up to 80.0	50–100
Tear strength	N	140.0	90–1300
Static pushing with a plunger	N	60.0	45–450
Shear rate	%	54.0	60–100
Drainage capacity of the material under load	m^2/min	0.03×10^3	$0.01–2.0\times10^{-3}$

control area was performed with a pendulum device MP-3. The coefficient of adhesion was determined in the forward and reverse directions within the lanes of the carriageway, on the left lane at a distance of 1.0 m from the axis of the carriageway and the right lane – 2.6 m from the axis (Bieliatynskyi et al., 2022d). Before measuring the coefficient of adhesion, the road surface was moistened.

The values of adhesion coefficient for porous and dense asphalt concrete were determined three days after laying, 10 days, as well as in spring and autumn of one year, i.e., almost a season after laying. Analysing the data, we see that the values of the adhesion coefficient on a coating of porous asphalt concrete are higher than on a coating of dense asphalt concrete, due to its structure with an increased number of crushed stone fractions and a rough surface.

Some reduction of values in the course of operation is caused by insignificant grain crushing and a rough surface smoothing. Still the value of the adhesion coefficient is much higher than the requirements of DSTU 3587, which defines the minimum allowable value in hazardous areas – 0.3.

When arranging the construction of pavement with a coating of porous asphalt concrete with laying under the top coat of the basalt reinforcing layer – a continuous canvas brand PSB-D prevents the phenomenon of aquaplaning cars in the rain or melting snow, provides the estimated speed of vehicles, increases traffic safety in the number of accidents and the severity of their consequences, efficiency and comfort of transportation.

Determination of economic efficiency of car aquaplaning prevention and by that increase of traffic safety by laying the developed road design was carried out according to IN USSR 003-84 (1984). The obtained indicators are provided in Table 5.

Looking at the economic effect of the new measure introduction in road construction, the effectiveness of measures to improve road safety should be understood as a quantitative change in accident rates – the number of accidents and the severity of their consequences. In general, the cost-effectiveness of a measure is the ratio of the savings received during the year as a result of increased traffic safety to the costs associated with it. After all, the economic efficiency of eliminating the emergence of aquaplaning is primarily aimed at improving road safety and consists of three parts:

- Accounting for costs associated with the occurrence of an accident in the area of aquaplaning;
- Determining the reduction of accidents and, as a consequence, economic losses;

– Calculation of the funds spent and reduction of economic loss ratio.

The authors of the article conducted experimental studies of the physical-mechanical, deformation, and durability properties of porous asphalt concrete that showed it was a sufficiently strong material and performed the functions of removing excess water from the road structure. The conducted laboratory studies confirmed the theoretical suggestions regarding the rationality of laying porous asphalt concrete to eliminate aquaplaning under the influence of heavy weather conditions in areas with an increased level of danger of aquaplaning. Porous asphalt concrete increases its strength characteristics when in service, which is explained by polymerization and oxidation occurring in bitumen. Samples of porous stone asphalt concrete show tensility at low temperatures, which is not less than that of dense fine-grained asphalt concrete. For example, the ultimate tensile strength in bending for porous stone asphalt concrete is 7.9 MPa at 20° C below zero, while this indicator is 6.7 MPa for dense fine-grained asphalt concrete. Indicators of the shear resistance of porous asphalt concrete are at the same level as those for dense fine-grained asphalt concrete.

Table 5. Physico-mechanical parameters of samples of reshaped cores

No.	Name of indicators	Designation of ND	Requirements of DSTU B B.2.7-119: 2011	Research area				Control area			
				Actual indicators			Arithmetic mean	Actual indicators			Arithmetic mean
1	Compressive strength, MPa, temperature 20 °C	DSTU B B.2.7-319: 2016, p.16.3	Not less than 2.6	3.5	3.4	3.6	3.5	3.4	3.5	3.4	3.4
2	Compressive strength, MPa, temperature 50 °C	DSTU B B.2.7-319: 2016, p.16.3	Not less than 1.3	1.5	1.4	1.4	1.43	1.4	1.4	1.3	1.36
3	Compressive strength, MPa, temperature of 0 °C	DSTU B B.2.7-319: 2016, p.16.3	No more than 12.0	8.7	8.7	8.8	8.7	8.9	9.0	8.5	8.8
4	Water saturation, %	DSTU B B.2.7-319: 2016, p.14.2	No more than 4.0	1.3	1.5	1.5	1.4	1.7	1.8	1.8	1.8

Conducted studies to determine the effect of through basalt cloth of the PSB-D brand (impregnated) showed that the reinforced road structure increased its strength and reliability by 2.5 times. The suggested road structure on the section of the Lviv-Ternopil highway (km 60+500 – km 62+700) meets all the strength criteria. In order to prevent the phenomenon of aquaplaning, the authors of the article suggested using a pavement structure consisting of the following layers during the construction of a section of the Lviv-Ternopil highway: porous stone asphalt concrete; through basalt cloth of the PSB-D brand (impregnated); coarse-grained asphalt concrete; crushed stone-sand mixture of size fraction 40 (treated with cement); crushed stone-sand mixture C-5; coarse sand. When non-rigid pavement based on modern materials, such as porous asphalt concrete and through basalt cloth of the PSB-D brand (impregnated), is paved, it can ensure timely water drainage from the roadway surface and prevent the occurrence of aquaplaning on problem sections of roads. Transport and operational indicators (strength, smoothness, and adhesion) were studied on two sections of the Lviv-Ternopil highway (research – km 60 + 500 – km 62 + 700 and control – km 62 + 700 – km 65 + 000). The results showed that the porous asphalt concrete pavement had a high strength factor and low water saturation in the upper layer, which indicated its durability. The values of the adhesion factor on the experimental section of the road fall within the limits determined by the regulatory documents. During rain and snowmelt, no water layer was found on the surface of the experimental section of the Lviv-Ternopil highway of porous asphalt concrete. During the construction of the Lviv-Ternopil highway section (km 60+500 – km 62+700), the authors developed the technology for laying asphalt concrete pavement using porous asphalt concrete and through basalt cloth of PSB-D brand (impregnated) in the upper layer. The designed pavement structures show economic efficiency in terms of the prevention of aquaplaning on the Lviv-Ternopil highway section (km 60 + 500 – km 62 + 700). The annual economic effect of improving traffic safety on the studied section of the road was approximately UAH 500 000.

As a rule, the standard payback period reaches eight years. When using our method with a coating that prevents the risk of aquaplaning cars and reduces the number of accidents, even without taking into account the economic effect of improving speed and comfort, the payback period is 2 years.

3. Discussion

The analysis of the conducted studies testifies that statistical models for definition of sites of roads with unsecured estimated speed of traffic and the increased risk of road accident assign a significant role to sites where there is an increased level of aquaplaning danger. The appearance of aquaplaning depends on the action of weather and climatic factors, but is caused by the action of many factors (TEP, textural, constructive), the combination of which leads to one or another probability of the aquaplaning beginning. Establishing the dependence of the speed of the car on a layer of liquid – the "probability of aquaplaning" – is an important task to reduce accidents on the roads during operation (by limiting the speed or changing the marks of the longitudinal and transverse profiles of the road). At the moment, studies of the sliding of the car wheel on a liquid layer in the absence of the tire contact with the coating in different road and climatic zones of Ukraine have not been conducted and need to be carried out.

The analysis of road accident registration cards in different climatic zones of Ukraine showed that only the number and severity of road accidents on dry, wet and slippery surfaces are taken into account. The number of accidents related to aquaplaning of the car has not been determined. Only the condition of the carriageway (dry, wet, dirty, snowy), road conditions accompanying the accident, low traction and poor condition of the roadsides are noted. In the presence of a 5 mm layer of water on the surface, aquaplaning of a car occurs not only on tires with extreme tread wear, but also in the presence of a tread pattern height of 3 mm and a speed of 80 km/h or more (ROSAVA, 2020).

When the car is moving at a speed of 100–120 km/h and a water layer thickness of 2.5–3.8 mm, the phenomenon of aquaplaning is possible even for a tire with an unworn tread. In addition, studies (Zariņš, 2011) have shown that the appearance of aquaplaning is significantly influenced by the internal air pressure in the wheel chamber. At low pressure (170 kPa), accidents related to aquaplaning occur at speeds of 50 km/h, and at high tire pressure (250 kPa) aquaplaning is possible at a speed of 80 km/h. As the internal pressure in the wheel chamber increases, the probability of an accident related to the car aquaplaning decreases. The internal air pressure in the wheel chamber is almost equal to the pressure of the wheel on the surface and is proportional to the mass of the car (Li, 2021). Therefore, the consideration of speed indicators in the statistical calculations of the edge is necessary, as well as the development of coverage that allows driving at the standard speed, and the level of tire treads.

Therefore, the speed of the car and the depth of water on the surface must be determined simultaneously, taking into account the density of both parameter distribution. The same applies to other parameters (roughness, tread condition, etc.), which must be considered when assessing the likelihood of car aquaplaning. To prevent the phenomenon of aquaplaning, the use of high-risk drainage pavement made of porous asphalt concrete, which has the ability to absorb water, helps to quickly dry the surface and prevent water stagnation on the pavement after precipitation turns out to be a relevant problem.

Porous (draining) asphalt concrete (residual porosity > 10%) is an artificial building conglomerate, which is a mixture of mineral materials (gravel, sand and mineral powder) with bitumen in reduced quantities and manufactured in certain technological modes that can be laid and compacted in upper layers of pavement, on roads sections with a high level of aquaplaning danger. Moreover, porous asphalt concrete is designed for rapid drainage of water from the road surface.

In the United States, porous (draining) asphalt concrete is called "Open graded friction course (OGFC)" and has been used for over 60 years. These mixtures have been developed to increase road safety in areas with high rainfall. The selection of the mixture was used in such a way that the compacted material had a system of connected pores, through which water was removed from the road surface much faster than from the coating of dense mixtures. This was achieved due to the peculiarities of the particle size distribution of the mixture, a significant proportion of which was one-dimensional crushed stone. Much more widely porous (draining) asphalt concrete has been used in the United States since the 1980s, when the Federal Road Agency's (FHWA) anti-skid program began.

FHWA together with the National Center for Asphalt Research (NCAT) developed granulometric compositions of draining asphalt mixtures and determined the optimal amount of binder. ASTM D6932 / D6932M regulates the arrangement of the upper layers of wear of porous (draining) asphalt concrete to improve traffic safety and prevent the phenomenon of aquaplaning cars (ASTM International, 2021).

To increase the corrosion resistance of draining asphalt concrete, the introduction of adhesive additives to bitumen is recommended. To increase the surface roughness of the coating and TEP, it is possible to add fiber additives of different types (disperse reinforcement of asphalt concrete mix) (Bieliatynskyi et al., 2022e; Bieliatynskyi et al., 2022f).

Besides the United States, the active use of porous (draining) asphalt concrete was carried out in other countries –Japan, Britain, the Netherlands, France, and Germany. Unlike drainage asphalt concrete used in the United States, in Europe these materials have a porosity of

18–22% (15–16% in the United States) and require the use of polymer-bitumen binder.

As a result of the accumulated experience, the normative document EN 13108-7 Bituminous Mixtures was developed, where the general European requirements to the composition and properties of porous (draining) asphalt concrete are given (European Standard, 2016). According to this document, the porosity is defined in the range of 24–28%, the minimum content of binder bitumen 5.5–6.5% depending on the maximum grain size of gravel is not more than 20 mm. It is recommended to use modified bitumen and cellulose fiber as a reinforcing additive. Therefore, our product fully complies with the recommendations of international institutions (Economic and Social Council of UN, 2021).

Conclusion

An analysis of existing methods for assessing the safety of cars on the road showed that to prevent reduced traction of the wheel with the coating and prevent aquaplaning, under the influence of adverse weather conditions, it is necessary to consider a number of factors which should be included in the calculations and described above.

When researching and forecasting the reasons for the existence of areas with a high level of danger of aquaplaning, it was found that the main transport and operational indicators should be: evenness, coefficient of adhesion and roughness. A number of dependences have been introduced into the mathematical model for calculating the prevention of aquaplaning. The size of the critical water depth at which aquaplaning occurs was introduced. The dependence of the front wheels ascent on the speed of the car and the depth of the liquid layer on the pavement was established. The probability of ascent of the wheels is 1×10^{-3}, if the depth of the liquid layer is 3.5 mm and a speed of 70 km, and at a speed of 90 km/h the probability of ascent increases by two orders of magnitude.

The improved mathematical model for estimating the impact of coverage irregularities on the speed of the car aquaplaning determines the dependence of the length and time of the ascent of the wheel on the state of the coating. To take into account the influence of coating irregularities that have arisen during operation, the following values should be determined in the mathematical model: the speed at which the aquaplaning phenomenon may occur; the angle of the car wheel ascent; the critical thickness of the liquid layer, at which the probability of aquaplaning corresponds to 50% of the risk; the coefficient of the runoff layer critical depth variation.

The results of the research allowed taking the optimal from the point of view of prevention of porous crushed asphalt concrete aquaplaning composition phenomenon (in% by weight): granite crushed stone fr. 20–40 mm – 15%; crushed stone granite fr. 5–20 mm – 50%; screening of crushing – 30.5%; bitumen oil BND 60/90 – 4.5%.

Experimental study of physical and mechanical, deformation properties, as well as the durability of porous asphalt concrete showed that it was a strong material that performed the functions of drainage of excess water from the road structure. The conducted laboratory studies confirmed the theoretical provisions on the rationality of laying porous asphalt concrete to eliminate the appearance of car aquaplaning during the action of negative weather conditions in areas with a high level of aquaplaning danger. Porous asphalt concrete in operation increases its strength, due to the processes of polymerization and oxidation that occur in bitumen. Samples of porous crushed asphalt concrete show elongation at low temperatures, which is not less than that of dense fine-grained asphalt concrete. For example, at a temperature of −20 °C, the tensile strength in bending of porous crushed asphalt concrete is 7.9 MPa, while in dense fine-grained asphalt concrete, this figure is 6.7 MPa. The shear strength indicators of porous asphalt concrete are on a par with the indicators for dense fine-grained asphalt concrete.

Studies to determine the impact of basalt solid canvas brand PSB-D (impregnated) showed that the reinforced road structure increased its strength and reliability by 2.5 times. The proposed road construction on the experimental section of the highway meets all the criteria of strength.

In order to prevent the phenomenon of aquaplaning, the construction of pavement consisting of the following layers was proposed and implemented during the construction of the highway section: porous asphalt concrete, crushed stone ASG. Dr. PA - B.NP.I. BND 60/90; basalt continuous cloth of the PSB-D brand (impregnated); coarse-grained asphalt concrete; crushed stone-sand mixture CSSM 40 (treated with cement); crushed stone-sand mixture C-5, coarse-grained sand. Arrangement of rational construction of non-rigid pavement with the use of modern materials – porous asphalt concrete and basalt solid canvas brand PSB-D (impregnated) – will ensure timely drainage of water from the road surface and prevent aquaplaning on difficult sections of roads. Studies of transport and operational indicators (strength, equality and adhesion) were performed on two sections of the road. The research results showed that the coating of porous asphalt concrete in the upper layer had a sufficiently high value of the coefficient of strength and low water saturation, which indicated its durability. The values of the adhesion coefficients on the test section of the highway are within the limits set by regulations. During the rain and melting snow, no layer of water was found on the surface of the highway research section made of porous asphalt concrete.

The construction of the experimental highway section involved the development and implementation of a technology for arranging asphalt concrete layers. This technology incorporated the use of porous asphalt concrete in the upper layer, along with the installation of a continuous basalt layer of PSB-D (impregnated). The annual economic effect of improving traffic safety on the studied section of the highway was calculated. The payback period of the costs associated with the installation of coverage, which prevents the risk of aquaplaning cars and reduces the number of accidents, even without taking into account the economic effect of improving speed and comfort, is 2 years.

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