Changes in rheological behaviour of sod-podzolic and chernozem soils involved in agricultural use

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Abstract. Presented are the results of comparative studies of sod-podzolic soil, typical chernozem and chernozem merged in different land use conditions. While identifying the physico-mechanical properties under loading-unloading cycle, it was revealed that the soils with the highest percentage of physical clay demonstrate a higher capability of restoring the soil structure.

1. Introduction
Arable soils are in a state of constant change in their physical and mechanical properties not only due to the influence of climatic and biological factors, but also because of agricultural equipment use [1]. Intensive agricultural use without appropriate compensation measures leads to a loss of humus, a decrease in the water resistance of the aggregates, and a transformation of the particle size distribution [2]. Thus, studies of agro landscapes of the Kursk region [3] showed that most of the chernozems involved in active agricultural land use are degrading. Changes in the above-mentioned basic soil properties affect the strength of the structure and the type of structural bonds, which determine the rheological behavior of the soil. Under laboratory conditions, a detailed study of the deformation behavior of the soil is made possible by conducting experiments in load-unloading cycles. The growing interest in the study of rheological properties of soils is due to the ability to assess the strength of structural bonds, to predict their behavior under various influences, and to identify the features of rheological behavior of soils involved in agricultural activities. The goal of this work was the study of changes in rheological behavior of soils in agricultural use as exemplified by sod-podzolic and chernozem soils.

2. Objects and methods
The objects of the study were soils in different conditions of land use: agro-sod-podzolic soil (deposit (N 56.1313°; E 37.8035°)) and sod-podzolic soil (forest (N 56.0983°; E 37.8216°)) of Pushkin district of the Moscow region; typical agrochernozem (arable land (N 51.6202°; E 36.2597°)) and typical chernozem (forest belt (N 51.6204°; E 36.2565°)) of the Kursk region (Kursk Scientific-Research Institute of Agroindustrial Production), agrochernozem merged (arable land (N 44.4316°, E 40.0336°), deposit (N 44.4314°, E 40.0337°)) of the Maikop District of the Republic of Adygea.

The particle size and microaggregate compositions were measured using the Analysette 22 comfort laser diffraction method (Fritsch, Germany) [4,5]. Total carbon content was determined with AN - 7529.
express carbon analyzer using the method of dry burning, density of the solid phase of the soil was gauged using pycnometers. The rheological properties were studied through rheological curves: flow curves (main and additional), obtained on the "REOTEST - 2" rotational viscometer with a cylindrical measuring device. The experiment was carried out after daily saturation, when the humidity reached the value of capillary capacity, and the soil acquired a viscous-fluid consistency. The measurements were carried out for two cycles, which consisted of a forward stroke (from 1 to 12 gears in the range of the gradient of the shear rate from 0.167 to 145.8 s\(^{-1}\)) and the reverse (from 12 to 1 gears). The time of deformation at each speed was three minutes and one minute, respectively. Two rheological curves were analyzed: the main and the additional ones. The former expresses the dependence of the shear stress (τ, Pa) on the shear rate (γ, 1/s). Based on this curve, the following was determined: Pk1, the Shvedov limit, the beginning of the flow of the soil suspension; the second critical shear stress Pk2 is the onset of failure; Pm is the limit of plastic-viscous destruction of the structure, corresponding to the almost complete destruction of the structural bonds of the sample under study [6]. The additional rheological curve expresses the dependence of the effective viscosity (ƞ, Pa\(\cdot\)s) on the shear rate (γ, 1/s). Using the obtained viscosity values, the following parameters were determined: ƞPk1 which is viscosity of the beginning of the flow (the highest structural viscosity); ƞfin – which is final viscosity, which corresponds to the lowest strain rate along the inverse rheological curve. The ƞfin/ƞPk1 ratio characterizes the ability of structures to recover, the Pm/Pk1 ratio is the strength of coagulation bonds between soil particles, the Pk1/Pk2 ratio shows the presence of dilatant properties.

3. Results and discussion

The most dispersed and least microaggregated of all the soils studied in this work are sod-podzolic soils. In the soils involved in agricultural use, the total carbon content is noticeably lower, and the density of the solid phase is higher (table 1). The content of particles <0,01 mm is higher in chernozem which is in active agricultural use. In the sod-podzolic soil, a lighter grain size distribution is observed in the native soil.

Figure 1 shows the rheological curves of some horizons for sod-podzolic soil, typical chernozem, and chernozem merged, experiencing different land use conditions. The forward branch captures the behavior of the soil under load, as well as the nature of the destruction of its structure, and the reverse branch indicates the soil's ability to restore the system. The numerical values of the shear stress are much higher in soils less susceptible to anthropogenic impact. Soils of heavy particle size distribution have a wider range of shear stresses.

In all the graphs, dilatancy loops can be seen [7, 8], representing an increase in the strength of the structure with decreasing load at high speeds. This is due to the fact that the bonds between the particles are destroyed, the particles are displaced relative to each other, they are reorganized leading to the formation of a denser particles packing. This phenomenon may be accompanied by a spontaneous restoration of the initial resistance to deformation due to gravity after the action of mechanical forces is terminated of. A special behavior is observed in the chernozem of the fused (deposit) 20–40 cm: the rheological curve reveals a difference in the shear stress values of the beginning and the end of the cycle, which indicates the phenomenon of thixotropy [9]: restoration of the structure after cessation of exposure, and after loading the structure is restored almost completely.

When studying the rheological parameters (table 2), it was found that the Shvedov limit corresponding to the onset of deformation processes and the initial viscosity is higher for soil samples that are not in agricultural use. In typical chernozem and chernozem merged, several strengths are distinguished, corresponding to the stepwise destruction of the structure and the drop in effective viscosity. The Pk1/Pk2 ratio expressing the presence of dilatant properties is minimal in agrochernozem merged (deposit). The highest values of the calculated parameter ƞfin/ƞPk1 are observed for agrochernozem merged and BT2 horizon of sod-podzolic soil. The limit of plastic-viscous destruction of the structure (Pm) for agrochernozem merged is not specified in the table, since the values are beyond the scope of a possible determination on the instrument used. This means that to break the structural bonds, it is necessary to apply a higher load.
| Horizon (depth, cm) | Content of particles <0.01 mm, % | Soil texture (Russian classification of N A Kachinsky) | Soil texture (Ferre triangle) | C_{tot}, % | ps, g/cm³ |
|---------------------|---------------------------------|-----------------------------------------------------|-----------------------------|-----------|---------|
| Agro-sod-podzolic soil (deposit) | | | | | |
| P (0-18 cm) | 32.51 | | | 1.21 | 2.52 |
| EL (36-42 cm) | 28.17 | Medium loam | Loam | 0.72 | 2.46 |
| ELB (42-51 cm) | 30.39 | Medium loam | Silty loam | 0.54 | 2.54 |
| BT1(50-80 cm) | 33.10 | | | 0.24 | 2.52 |
| BT2 (80-95 cm) | 40.59 | | | 0.10 | 2.54 |
| Sod-podzolic soil (forest) | | | | | |
| AY (4-15 cm) | 42.73 | | | 4.31 | 2.34 |
| EL (15-28 cm) | 34.28 | Heavy loam | Silty loam | 1.63 | 2.52 |
| ELB (28-35 cm) | 42.57 | Heavy loam | Silty loam | 0.36 | 2.51 |
| BT1 (35-70 cm) | 46.05 | | | 0.24 | 2.46 |
| Typical agrochernozem (arable land) | | | | | |
| PU1 (0-10 cm) | 54.72 | | | 3.21 | 2.47 |
| PU2 (15-25 cm) | 63.34 | | | 2.77 | 2.45 |
| PU3 (12-35 cm) | 53.46 | Heavy loam | Loam | 1.82 | 2.45 |
| AU (40-50 cm) | 49.15 | | | 1.68 | 2.53 |
| AB (70-90 cm) | 44.37 | | | 1.21 | 2.48 |
| Typical chernozem (forest belt) | | | | | |
| AU1 (0-12 cm) | 50.68 | | | 4.0 | 2.43 |
| AU2 (12-35 cm) | 60.03 | Heavy loam | Silty loam | 3.47 | 2.52 |
| AU (35-65 cm) | 43.81 | | | 3.18 | 2.60 |
| BCAv1 (65-110 cm) | 59.02 | | | 1.89 | 2.56 |
| Agrochernozem merged (arable land) | | | | | |
| PU1, PU2 (0-20 cm) | 66.43 | | | 3.20 | 2.54 |
| PU2 (20-40 cm) | 68.67 | Light clay | Silty loam | 2.78 | 2.57 |
| Auv (40-60 cm) | 62.65 | | | 1.81 | 2.65 |
| BCAv (60-80 cm) | 66.68 | | | 1.67 | 2.60 |
| Agrochernozem merged (deposit) | | | | | |
| AU1, AU2 (0-20 cm) | 64.70 | | | 4.0 | 2.52 |
| Auv (20-40 cm) | 64.64 | Light clay | Silty loam | 3.45 | 2.52 |
| BCAv1 (40-60 cm) | 65.96 | | | 3.17 | 2.55 |
| BCAv2 (60-80 cm) | 65.40 | | | 1.89 | 2.59 |
Figure 1. Dependence of shear stress ($\tau$, Pa) on shear rate ($\gamma$, s$^{-1}$): (a) - agro-sod-podzolic soil (deposit); (b) - sod-podzolic soil (forest); (c) – typical agrochernozem (arable land); (d) – typical chernozem (forest belt); (e) – agrochernozem merged (arable land); (f) - agrochernozem merged (deposit). The forward stroke is represented by a solid line, the reverse is a dotted line.
**Table 2.** Rheological parameters of the studied soils.

| Horizon (depth, cm) | Pk1, Pa | Pk2, Pa | Pm, Pa | ηPk1, Pa*s | ηfin, Pa*s | Pk1/Pk2 | ηfin/ηPk1 |
|---------------------|---------|---------|--------|------------|------------|---------|-----------|
| **Agro-sod-podzolic soil (deposit)** |         |         |        |            |            |         |           |
| P (0-18 cm)         | 77.4    | 35; 32.5| 51.3   | 455.0      | 276.4      | 2.2     | 0.6       |
| ELB (42-51 cm)      | 14.7    | 15      | 20.0   | 86.7       | 230.7      | 1.0     | 2.7       |
| BT2 (80-95 cm)      | 13.8    | 17      | 21.4   | 80.9       | 205.2      | 0.8     | 2.5       |
| **Sod-podzolic soil (forest)** |         |         |        |            |            |         |           |
| AY (4-15 cm)        | 396     | 60      | 87.6   | 2329.5     | 502.9      | 6.6     | 0.2       |
| BT1 (35-70 cm)      | 8.8     | 18      | 62.2   | 51.6       | 674.5      | 0.5     | 13.1      |
| **Typical agrochernozem (arable land)** |         |         |        |            |            |         |           |
| PU1 (0-10 cm)       | 188.7   | 316.5; 180.5; 7.5 | 119.9 | 1132.1 | 212.8 | 0.6 | 0.2 |
| AU (40-50 cm)       | 186.1   | 295.6; 150 | 89.2  | 1116.6 | 220.8 | 0.6 | 0.2 |
| AB (70-90 cm)       | 37      | 22.5; 27.6; 20.4 | 97.9  | 221.7  | 136.6 | 1.6 | 0.6 |
| **Typical chernozem (forest belt)** |         |         |        |            |            |         |           |
| AU1 (0-12 cm)       | 196.1   | 49.3; 244.3 | 179.2 | 1176.4 | 520.7 | 4.0 | 0.4 |
| BCAv1 (65-110 cm)   | 130.4   | 75.1    | 90.1  | 782.1 | 192.5 | 1.7 | 0.2 |
| **Agrochernozem merged (arable land)** |         |         |        |            |            |         |           |
| PU1, PU2 (0-20 cm)  | 200.3   | 398.4; 300; 655.1(278.6) | -     | 1201.3 | 3911.9 | 0.5 | 3.3 |
| PU2 (20-40 cm)      | 425.5   | 481.6; 353.2; 453.4 (2402) | -     | 2552.4 | 5083.8 | 0.9 | 2.0 |
| BCAv (60-80 cm)     | 162     | 230.4; 148.4; 477.4 | -     | 971.6  | 3928.8 | 0.7 | 4.0 |
| **Agrochernozem merged (deposit)** |         |         |        |            |            |         |           |
| AU1, AU2 (0-20 cm)  | 202.3   | 628.4; 398.5; 128.3 | -     | 1213.3 | 1165.8 | 0.3 | 1.0 |
| Auv (20-40 cm)      | 193.5   | 521.5; 2701.4 | -     | 1160.9 | 9174.3 | 0.3 | 7.9 |
| BCAv2 (60-80 cm)    | 205     | 409.9; 2500 | -     | 1229.7 | 5465.7 | 0.5 | 4.4 |
4. Conclusions
Based on the obtained results, the following conclusions can be drawn: first, the rheological properties of the studied soils naturally vary in profile depending on the content of organic matter and particle size distribution, soils with a high content of fine fraction have the strongest; second, structure strength properties are more pronounced in soils which are not a subject to anthropogenic impact; third, in arable soils, the highest ability to restore the soil structure is observed in agrochernozem merged.

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