Improving the efficiency of technological machines in the interaction with adhesive materials at negative temperatures

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Abstract. In this paper, the object of study is a technological machine that develops the cohesive ground. The MAXFLIGHT 04 anti-icing fluid is considered as a means of controlling the adhesion of the “soil-to-metal” system used in the operation of technological machines while developing moist cohesive soils under negative temperatures. The aim of the study is to increase the productivity and efficiency of technological machines in the developing wet cohesive soils at negative temperatures by reducing the soil-to-metal adhesion. Mathematical processing of the research results allowed us to obtain regression equations for two working conditions: a regression equation without using prophylactic agents to reduce soil adhesion and a regression equation using the MAXFLIGHT 04 anti-icing fluid. Using the obtained regression equations, the proportionality coefficient (the reduced friction coefficient $f$) was calculated. According to the calculation results, the values of the obtained proportionality coefficient depend on the shear plane of the temperature.

1. Introduction
One of the main factors resulting in the productivity decrease of technological machines is the friction and adhesion increase during the development of wet cohesive soils under negative ambient temperatures.

There are four methods to control sticking and freezing of the soil to the working bodies of technological machines. The first method is the formation of an intermediate layer in the “soil-to-metal” contact. The second group includes methods which function is to reduce the soil-to-metal adhesiveness by external action. The third group includes technological and mechanical methods to control adhesion. Finally, the fourth group includes the methods that combine two or more approaches to reduce the soil adhesion and friction described above [1–9].

2. Materials and methods
One of the most common and promising method is prophylactic one [3, 9] which involves the creation of an intermediate layer in the contact point of the working organ and the moist soil. The intermediate layer serves as a protective shield for intermolecular interaction, providing the frictionless surface movement of the phase surfaces. The intermediate layer is divided into liquid, solid, and gaseous parts.

The prophylactic fluids “MAXFLIGHT 04” and “OCTAFLO EG” are propylene glycol anti-icing substances intended for ground anti-icing aircraft treating. The liquids are good for anti-icing and perform efficiently when heated up to +70 ºC without any operational restrictions. The anti-icing liquid must be kept on the wings (Holdertime) from 3 min to 12 h. It has the lowest limits of viscosity of all the SAE Type IV fluids, in some cases even lower than those of the SAE Type II [3] liquids.
During the experimental studies, the soil of category IV (loam) was used as the most common in the northern areas of the Irkutsk region. The soil moisture was 7.5, 12.5, and 17.5%; the time of the “soil-to-metal” system contact with metal surface was 3, 5, and 7 min. This corresponds to the operating parameters of technological machines. The plan and the results of the experiment are shown in table 1.

Table 1. The plan and the results of the experiment

| Ambient temperature $T_{\text{at}}$, °C | Soil moisture $W$, % | The contact time of the soil-to-metal system $t$, min | Without the impact | With the MAXFLIGHT 04 impact |
|---------------------------------------|---------------------|--------------------------------|------------------|-----------------------------|
| -35                                   | 7.5                 | 3                              | 92.73            | 30.4                        |
|                                       | 7.5                 | 7                              | 174.2            | 62.74                       |
|                                       | 12.5                | 5                              | 186.54           | 78.91                       |
|                                       | 17.5                | 3                              | 218.54           | 134.2                       |
|                                       | 17.5                | 7                              | 400              | 159.89                      |
| -15                                   | 7.5                 | 5                              | 63.74            | 38.25                       |
|                                       | 12.5                | 3                              | 78.45            | 50.01                       |
|                                       | 12.5                | 5                              | 144.2            | 56.88                       |
|                                       | 12.5                | 7                              | 240.3            | 58.84                       |
|                                       | 17.5                | 5                              | 228.5            | 94.14                       |
| 5                                     | 7.5                 | 3                              | 11.6             | 4.2                         |
|                                       | 7.5                 | 7                              | 15.2             | 5.1                         |
|                                       | 12.5                | 5                              | 17.9             | 8.3                         |
|                                       | 17.5                | 3                              | 24.3             | 14.8                        |
|                                       | 17.5                | 7                              | 31.7             | 17.4                        |

3. Results and discussion

Mathematical processing of the obtained results was carried out by using the MODEL program for the multifactor dependencies using the least square method. As a result of experimental data processing, the regression equations were obtained: the one without the impact of the lubricant and the one with applying the anti-icing fluid “MAXFLIGHT 04”.

Without the impact [3]:

$$
\tau_{\text{at}} = 134.3 + 1.026 \cdot T_{\omega} - 4.3 \cdot W - 46.08 \cdot t - 0.1 \cdot T_{\omega}^2 + 0.1074 \cdot W^2 + 3.985 \cdot t^2 - 0.4 \cdot T_{\omega} \cdot W - 0.8 \cdot T_{\omega} \cdot t + 1.3 \cdot W \cdot t
$$

(1)

With the impact of “MAXFLIGHT 04” [3]:

$$
\tau_{\text{MAXFLIGHT}} = 41.22 + 0.66 \cdot T_{\omega} - 8.14 \cdot W + 4.4 \cdot t - 0.03 \cdot T_{\omega}^2 + 0.43 \cdot W^2 - 0.27 \cdot t^2 - 0.22 \cdot T_{\omega} \cdot W - 0.17 \cdot T_{\omega} \cdot t - 0.062 \cdot W \cdot t
$$

(2)

Taking into account the adhesion, the friction force of the soil-to-metal surface sliding is determined by the equation [4]:

$$
F = fP + f_1 \cdot \rho_n \cdot S
$$

(3)

where $P$ is the resultant force of the normal contact pressure; $\rho_n$ – the specific adhesion strength, Pa; $f$ – the proportionality coefficient for the deformation component of the friction force; $f_1$ – the proportionality coefficient for the adhesion component of the friction force; $S$ – contact area. With $f = f_1$ the well-known Derjaguin-Krotova formula is obtained.
The shear resistance can be calculated: [4]

$$\tau = \frac{f_P + f \rho_t \cdot S}{S}$$  \hspace{1cm} (4)

The analysis of the equation (4) shows that the resistance (voltage) to the displacement of the soil over the metal surface includes the deformation ($f_P$) and adhesion ($f, \rho_t, S$) forces. It depends on the pressure and the contact area as well as the properties of the shear surfaces and the movement speed of the sample.

The proportionality coefficient is determined by the equation [4]:

$$f = \frac{rS}{p} = f + f_1 \cdot \rho_n \cdot \frac{S}{p}$$  \hspace{1cm} (5)

The proportionality coefficient, or the given friction coefficient $f$, takes into account the shear characteristic when determining the force of the soil-to-metal friction. The value includes the deformation and adhesion and depends on the same parameters as the shear resistance, namely: contact time $t$, pressure $P$, moisture $W$, dispersity of the soil $D$, temperature in the shear plane $T$, and the metal surface state.

The equation (4) determines the shear resistance under the soil freezing to the sliding surface. And the proportionality coefficient $f$ reflects the adhesion effect under negative temperature and is determined by equating the analytical dependence (4) and the dependences on the special shear stand obtained experimentally (1-2), where $\tau = f(D, F, P, W, T, t)$.

Shear stress $\tau$, contact area $S$ and contact pressure $P$ are measured. This allows us to experimentally determine the friction coefficient $f$ under the soil-to-metal surface freezing of the working body elements.

Without the effects of intensifiers, taking into account the dependence (1), one can get:

$$f = (134.3 + 1.026 \cdot T_{cp} - 4.3 \cdot W - 46.08 \cdot t - 0.1 \cdot T_{cp}^2 + 0.1074 \cdot W^2 + 3.985 \cdot t^2 - 0.4 \cdot T_{cp} \cdot W - 0.8 \cdot T_{cp} \cdot t + 1.3 \cdot W \cdot t) \cdot \frac{S}{p}$$  \hspace{1cm} (6)

By using a liquid intermediate layer, taking into account the dependence (2):

$$f = (41.22 + 0.66 \cdot T_{cp} - 8.14 \cdot W + 4.4 \cdot t - 0.03 \cdot T_{cp}^2 + 0.43 \cdot W^2 - 0.27 \cdot t^2 - 0.22 \cdot T_{cp} \cdot W - 0.17 \cdot T_{cp} \cdot t - 0.062 \cdot W \cdot t) \cdot \frac{S}{p}$$  \hspace{1cm} (7)

The results of the calculation of the proportionality coefficient dependence on the temperature are given in tables 2-4.

**Table 2.** Controlled values of the proportionality coefficient $f$ depending on the temperature in the shear plane.

| Ambient temperature $T_{at}$, °C |  +5  |  -5  |  -15 |  -25 |  -35 |
|----------------------------------|------|------|------|------|------|
| Without the impact              | 0.39 | 1.1  | 1.7  | 2.16 | 2.5  |
| With the impact of “MAXFLIGHT 04” | 0.11 | 0.38 | 0.61 | 0.81 | 0.97 |

The values of the proportionality coefficient $f$ are determined by taking into account the following values of external factors: pressure stress $P = 20$ kPa, moisture $W = 17.5 \%$, contact time $t = 7$ min. Interpretation of the obtained results is shown in figures 1-3.
The analysis of the graphs (figure 1) shows that under the above-zero temperature of +5 °C, when the liquid “MAXFLIGHT 04” is applied, the proportionality coefficient $f$ is 3.5 times lower than $f$ without using prophylactic agents. At the negative temperature of –5 °C, when the liquid is applied, the proportionality coefficient is 2.9 times lower than $f$ without using prophylactic agents. At the negative temperature of –15 °C, when the liquid is applied, the proportionality coefficient $f$ is 2.8 times lower than $f$ without using prophylactic agents. At the negative temperature of –25 °C, when the liquid is applied, the proportionality coefficient $f$ is 2.7 times lower than $f$ without using prophylactic agents. At the negative temperature of –35 °C, when the liquid is applied, the proportionality coefficient $f$ is 2.6 times lower than $f$ without using prophylactic agents.

Table 3. Controlled values of $f$ depending on the temperature in the shear plane.

| Ambient temperature $T_{at}$, °C | +5 | –5 | –15 | –25 | –35 |
|---------------------------------|----|----|-----|-----|-----|
| Without the impact              | 0.05 | 0.52 | 0.86 | 1.08 | 1.18 |
| With the impact of “MAXFLIGHT 04” | 0.04 | 0.18 | 0.27 | 0.33 | 0.36 |

These $f$ values are determined by taking into account the following external factors: pressure stress $P = 20$ kPa, moisture $W = 7.5 \%$, contact time $t = 7$ min.
Figure 2. The change of values of the proportionality coefficient.

Table 4. Controlled values of $f$ depending on the temperature in the shear plane.

| Ambient temperature $T_{at}$, °C | +5  | −5  | −15 | −25 | −35 |
|----------------------------------|-----|-----|-----|-----|-----|
| Without the impact              | 0.2 | 0.79| 1.26| 1.6 | 1.82|
| With the impact of “MAXFLIGHT 04” | 0.1 | 0.21| 0.38| 0.5 | 0.6 |

These values of the coefficient of proportionality $f$ are determined by taking into account the following values of external factors: pressure stress $P = 20$ kPa, moisture $W = 12.5$ %, contact time $t = 7$ min.

Figure 3. The change of values of the proportionality coefficient.
4. Conclusion

The analysis of the obtained values of the proportionality coefficient \( f \) allows us to conclude that if the temperature of the contacting surfaces decreases in the range of +5 °C ...−35 °C, the coefficient of proportionality \( f \) increases if the anti-icing fluid brand “MAXFLIGHT 04” is used. However, its value is 2...3.5 times lower than the proportionality values without using prophylactic agents to reduce the adhesion of the soil.

Resulting formulae (6-7) enable one to calculate the value of the proportionality coefficient with given outside factors (operating conditions) and define friction force between soil and the metal surface of the working body taking into account freezing adhesion and outside exposure. This allows one to save time for removing the adhesive substances from the technological machines and to increase their productivity under winter maintenance. As a direction for further research, it is proposed to explore other prophylactic fluids.

References

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