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CONSTRUCTION ON PERMAFROST

ROLE OF THE CONTACT ZONE BETWEEN FROZEN SOILS AND FOUNDATIONS IN FORMING THE STRENGTH OF ADHESIVE BONDS

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The dependence of the strength of the adhesive bond of soils frozen to foundation materials over a broad range of negative temperatures on the structure, properties, and character of failure of their contact zone is examined on the basis of our data and data obtained by other researchers. *The study was performed with financial support from the Russian Fund for Fundamental Research, Russian Academy of Sciences (Project No. 96-05-65774).*

The strength of the adhesive bond between soils frozen to foundation materials is determined, for the most part, by the structure of their contact zone. A number of researchers [1-6 and others] point out the existence on this contact of an intermediate ice interlayer, the formation of which depends on the conditions under which the frozen bond forms. A continuous ice interlayer will form between the soil and surface of the foundation under some conditions, while the contact is accomplished by ice-cement, which bonds the soil particles, under others. In intermediate cases, the contact interlayer of ice may be very thin or discontinuous in nature over the area.

In cases where an ice interlayer forms in the freezing zone, the character of the failure will depend on its thickness under conditionally instantaneous shear. This is associated with the fact that the ice on the contact is influenced by the surface force fields of the foundation material and soil particles [7]. In the case of a relatively thick ice interlayer, shear failure will occur along the ice, and the strength of the frozen adhesive bond will correspond to the strength of this ice. If, however, the ice interlayer is sufficiently thin, it will be distinguished by increased strength [8], while the strength of the frozen bond will be determined by the difference in the strength of the frozen-soil/ice-interlayer and ice-interlayer/foundation contacts, and correspond to the strength of the weaker contact.

Results of investigation of the dependence of the strength of the frozen adhesive bond on temperature and the structure of the contact zone are presented below on the basis of data derived by the author and other researchers.

Method of Investigation

We investigated frozen specimens of polymineral clay (mC, Gzhel') and sandy loam (aQ_{IV}, Yakutsk). The gradation of the soils investigated is presented in Table 1, and their physical properties in Table 2. The polymineral clay is montmorillonite (60%), and hydromica (30%) in the clay fraction, and quartz and feldspar in the sand fraction. The sandy loam contains quartz, montmorillonite, and hydromica. According to Okhotin's classification, the soils under investigation are referred to as a medium silty clayey loam and light sandy loam, respectively, and as a clay and sandy loam, respectively, on the basis of plasticity index.

The tests were conducted at a temperature of from $-1°$ to $-12°C$ on disturbed soil specimens frozen to steel on a single-plane shearing device designed by the Scientific-Research Institute of Foundations and Underground Structures. Shearing was carried out for 20-30 sec to failure under a load of 0.1 MPa. At each temperature, the tests were repeated on 6-10 specimens. The average strength of the frozen bond was determined from the test results.

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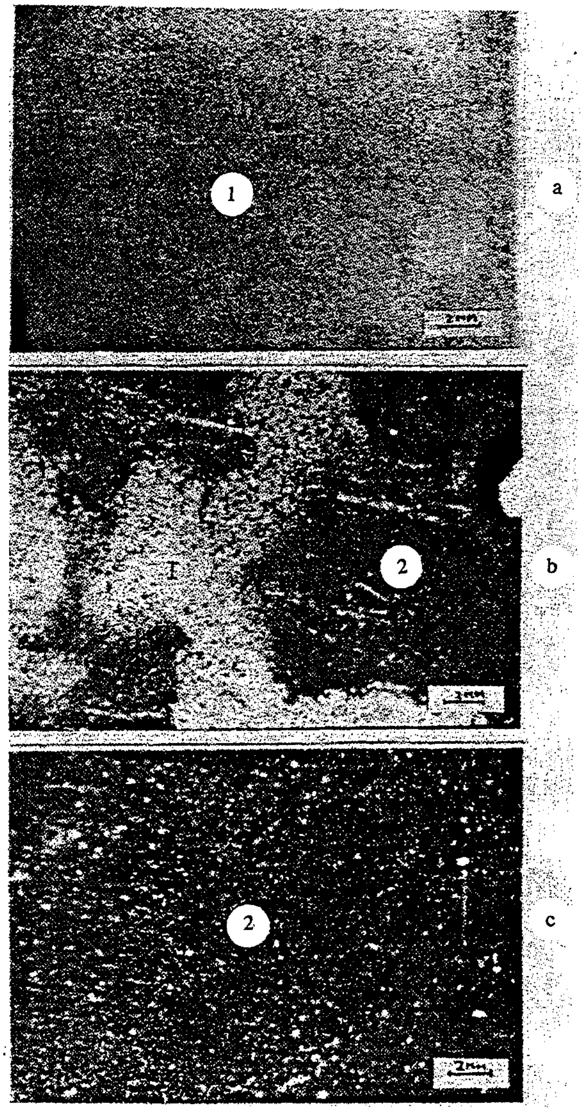

Fig. 1. Cryogenic structure of clay surface frozen to steel after shear at temperatures of: a) −3°C; b) −4°C; −5°C. 1) Ice; 2) mineral skeleton.

After completing the tests, we removed replicas from the surfaces of specimens adjacent to the foundation to investigate the pattern of their failure; the replicas were prepared in accordance with the procedure outlined in [9] and photographed through a light microscope.

Pattern of Shear Failure of Soils Along Surface of Frozen Adhesive Bond

In all cases, the existence of a continuous contact ice interlayer up to 0.6 and 0.05 mm thick is noted on the frozen clay/steel and sandy-loam/steel boundaries, respectively. The thickness of the ice interlayers decreases with decreasing temperature.

At a temperature of from 0 to −3°C, shear occurs along the contact ice/foundation boundary for both the clay and sandy loam (Figs. 1a and 2a). For the clay at temperatures from −3 to −5°C, shear occurs partly along the contact-ice/foundation boundary, partly along the contact-ice/soil boundary, and through the soil (Fig. 1b). A section of the ice interlayer remains on the foundation; in that case, the lower the temperature, the greater the area of this section. At temperatures below −5°C, the clay specimens fail completely along the ice-interlayer/soil boundary and through the soil (Fig. 1c). The same law is also observed for the sandy loam at temperatures below approximately −3.5-(−4.0)°C (Fig. 2b).

TABLE 1

Particle size, mm	Content of fractions, %	
	clay	sandy loam
0,5 - 0,25	0,2	3,2
0,25 - 0,1	4,4	57,0
0,1 - 0,05	11,8	12,3
0,05 - 0,01	50,0	10,1
0,01 - 0,005	13,6	7,3
0,005 - 0,001	15,0	6,1
<0,001	5,0	4,0

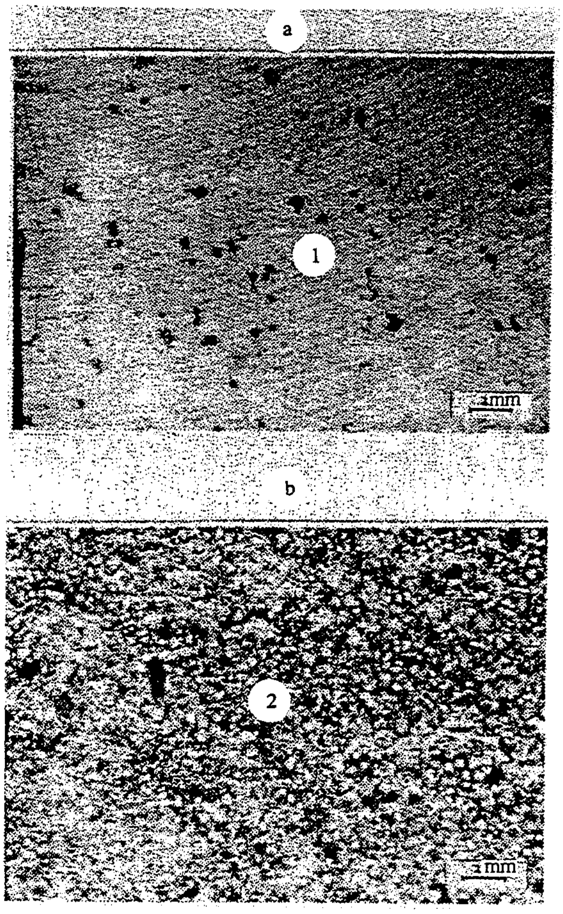

Fig. 2. Cryogenic structure of surface of sandy loam frozen to steel after shear at temperatures of: a) $-2°C$; b) $-4°C$. 1) Ice; 2) mineral skeleton.

Similar results were previously obtained by Savel'ev and Shusherina [10]. Savel'ev, who conducted pull-out tests on wooden and steel piles from frozen sand, kaolin, clayey loam, and askanite at the freezing point and a test temperature of -0.7 and $-5°C$ at a rate of 20 mm/min, points out that an ice layer approximately 1 mm thick remains on the surface of the pile at $-5°C$, while virtually no ice remains on the pile surfaces at $-0.7°C$. According to Shusherina, who studied the conditional-instantaneous rupture strength of the frozen bond formed by alluvial clayey loam and processed sand, a temperature drop leads to an increase in the surface area of failure in the frozen soil, and also to an increase in the overall failure surface [15].

In Savel'ev's opinion, the phenomenon described is explained by the following. At negative temperatures close to the temperature of the phase transitions of water, failure on the contact-ice-interlayer/foundation boundary will occur as a result of the existence on the boundary of a diffusion layer of unfrozen water, which lowers the adhesion forces. Since production materials usually exhibit a lower chemical affinity for water than soils, and their surface is not always characterized by maximum possible contact due to incomplete desorption of gases owing to microirregularities, the ice/frozen-soil contact is

TABLE 2

Property	Clay	Sandy loam
Strength, g/cm^3	1,88-1,89	1,88-1,89
Gravimetric moisture content, %	31-32	26-27
Particle density, g/cm^3	2,73	2,60
Gyroscopic moisture content, %	3,2	
Maximum molecular moisture capacity,%	13,9	
Plastic limit, %:		
lower	24,3	32,0
upper	46,6	39,0
Plasticity index, %	22,3	7,0

stronger. An adsorption layer of water with extremely high bonding forces remains during a temperature drop, which contributes to freeze-induced destruction of the diffusion layer; this gives rise to an increase in adhesion forces on the ice/foundation boundary and to a reduction in the mobility of the molecules in the surface layer of ice adjacent to the adsorption layer. For the case in question, therefore, failure occurs along the weaker ice/frozen-soil contact; this is determined by the weakening effect of the unfrozen water in the soil.

The laws described for the variation in the pattern of shear failure for frozen soils along the surface of the frozen bond enables us to explain the variation in the strength of the bond formed by frozen soils in different negative-temperature ranges.

Temperature Dependence of Strength of Frozen Adhesive Bond

The negative-temperature value is an extremely important factor affecting the shear strength of frozen soils along the surface where a frozen adhesive bond forms with the materials in foundations. Research [6, 12, 13, and others] has demonstrated that, as a rule, the strength of the frozen adhesive bond increases nonlinearly in smaller and smaller increments with decreasing temperature. A number of researchers have proposed different empirical formulas for quantitative estimation of this relationship [6, 12, 14, and others].

The results that we obtained in testing the clay and sandy loam, which were frozen to steel, at different temperatures are presented in Fig. 3. Curves of the temperature dependence of average strength values of the frozen adhesive bond of the soils that we tested have inflection points at certain temperature values. After a smooth increase in frozen-bond strength, the latter begins to increase more rigorously when the temperature drops below certain values (−4.5 and −3.5°C for the clay and sandy loam, respectively). With a further drop in temperature, a second point appears on the curves, after which the rate of increase in frozen-bond strength drops off rapidly. It corresponds to temperatures of −7 and −4.5°C for the clay and sandy loam, respectively.

Curves plotted from Tsytovich's data [15] for the temperature dependence of the ultimate strength of the frozen adhesive bond for clay, alluvia, and sandy loam with wood take on a similar form.

The appearance of the first inflection point on the curves can be explained in the following manner. As has been indicated above, shear failure along the surface of the frozen adhesive bond occurs along the contact-ice/foundation boundary in the temperature range from 0 to −3°C, and along the contact-ice/soil boundary or through the soil below temperatures of −5°C for the clay and −3.5°C for the sandy loam. According to a number of researchers [11,16, 17, and others], the shear strength of frozen soils is appreciably higher than the strength of their frozen bond with the foundation. Here, the rate of increase of the first of these strengths is greater than that of the second with decreasing temperature.

The appearance of the second inflection point is observed under conditions when the specimens fail in the soil. The reason for this should obviously be sought in the variation of the properties of the soil itself. If we reconstruct the curves of the content of unfrozen water in the clay and sandy loam versus temperature in logarithmic coordinates (Fig. 4), it is possible

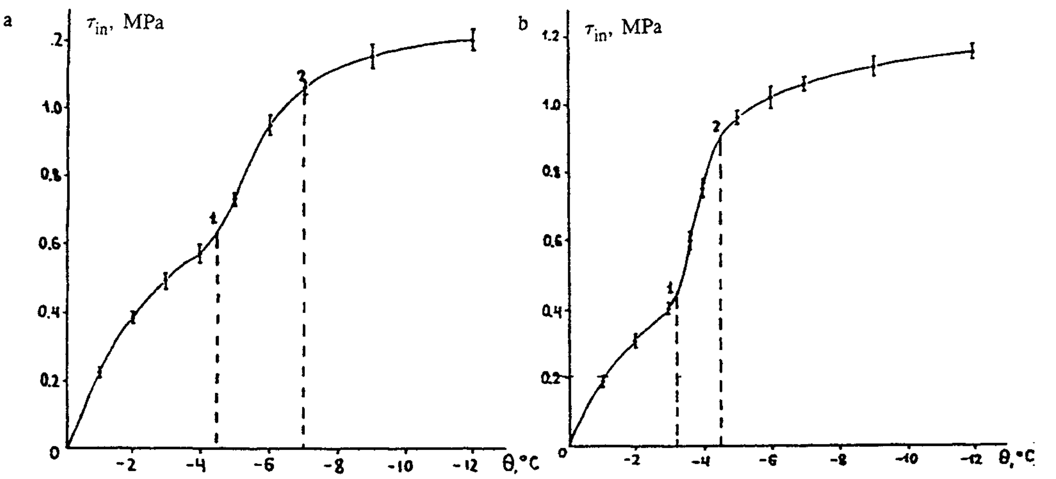

Fig. 3. Temperature dependence of strength of frozen adhesive bond between clay (a) and sandy loam (b) and steel: 1, 2) inflection points.

to see that the plots obtained are discontinuous with break points corresponding to temperatures of −7.3°C and −4.2°C for the clay and sandy loam, respectively. These same temperatures correspond with a rather high accuracy to the appearance of a second inflection point on the curves of the strength of the frozen adhesive bond versus temperature. It is interesting that Zhu and Carbee [18] note break points on plots of the peak tensile strength of frozen muds and the content of frozen water in the muds versus temperature.

Dependence of Strength of Frozen Adhesive Bond on Soil Type

It is established by numerous investigations of the strength of the frozen bond between soils and foundation materials [3, 4, 14, and others] that it depends on the type of soil. This relationship is usually illustrated by a familiar plot from [14], which is constructed for various soils frozen to wood. As follows from this plot, sands, and rubbly soils and gravels are characterized by maximum and minimum strength of the frozen adhesive bond, respectively. Frozen clays have a somewhat lower frozen-bond strength as compared with saturated sands; this is explained by the high content of unfrozen water in these clays. This representation is simplified.

Analysis of the relationship between the strength of the adhesive bond developed between the clay and sandy loam frozen to steel (see Fig. 3) indicates that this relationship assumes a different character in different temperature ranges. Thus, the strength of the frozen adhesive bond developed by the clay is approximately 1.2 times higher than the same quantity for sandy loam in the interval from 0 to −3.5°C. This relationship changes at temperatures of from −3.5 to −7°C, and with a further drop in temperature, the strength of the frozen bond developed by the clay again becomes somewhat higher than that developed by the sandy loam.

Analogous results are also cited by other researchers. According to Savel'ev, who obtained ultimate strengths of the bond for askanite, kaolin, and sand frozen to wood and steel, the ultimate strengths of the frozen adhesive bond between askanite and kaolin and both wood and steel at −0.7°C is higher than that for the sand, and amount to 0.61, 0.57, and 0.52 MPa with the wood, and 0.33, 0.3, and 0.25 MPa with the steel. At −5°C, however, the ultimate strengths of the frozen adhesive bond for the askanite, kaolin, and sand are, respectively: 0.76, 1.13, and 1.22 MPa for the wood, and 0.7, 0.93, and 1.24 MPa, respectively, for the steel, i.e., the inverse relationship is observed [8]. Vyalov obtained essentially equal strengths for the frozen adhesive bond developed between clayey loam and sandy loam and wood at −0.4°C on models of frozen-in (0.42 and 0.41 MPa) and driven piles (0.46 and 0.48 MPa) [4]. According to Tsytovich [15], the ultimate strengths for the frozen bond between clay and sandy loam and wood are, respectively, as follows: 0.29 and 0.13 MPa at −0.2°C, and 1.11 and 2.08 MPa at −5.7°C, while the strength of the frozen bond for clay again becomes higher than that for sandy loam below −14°C, i.e., the character of the indicated relationship for the strength values is similar to what we obtained in this study.

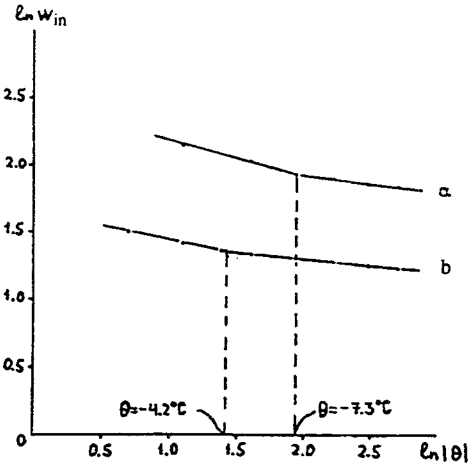

Fig. 4. Temperature dependence of content of unfrozen water in clay (a) and sandy loam (b) (in logarithmic coordinates).

An explanation for these results most likely follows from analysis of the state of the contact zone between the frozen soils and foundation, and the pattern of failure at different temperatures. According to Shusherina [17], the ice interlayer on the frozen-soil/foundation contact offsets the influence exerted by dispersity and other soil properties on the strength of the frozen adhesive bond. This is obviously manifested at relatively high negative temperatures for which failure occurs along the contact-ice/foundation boundary, and the influence of the strength of the soil itself on the strength of the frozen adhesive bond is minimal. At lower negative temperatures, however, when failure occurs along the contact-ice/soil boundary, or through the soil, the opposite relationship should be observed for clayey and sandy soils. An increase in the strength of the frozen adhesive bond for clayey soils as compared with that for sandy soils at temperatures below the range of vigorous phase transitions of the water in the frozen soils is most likely associated with the fact that the difference in the content of unfrozen water begins to compensate for the large specific surface of the particles of the clayey soil.

CONCLUSIONS

1. The strength of the frozen adhesive bond developed between soils and foundation materials depends on the structure of their zone of contact.
2. A different pattern of failure of the contact zone is observed in different negative-temperatures ranges.
3. A complex relationship between the strength of the frozen adhesive bond and temperature, which is governed by the different pattern of failure of the contact zone and by the relationship between the content of unfrozen water in the frozen soil and on the boundary of the frozen adhesive bond, is noted in different negative-temperature ranges.
4. The relationship between the strength of the frozen adhesive bond developed by sandy and clayey soils at different temperatures is not well defined.

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