Influence of intermediate layer on the strength of freezing of soil with the metal surface of machines at negative temperatures

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Abstract. The development of moist cohesive soils in conditions of negative temperatures leads to a decrease in the productivity of earth-moving machines due to the increase in adhesion and friction. When wet soil and a metal bucket interact, the soil freezes to the sides of the bucket, which leads to a decrease in the useful volume of the bucket and, therefore, to a decrease in the productivity of the machine. The experimental studies have been carried out on the effect of the intermediate layer at the interface between the soil and the working body of the machine, on adhesion. The prophylactic lubricant "Niogrin" was used as an intermediate layer. As a result of processing the obtained experimental data, a regression equation was obtained; the dependence of the soil shear stress on various factors is presented and the influence of external factors on the adhesion of soils at negative temperatures is estimated. The comparison of the obtained dependencies showed that the strength of soil freezing when using a preventive liquid decreases 1.5-2 times.

1. Introduction
To date, there are various ways to combat soil freezing to the working bodies of earth-moving machines when operating in freezing temperatures. These methods can be divided into four groups: the formation of an intermediate layer at the contact boundary; external influence (for example, thermal effect) on the working body in the contact zone; design and technological method; a combination of two or more of the previously listed methods.

2. Formulation of the problem and method of solution
The experimental studies of the effect of the intermediate layer on adhesion to the surface of excavator buckets at negative temperatures have been carried out using the methods of physical modeling of systems and the mathematical theory of planning experiments.

The research data on the establishment of the dependence of the shear stress on the main factors that determine the adfreezing strength of soils with a metal sliding surface were carried out using a matrix of rotatable central compositional planning, the basis for which was the analysis of a priori information and the conditions for conducting experiments.

The parameters of the equipment for creating an intermediate layer (their rational values) did not change during the experiment. The prophylactic lubricant "Niogrin" was used as a preventive liquid.

Factor levels and variation intervals are presented in table 1.
Table 1. Factor levels and variation intervals for preventive exposure

| Factor | -2 | -1 | 0  | 1  | 2  | Variation intervals |
|--------|----|----|----|----|----|---------------------|
| $X_1$ – dispersion of soil, D, mm | 9·10^{-3} | 7·10^{-3} | 5·10^{-3} | 3·10^{-3} | 1·10^{-3} | 2·10^{-3} |
| $X_2$ – normal ground pressure, P, kPa | 0 | 10 | 20 | 30 | 40 | 10 |
| $X_3$ – weight soil moisture, W, % | 7.5 | 12.5 | 17.5 | 22.5 | 27.5 | 5.0 |
| $X_4$ – ambient temperature, T, °C | 5 | -5 | -15 | -25 | -35 | 10 |
| $X_5$ – duration of soil contact with metal, t, min | 0.5 | 10.5 | 20.5 | 30.5 | 40.5 | 10 |

The planning matrix and the results of a multifactorial experiment with preventive exposure are presented in table 2.

Table 2. The planning matrix and the results of a multifactorial experiment with preventive exposure

| Experience number | $X_1$ | $X_2$ | $X_3$ | $X_5$ | $X_4$ | $Y_{av}$, kPa | $Y_{prev}$, kPa | $K_{ef}$ |
|-------------------|-------|-------|-------|-------|-------|---------------|----------------|--------|
| 1                 | -     | -     | -     | -     | -     | 29.15         | 16.03          | 1.84   |
| 2                 | +     | -     | -     | -     | +     | 42.26         | 25.39          | 1.69   |
| 3                 | -     | +     | -     | -     | +     | 62.65         | 28.22          | 2.24   |
| 4                 | +     | +     | -     | -     | -     | 40.22         | 12.08          | 3.35   |
| 5                 | -     | -     | +     | -     | +     | 105.23        | 36.84          | 2.88   |
| 6                 | +     | -     | +     | -     | -     | 53.94         | 21.59          | 2.52   |
| 7                 | -     | +     | +     | -     | +     | 48.36         | 19.36          | 2.52   |
| 8                 | +     | +     | +     | -     | -     | 150.65        | 78.35          | 1.94   |
| 9                 | -     | -     | -     | +     | +     | 128.06        | 61.47          | 2.06   |
| 10                | +     | -     | -     | +     | -     | 68.54         | 39.76          | 1.74   |
| 11                | -     | +     | -     | -     | +     | 82.08         | 35.26          | 2.35   |
| 12                | +     | +     | -     | +     | +     | 212.38        | 78.59          | 2.72   |
| 13                | -     | -     | +     | +     | -     | 124.37        | 41.06          | 3.05   |
| 14                | +     | -     | +     | +     | +     | 275.67        | 104.78         | 2.65   |
| 15                | -     | +     | +     | +     | +     | 294.96        | 106.17         | 2.76   |
| 16                | +     | +     | +     | +     | +     | 269.38        | 80.83          | 3.35   |
| 17                | -2    | 0     | 0     | 0     | 0     | 50.26         | 16.06          | 3.14   |
| 18                | 2     | 0     | 0     | 0     | 0     | 120.37        | 58.97          | 2.06   |
| 19                | 0     | -2    | 0     | 0     | 0     | 69.88         | 35.65          | 1.98   |
| 20                | 0     | 2     | 0     | 0     | 0     | 164.17        | 77.19          | 2.15   |
| 21                | 0     | 0     | -2    | 0     | 0     | 68.56         | 25.39          | 2.72   |
| 22                | 0     | 0     | 2     | 0     | 0     | 202.37        | 96.47          | 3.05   |
| 23                | 0     | 0     | 0     | -2    | 0     | 40.14         | 19.28          | 2.06   |
| 24                | 0     | 0     | 0     | 2     | 0     | 305.13        | 100.67         | 3.05   |
| 25                | 0     | 0     | 0     | 0     | -2    | 59.55         | 27.96          | 2.15   |
| 26                | 0     | 0     | 0     | 0     | 2     | 239.47        | 90.97          | 2.65   |
| 27                | 0     | 0     | 0     | 0     | 0     | 185.76        | 59.46          | 3.14   |
| 28                | 0     | 0     | 0     | 0     | 0     | 179.35        | 55.62          | 3.25   |
| 29                | 0     | 0     | 0     | 0     | 0     | 192.05        | 74.87          | 2.58   |
| 30                | 0     | 0     | 0     | 0     | 0     | 187.38        | 56.23          | 3.35   |
| 31                | 0     | 0     | 0     | 0     | 0     | 184.55        | 92.28          | 2.02   |
| 32                | 0     | 0     | 0     | 0     | 0     | 184.43        | 88.54          | 2.06   |
As a result of the implementation of the experiment planning matrix (table 2) with varying the main factors (table 1), causing the adhesion of soils to the metal surface of the working body at negative temperatures, and processing the results of experimental studies using the "MODEL N" program, a regression equation was obtained that approximates experimental data:

- with preventive exposure in coded form:

\[
Y_{prev} = 71.46 + 7.61X_1 + 7.29X_2 + 13.93X_3 + 19.71X_4 + 15.83X_5 - 8.71X_1^2 - 3.99X_2^2 - 2.86X_3^2 - 3.1X_4^2 - 3.23X_5^2 + 1.54X_1 \cdot X_2 + 4.21X_1 \cdot X_3 + 1.44X_1 \cdot X_4 + 0.74X_1 \cdot X_5 + 4.31X_2 \cdot X_3 + 0.98X_2 \cdot X_4 + 2.1X_2 \cdot X_5 + 2.71X_3 \cdot X_4 + 4.55X_3 \cdot X_5 + 3.4X_4 \cdot X_5; 
\]

(1)

- with preventive exposure in natural form:

\[
\tau_{prev} = 6227.75D + 0.34P + 2.73W - 0.85T + 0.8t - 5.4 \cdot 10^5 D^2 - 9.97P^2 - 2.86 \cdot 10^{-2} W^2 - 7.77 \cdot 10^{-3} T^2 - 8.07 \cdot 10^{-3} t^2 - 19.25D \cdot P - 100.25D \cdot W + 18D \cdot T - 9.25D \cdot t + 2.15 \cdot 10^{-3} P \cdot W - 2.45 \cdot 10^{-3} P \cdot T + 5.27 \cdot 10^{-3} P \cdot t - 1.35 \cdot 10^{-2} W \cdot T + 7.7 \cdot 10^{-3} W \cdot t - 8.5 \cdot 10^{-3} T \cdot t - 17.7; 
\]

(2)

3. Results and discussion

The analysis of equation (1) for the optimum showed that such a point is in the negative response region. All factors in the investigated range mainly contribute to an increase in the freezing strength. In ascending order of increasing adhesion, they make up the series: D, P, t, T, W.

The increase in the influence of pressure during preventive exposure can be explained by the disappearance of the cementation bonds of ice (its melting) under the influence of thermal energy and the transition of bound water into loose and free water.

The quasi-one-factor dependences of the shear stress under preventive action on external factors are shown in figures 1-5.

**Figure 1.** Dependence of the shear stress of the soil on its dispersion at P=20 kPa; W=17%; T=−15 °C; t=20.5 min
Figure 1 shows that with an effective particle diameter $D = 3 \cdot 10^{-3}$ mm, the maximum freezing strength is observed.

The resulting dependence of the effect of soil dispersion on the strength of soil freezing to a metal surface during the formation of an intermediate layer can be described by the empirical formula:

$$\tau_{\text{prev}} = 67.41 + 3541.25D - 544375D^2$$

(3)

where $\tau_{\text{prev}}$ - resistivity to shear during preventive treatment, kPa; $D$ – soil dispersion, mm.

With an increase in pressure, the shear stress increases, which is explained by an increase in the true area of contact between the soil and the surface, after which the pressure affects the shear stress insignificantly (figure 2).

The resulting dependence of the influence of the initial pressing pressure on the strength of freezing of the soil to the metal surface during the formation of an intermediate layer can be described by the empirical formula:

$$\tau_{\text{prev}} = 60.2 + 0.76P - 9.97 \cdot 10^{-3}P^2$$

(4)

where $\tau_{\text{prev}}$ - resistivity to shear during preventive treatment, kPa; $P$ – initial contact pressure, kPa.

![Figure 2](image)

**Figure 2.** Dependence of the soil shear stress on the initial pressing pressure at $D = 5 \cdot 10^{-3}$ mm; $W = 20\%$; $T = -15^\circ C$; $t = 20.5$ min.

The analysis of the dependence of soil shear stress on moisture (figure 3) shows that with increasing moisture, the shear stress increases.

The obtained dependence of the influence of the weight moisture content of the soil on the strength of freezing of the soil to the metal surface during the formation of an intermediate layer can be described by the empirical formula:
\[ \tau_{\text{prev}} = 2.33W + 27.87 - 2.86 \cdot 10^{-2} W^2 \]  

where \( \tau_{\text{prev}} \) - resistivity to shear during preventive treatment, kPa; \( W \) - weight soil moisture, \( \% \).

Figure 3. Dependence of the soil shear stress on the weight moisture content of the soil at \( D = 5 \cdot 10^{-3} \) mm; \( P = 20 \) kPa; \( T = -15 \) °C; \( t = 20.5 \) min.

The temperature in the zone of contact between the soil and the surface of the working body is one of the main factors affecting the adhesion of the soil (Figure 4).

The dependence of the shear stress in the investigated range of variation of the factors is practically directly proportional to the change in temperature.

The resulting dependence of the effect of temperature in the contact zone on the strength of freezing of soil to a metal surface during the formation of an intermediate layer can be described by the empirical formula:

\[ \tau_{\text{prev}} = 54.96 - 1.22T - 7.77 \cdot 10^{-3} T^2 \]  

where \( \tau_{\text{prev}} \) - resistivity to shear during preventive treatment, kPa; \( T \) - contact zone temperature, °C.

The quasi-one-factor dependence of the shear stress on the contact time (figure 5) shows that with an increase in the time of contact between the soil and the metal surface, the shear stress increases.

The obtained dependence of the influence of the contact time on the strength of freezing of the soil to the metal surface during the formation of the intermediate layer can be described by the empirical formula:

\[ \tau_{\text{prev}} = 51.91 - 1.12t - 8.07 \cdot 10^{-3} t^2 \]  

where \( \tau_{\text{prev}} \) - resistivity to shear during preventive treatment, kPa; \( t \) - duration of soil contact with a metal surface, min.
Figure 4. Dependence of the soil shear stress on the temperature in the contact zone at $D = 5 \cdot 10^{-3}$ mm; $P = 20$ kPa; $W = 17\%$; $t = 20.5$ min.

Figure 5. Dependence of soil shear stress on the contact time at $D = 5 \cdot 10^{-3}$ mm; $P = 20$ kPa; $W = 17\%$; $T = -15$ °C.
4. Conclusion

1. It was experimentally established that of the variety of external factors affecting the adhesion of soils at negative temperatures, the main ones (in decreasing order of the degree of influence of the factor) were: weight moisture content of the soil, temperature in the contact zone, contact time, pressure of initial pressing, dispersion of the soil.

The equations (1.2) were obtained that connected these factors with the freezing force. It was found that in the selected range of changes in external factors, all factors contributed to the increase in freezing strength.

2. As a result of studying the preventive effect on the adhesion of the soil at negative temperatures, equations (3-7) were obtained, connecting external factors with the freezing force.

All the factors in the investigated range contribute to the increase in the freezing strength. In an ascending order of increasing influence on adhesion, they made up the series: D, P, t, T, W.

3. The comparison of the obtained dependences showed that the strength of soil freezing when using a preventive liquid decreases 1.5-2 times.

References

[1] Zadneprovskiy R P 2005 Theory of Sliding Friction (Volgograd: Ofset) p 51
[2] Rajaram G and Erbach D C 1999 J. of Terramechanics 36 39–49
[3] Zenkov S A, Balahonov N A and Kirichenko O P 2018 Decrease of soil adhesion to working bodies of earth-moving machines Advances in Engineering Research 158 468–73
[4] Zenkov S A, Balahonov N A and Kirichenko O P 2019 Improving the efficiency of technological machines in the interaction with adhesive materials at negative temperatures IOP Conf. Ser.: Mater. Sci. Eng. 560 012097
[5] Sharma V K, Drew L O and Nelson L 1977 Transactions of the ASAE 20 46–51
[6] Tong J, Ren L, Yan J, Ma Y and Chen B 1999 Int. Agricultural Eng. J. 8 1–22
[7] Wang X L, Ito N, Kito K and Garcia P P 1998 J. of Terramech. 35 87–101
[8] Azadegan B and Massah J 2012 Effect of temperature on adhesion of clay soil to steel Cercetiiiri Agronomice in Moldova XLV 2(150) 21-7
[9] Zadneprovsky R P 1992 Working Bodies Earthwork and Reclamation Machines and Equipment for Soil and High Humidity Materials (Moscow: Mashinostroenie) p 176