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THEORETICAL MODEL FOR ANCHORING A PARTICLE OF PREHEATED SAND INTO AN ICE FORMATION

*Abdy Kiyalbayev[1], Saniya Kiyalbay[2], Temirkhan Tolkynbayev[2], Gulshat Tleulenova[2]

[1]L.B. Goncharov Kazakh Automobile and Road Institute, Almaty, Kazakhstan
[2]Department of Civil Engineering, L.N. Gumilyov Eurasian National University, Kazakhstan

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ABSTRACT: Treatment of the coating with anti-icing materials, which contribute to a more intensive interaction of the wheel of a moving car with the road surface. Sand, screenings, crushed stone, and similar friction materials are used as anti-icing materials, and the value of the friction coefficient is mainly influenced by the size and the rate of their distribution on the icy surface. At the maximum spread rate, the treatment will result in a surface that resembles surface treatment. Taking this into account, the requirements for material dimensions, roughness, etc., imposed on surface treatment can be applied to the resulting surface. This coating will provide a slightly smaller actual contact area (compared to the untreated coating), but due to a significant increase in the mechanical component of the friction force, the interaction of the wheel with the coating will be more intense, which will contribute to an increase in the friction coefficient. But in the practice of winter maintenance, a complete analog of this method is uneconomical. Wherein, regardless of the amount of anti-icing materials consumption, the main disadvantage of this method is the weak fixation of friction material particles on the coating, which leads to a decrease in the effectiveness of anti-icing treatment and, as a result, to the uneven coefficient of adhesion and the need for repeated treatments. Therefore, to increase the efficiency of the use of friction materials, the main attention should be paid to ensuring the reliability of their fastening on the surface of coatings, especially icy ones.

Keywords: Types of winter slipperiness, Ice coating, Friction coefficient, Friction materials, the Distribution rate

1. INTRODUCTION

One of the main tasks of the road industry of the country and the public utilities of large cities in the organization of work to prevent the formation of slipperiness on the roads and its timely elimination, taking the necessary measures to ensure the safe and uninterrupted passage of vehicles on the roads and to prevent traffic interruptions due to unsatisfactory winter road maintenance [1-2]. To prevent slipperiness on automobile and city roads, chemical reagents are mainly used.

Although chemical reagents for a sharply continental climate do not work to their full potential, i.e. daily fluctuation of air temperature significantly reduces the efficiency of chemical reagents. The use of friction materials is also ineffective due to their short duration. The reason is the weak fixation of the particles of friction materials on the snow-ice surface of the coating. Depending on the intensity of traffic, the effective action of friction materials lasts only up to 30-45 minutes.

Thus, in road maintenance and urban public utilities, a problem arises associated with a decrease in the coefficient of adhesion of road surfaces in winter slippery conditions.

Here the main task arises - this is the extension of the time of action of friction materials, corresponding to the minimum allowable norm of the coefficient of adhesion φ_{min} = 0.28 for low, i.e. IV-V technical categories of roads and φ_{min}=0.40 - for roads with a traffic intensity of more than N=3500 vehicles/day [3-5].

Friction materials (anti-icing) are solid, loose, water-insoluble materials distributed over the surface of the pavement to eliminate the formation of winter slippery by increasing the coefficient of traction of the wheels of vehicles, due to the increased roughness of the snow and ice deposits [6]. Coarse-grained sand, fine gravel, slag materials, screening of stone materials, etc. are widely used as friction de-icing materials (FGM) in Kazakhstan and the countries of Central Asia, the required particle size modulus of which is $1 \leq d < 7$ mm.

The content of clay particles and particles with a diameter less than 0.315 mm should not exceed 5% of the total volume of the material. Thus, the effective time of action of bulk materials largely depends on their granulometric composition [6,7,11].

2. RESEARCH SIGNIFICANCE

The paper considers a model of fixing a sand particle on an icy surface of coatings under conditions of winter slipperiness. At the same time, the depth of their embedding is considered depending on the physical and mechanical properties of the snow-ice formation and the thermal characteristics of the friction material. The results of this calculation make it possible to increase the time of effective action with an increase in the adhesion coefficient of an icy coating treated with preheated anti-icing materials.

3. MATERIALS AND METHODS

Each meteorological factor is characterized by the probability of occurrence (repeatability), duration of action, aftereffect, and intensity.

Winter slipperiness of road surfaces is characterized by five types of snow and ice deposits, which include: all types of icing that occur when the air temperature drops and the water on the road surface freezes. This is a hydration type of icing that occurs after a thaw when the air temperature drops below 0 °C; icing that occurs on the dry surface of the road pavement as a result of crystallization (sublimation) of water vapor from the air and the formation of frost during radiation cooling of the pavement below the dew point temperature; solid ice coating that appears when precipitation freezes (rain, sleet), falling on the road surface, cooled below the freezing point of water; icing formed when supercooled rain or drizzle (icy ice) falls on the road surface; snow-ice deposits, which are formed from the compaction of a layer of snow on the road surface by the wheels of passing vehicles (induced, the artificial slipperiness of the road surface).

Measures to combat winter slipperiness of road surfaces are divided into three groups: treatment of the ice surface with friction materials without removing ice (scatter of sand, sand-salt mixture, fine gravel, crushed stone crushing waste, ash, slag, etc.); treatment of the ice surface with chemicals to lower the melting point of ice and remove water and ice residues (thermal, chemical method and combinations: chemical-mechanical; chemical-friction); preventive measures to prevent the appearance of ice on the surface of the carriageway - treatment of the coating with chemicals, the use of water-repellent additives in the wear layers, which reduce the adhesion properties of ice with the road surface, etc.

There are the following main types of snow and ice formations on roads, airfields, and streets: hoarfrost, ice, snow cover, snow run, snow-ice run, snow-ice flour, snow-ice porridge, and ice [10].

In terms of physical and mechanical properties, snow-ice formations differ sharply from each other, which is explained by different conditions for their formation and development. The density of artificially compacted snow is much higher than that of natural snow cover. The hardness of the snow roll varies between 0.5-5 MPa. The snow roll formed by the compaction of wheeled vehicles has a hardness of 1.0 MPa, and the snow roll as a result of compaction by pedestrians is 0.46 MPa. The hardness of snow-ice run-up varies over a wide range from 5.0 to 18.0 MPa.

The change in the hardness of the snow-ice run-up is significantly influenced by passing vehicles. On the one hand, this effect is manifested in a decrease in the hardness of snow-ice run-up as a result of the melting of compacted snow under the action of transport loads and a decrease in the reflection coefficient, which is due to an increase in snow pollution. On the other hand, the hardness of the snow-ice run increases as a result of mechanical mixing under the repeated action of transport loads. Further compaction occurs at stable negative temperatures and with an increase in the age of the run. The hardness of the snow-ice run can reach up to 8.0-18.0 MPa. The upper limit of the hardness of snow-ice run is close to the hardness of ice.

Characteristics of the main methods of combating winter slippage are presented in Table 1.

Table 1 Characteristics of the main methods of combating winter slippage

Indicators	Characteristics of the main methods of combating winter slippage			
	chemical	friction	Physical-chemical	physical chemical
1	2	3	4	5
Used materials	salts, deicing agents	sand, crushed stone, slag	friction material + chemical reagent	additives in asphalt concrete, hydrophobized
Material distribution time	before, during, or after the formation of winter slippery conditions	after the formation of winter slipperiness	during or after the formation of winter slipperiness	during the paving period

Table 1 continued

1	2	3	4	5
Duration of action	Depending on traffic and weather conditions			additives in asphalt concrete - up to 7 years hydrophobized - up to 2 years
Efficiency of use	high if the technology is followed	medium	medium	medium
Advantages	- high melting capacity. - low consumption rate. - processing of a large area with one vehicle	- simplicity. - low material cost	- a rapid increase of the coefficient of adhesion	allows you to reduce the cost of eliminating ice on the roadway
Disadvantages	- the high cost of the material. - limited conditions of use (in terms of temperature, intensity motion); - Strict requirements for observance of work technology	- large placer norm. -an insignificant increase in the coefficient of adhesion. - a large number of distributors. - a large volume of blank anti-icing material. - weak fixation of the anti-icing material on the pavement	- technology violations drastically worsen traffic conditions. - high requirements for the quality of the blank material	reduces the service life of the coating

One possible way to increase the efficiency of friction materials is to use them in a preheated state. The principle of operation of such anti-icing treatment is to heat the friction material with its subsequent rational distribution over the road surface. This process is fixing preheated sand on an ice surface in the form of a model shown in Figure 1. The essence of the model is that a hot sand particle (as an example), falling on the surface of the coating, melts snow-ice deposits around itself, gradually sinking into them and cooling down. The resulting water will fill the voids between the particle and the coating, and then, freezing will contribute to the freezing of the sand particle with the surface of the coating [6,9].

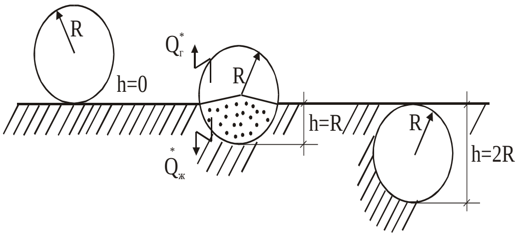


Fig.1 Spherical model of particle embedding friction material into ice

When a sand particle is immersed in ice, the initial temperature before distribution can be described as follows [9]:

$$\mathbf{t}_{\boldsymbol{p}} = \mathbf{t_1} - \mathbf{t_2} - \mathbf{t_3} - \mathbf{t_4} \tag{1}$$

where t_1 is the temperature of the sand particle at the outlet of the distributor; t_2 is the temperature of the sand at the moment of falling onto the surface of the coating; t_3 is the temperature of the sand during its cooling on the coating surface; t_4 is the temperature of the sand by the end of cooling, equal to the road pavement temperature t_n.

Considering the required sand particle size on the contact patch, the material consumption of a given size should be:

$$\mathbf{D} = \frac{\mathbf{m_{s \cdot N}}}{\mathbf{S}}, \tag{2}$$

where N is the number of particles on the contact spot, pieces; S is the area of the contact patch of the wheel with the road pavement, m^2.

Thus, the minimum consumption of material (theoretically), providing an increase in the coefficient of adhesion (by 1.2-1.5 times), should be (Fig. 2): a) 30-40 g/m2 - for material with a fraction of 3-5 mm ; b) 70-80 g/m^2 - for the material fraction

5-10 mm; c) 220-230 g/m2 - for material fraction 10-15 mm; d) 360-370 g/m2 - for material fraction 15-20 mm.

An aspherical particle with radius R and initial temperature t0 is on a horizontal ice surface. At the point of contact, ice begins to melt. A segment with a variable is melted in the ice mass (Fig. 3), a spherical sand particle descends into this segment under the action of gravity [6].

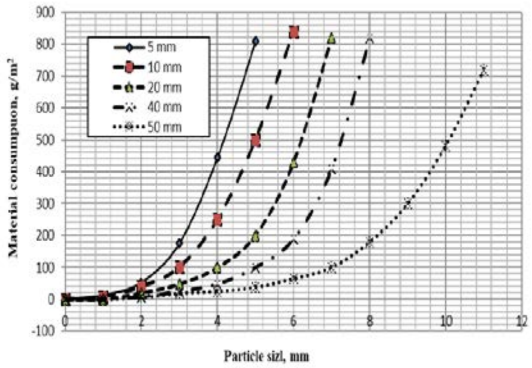


Fig.2 Influence of particle size and quantity under the wheeled vehicle for consumption of friction material

Assuming that the decrease in the enthalpy of the particle is equal to the heat spent on melting the ice. In reality, part of the heat is removed from the water-ice interface into the ice mass, which in the general case can have a temperature below 0 °C. The enthalpy of a particle is determined by its average temperature. Due to the complexity of determining the temperature field of the ball, in the non-standard process of asymmetric cooling considered here, a simplified temperature field is adopted.

The ball is conditionally divided into two sectors - the lower one, the surface of which is in contact with the ice, and the upper one, the surface of which is in contact with the air. The cooling rate of each sector is determined by the heat transfer from its surface. The average temperature of each sector changes in time according to the law of the usual symmetrical cooling of the ball. The average temperature of the entire ball is defined as the average over the mass [6,10,11]:

$$\mathbf{t_a} = \frac{\mathbf{t_l \cdot V_l}}{\mathbf{V}} + \mathbf{t_g} \cdot \frac{\mathbf{(V - V_l)}}{\mathbf{V}}, \tag{3}$$

where t_a is the average temperature of a spherical particle; t_l is the average temperature of the lower sector (its surface is in contact with the liquid film separating the particle and ice); V_l is the volume of the lower sector; V is the volume of the ball; t_g is the average temperature of the upper sector (index "g" means the contact with gas, i.e. with air).

The volume of the sector is:

$$\mathbf{V_l} = \frac{2}{3}\boldsymbol{\pi} \cdot \mathbf{R^2} \cdot h \tag{4}$$

The relative volume of the sector is:

$$\frac{\mathbf{V_l}}{\mathbf{V}} = \frac{\frac{2}{3}\cdot\boldsymbol{\pi}\cdot\mathbf{R^2}\cdot\mathbf{h}}{\frac{4}{3}\cdot\mathbf{R^3}\cdot\boldsymbol{\pi}} = \frac{1}{2}\cdot\frac{\mathbf{h}}{\mathbf{R}} \tag{5}$$

The average temperature of a spherical particle is thus given by:

$$\widetilde{\mathbf{t}} = \widetilde{\mathbf{t}}_{\mathbf{l}} \cdot \frac{1}{2}\cdot\frac{\mathbf{h}}{\mathbf{R}} + \mathbf{t_g}\cdot\widetilde{\left(1 - \frac{1}{2}\cdot\frac{\mathbf{h}}{\mathbf{R}}\right)} \tag{6}$$

here h changes from zero to the maximum value hм, and and t_g decreases from the initial temperature tн to the final temperature tк following the solution of the heat equation for the ball under the boundary conditions of the third kind [10]. If do not take into account the supercooling of the particle to the temperature of the ice mass, then t_c<0°C [12-15].

The second condition is a simplified version of the known boundary condition of the Stefan problem [11]. From here two equations:

$$\frac{\mathbf{dH}}{\mathbf{d\tau}} = \mathbf{Q_l^*} + \mathbf{Q_g^*} \tag{7}$$

$$\mathbf{Q_l^*} = \mathbf{p_i \tau_i}\frac{\mathbf{dV_i}}{\mathbf{d\tau}} \tag{8}$$

wher $\mathbf{Q_l^*}$is the heat flux on the surface of the lower sector; $\mathbf{Q_g^*}$is the heat flux on the surface of the upper sector; τ - time; $\mathbf{p_i}$is the ice density; $\boldsymbol{\tau_i}$is the heat of ice melting; $\mathbf{V_i}$ is the volume of melted ice segment.

The heat flux on the surface of a spherical particle is determined by the simplified two-sector model of the temperature field proposed above:

$$\mathbf{Q_g^*} = \mathbf{Q_g}\left(\mathbf{1} - \frac{\mathbf{F_l}}{\mathbf{F}}\right) \tag{9}$$

where $\mathbf{Q_g^*}$is the heat flux on the symmetrical surface of the cooled ball with the boundary conditions of the lower sector; Q_g is a similar heat flux for the upper sector; F_l is the area of the outer surface of the lower sector; F is the area of the spherical surface of the particle. The maximum depth of the melted ice segment will correspond to the case $\left|Q_m^*\right| = \left|\Delta H\right| = H_s - H_к$, in this case, the entire enthalpy of the particle is spent on the melting of ice. The relative volume of melted ice established by us is equal to the value A. The coefficient is equal to the reciprocal of the known Kossovin number [10].

$$\mathbf{A} = \frac{\mathbf{p_s C_p^n \ \ (t_0 t_k)}}{\mathbf{p\ r_i}} \tag{10}$$

where $\boldsymbol{p_s}$ is the sand density, t/m^3; $\boldsymbol{C_p^n}$ – specific heat capacity, kJ/(kg·K); to is the temperature of sand heating, °C; tk is the temperature at the time of sand distribution, °C; ρ_l – ice density, t/m^3; r_l is the heat of ice melting, kJ/(kg·K). If A>0.5, then the melted volume consists of half a ball and a cylindrical layer, the last equation will be different. If A=1, then in the considered hypothetical case (b=1) the volume of molten ice has the shape of a hemisphere. With the optimal solution of problems, the depth of sand particles embedded in ice is h_{max}=0.67·R.

It is convenient to consider the process in developing time because the quantity $\mathbf{dt_l/d}\iota$ and $d\bar{t}_r / d\tau$ must be determined for the same moment in time. These functions of time are determined from the solution of the classical problem of the heat conduction of a ball under boundary conditions of the third kind [6,10-12]. In this way:

$$\tilde{\mathbf{h}} = +\frac{3}{2} \pm \sqrt{\frac{9}{4} - 2\ \mathbf{Ab}\ (\mathbf{1} - \mathbf{t})} \qquad (12)$$

If take a "minus", then a return leads to growth $\boldsymbol{h}$, then it corresponds to the physical meaning.

Based on the above model of sand particles embedded in ice, the duration of cooling of friction materials to the freezing point of ice (0 °C) strongly affects the technology of using heat-treated (heated) friction materials.

Depending on the duration of cooling, you can determine the scope of their application. For example, on roads with high traffic intensity, there may be cases when particles of friction materials do not have time to fully fix themselves in the ice and are swept away by the wheels of moving vehicles outside the runway.

Therefore, the cooling time of friction materials affects the strength of fixing their particles in ice and the possibility of using them on roads with high traffic intensity, as well as in windy weather, when the speed and strength of the wind drastically reduce the cooling time [16-18]. Determination of the optimal heating temperature of a sand particle to when it touches an ice surface.

Data: p_s=1320 kg/m^3, $\mathbf{C_p^n} = \mathbf{0.75\ kJ/(kg \cdot K)}$, λ_s=0.44 W/(m·K); for ice p_l=900 kg/m^3, r_k=3.35·105 kJ/(kg·K), at air pressure p_a=760 mm Hg. Radius of sand particle R=0.63 mm.

The thermophysical properties of some friction materials used in the fight against slipperiness are shown in Table 2.

Table 2 The thermophysical properties of friction materials

Name of materials	Humidity, %	ρ·10^3, kg/m^3	W_{ed}, kJ/(kg·TO)	λ, W/(m·TO)
1	2	3	4	5
Sand quartz	1.0	1.32	0.75	0.44
	5.0	1.52	0.92	0.81
	10.0	1.85	1.32	1.32
Ash (powder)	-	2.20	0.84	1.50
Sand and gravel		1.90	0.90	2.25
Sand with fly ash 14-20%	-	1.60	1.10	1.10
Slag	-	0.50	-	0.11
Large river sand	0	1.46	0.80	0.28
	4.3	1.50	1.02	0.51
	15.6	1.60	1.54	1.85
brick sludge	0	1.08	0.88	0.77
Ice	-	0.917	2.30	2.20
Fiberglass	-	1.8-1.9	-	0.21-0.33

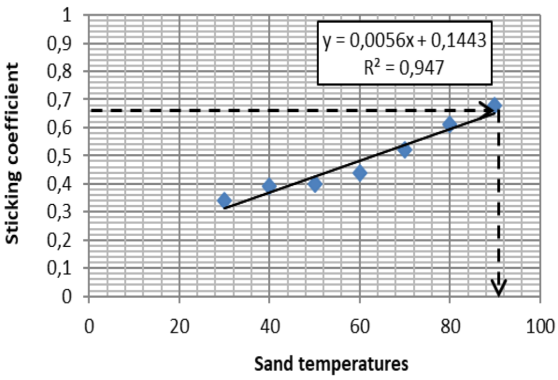
To distribute the depth of sand particles embedded in ice h, using formula (12), calculate the relative volume of melted ice A, which takes into account the thermophysical characteristic of the friction material $(\boldsymbol{C_p^s}, \boldsymbol{p_s}, \boldsymbol{\lambda_s})$, the heat of fusion rl, and density ρl of ice, as well as the initial to and final temperature of heating of a sand particle tк. Since the process of embedding or movement of sand particles into ice occurs at a temperature of 0 °C - tk = 0 °C.

Coefficient A establishes the following three important dependences of the depth of embedding: particle material $(\mathbf{C_p^s}, \mathbf{p_s}, \boldsymbol{\lambda_s})$; ice density (ρl); the initial temperature of the particle to at the moment of contact with the ice surface.

Thus, coefficient A establishes the dependence of the depth of penetration on the material of the particle, the density of ice and the initial temperature of heating of the particle and can be expressed as a function depending on these indicators:

$$h = f(\rho_s, Cs, t_o, \rho_i) \qquad (13)$$

When a particle is immersed in ice, it is surrounded by a liquid film, the thickness of which can be taken equal to $\delta l = 0{,}1 \cdot 10^{-3} м$. Initially, the value of to is taken based on the results of field measurements of the friction coefficient. In this example, this value is equal to to=+90°C, corresponding to the maximum value of the adhesion coefficient equal to φ=0.64. Figure 3 shows the value of the adhesion coefficient depending on the temperature of heating of the sand particles before their distribution. The adhesion coefficient values were measured with a portable device IPKp-M (Fig. 3, b). Field measurements were taken 30 minutes after the distribution of heated sand on the ice cover [25-27].



a

b

Fig. 3 Values of the friction coefficient depending on the heating temperature of the sand

Further, for quartz sand at ρl=900 kg/m3 and to=+90 °C according to equation (11):

$$\mathbf{A} = \frac{\mathbf{1320 \cdot 750 \cdot (90 - 0)}}{\mathbf{900 \cdot 3.35 \cdot 10^{-5}}} = \mathbf{0.296}$$

4. RESULTS

When determining the depth of embedding, the value of the similarity criteria (Bi, Fo) is calculated from the given values of r, according to which the dependence of the embedding depth on the duration of cooling to 0°C and the thermophysical properties of materials (C_p^s, ρ_s, λ_s). To determine the average particle temperature to, the values of the similarity criteria Bi and Fo are also needed. Since the heat exchange process of a particle takes place in two media, the Biot number is calculated separately for the part that is in a liquid medium (BiL) and gaseous (BiG). When calculating Big, the heat transfer coefficient of sand in the air at V=0 m/s can be taken $\alpha_g = 15W/(m^2 \cdot K)$, and for the part in the liquid phase, the heat transfer coefficient is obtained by calculation [9]:

$$\alpha_l = \frac{\lambda_l}{\delta_l} \tag{14}$$

where δl is the thickness of the liquid film formed when a particle is embedded in ice, $\delta_l = 0{,}1 \cdot 10^{-3} m; \lambda_l\ 0{,}551 W/(m \cdot K)$ [8,9]. Then:

$$\alpha_l = \frac{0{,}551}{0{,}1 \cdot 10^{-3}} = 5510 W/(m^2 \cdot K),$$

thus: $$B_{ig} = \frac{15 \cdot 0.63 \cdot 10^{-3}}{0.44} = 0.021$$

$$B_{il} = \frac{5510 \cdot 0.63 \cdot 10^{-3}}{0.44} = 7.89$$

Thermal diffusivity for quartz sand at λp=0.44 W/(m·K), R=0.63·10-3 m and Cps= 0.75 kJ/(kg·K).

$$\mathbf{Q_s} = \frac{\boldsymbol{\lambda_s}}{\mathbf{p_s \cdot C_p^s}} = \frac{\mathbf{0.44}}{\mathbf{1320 \cdot 750}} = \mathbf{0.44 \cdot 10^{-6} m^2/c}$$

Fourier numbers for R=0.63·10-3 m and τl =1 s.

$$F_o = \frac{\alpha_s \cdot \tau_l}{R^2} = \frac{0.44 \cdot 10^{-6} \cdot 1}{(0.63 \cdot 10^{-3})^2} = 1.109$$

Other possible Fourier numbers are shown in Table 3.

Table 3 - Fourier number depending on the size of the sand particle at λp = 0.44 W / (m·K)

Time, sec.				
1	2	3	4	5
0.0001	0.315	0.63	1.25	2.50
0.001	2	3	4	5
0.01	0.00044	0.000111	0.000028	0.000007
0.1	0.00443	0.001109	0.000282	0.000070
1.0	0.04435	0.011090	0.002820	0.000704
10.0	0.44355	0.110900	0.028205	0.007040
0.0001	4.43550	1.109000	0.282050	0.070400

Sand particles with a radius of R=0.63 mm, when they hit the icy surface of the road, begin to sink. Let us set the time of particle embedding into ice (for example, τzhi = 0.0001 s) and calculate the similarity criteria, Bi and Fo.

Based on the calculated values Bir=0.021, Vizh=7.89, and Fexp=0.000111 at τl1=0.0001 s, then we find the roots of the characteristic equation /54, 56/, then the constant coefficients are determined. The similarity criteria determine the process of particle cooling in a liquid and gaseous medium. The dimensionless value of the average temperature is calculated by the formula:

$$\overline{\Theta}_s = \sum_{n=1}^{\infty} B_n exp(-\mu_n^2 \cdot F_o) \qquad (15)$$

For very small values of Bi, it suffices to determine Θr from the first term μ1 and B1. Thus μ1=0.7755 and B1=1. For these values, Θg is equal to:

$$\Theta_{\Gamma} = 1 \cdot \left[\exp\left(-0{,}7755^2 \cdot 0{,}000111\right)\right] = 1.$$

Thus, at τ1=0.0001 s, the temperature on the surface of the particle practically remains unchanged, therefore, in the next approximation, we take the time of embedding equal to τ2=0.001 s. The calculation is repeated until the values of Θg and Θl take on a value equal to $\overline{\Theta}$.

The duration of cooling of friction materials to the freezing point of ice (0 °C) strongly affects the technology of using heat-treated (heated) friction materials. Depending on the duration of cooling, you can determine the scope of their application. For example, on roads with high traffic intensity, there may be cases when particles of friction materials do not have time to fully fix themselves in the ice and are swept away by the wheels of moving vehicles outside the runway.

Therefore, the cooling time of friction materials affects the strength of fixing their particles in ice and the possibility of using them on roads with high traffic intensity, as well as in windy weather, when the speed and strength of the wind drastically reduce the cooling time [19-24].

With the help of the graph in Fig. 4, it is easy to determine that the duration of cooling of a particle with a radius R=0.63 mm in the liquid phase is about τ=1.001 s., while the relative depth $(\overline{h} = h/R)$ equals 0.55.

The process of embedding heated particles in less dense snow-ice formations occurs much more intensively than in denser ones. This is due to the thermal conductivity and specific heat capacity of snow-ice formations.

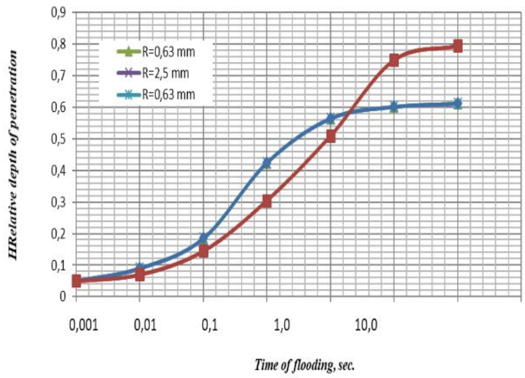


Fig. 4 Dependence of duration embedding on particle size (15)

The density of freshly fallen snow is equal to ρl=200kg/m^3, respectively λl=0.105 W/(m·K), Cp=2.1 kJ/(kg·K); compacted snow: ρl=350kg/m^3, λl=0.5 W/(m·K), Cp=2.1 kJ/(kg·K); ice: ρl=917kg/m3, λl=2.2 W/(m·K), Cp=2.3 kJ/(kg·K). With an increase in density (ρl), thermal conductivity λl increases, however, the specific heat capacity (Cp) remains unchanged (or almost unchanged), therefore, the embedding of a particle at the same heating temperature (to) and the same particle size (R) on denser ice bases occurs more slowly and on shallower depth (Fig. 5).

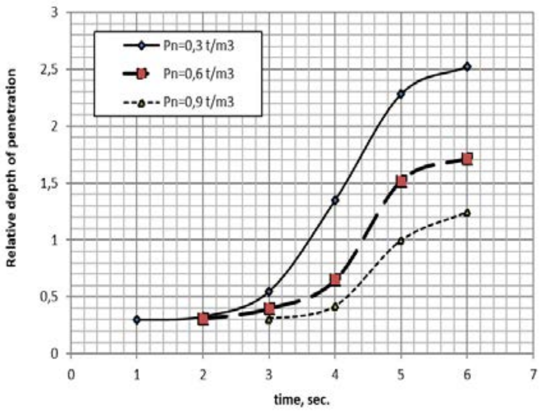


Fig. 5 Dependence of the depth of embedding of heated particle sand on ice density at R=2.5 mm, t=90 °C

Embedding is understood as the ratio of the depth of embedding and the diameter of the particle - Kv=h/d. The optimal value of the depth of embedding is determined experimentally, depending on the relationship between the temperature of the particle and the adhesion coefficient. In this case, the adhesion coefficient is determined not by the depth of penetration, but by the height of the protrusions of the particles above the icy surface of the carriageway.

It should be noted that for particles of different diameters, the same value of embedding will mean different heights of the protrusion above the ice surface. Let's take two particles: one with a diameter -of 1.25mm, the second – of 5 mm. Let's take Kv equal to 0.6. Then in the first case, the height of the protruding part (hв) will be equal to0.5 mm, and in the second 2.0 mm. From what has been said, it follows that if to obtain a certain height of the upper part of the friction material grain protruding above the ice, then larger particles must sink deeper, i.e. they should have higher penetration.

5. CONCLUSIONS

The process of particle embedding into ice, along with the density of the snow-ice formation and the friction material, is greatly influenced by the initial temperature of the heated particles of the friction material at the moment of contact with the ice surface (to). Even the largest particles (R=2.5 mm) at to=+110-130°C can sink too deep into the ice (or snow run), reducing the coefficient of adhesion.

In the calculation, the initial value of the sand heating particle is taken from the results of field measurements and establishes the relationship between the friction coefficient and the temperature of the sand heating. According to the calculation, the maximum depth of the segment (the embedded part of the particle into the ice) by formula (11) is equal to A=0.296.

It should be noted that for particles of different diameters, the same value of embedding will mean different heights of the protrusion above the ice surface.

Two particles are accepted of friction material: one with a diameter -of 1.25mm, the second – of 5 mm. In this case, take Kv \u003d 0.6. Then, in the first case, the height of the protruding part of the friction material will be hv =0.5 mm, and in the second - hv =2.0 mm. From what has been said, it follows a certain height of the upper part of the friction material grain protruding above the ice, then larger particles must sink deeper, i.e. they should have higher penetration.

The embedding of a particle of friction materials into ice directly depends on the thermophysical properties of the material. Therefore, when choosing anti-icing materials, this is of particular importance. For example, brick chips are more suitable in terms of their thermophysical properties; retain heat longer than quartz sand (if you do not take into account their strength properties).

Based on the research results, the following conclusions can be made:

1. The use of chemical reagents to prevent slippery road surfaces in climatic zones with sharply continental climates leads to technical difficulties associated with the difference in the daily air temperature during the day and limited heat dissipation.

2. The main disadvantage of using friction materials is related to the weak anchoring of their particles in the body of the snow-ice formation. In this case, the effective action time of friction materials does not exceed 35-40 minutes.

3. Thermal processing of frictional materials significantly increases the efficiency due to the duration of their action. The depth of fixation of sand particles depends on the optimal heating. In the examples under consideration, the optimal heating temperature for quartz sand is +91oC.

4. Based on the results of field measurements and calculations, correlation relationships between the coefficient of adhesion of icing, the size of sand particles, and the initial temperature of their heating were established.

5. The method of distribution of friction materials in the preheated state is unacceptable in climatic zones with high humidity (in II and III road climatic zones).

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