Impact of Anthropogenic Load on Rheological Properties of Typical Chernozems (Kursk Region, Russia)

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Abstract

Rheological approach provides the means for evaluation of interpartical interactions, micromechanical behavior, and fundamental information on soil structure deformations and its consequences.

The top layer 0-10 cm of silty clay typical chernozems from native steppe, bare fallow soil, plowed twice a year since 1947 and oak forest of State Central Chernozem Reserve (Streletzkaya Steppe, Kursk, Russia) and from agricultural arable land and adjacent forest belt were used. Highest concentration of soil organic carbon (SOC) was detected in native steppe and the lowest - in bare fallow.

The study of rheological behaviors of saturated soil pastes using distilled water were conducted on a modular compact rheometer (MCR 302, Anton Paar, Austria) at a constant temperature of 20°C, controlled by circular thermostat. Flow curve tests were conducted using coaxial cylinder measuring systems. This test procedure linearly ramps the shear rate from 0,16 to 300 s^{-1} and back and determines the resulting up- and down- shear stress curves.

Shear stress at initially set shear rate close to zero (P1) shows the strength of structural bonds in the soil paste at the beginning of the experiment (bare fallow -60 Pa, arable land -77 Pa, forest belt -296 Pa, oak forest -320 Pa, native steppe – 873 Pa). In the first stress cycle yield points (Schramm, 1998) have been reached only in two soil sample pastes - bare fallow and plough. For the forest belt, oak forest and native steppe soils one stress cycle was not enough for complete destruction of structural bonds. Relation of viscosity at the end of experiment to viscosity at the beginning of experiment at the shear rates close to zero allows us to estimate the percentage of thixotropic structure restoration. Thixotropic structure restoration was highest in oak forest soil (79%), lowest in bare fallow (16%). This may be explained by the large share of silt and organic matter in the soils under oak forest.

To estimate the reliability of established differences between soils, the obtained curves were approximated by power equation. Approximation

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parameters are the highest in native steppe and the lowest in bare fallow. Significant difference in structural conditions in plots under anthropogenic influence and virgin soils was found. Close correlation between SOC content and the strength of interparticle bonds was shown.

Rheological approach was proven as a responsive and statistically reliable method to study soil properties behavior in quantitative terms, such as strength of interparticle bonds, percentage of thixotropic structure recover and detection of soil structure changes.

Keywords: Rheology, shear stress, viscosity, soil structure, thixotropy

Introduction

The problem of land degradation is recently being investigated comprehensively, through various methods and approaches. Particular attention is paid to the methods for assessment of the structural soil state degradation, among which the studies of soil rheological characteristics are used very intensively. Rheological analyses of soil structure allows studying the mechanical behavior of soils under load, which delivers a quantitative description of the inter-particle interactions and fundamental information about the structural deformation of soils and consequences of these deformations. Key information on inter-particle interactions may be obtained from the characteristic curve which demonstrates the dependence of shear stress on shear rate (flow curve). Rheological curves - obtained with increasing shear rate (up curves) - , reflect the process of the destruction of structural connections. Under decreasing shear rate, rheological curves characterize the recovery of structural connections (down curves). Rheological up and down curves do not match but form a hysteresis, which is defined as thixotropy (the down curve is to the left of the line), or rheopexy (down curve is to the right of the line)(Schramm, 2003). The type of flow behavior, the shape of the curves are important to assess the nature of prevailing structural relationships in the soil under study. If the down curve is to the left of the line, it indicates that weak coagulation structures are predominant in the soil. If the rheopexy loop is formed, the down curve is to the right of the straight line. This shape means that strong inter-aggregate condensation structural links prevail in this soil; these links release an increasing number of fine particles as destruction proceeds. Thus, the shape of the up and down rheological curves is an important diagnostic characteristic of the structural links type.

The aim of this work was to study the rheological characteristics of typical chernozems under anthropogenic load.

The purposes of the work were: (1) to study physical properties of a chernozem (Kursk region, Russia) under different land use, (2) to obtain rheological curves using a modular rheometer MCR 302 (Anton-Paar, Austria), and (3) to analyze comparatively parameters of the rheological curves to determine the differences which can be used to define the degradation processes in typical chernozems under study.

Material and methods

Site description and general physical and chemical analyses

The typical chernozems of the Central State Chernozem Reserve (CSR, the site "Strletskaya steppe", Kursk region, Russia; established in 1935) and chernozems that are currently under agricultural use (settlement Petrinka, Kursk region) were studied. We studied the top 0-10 cm of virgin native steppe soil, adjacent bare fallow soil (plowed twice a year to 25 cm depth since 1947), soil under oak forest (Central State Chernozem Reserve), soils of agricultural arable land and adjacent forest belt soils (forest planted ~45 years ago). These chernozems developed on 2m fine-silt loess loam with a mean annual temperature of 5.5^{o}C and mean annual precipitation of 550-600 mm.

The particle size distribution and total carbon content were determined. for all soil samples. Soil organic carbon (SOC) contents were determined by combustion (AN-7529 analyzer). Granulometric composition was determined on Fritsch Laser Diffraction Particle Sizer ANALYSETTE-22 (Germany). Laser-diffraction analysis was conducted with wet dispersion in deionized water. Samples were dispersed ultrasonically (450-500 J·ml^{-1}) with a Branson Sonifier 250 (Branson, CT, USA) for 5 min. Table 1 informs about the particle size distribution and SOC content in soil samples.

Table 1: Particle size distributions and soil organic carbon contents for the test soils

Plot	Particle size (µm) distributions (%)						SOC
	<1	5-1	10-5	50-10	250-50	>250	%
Bare fallow	9.7	30.09	13.42	45.93	0.86	0	3.14
Arable land	8.14	27.86	13.39	31.74	7.45	11.42	3.42
Forest belt	5.77	18.6	12.01	31.83	30.01	1.78	6.1
Oak forest	8.98	32.32	16.24	41.72	0.74	0	6.51
Native steppe	5.44	22.99	14.07	51.63	4.94	0.93	6.7

The topsoils of all investigated sites can be characterized as silt loam according to USDA classification system. Only the soils of bare fallow have slightly higher clay contents. When sorted by organic matter content, the soils can be divided into two groups: (1) virgin soils, not affected by anthropogenic influence (native steppe, oak forest, forest belt), with SOC contents between 6,1 and 6,7%, and (2) agricultural soils (bare fallow, arable land), in which SOC content has decreased by half to 3.1-3.4%.

Rheological measurements

The study of rheological behavior of soil pastes was carried out with a modular rheometer MCR302 (Anton Paar, Austria) using a coaxial cylinder measuring system (C-CC27-SN25811). The "flow curve", or dependence of shear stress on shear rate, which characterizes the behavior of flowing matter, was determined.

Constant temperature of 20 °C was maintained during the whole experiment using water circulation thermostat. The flow of the soil paste occurred in a 1.13 mm gap between two concentric cylinders. The outer cylinder remained fixed, while the inner cylinder rotated at a predetermined speed. The flow of soil paste was determined as a shift of concentric layers of soil paste in relation to each other (Schramm, 2003). In the flow curves obtained, the X-axis denotes shear rate ($\dot{\gamma}$ [s^{-1}]), and Y-axis - shear stress (P [Pa]) (Schramm, 2003). Up and down curves were measured. The up branch of the flow curve was determined by measuring shear stress with shear rate ($\dot{\gamma}$ [s^{-1}]) increasing from 0,16 to 300 s^{-1}. The down branch of the curve was determined by measuring shear stress with a shear rate decreasing from 300 to 0,16 s^{-1}. The Viscosity curve (ratio of shear stress to shear rate vs. shear rate) was obtained based on the flow curve data. Table 2 shows the main parameters of the flow curve test.

Table 2: General pre-settings of flow curve test

Parameters	*Characteristics*
Measuring system	CC27-SN25811; d=26.656 mm
Number of data points	12
Time settings on 1 point	30 s
Shear rate	0.16-300 s-1- up 300-0.16 s-1- down

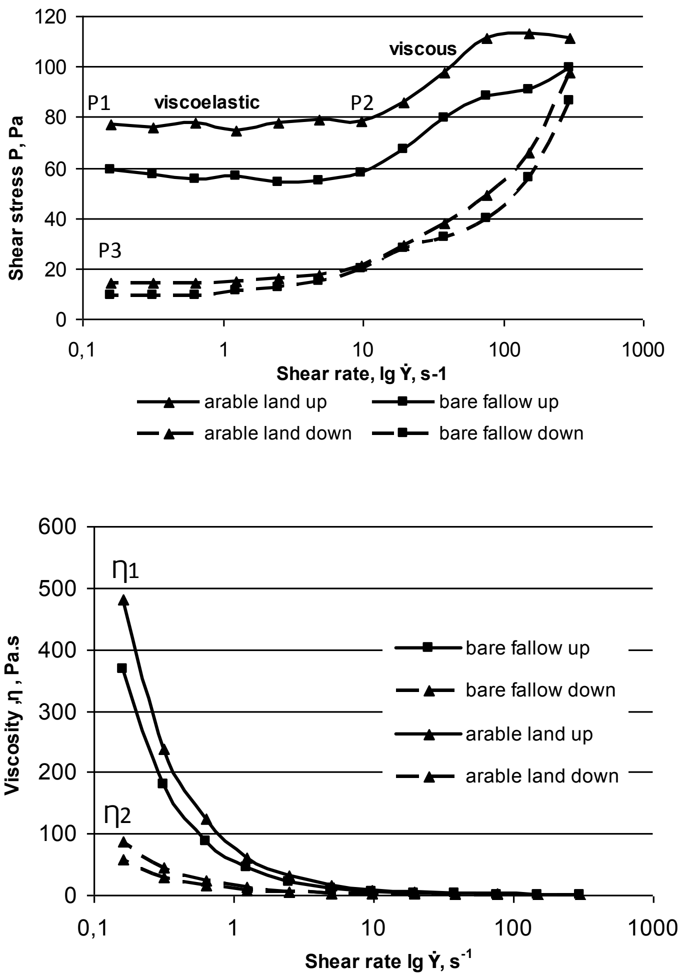
Preparation of samples

The soil samples were prepared as follows: 19 g of soil were graded with a rubber tip pestle and sieved through a 0.25 mm sieve, then filled into small cylinders (42 cm^3) at a density of 1.08 g/cm^3 and saturated with distilled water for 24 hours. Following the saturation, the soil was placed in the rheometer measurement system.

Results and discussion

Rheological properties of the A horizons under various soil management systems

Fig. 1a shows the dependency of shear stress on shear rate for soil pastes of bare fallow and arable land, documented as up and down curves. The P1 value on up curve indicates the shear stress, or the strength of structural links in the original soil paste at the beginning of the experiment at a shear rate close to zero. P1 was ~60 Pa for bare fallow soil and ~77 Pa for arable land soil. At first, the shear stress was not changing too far from the initial value with increasing shear rate, but at a shear rate of 10 s^{-1}, the shear stress (P2) became proportional to the applied load, which defines the destruction of structural links. The moment of the “up curve course” change may probably indicate the point of structure destruction, which is defined as the so-called yield point (Schramm, 2003).

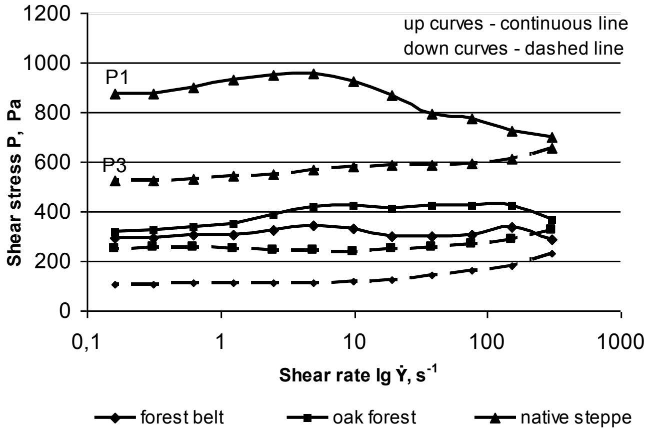


a)

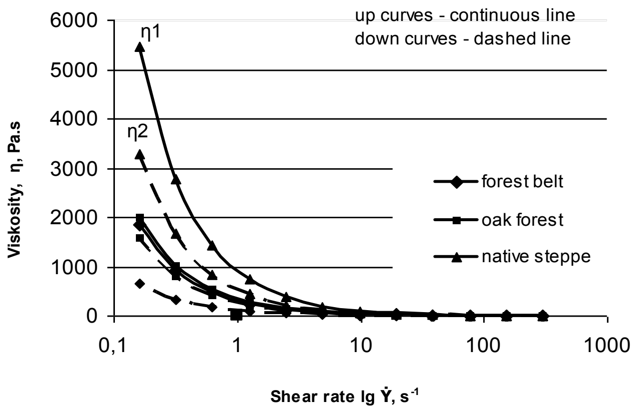
b)

Fig.1: Flow curves; a) dependence of shear stress on shear rate, up and down curves for a bare fallow and arable land; P1 – shear stress of soil paste at the initial state; P2 – transgression from viscoelastic to viscous state; P3 – shear stress of soil paste at the end of the cycle, after removal of stress; b) dependence of viscosity on shear rate, up and down curves; η1 – viscosity of soil paste at the initial state; η2 – viscosity of soil paste at the end of the cycle.

It should be noted that the P2 point divides the experimental up curve into two parts. From P1 to P2: region of viscoelastic behavior; from P2 to the last point of the up curve: region of viscous behavior, i.e. region with insignificant disruption of structural links and region with extensive destruction of bonds. Point P3 characterizes recovery or non-recovery of structural links as the shear rate decreases. Down curves go below the up curves and do not return to the starting point. Rheopectic loops are formed, which indicates the presence of strong interaggregate condensation links. The value of shear stress at a shear rate close to zero (P3) shows the strength of structural links after soil destruction or removal of stress. Only two soil pastes reached the destruction point after the first cycle – bare fallow and arable land.



a)



b)

Fig. 2: Flow curves; a) dependence of shear stress on shear rate, up and down curves for the forest belt, under oak forest and native steppe; P1 – shear stress of soil paste at the initial state; P3 – shear stress of soil paste at the end of the cycle, after removal of stress; b) dependence of viscosity on shear rate; up and down curves; η1- viscosity of soil paste at the initial state; η2 - viscosity of soil paste at the end of the cycle.

As can be seen from Fig.2, a single stress cycle was insufficient to completely destroy the structural links in the soil samples of native steppe, oak forest and forest belt; this phenomenon was stated previously by Manucharov and

Abrukova (1982) in their study of chernozems. Chernozem soil pastes from native steppe, oak forest and forest belt did not reach full destruction of structural links in a single cycle of the rheological experiment. The up curves (Fig. 2a) show absence of yield points (P2), after which behavior of the soil pastes becomes similar to the flow of viscouse body. It testifies that the structure completely is not destroyed.

Down branches of all flow curves are situated to the right or below the up branch, which probably indicates the presence of strong interaggregate condensation links. The appearance of rheopectic loops in the rheological curve is caused by complex processes of structural links redistribution: moistening and deformation are accompanied by the weakening of intra-aggregate (mainly cohesional) bonding forces. This leads to the destruction of hardened aggregates, increase in the number of microaggregates and strengthening of interaggregate (mainly adhesional) bonding forces. Rheopectic loops are characteristic only for fine textured soils possessing strong coagulative and condensation structural links (Abrukova, 1976). The difference between strength of structural links at the beginning and at the end of the experiment, or between P1 and P3, shows the amount of destroyed links.

The ratio of shear stress to shear rate is defined as dynamic viscosity (η, Pa*s). Fig.2b) shows the dependence of viscosity on shear rate, up and down curves.

The ratio of viscosity values at the end of the experiment (η_2) and viscosity values at the beginning of experiment (η_1), multiplied by 100, describes the percentage of thixotropic strengthening of structure.

Table 3 presents the quantitative parameters of flow curves for all plots under study.

Table 3: Quantitative parameters of flow curves for all plots under study

Plot	*P1, Pa*[*]	*P3, Pa*[**]	*P1–P3*	*η1, Pa*s*	*η2, Pa*s*	*% thixotropic recovery (η2/η1)*100*
Bare fallow	*58.8*	*9.2*	*49.6*	*367*	*57*	*15.6*
Arable land	*76.8*	*14.1*	*62.7*	*480*	*88*	*18.4*
Forest belt	*296.0*	*104.0*	*192.0*	*1850*	*648*	*35.0*
Oak forest	*320.0*	*253.0*	*67.0*	*2000*	*1580*	*79.0*
Native steppe	*873.0*	*523.0*	*350.0*	*5450*	*3270*	*60.0*

P1, Pa [*] - shear stress at shear rate close 0 of up curve
P3, Pa[**] - Shear stress at shear rate close 0 of down curve
P1 – P3 - Range of structural degradation
η1- Viscosity at shear rate close 0 of up curve
η2 - Viscosity at shear rate close 0 of down curve

The comparison of P1 values, or the strength of the original paste of all studied soil samples, showed significant differences (Table 3). Soil samples were thus divided into two groups: affected and not affected by anthropogenic impact. The strength of structural bonds in arable soils is approximately one order of magnitude smaller than in virgin soils. In the series of forest belt - oak forest - native steppe, the strength of soil bonds increases. High strength of inter-particle bonds in forest belt soil demonstrates the ability of these soils to restore their structure in absence of external stress. The forest belt consisting of broad-leaved trees was planted in 1966 on former cropland. The absence of plowing for 45 years has contributed to the restoration of soil structure.

At the same time, the degree of structural bonds strength is in close correlation with the organic matter content (Table 1). Constant plowing leads to an accelerated mineralization of organic matter; which is supported by the data of SOC content under bare fallow, where the SOC content has decreased more than two times during 65 years of constant plowing. The soil of this plot has also the lowest strength of structural bonds. Thus, the concept that the structural state of chernozems is sustained by high contents of SOC (W.Markgraf et al., 2010, Shein E. et.al. 2011,) was confirmed.

The ratio of viscosity at the end of the cycle and viscosity at the beginning of the cycle, at shear rates close to zero, multiplied by 100, gives the percentage of thixotropic structure recovery upon removal of stress. Due to their ability to restore soil structure, the studied samples form the following series, from lowest to highest (Table 3): bare fallow soil - arable land - forest belt - native steppe - oak forest.

Analysis of viscosity curves

To assess the reliability of obtained differences between the studied soils from various land use plots we have approximated the curves by the following power equation:

$$\eta = \alpha \cdot \dot{\gamma}^{-b}$$

where η - soil viscosity, Pa·s;
$\dot{\gamma}$ - shear rate, s^{-1};
a and *b* - approximation parameters

In this model, parameter *a* characterizes the position of the curve relative to the Y-axis: the higher *a*, the higher is the viscosity at a given soil moisture level (i.e., the stronger the interparticle bonds are). Parameter *b* describes the shape of the curves. Approximation results are presented in Table 4.

Table 4: Approximation parameters

Plot	Equation parameters			
	a	***b***	***R2***	t_a
Bare fallow	57	-0.92	0.997	
Arable land	77	-0.93	0.999	30.7
Forest belt	310	-0.99	0.994	73.4
Oak forest	357	-0.96	0.999	9.1
Native steppe	907	-1.03	0.999	93.8

a is highest in native steppe and the lowest in bare fallow soil. *a* of the bare fallow and arable land is significantly lower as compared to the rest of the land use plots.

Knowing the parameters of approximation and their statistics (in particular, the mean square error Sa), the studied soils can be compared statistically. Student's *t*-test was conducted for coefficient *a* of different samples (Table 4.) and confirmed the statistical significance of differences in rheological properties of the studied soils with a level of confidence of 95%.

The rheological approach and use of modular rheometers to examine micro-mechanical behavior of soils are highly sensitive and applicable for diagnostic studies of soil structure degradation and/or recovery processes, in dependence on various anthropogenic impacts.

Conclusions

1. The analysis of the rheological behavior of chernozems in the Kursk region points out their high structural stability.
2. Significant differences in structural conditions have been observed between samples of virgin soils (Forest Belt, Oak Forest, and Native Steppe) and those of land use plots that were exposed to anthropogenic influence.
3. Strengthening of the structural bonds is supported by SOC accumulation and more hydrophobic properties of SOC in soils under forests. There are other factors, e.g. different drying intensity under different land uses
4. The rheological approach (relation of shear stress to shear rate) has been proven to be a responsive and statistically reliable method for the study of soil properties and detection of soil structure changes.
5. Rheological approach allows us to describe soil properties behavior in quantitative terms, such as the strength of interparticle bonds, the range of destroyed interparticle bonds and the percentage of thixotropic structure recovery.

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