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Влияние температуры и структуры снега на трение по кровельным покрытиям

The influence of the temperature and the structure of snow on the roof covering

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КЛЮЧЕВЫЕ СЛОВА

снеговая нагрузка;
разрушение кровли;
трение снега;
покрытие;
трибометр;

ИСТОРИЯ

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АННОТАЦИЯ

При проектировании конструкции кровли здания важным является расчет максимальной снеговой нагрузки. Помимо основных этапов расчета, необходимо также учитывать коэффициент трения снега по кровле. Данный параметр может зависеть от структуры и температуры снега, а также от материала покрытия. При определении зависимости коэффициента трения от перечисленных параметров использовалась методика, разработанная научно-испытательной лабораторией «Политех-СКиМ-Тест» с использованием трибометра. В исследованиях были рассмотрены различные состояния снега, а также два вида кровельного покрытия – ПВХ-тент и Пурал. Результатами испытаний являются зависимости величины коэффициента трения по различным материалам от скорости скольжения снега. Также были получены значения силы трения снега по покрытию при различной температуре окружающей среды.

ABSTRACT

Analysis of the highest snow load is important in the process of designing of a roof structure. It is also necessary to take into account a coefficient of snow friction in addition to the main stages of calculation. This parameter may depend on the structure and temperature of the snow and the coating material. The dependence of the friction coefficient of these parameters were determined using techniques developed by research and testing laboratory “Polytech-SKiM-Test” with using of tribometer. Various snow conditions and two types of roof coverings - PVC-tent and Pural were considered in the research. The results of experiments are the dependencies of the coefficient of friction on various materials and slipping speeds. Moreover, values of frictional forces of the snow on the coating at different temperatures were defined.

Contents

1. Introduction

The maximum snow load calculation is one of the important roof designing stages, which determines the type of a construction system and the thickness of its elements. In Russia, the estimated value of snow load depends on the location of the building and normative documents. The calculation of the value of snow load is performed in the design of the roof to reduce the probability of adverse consequences caused by the action of the weight of the snow mass.

During the snowfall, the accumulated load may deform elements of bearing constructions, the rafter system or roof covering. The structural analysis based on snow load action occurs at the design stage to prevent this [1].

Another key factor is the snow stability on the roof. Depending on the construction type of a roof and the purpose of a building, requirements for roofing change [2]. For example, the roof slope in tent constructions should be sufficiently great to allow the snow mass to slide from it independently. Otherwise, the snow accumulation and the increase of snow load may lead to an expansion with a subsequent collapse [3].

On the other hand, in a case of a pitched roof, it is more sustainable to apply materials for a roof coating with a high coefficient of friction to improve the stability of the snow mass and to prevent its sliding [4, 5]. Thermal resistance of snow cover increases with its growth, so eventually snow on the roof begins to melt because of the heat transmitted from the interior space [6, 7]. In consequence, the formation of icicles happens with decreasing temperature, which may pose a serious risk to pedestrians and vehicles [8, 9].

Roof ice rakes are applied to prevent a slipping of a melted snow and a falling of icicles [10, 11]. Moreover, this construction prevents mechanical damage of the roof (scratches, cracks) formed as a result of ice mass sliding [12]. Therefore, the load calculation on roof ice rakes is also an important part of a pitched roof design.

Thus, it is necessary to take into account the coefficient of snow friction along the roof, which depends on the type of snow precipitations, the structure of the snow cover, the snow temperature and the presence of the water layer in the process of calculation of load-bearing structures and choosing the roof coating material, among other parameters [13–15].

The purpose of this research is the investigation of the dependence of the snow friction on different temperatures and coating materials, to obtain its values for practical purposes [16, 17]. The results of the work can be used in roofs design and also in calculation of the durability of ice rakes and other structural elements.

Currently, the normative literature about the methods of testing the friction of the snow does not exist [18-20]. Present methods of determining the coefficient of friction are regulated by Russian State Standards GOST 27640-88, GOST 11629-75, GOST 55951-2014 and cover solid materials such as metals and their alloys, plastics, wood cannot be directly used for a test of snow.

The snow pressed under the load changes its true density on the sliding surface unlike the materials mentioned above [21–23]. The needle-like crystals of snow, located chaotically at the beginning of the test, are oriented along the direction of motion under the action of a sliding body [24, 25]. The snow may melt under the counter body because of the heat released during friction [26, 27]. All these processes create instability of friction characteristics.

The technique developed in the research laboratory "Polytech-SKiM-Test" of the St. Petersburg State Polytechnic University was organized with the consideration of similar experiments in papers [28, 29].

The mission of this work is to determine the dependencies of friction coefficient on the structure, temperature of the snow and the type of coating material. It is also necessary to define practical values of frictional forces of the snow on the coating at different temperatures.

There are several main tasks, set in this paper:

1. Determination of the law, that the frictional force follows in case of the fine-grained dry snow structure;
2. Finding out the relation between the frictional force and the sliding speed on different types of covering material;
3. Definition of the frictional force at the moment of breakaway;
4. Estimation of practical values of the frictional force depending on the sliding speed and types of covering material;
5. Determination of the friction of rest before a start of the movement and after a stop.

2. Methods

The tribometer machine with special modifications was applied in laboratory conditions to estimate the parameters of snow friction on roof coatings. The tribometer design is shown in Fig. 1.

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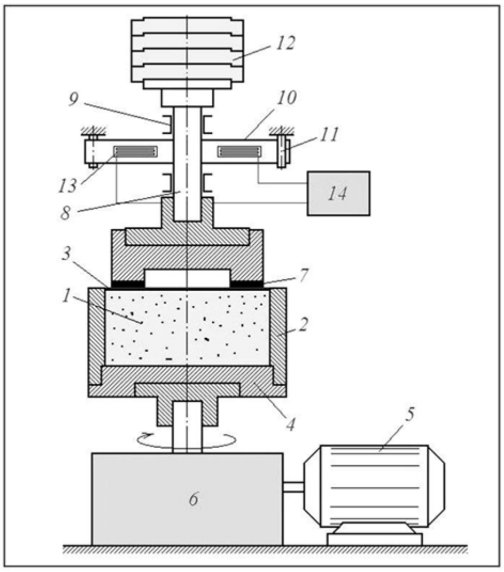

Figure 1. The tribometer design

There were two types of counter bodies, which were used in the experiments due to their availability:

1. The soft covering of a tent hangar made of reinforced poly vinyl chloride membrane (PVC coating);

2. Metal roof sandwich panel with a polyurethane powder coating "Pural".

A sample of snow 1 in the plastic cage 2 is mounted on the flange 4 and is driven into rotation by a direct current electric motor 5. The frequency of rotation is regulated by a step-by-step gearbox 6 and by a smooth changing of motor voltage and was measured with a tachometer generator. The surface of the sample covered with a layer 3 (or uncovered) is brought into a frictional contact with the counter body 7, which is made of a roof covering material in the form of a ring. The outer and inner diameters of the ring are 97.3 and 57.0 mm, respectively. The shaft 8 is located in bearings 9 coaxially with the sample 1 and can freely move along the vertical axis. The elastic plate 10 is rigidly connected with the shaft and is rested on block stops 11. It restrains the counter body from rotation. When the sample 1 is rotated, counter body 7 is sliding along its surface.

The counter body 7 is pressed against the surface of the sample by the weight of the moving part of the tribometer and by the set of interchangeable loads 12. The torque transmitted to the counter body 7 due to the friction is recorded by a dynamometer, which consists of an elastic element 10 with a wire resistive-strain sensor 13 glued to it. An electric signal from the dynamometer is feed to the measuring device 14. The torque M, transferred to the counter body because of the friction, is determined by formula:

$$M = 2\pi \int_{r1}^{r2} \tau \cdot r^2 \cdot dr; \tag{1}$$

where: r1 and r2 are the inner and outer radius of the counter body ring;

τ – the frictional stress.

The frictional force F is calculated under the assumption that | does not depend on r, and is determined by the formula:

$$F = \frac{3M}{2\pi\,(r_2^3 + r_1^3)} \cdot S_k. \tag{2}$$

During the test, the normal load was applied in steps of 2 kg by means of interchangeable weights 12. After the installation of the next cargo, the sample was rotated. In this moment the torque of a breakaway friction of the rubber counter body and the sliding friction torque were recorded. After this, the rotation was stopped and the torque of frictional rest was recorded. Torques of the breakaway friction and the movement greatly differed in their value. The torque of static friction turned out to be generally lower than of the sliding friction.

3. Results and discussion

3.1. Fine-grained dry snow

At the moment of the beginning of the movement, the force of friction instantaneously increases to the highest value. For example, Fig. 2 shows its dependency from the breakaway and for 4 following minutes.

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Apparently, the force of friction after the initial jump gradually decreases; this is a typical plot for dry snow at low temperature.

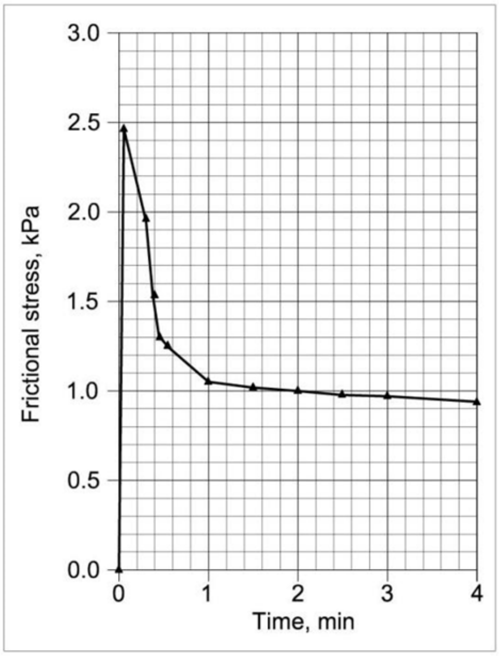

Figure 2. The friction of fine-grained dry snow along the "Pural" covering under a load of 56.2 kPa at the temperature of -16°C and the slipping speed of 6 cm/s

As time passes, the friction force stabilizes, however, the reproducibility of friction remains is low, because it depends on many factors that are difficult to take into account (actual contact area, snow density under the counter body, temperature change, etc.). The divergence between these experiments can be judged from Fig. 3, which shows the variance of experimental points with an eightfold repetition of the same experiment.

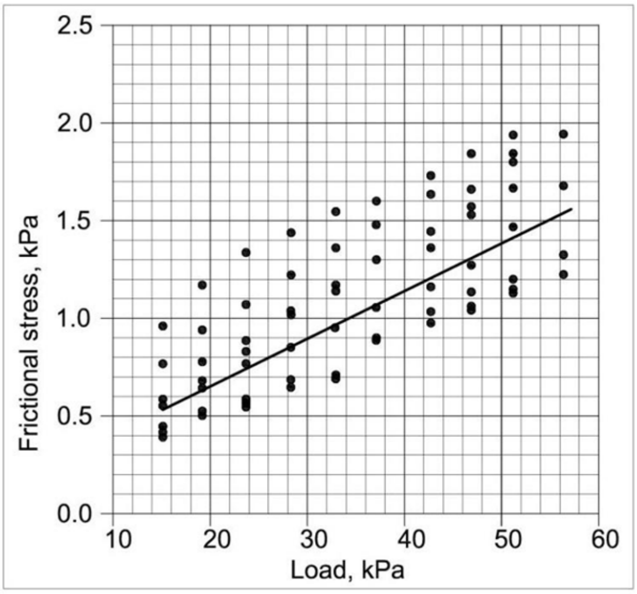

Figure 3. The friction of fine-grained dry snow along the PVC-coating depending on the load at the temperature of -16°C and the sliding speed of 5.9 cm/s

The processing of the results by the least square method shows that the dependence of the frictional force of snow on the PVC coating of the tent hangar from the load is most closely described by the power law $\sigma_{fr}=0.0683\ \pi^{0.7756}$ with a correlation parameter $R^2=0.6208$ and slightly worse with linear relation $\sigma_{fr}=0.024\ \pi+0.2535$ with a correlation parameter $R^2=0.5767$. However, in the case of the linear approximation it is possible to assume the friction coefficient as a constant value, equal in this case to 0.0240, and the value of adhesion pressing 0.2535 kPa.

Close values of the coefficient of friction 0.237 and adhesion pressing 0.2615 kPa (Fig. 4) were obtained for linear approximation with a simple averaging of the results (Table 1).

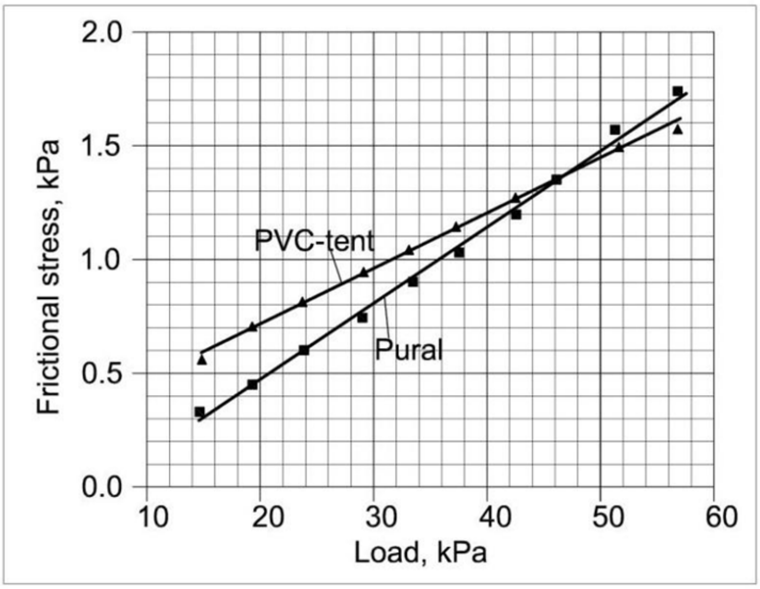

Figure 4. The friction of fine-grained dry snow along the PVC-coating and the "Pural" coating, depending on the load at the temperature of -16°C and the sliding speed of 5.9 cm/s

Table 1. The friction stress of fine-grained dry snow on the PVC-coating depending on the load at the temperature of -16°C and the sliding speed of 6 cm/s

Load, kPa	Friction stress, kPa								
	Particular value								Average
	1	2	3	4	5	6	7	8	
14.7	0.45	0.40	0.59	0.78	0.43	0.95	0.41	0.57	0.57
19.3	0.65	0.50	0.78	0.94	0.51	1.15	0.53	0.68	0.72
23.9	0.83	0.56	0.90	1.08	0.58	1.33	0.61	0.77	0.83
28.5	1.04	0.66	1.01	1.22	0.70	1.46	0.69	0.86	0.95
33.1	1.16	0.77	1.13	1.37	0.80	1.54	0.78	0.94	1.06
37.8	1.29	0.87	1.29	1.48	0.88	1.60	0.89	1.05	1.17
42.4	1.40	0.98	1.48	1.62	0.98	1.74	1.01	1.19	1.30
47.0	1.52	1.05	1.65	1.57	1.07	1.86	1.13	1.27	1.39
51.6	1.70	1.15	1.77	1.57	1.14	1.91	1.21	1.31	1.47
56.2	1.68	1.24	1.93	1.68	1.24	1.93	1.32	1.35	1.55

From now forward the average value of the friction force and the linear approximation corresponding to Coulomb's law will be applied.

Apparently, the friction force of snow on the PVC-covering is higher under the load less than 45 kPa and at loads more than 45 kPa it is lower than on the Pura (Fig.4). The friction coefficient for PVC-covering (0.0237) is lower than for the Pural (0.0342).

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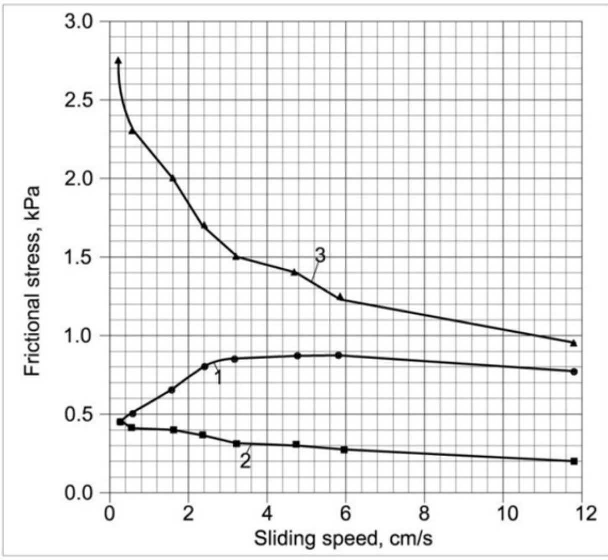

Figure 5. The influence of the sliding speed of fine-grained dry snow on roof coverings: 1 – the PVC-coating at the load 14.7 kPa; 2 – the "Pural" coating at the load 14.7 kPa; 3 - the same at lthe oad 56.2 kPa

The influence of the sliding speed of fine-grained dry snow on roof coverings is shown in Fig. 5. It is notable that the friction force increases with the increasing of sliding speed in the case of the elastic PVC-coating, and it decreases in the case of the polymer coating the "Pural", on the contrary. The greater of the load pressing the counter body to the snow surface, the more intensively reduction of the frictional force on the "Pural" coating occurs.

3.2. Coarsely crystalline snow

The influence of a temperature. Samples and counter bodies were kept in a freezer at a temperature of -24°C. After the experiment, the temperature of the sample was measured with a thermocouple, which was pressed against the surface by a counter body. For the samples tested immediately after removal from the freezer, the temperature after the test was -18 ... -19°C. The samples held in the room had different temperatures. The snow removed from the snowdrift had 0 °C temperature. This snow was tested in the natural state with a significant amount of water. At snow temperatures in the interval from -12 to -19°C, the results differed little among themselves. Therefore, the data obtained at temperatures in this range were averaged. The friction of snow at these temperatures can be attributed to dry friction. At the temperature of -8°C, apparently, there was a thawing of snow because of the friction heat. As a result, friction sharply decreased. However, the surface of the snow after the experiment remained dry, which can be explained by the water layer freezing due to the cooling from the snow with a negative temperature. At 0°C, the friction was also insignificant.

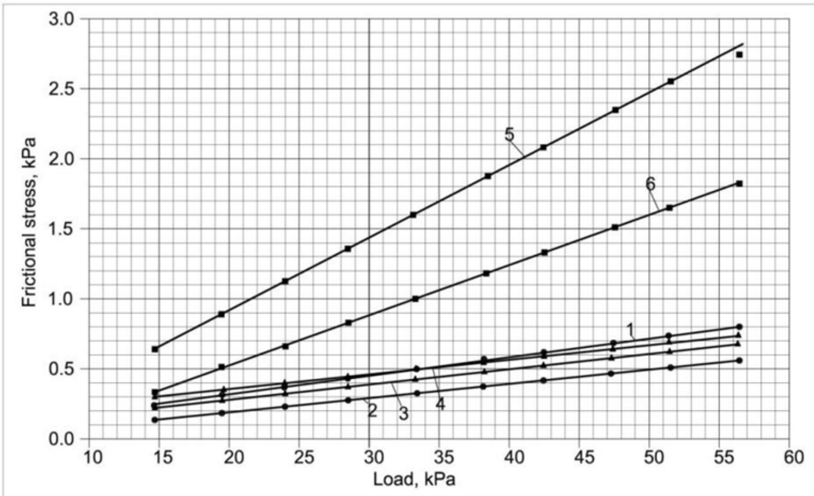

Figure 6. The effect of the temperature on the friction of coarsely crystalline snow on roof coverings at the sliding speed of 5.9 cm/s: 1, 3 and 5 – the PVC coating; 2, 4 and 6 – the "Pural" coating; 1 and 2 - at the temperature of 0°C; 3 and 4 at -8°C; 5 and 6 - at -12... -19°C

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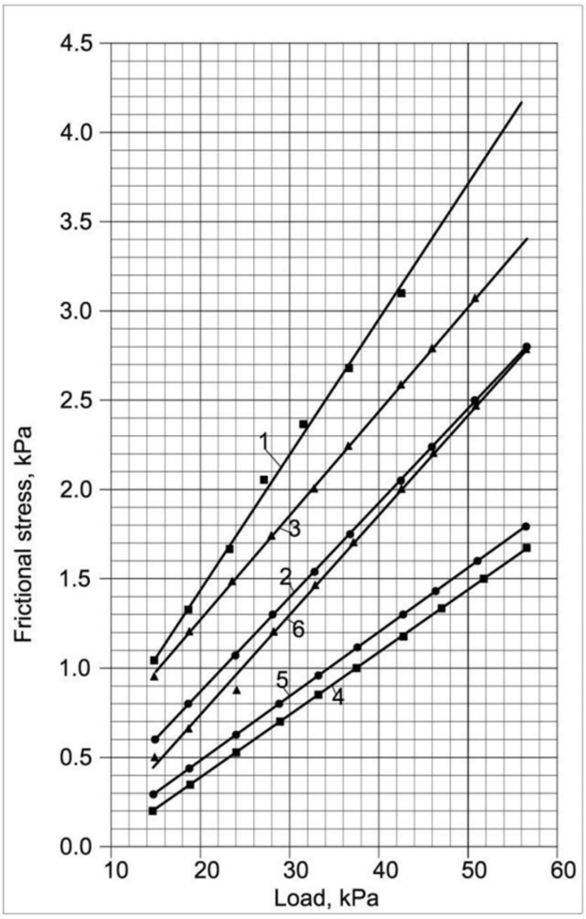

Figure 7.The influence of the slipping speed on the friction of coarsely crystalline snow on roof coatings at -18°C: 1-3 – the PVC coating; 4-6 – the "Pural" coating; 1 and 4 - at the sliding speed of 1.5 cm/s; 2 and 5 - at 5.9 cm/s; 3 and 6 - at 11.8 cm/s

Table 2. Coefficients of the friction of coarsely crystalline snow on roof coverings as a function of temperature

Type of a roof covering	Coefficients of friction at various temperatures, °C		
	0	-8	-12…-19
PVC	0.0135	0.0111	0.0539
"Pural"	0.0103	0.0111	0.0371

The influence of a sliding speed. The curves of the friction force at different sliding speeds are shown in Fig. 9. The line chart shows the force and coefficient of friction have higher values for the PVC-covering. The highest friction occurs at the lowest speed of 1.5 cm/s. The friction force decreased with an increase of velocity to 5.9 cm/s, and the friction force increased in the experiment with a higher sliding speed of 11.8 cm/s. Unlike the PVC-covering, the friction force and the coefficient of friction for the "Pural" coating also increased with an increase of sliding speed.

Values of the friction coefficient as a function of the sliding speed are given in Table. 3.

Table 3. Coefficients of the friction of coarsely crystalline snow on roof coverings as a function of the sliding speed

Type of a roof covering	Coefficients of friction at various slipping speeds, cm/s		
	1.5	5.9	11.8
PVC	0.0734	0.0539	0.0575
"Pural"	0.0347	0.0371	0.0571

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The results given in the Fig. 7 and the Table 3 are not consistent with the dependence of friction on the slipping speed, obtained in other conditions of the experiment, when the speed was varied in the process sliding with a constant load (Fig. 8, Fig. 9).

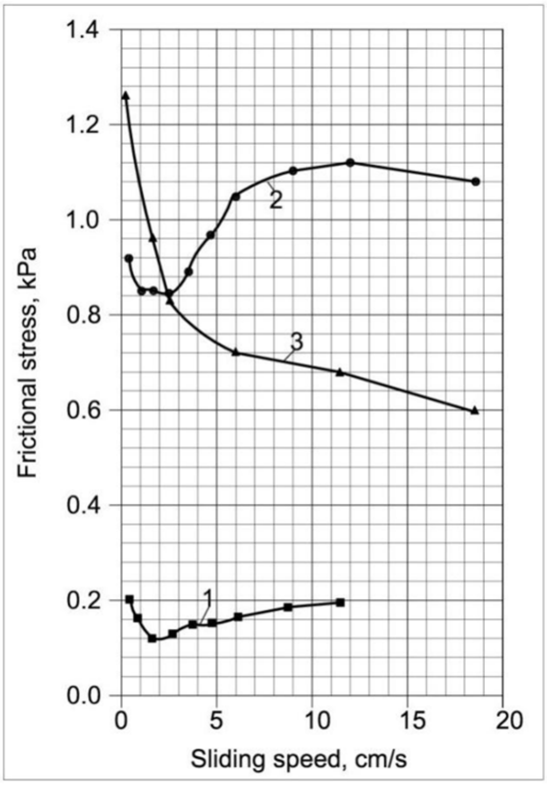

Figure 8. The influence of the sliding speed on the friction of coarsely crystalline snow on the PVC-coating: 1 - at the temperature of -8°C and the load of 14.7 kPa; 2 - at the temperature of -8°C and the load of 56.2 kPa; 3 - at the temperature of -18°C and the load of 33.1 kPa

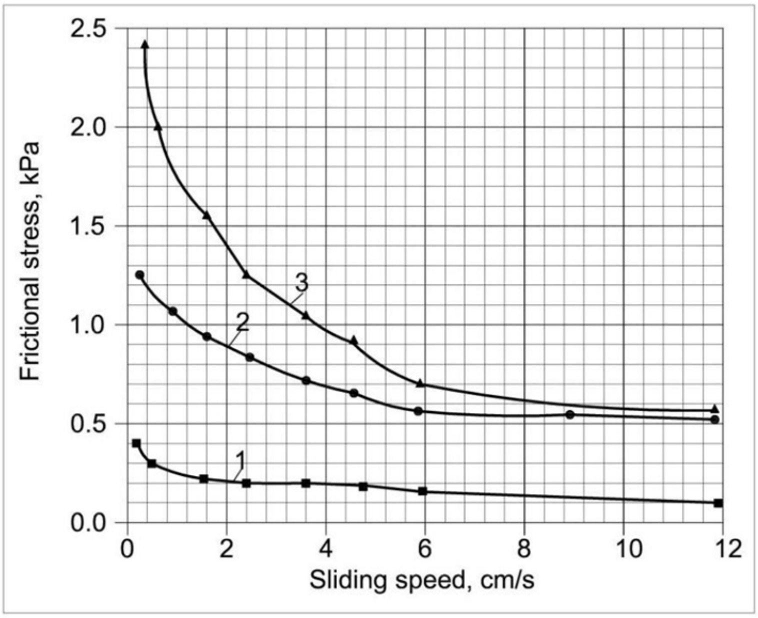

Figure 9. The influence of the sliding speed on the friction of coarsely crystalline snow on the "Pural" coating: 1 - at the temperature of -8°C and the load of 56.2 kPa; 2 - at the temperature of -18°C and the load of 14.7 kPa; 3 - at the temperature of -18°C and the load of 56.2 kPa

The friction of rest. The friction of rest was determined in a stop after sliding and in a breakaway moment. In the first case, the friction of rest is much lower than the sliding friction. There is a slow decaying motion of the counter body in the direction opposite to the original one, due to the dynamometer elastic element release from

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deformation after cessation of the snow sample rotation. The results of the experiment of the friction of rest after the cessation of slipping are demonstrated in Fig. 10.

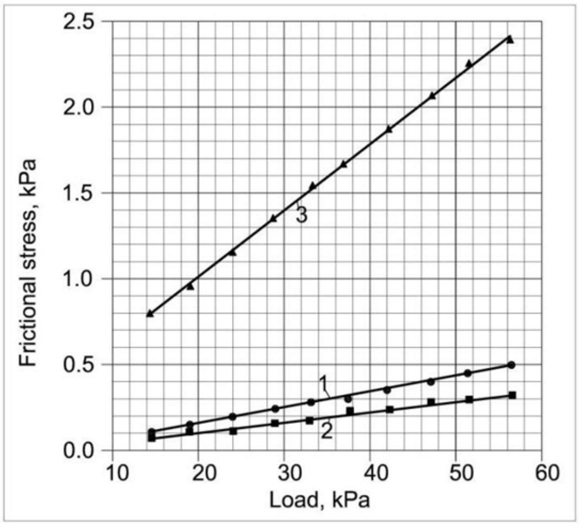

Figure 10. The temperature effect on the friction of rest after cessation of slipping of coarsely crystalline snow along the PVC coating: 1 - at the temperature of 0°C; 2 - at -8° C; 3 - at -18°C

The friction of breakaway. The friction of breakaway significantly exceeds friction of sliding and depends on the duration of contact. The results with contact duration less than 3 s are shown in Fig. 11 and Table. 4.

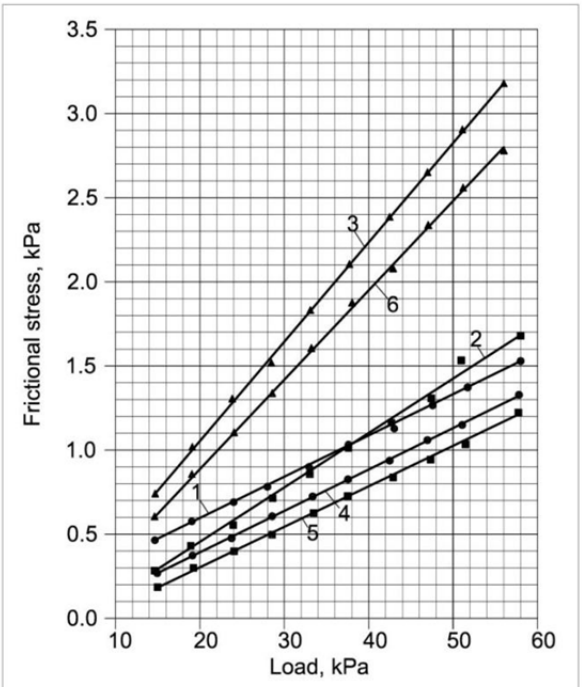

Figure 11. The temperature effect on the friction of rest of coarsely crystalline snow on roof coverings: 1-3 – the PVC coating; 4-6 – the "Pural" coating; 1 and 4 - at the temperature of 0°C; 2 and 5 - at -8°C; 3 and 6 at -18°C.

Table 4. Friction of rest coefficients of coarsely crystalline snow in the breakaway moment as a function of temperature

Type of a roof covering	**Friction coefficients in various temperatures, °C**		
	0	-8	-18
PVC	0.0260	0.0349	0.0583
"Pural"	0.0278	0.0257	0.0523

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The effect of the duration of the immovable contact of snow with the counter body on the friction of rest at the moment of breakaway is given in Fig. 12.

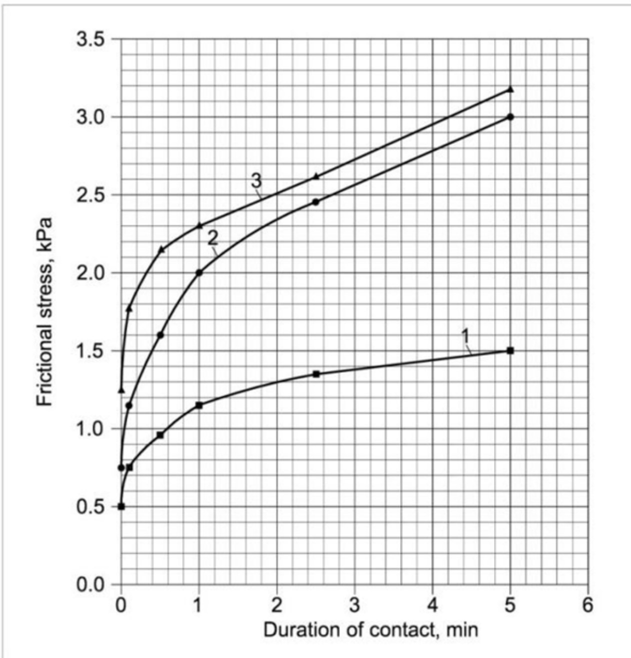

Fig. 12. The influence of the duration of the immovable contact of coarsely crystalline snow on the friction of rest at the moment of breakaway for the PVC-coating: 1 – the load 14.7 kPa; 2 - 28.5 kPa; 3 - 42.4 kPa

4. Conclusion

1. The friction of snow follows the Coulomb's linear law on the tested roofing coatings. In the case of fine-grained dry snow at the moment of the movement beginning (breakaway of the counter body) the friction force has the highest value, which then decreases with the motion, tending to a relative constancy. The coefficient of friction along the PVC-tent (0.0237) is lower than along the Pural (0.0342) at a temperature of t = -16°C.

2. The frictional force also increases as a sliding speed of fine-grained dry snow along the PVC coating increase, and it decreases in the case the "Pural" coating, on the contrary. The greater the load pressing the counter body to the snow surface, the more intensively reduction of the frictional force on the "Pural" coating occurs.

3. The frictional force of a breakaway and subsequent sliding varies little in the case of coarsely crystalline wet snow at a temperature about 0°C. When melted snow freezes, the resistance of breakaway exceeds the sliding friction force. Friction increases with the decreasing of temperature. However, at a snow temperature in the range from -12 to -19°C, the results differed little among themselves. The friction of snow at these temperatures can be attributed to a dry friction. At the temperature of -8 ° C, apparently, there was a thawing of snow because of the friction heat. As a result, friction sharply decreased. At 0 °C, the friction was also insignificant. Friction force and coefficient are higher in the case of PVC-covering, than in case of the "Pural" covering.

4. The character of the influence of the sliding speed depends on the conditions of the experiment and can change in the opposite way. Thus, for example, when the load changes at a constant speed, the highest friction force of the PVC-covering took place in the case of the lowest speed 1.5 cm/s. With increasing of speed up to 5.9 cm/s, the frictional force decreased, and at a speed of 11.8 cm/s again increased. Unlike the PVC-covering, with an increase of sliding speed the friction force and the coefficient of friction for the "Pural" coating also increased. With a change of speed in the case of a constant load, a different character of these dependencies was obtained.

5. The friction of rest may have a different value depending on whether it is measured before the start of the movement or after a stop. Fiction of rest after the stop is very low - significantly less than friction of sliding. Friction at the moment of breakaway considerably exceeds the sliding friction and depends on the duration of contact. The longer the immovable contact with the snow, the greater the effort it takes to overcome the friction of rest. The static friction coefficients for the before begging of the snow sliding and at low temperatures are efficient to take as the initial parameters in engineering calculations that involve the

tangential effect on the roof covering. However, in roof ice rakes stability analysis the parameters of melted snow friction in the sliding mode should be applied.

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