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SOIL PHYSICS

Rheological Features of the Coagulative Structure of Northern Taiga Peaty Podzolic Semi-Gley Soils of the European Northeast

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Abstract—The results of rheological studies using a MCR 302 modular research rheometer of soil pastes of northern taiga peaty podzolic semi-gley soils are presented. It was found that their coagulative structure has weak structural links. They are little resistant to mechanical stress and their stability decreases in the direction from the northern to the extreme northern taiga by about two times. The strongest coagulative links between soil particles characterize the horizons with increased organic contents and the horizons that are transient in terms of granulometric composition, which lie at the border where light deposits shift heavier ones.

Keywords: northern taiga soils, structure formation, rheology

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INTRODUCTION

The growing intensive human economic activities in the northern regions (construction of roads, pipelines, mining, etc.) negatively affect the state of the soil cover. In particular this applies to mechanical disturbances. This paper studies the structural state of soils from the standpoint of physico-chemical mechanics, namely the rheological properties of the coagulative structure, in order to identify their quantitative characteristics. Many scientific papers note the high sensitivity of the rheological approach for evaluation of interparticle structural links depending on various factors [1, 9, 12–14].

One of the most important mechanical properties of disperse structures is strength [11], whose value determines a system's ability to resist fracturing under applied stress. Peaty podzolic semi-gley soils are characterized by the coagulative type of structure, where the interaction of particles in contacts is limited to their "touching" through the layers of the aquatic environment. Such contacts and structures are generally characterized by mechanical reversibility, i.e., the ability to make a spontaneous recovery after mechanical destruction (thixotropy) [10]. A coagulative structure, depending on the applied mechanical stress, can exhibit properties of both liquids and solids [8]. Rheology, using a limited number of parameters, allows one to describe a system's reaction to mechanical interaction. As these parameters, shear stress (P, Pa) and shear rate (D, s^{-1}) are used. The ratio between the shear stress and its rate characterizes the rheological behavior of the system under study [7, 8]. Shear stress at its first given rate close to zero (P_i) shows the strength of the structural links of the soil paste at the beginning of the experiment. As the load or shear rate increases, there comes a moment when there is a proportional increase in shear stress, indicating the destruction of structural links [10, 14]. The shear-stress value on the backward stroke at a shear rate close to zero (P) shows the strength of the recovered structural links after destruction; the difference between P_i and P_f is the range of the destroyed links. With respect to the viscosity at the end of the experiment to that at the beginning at shear rates close to zero one can calculate the percentage of the thixotropic recovery of the structure.

MATERIALS AND METHODS

Peaty podzolic semi-gley soils are the most common subtype of semi-hydromorphic bog-podzolic soils of the taiga zone [1]. In terms of the temperature regime, they are seasonally frozen soils of the semi-hydromorphic series; their water regime is washing with periodic stagnant moistening. The parent rocks are coarse-pulverescent loamy sands underlain by coarse-pulverescent moraine loams. Earlier studies [4, 5] showed that in the northern part of the taiga zone they are podzolized and gleyed throughout the profile; horizon A2g shows signs of thixotropy. Our work was carried out in two natural subzones, viz., the northern and extreme northern taiga.

In the northern taiga the section was placed on the watershed interfluvial ridge of the Pechora Basin. The absolute height at this location is 215 m above sea level. The terrain is flat with a gentle slope to the southwest. The soils are developed on sandy loams underlain by 80 cm of light loams. The average annual temperature is

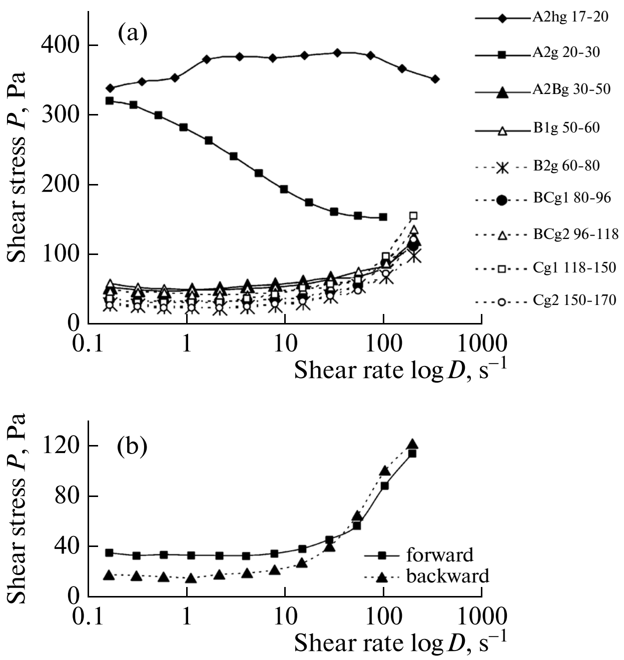

Fig. 1. Curves of the dependence of the shear stress (P, Pa) on shear rate (D, s^{-1}) of peaty podzolic semi-gley soil of northern taiga (P-3-X): (a) for all horizons of profile; (b) for the BCg1 horizon (80–90).

1.05° [3]. The following horizons are defined in the section: O (0–13 cm), A2hg (17–22 cm), A2g (22–30 cm), A2Bg (30–50 cm), B1g (50–60 cm), B2g (60–80 cm), BCg (80–150 cm), and Cg (150–180 cm).

In the extreme northern taiga the section was placed on the watershed ridge of the Usa River Basin. The absolute height is 119 m above sea level at this location. The soils are developed on sandy loams underlain with 41 cm of light loams. The average annual temperature is –5° [3]. The following horizons are defined in the section: O (0–13 cm), A2hg (13–17 cm), A2g (17–25 cm), A2Bg (25–41 cm), B1g (41–70 cm), and B2g (70–90 cm).

The physico-chemical properties of the soils were studied using standard methods: water and saline pH were determined potentiometrically with glass and silver chloride electrodes; oxalate soluble forms Fe_2O_3 and Al_2O_3 were determined by Tamm; the granulometric composition was determined by the Kaczynski method with dispersion and boiling in the presence of NaOH; and the organic-matter content was determined using an EEA-1110 CNHS-O-analyzer (Carlo Erba, Italy). The rheological parameters of the behavior of the soil pastes were determined on an MCR-302 modular rheometer (Anton Paar, Austria). After it was pounded by a rubber pestle and sifted through a sieve with apertures of 1 mm, the soil weight of 19 g was capillarily saturated with distilled water until it reached a visco-plastic condition for 3 h. The upper peaty horizons in this study were not considered, as their strength characteristics are significantly higher than those of other horizons. The measurements were carried out in the range of shear rates of 0.16–200 s^{-1} and back at 20° by measuring the system type of "a cylinder in a cylinder." The complete rheological curves (both the forward and backward branches) were obtained.

In the modular rheometer, the shear rate values (x axis) were preset; as a result of measuring the shear the stress values (y axis) were obtained.

RESULTS AND DISCUSSION

The results of the physico-chemical analyses are presented in Table 1. The soils under study have high acidity; they are leached from exchangeable bases and gleyed throughout the profile. There is a low quantity of humus, 0.3–0.9%; it is slightly accumulated, up to 0.9%, on the border of loamy sands underlain by loams. The high humus content in the A2hg horizon (3.7–11%) is explained by the presence of a large number of slightly-decomposed plant residues here, as well as by the receipt from the litter of water-soluble organic and organo-mineral compounds. In these soils, there is a developed downward migration of unsaturated organic acids and organo-mineral complex compounds with oxalate-soluble oxides of iron and aluminum [3].

The section in the northern taiga (P-3-X) has a bulk density of mineral horizons of 1.3–1.4 g/cm^3 and porosity in the range of 51.3–51.9%. In the region of transition of the sandy loam into the loamy rock the porosity increases to 52.2% due to the emergence of a platy-nuciform structure. The profile of the peaty podzolic semi-gley soil in the extreme northern taiga (P-4-X) is characterized by a more compact density, viz., 1.5–1.6 g/cm^3 and smaller porosity, 43–44% as compared with the section in the northern taiga.

The data of the rheological studies are presented in Table 2 and Figs. 1 and 2. The obtained dependences of shear stress versus shear rate showed a clear distribution of the rheological behavior of the studied horizons in the soil profile.

In the soil section of the northern taiga the strongest horizon is A2hg. The shear stress (P_i) at the beginning of the experiment at $D = 0.16$ s^{-1} is 341 Pa (Fig. 1a). An increase of pressure to 700 s^{-1} did not lead to destruction of the structure of this horizon. Under the term "structural destruction" we mean such a relationship between the shear rate and shear stress where the shear-rate change causes a proportional change in shear stress. The strength in the A2hg horizon is probably due to an increased content of slightly decomposed plant residues that prevent movement of the measuring cylinder. In the podzolic horizon A2g, as the strain rate (D) increases, the shear stress (P) was gradually decreasing, which could possibly indicate manifestation of dilatancy (hardening of the system as a result of a more dense packing) [8, 9]. When D reached the value of 55.9 s^{-1}, the structure began to collapse. The reverse branch decreased gradually to

Table 1. The physico-chemical properties of peaty podzolic semi-gley soils

Horizon, depth, cm		pH		C_{org}, %	V*, %	Fe_2O_3, %	Al_2O_3, %	Content of particles, %		ρ**, g/cm^3	Porosity, %
		H_2O	KCl					<0.001 mm	<0.01 mm		
Section R-3-X, northern taiga											
O'	0–8	3.7	2.9	39.5	4	0.04	0.17	–	–	0.06	–
O''	8–14	3.9	3.2	37.7	2	0.43	0.71	–	–	0.07	94.0
O'''	14–17	3.9	3.5	33.4	1	1.68	1.19	–	–	0.2	88.4
A2hg	17–20	3.8	3.5	6.59	1	0.17	0.6	11	15	0.9	62.2
A2g	20–30	4.3	4.1	0.45	1	0.46	0.34	10	15	1.4	51.3
A2Bg	30–50	4.5	4.1	0.25	6	0.33	0.28	9	14	1.3	51.3
B1g	50–60	4.7	4.1	0.16	10	0.51	0.35	10	18	1.3	51.9
B2g	60–80	5.0	3.9	0.30	58	0.29	0.21	13	19	1.3	51.6
BCg1	80–96	5.1	3.8	0.17	55	0.47	0.28	21	26	1.3	52.2
BCg2	96–118	5.2	3.8	0.16	66	–	–	23	26	1.3	52.0
Cg1	118–150	5.1	3.9	0.15	68	0.44	0.2	20	27	1.3	51.9
Cg2	150–170	5.6	4.0	0.18	78	0.45	0.17	21	30	1.4	48.5
Section R-4-X, extreme northern taiga											
O'	0–7	4.1	3.3	41.4	–	0.06	0.05	–	–	0.06	93.8
O''	7–13	3.9	3.4	31.9	3	0.87	0.76	–	–	0.2	87.9
A2hg	13–17	4.3	3.6	2.14	2	0.65	0.29	12	26	1.0	63.6
A2g	17–25	4.4	3.9	0.27	15	0.40	0.17	10	17	1.5	43.6
A2Bg	25–41	4.4	3.9	0.51	2	0.52	0.22	8	18	1.6	39.8
B1g	41–70	5.1	3.9	0.24	36	0.41	0.21	11	20	1.6	40.5
B2g	70–90	5.1	3.9	0.24	36	0.46	0.22	9	20	1.5	44.2

"–", was not defined; * V, base saturation; ** ρ, soil bulk density.

58.4 Pa and a broad field of hysteresis was formed between the forward and backward branches. The difference between the shear stress at the beginning of the experiment (P_i) and at the end of the return cycle (P_f) at close to zero speed values of the deformation D may serve as a range of destroyed links. For this horizon, P_i–P_f is 263 Pa.

According to the ratio of the viscosity value at the beginning of the experiment at a rate of the forward stroke that is close to zero to that at the end of the experiment at a shear rate of the return stroke that is close to zero one can determine the percentage of thixotropic recovery of the structure: over 6 min of the backward stroke and lowering of D recovery occurred by 18% of the initial undisturbed state. This suggests that this horizon has thixotropic–thixolabile properties. Down the profile, to the region where loamy sand transits into loam, the coagulative structure strength decreases; structural links are rapidly destroyed. However, in the region of transition of the loamy-sandy rock into loamy rock, viz., horizon BCg1 (80–96), there is an increase in the strength of the structure. The same horizon is characterized by the greatest thixotropic restoration of the structure, 52%. This is probably a consequence of the accumulation in this region of organic-mineral compounds and amorphous forms of iron, which link silt and colloidal particles into microaggregates. Upon drying the sample, the soil microaggregates become even stronger due to dehydration of soil particles and formation of strong bonds in condensation–crystallization links. In nature, the process of soil freezing apparently has a similar effect [2]. During thawing and stronger moistening the condensing structural links gradually move into coagulative ones. Under deformation (D), the microaggregates begin to collapse; therefore the number of soil particles per unit of volume becomes larger and the viscosity of the system increases correspondingly [1]. This in turn affects the rheological curve, which forms a rheopectic loop (Fig. 1b). When the stress decreases, there is a reverse process of recovery of the microaggregates, but the forming coagulative links between the recovered microaggregates are less stable, so the rheopectic loop gradually transforms into a thixotropic loop. The fracture range in this horizon (P_i–P_f) reaches minimum values, viz., 17 Pa, due to hardening of the structure under rheopecty. In the lower loamy horizons the rheological curves are similar to the curves of the BCg1 horizon, but down the profile the strength gradually decreases.

Table 2. Rheological parameters of behavior of peaty podzolic semi-gley soils

Soil, horizon, depth, cm		Structure breaking point		P_i	P_f	Range of structure destruction, Pa (P_i–P_f)	Thixotropic recovery of structure (η_f/η_i) × 100%	Type of structure
		D, s^{-1}	P, Pa					
Section R-3-X, northern taiga								
A2hg	17–20	–	–	341	244	–	–	thixolabile
A2g	20–30	100	155	321	58	263	18	dilatancy
A2Bg	30–50	1.15	50.2	55	5	50	10	thixotropic–thixolabile
B1g	50–60	4.18	52.7	60	7	53	12	same
B2g	60–80	4.18	25.9	29.4	7	22.4	24	"
BCg1	80–96	4.18	33.5	35.6	18	17.6	52	rheopecty
BCg2	96–118	4.18	44.4	49.6	22	27.6	44	same
Cg1	118–150	2.2	33	37.4	14	24	37	"
Cg2	150–170	2.2	24.8	28.8	8	21	26	"
Section R-4-X, extreme northern taiga								
A2hg	13–17	105	25	76.5	4	72	5.2	thixotropic–thixolabile
A2g	17–25	4.18	10.3	12	2	10.5	13.3	same
A2Bg	25–41	104	114	181	8	173.5	4.12	"
B1g	41–70	4.18	11.4	11.7	3	8.9	24.1	"
B2g	70–90	4.18	13.5	13.2	3	10.7	19.3	"

P_i, initial strength value of at $D = 0.16$ s^{-1} of forward stroke; P_f, final strength value at $D = 0.16$ s^{-1} of backward stroke; η_f, final viscosity value at $D = 0.16$ s^{-1} of backward stroke; η_i, initial viscosity value at $D = 0.16$ s^{-1} of forward stroke.

The rheological studies of peaty podzolic semi-gley soil in the extreme northern taiga showed lower values of the coagulative structure strength in comparison with the northern taiga soil by about two times. The decrease in strength is probably due to the water regime and climatic conditions in which the soils under study are developed: peaty podzolic semi-gley soils, being semi-hydromorphic, experience seasonal waterlogging. Waterlogging, as is known, is accompanied by anaerobic recovering conditions under which the film iron that covers the surface of soil particles transits into the motile ferrous form [6], which slows the processes of structure formation and reduces the strength of links between the particles. Since the evaporability decreases to the north, the period of waterlogged soil becomes longer; hence the small aggregation and low strength of soils of the extreme northern taiga occur.

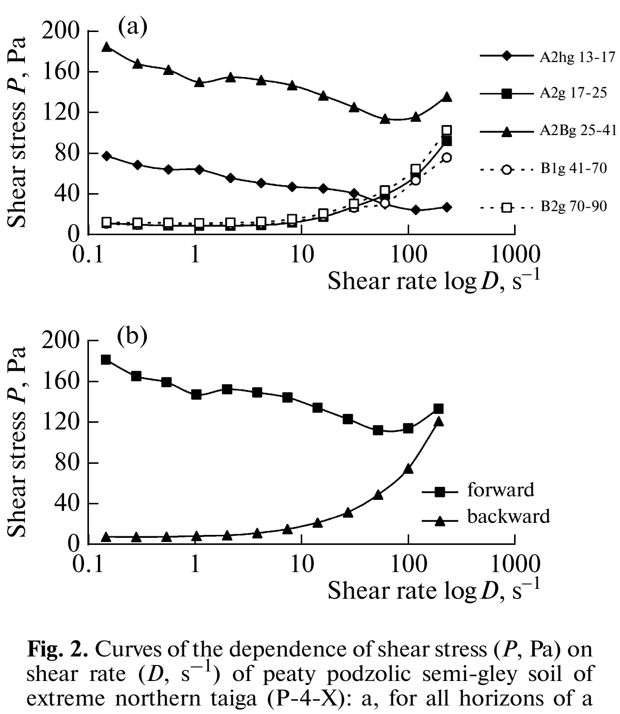

Fig. 2. Curves of the dependence of shear stress (P, Pa) on shear rate (D, s^{-1}) of peaty podzolic semi-gley soil of extreme northern taiga (P-4-X): a, for all horizons of a profile; b, for the A2Bg horizon (25–41).

The most durable in the profile of the peaty podzolic semi-gley soil of the extreme northern taiga is the A2hg horizon, the beginning of the deformation in which occurs at 76.5 Pa. The destruction of the structure begins when the D value reaches 105 s^{-1} and the shear stress is 25 Pa. The backward branch gradually decreases to a value of $P = 4$ Pa. A wide field of hysteresis is formed between the forward and backward branches. The range of the structure's destruction (P_i–P_f) is 72 Pa. Recovery of the structure during the backward stroke with lowering of D occurred by 5.16% of the initial undisturbed state. The second measurement after a 10-minute rest did not reveal recovery of the initial strength. From this it follows that the structural links collapsed and the soil thus acquired thixotropic-quicksand properties.

The podzolic A2g horizon has a very low strength of the structure (12 Pa) due to the destruction and eluvial removal of silt and colloidal particles during the process of podzol formation. Destruction of its structure occurs at $D = 4.18$ s^{-1} and a shear stress equal to 10.3 Pa; between the forward and backward strokes a small hysteresis loop is formed. The structure of this horizon has thixotropic–thixolabile properties. In terms of granulometric composition, the underlying A2Bg horizon is transient from loam sand to loams. It is characterized by sharply increased strength of structural links ($P = 181$ Pa) due to the accumulation in this part of the profile of humus and sesquioxides. Lowering of the forward stroke curve shows the manifestation of dilatancy. Destruction of the structure begins at $D = 105$ s^{-1} and $P = 114$ Pa, and its range is 173 Pa. A broad hysteresis loop is formed, but thixotropic recovery is low, viz., 4.12% (Fig. 2b). These two horizons, B1g and B2g, in terms of their rheological behavior and parameters are similar to the A2g horizon; the only difference is a narrow rheopectic loop that forms during the backward stroke of the rheological curve and almost immediately turns into a hysteresis. This suggests weak soil microaggregation in the extreme northern taiga. Almost all of its profile is exposed to thixotropic–quicksand processes due to the very weak structural links.

Thus, the structure of the soils we studied has weak coagulative links and slow reactivity to thixotropic recovery. In terms of strength, there are two horizons: A2hg, which is directly under the peat layer and is characterized by an increased content of organic matter, and a transient one in terms of granulometric composition, which is located on the border of the light and heavier granulometric composition. In the context of the northern taiga this is BCg1 horizon; for the extreme northern taiga is A2Bg horizon. The increase in strength is associated with accumulation in this part of the profile of humus and organic-mineral compounds, as well as silt and colloidal particles. Seasonal freezing of soil leads to dehydration of the soil particles and formation of condensation structures of increased strength. During thawing, when the soil is moistened, the soil particles are strongly hydrated, condensing links gradually transform into low-strength coagulative-thixotropic ones. The soil state under wetting becomes close to thixotropic–quicksand state. In the extreme northern taiga due to a long period of waterlogging the coagulative links become even less stable, which contributes to easier destruction and transition of links into coagulative–thixotropic ones; the soil mass has a uniform curd structure, higher density, and low porosity. Our research revealed that the rheological properties of peaty podzolic semi-gley soils of the extreme northern taiga are close to the properties of the tundra soils. According to V.V. Abrukova [1], the thixotropic gley horizons of the tundra surfactant semi-gley soil are characterized by weak coagulative structural links. She also noted the role of organic matter, which under reducing conditions and in the presence of ferrous iron forms serves as a stabilizer of the colloidal part of the soil, rather than a coagulator, slowing the processes of structure formation. Therefore, the extreme northern taiga peaty podzolic semi-gley soils can be regarded as transient in regard to the soils of the tundra zone.

FINDINGS

The coagulative structures of peaty podzolic semi-gley soils have weak structural links and are unstable to mechanical stress. The stability of these soils in the transition from the northern to the extreme northern taiga is reduced by approximately two-fold (from 29–55 to 12–13 Pa). Virtually the entire profile of the peaty podzolic semi-gley soil in the extreme northern taiga is prone to thixotropic-quicksand processes.

The rheological properties of the northern and extreme northern taiga peaty podzolic semi-gley soils on loamy sands underlain by loams caused by podzolic and gley processes, as well as seasonal freezing and thawing.

The horizons that accumulate organic matter and the transient horizons located on the border of the light and heavier granulometric compositions have increased strength.

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