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The rheological properties of undisturbed samples of Typical Chernozem and Vertic Solonetz

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Abstract. The rheological properties of undisturbed monoliths of the Typical Chernozem of Kursk Oblast (Russia) and the Vertic Solonetz of Voronezh Oblast (Russia) are presented in this article. The rheological properties were determined by the amplitude sweep test on the rheometer MCR–302 (Anton Paar, Austria). It has been shown that the linear viscoelastic range (LVE-range) of the Vertic Solonetz significantly exceeds the LVE-range of the Typical Chernozem, which is probably related to the more heavy texture of the Vertic Solonetz. The storage modulus G` in the LVE-range of the Vertic Solonetz is much lower than Typical Chernozem. Perhaps, this fact is due to the higher silt fraction content (> 40–55%) and predominance of smectite minerals in them. Also, the weakening of inter-particle bonds in the Vertic Solonetz is related to the high alkalinity (pH_{H2O} 8.5–9.3) and high content of exchangeable sodium (> 30%). Yield point of the Vertic Solonetz is considerably smaller than Typical Chernozem. The stability of the Vertic Solonetz to mechanical stresses is much less than the Typical Chernozem. The combination of heavy texture, smectite mineralogy, high alkalinity, exchangeable sodium percentage in soil leads to the degradation of the soil structure and reduces its resistance to mechanical loads.

1. Introduction

The problem of land degradation is recently being investigated comprehensively by various methods and approaches. The particular attention is paid to the methods for assessment of the degradation of soil structure, among which the studies of soil rheological characteristics are used very intensively. Rheological analyses allow studying the mechanical behaviour of soils under loads, which delivers a quantitative description of the inter-particle interactions and fundamental information about the deformation of soil structure and consequences of these deformations [1–3].

Rheological studies were carried out mainly on disturbed samples. In particular, the method of coaxial cylinders, which is actively used in studies of Manucharov and Abrukova [4], allowed to conduct tests only on samples with disturbed structure. They studied rheological characteristics of soils on the "Reotest-2" (Germany) and presented a number of interesting semiquantitative characteristics related more to the viscous behavior range. The application of amplitude sweep tests (AST) for determination of soil rheological properties on the MCR rheometers (Anton Paar, Austria) has been introduced by Markgraf [1]. A detailed description of the method and its theoretical foundations were published in the previous works [1–2, 5–6]. The amplitude sweep method involves the application of oscillating stresses.

The tests with oscillating stress are dynamic tests [7]. They give information about the viscous and elastic parts of the soil behavior under loads. The advantage of AST is possibility to study rheological properties of undisturbed soils [8]. This fact significantly approximates the obtained results to soil properties at their natural field state.

The presence of salts in the soil profile has a negative impact not only on plant nutrition, but also on the soil physical properties, in particular the structure and its changes under stresses. Therefore, rheological studies of saline complexes appear to be very relevant. The aim of our study was to study and compare the rheological properties of the undisturbed Vertic Solonetz of Voronezh Oblast (Russia) and Typical Chernozem of Kursk Oblast (Russia).

2. Materials and methods

The Typical Chernozem is Haplic Chernozem (Loamic, Aric, Pachic) according to the WRB classification [9]. It is located at a local watershed with ground water table below 10 m at the Middle-Russian Upland in Kursk Oblast (Russia). The soil profile comprises a chernic (0–40 cm), a mollic (40–80 cm) diagnostic horizons and a layer with protocalcic properties (80–160 cm). Carbonate accumulations are permanent filaments as pseudomicelia. The upper part of the chernic horizon till the depth of 25–30 cm is a plough layer. The parent rocks of the soil are loess-like loams.

The Vertic Solonetz is Nudinatric Vertic Stagnic Protosalic Solonetz (Clayic, Cutanic, Humic, Hypernatric) according to the WRB classification [9]. It is located at a long slope with ground water table at the depth of 1–1.5 m at the northern part of Kalach Upland in Voronezh Oblast (Russia). Parent rocks are loess-like silty clays. A soil profile of the Vertic Solonetz comprises a black (2.5Y 2.5/1) natric horizon (0–25(30) cm) with columnar structure and humus-clay cutans on all sides of aggregates, a dark-humus horizon (2.5Y 3/1, 3/2; 25(30) – 55(60) cm) with sporadic clay cutans and small (0.5–2 mm) brown ferrous accumulations, and an olive-brown (2.5Y 4/3, 5/3) vertic horizon (60(75)–150 cm) with spheroidal carbonate accumulations – white soft spots, ferrous accumulations and reductive conditions. The upper boundary of slickenside's existence varies at the depth 45–60 cm. There are many large slickensides (40–90 cm long in one dimension) in the vertic horizon.

Mineralogical composition of both soils is represented by the same association of clay minerals in clay fraction < 0.001 mm. This is typical for loess-like loams and clays of the East-European Plain [10, 11]. It comprises irregular mica-smectite interstratifications with low (< 50%) and high (> 50%) share of smectite layers, di- and trioctahedral hydromicas, kaolinite and chlorite. Contents of hydromica and mica-smectite interstratifications in the clay fraction of the Typical Chernozem are 45–48% and 36–40%, respectively. The clay fraction of the Vertic Solonetz has the inverse ratio, namely the contents of mica–smectite interstratifications and hydromica are 50–60% and 30–35%. The total content of kaolinite + chlorite is 10–17% in the clay fractions of both soils.

The texture of the studied soils was determined by the laser diffraction method on the Analysette 22 Comfort (Germany) after ultrasonic dispersion of water-soil suspension for 5 min [12]. The texture of the Typical Chernozem and the Vertic Solonetz is silt loam and silty clay, respectively. The organic carbon content was determined by dry combustion after dissolution of carbonates at the AN-7529 M analyser [12]. The exchangeable sodium percentage was determined by Pfeffer's method in modification of Molodtzov and Ignatova [13] (table 1).

The rheological properties were determined by the amplitude sweep test on the rheometer MCR-302 (Anton Paar, Austria). Amplitude sweep tests (AST) can be conducted with controlled shear deformation. The following technical test parameters were used: the plate diameter = 2.5 cm; the shear deformation γ = 0.001–100%; the angular frequency f = 0.5 Hz; the number of measuring points = 30; the sample temperature was maintained at a constant level of 20 °C with the integrated Peltier unit according to Markgraf et al. [1]. Undisturbed samples were cut from each selected horizon in soil boxes of 10x15 cm, which were wrapped with tape to avoid damage during transportation to the laboratory. Before the test, the soil sample was placed on filter paper in contact with distilled water for capillary saturation. Water saturation was carried out for 3 days, in order to avoid drying of the surface the monolith was covered by polyethylene film.

Table 1. Some physical and chemical properties of soils.

Horizon depth, cm	Sand	Silt	Clay	pH_{H20}	EC_{se}[a], dS m^{-1}	ESP[b], %	C_{org}[c], %	$CaCO_3$[d], %	Moisture, kg kg^{-1}
	%								
Typical Chernozem									
Ahp1 (10–13)	1	80	19	6.3	-	1	2.55	0	0.37±0.03
Ahp2 (20–23)	2	80	18	6.3	-	1	2.98	0	0.33±0.05
ABh (77–80)	1	83	16	6.5	-	1	1.89	0	0.41±0.04
Vertic Solonetz									
Bthn1 (12–16)	3	55	42	8.5	2.06	46	3.65	0	0.57±0.16
Bthn1 (19–23)	1	54	45	8.5	3.15	51	3.75	0	0.50±0.06
Bthn2 (28–32)	4	45	51	8.9	3.17	59	1.40	0.2	0.51±0.07
Bthikn (45–49)	1	44	55	9.2	3.44	67	1.53	1.2	0.51±0.08
Bgikn1 (70–74)	1	44	55	9.1	2.05	53	0.17	6.3	0.47±0.04
Bgikn2 (97–101)	1	44	55	8.9	1.29	38	0.06	15.6	0.37±0.06

[a] Electrical conductivity.
[b] Exchange sodium percentage.
[c] Organic carbon content.
[d] Inorganic carbon content.

Small samples for rheological measurements were cut from the water-saturated monolith using a metal ring with a diameter of 2.5 cm, height of samples was ~6±0.2 mm. The samples were analyzed in 3–5 replicates. The thickness of the samples varied due to different swelling during capillary moistening, on one hand, and lack of possibility of accurate cutting of a monolith sample to the certain thickness, on the other hand. Tests were carried out at control of normal force < 15 N. The characterization of soil samples was based on the following rheological parameters: Storage modulus G′ in LVE-range; linear viscoelastic range (LVE-range) which indicates the steady behaviour of samples; Crossover point or the transition from the viscoelastic to the viscous behaviour [1, 6].

3. Results and discussion

The storage modulus of the Typical Chernozem in the linear viscoelasticity range (LVE-range) is more than the Vertic Solonetz. Perhaps this is related to the higher content of silt fraction (> 40–55%) and the predominance of smectite minerals in them [11]. The predominance of smectite minerals leads to the formation of weak inter-particle bonds due to the expanding crystal lattice, and the greater amount of absorbed moisture that was also noted by Ghezzehei and Or [14]; Markgraf et al [1]; Khaydapova et al. [15]. Also, the weakening of bonds in the Vertic Solonetz is due to high alkalinity (pH_{H2O} 8.5–9.3), exchangeable sodium percentage (> 30%) and low total salt concentration in soil solution (electrical conductivity of soil saturated extract was 1.7–3.4 dS m^{-1}) and accordingly a wide double electrical layer. These factors do not allow the particles to form close contacts and facilitate soil dispersion. A similar conclusion was made by Markgraf et al. [5] who showed that in Na-saturated clay systems electrostatic repulsive forces are responsible for dispersion due to the high pH values > 8, ESP > 50% resulting in less stable conditions.

The storage modulus G` of the undisturbed Vertic Solonetz is differentiated by a depth, the lowest storage modulus is observed in humus horizons, where the organic matter content is 3.65–3.75%. Organic carbon increases water absorption, this phenomenon prevents the formation of close contacts. G` increases up to the depth of 47 cm, further it decreases (figure 1). The character of this distribution is identical to the distribution of exchangeable sodium percentage by the profile. Possibly, the increase of the salt concentration (67% ESP; 3.44 dS m^{-1}) at the depth of 47 cm led to the compression of the double electric layer and the subsequent increase of the storage modulus.

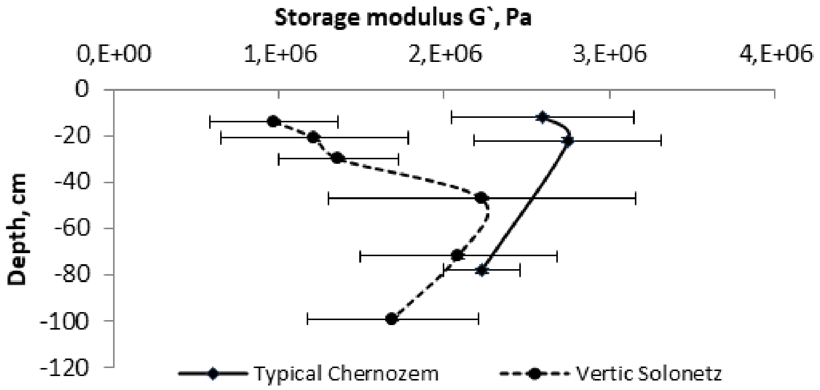

Figure 1. Storage modulus (G') of LVE-range.

Figure 2 demonstrates the curves of storage and loss moduli of Bthikn (45–49 cm) horizon of the Vertic Solonetz and Ahp2 (20–23 cm) horizon of the Typical Chernozem. The LVE-range limit of the Typical Chernozem is much smaller than the Vertic Solonetz. On the contrary, Crossover deformation (yield point) is less in the Vertic Solonetz than the Typical Chernozem. This fact reflects the more plastic behavior of the Chernozem. This is also evidenced by the sharper slope of the storage modulus curve of the Vertic Solonetz. This soil demonstrates low resistance to stress; it exhibits viscous behavior at low strains. The same results were obtained by Kawecka-Radomska et al. [16] in the study of the influence of different concentrations of ammonium nitrate on rheological properties of soil.

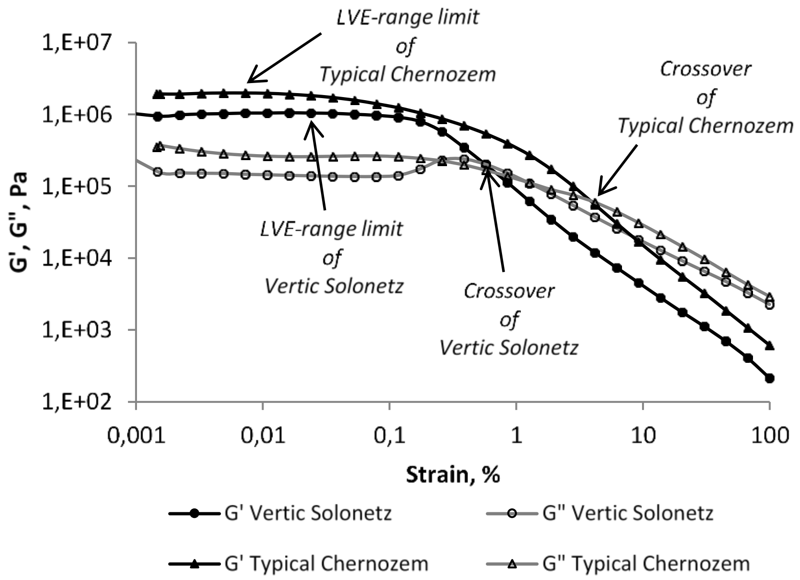

Figure 2. Storage (G') and loss (G") moduli of Bthikn (45–49 cm) horizon of Vertic Solonetz and Ahp2 (20–23 cm) horizon of Typical Chernozem.

Figure 3 shows the LVE-range values for all horizons of the investigated soils. The linear viscoelastic range of the Vertic Solonetz significantly exceeds Typical Chernozem. This fact is related to the more heavy texture and smectite clay mineralogy of the Vertic Solonetz (table 1). In addition, it can be assumed that Ca contributes to an increase of the LVE-range in the lower horizon. Ca ions cause aggregation of soil particles and strengthen the soil structure [5].

Figure 4 shows the deformation values of the intersection of storage and loss moduli (Crossover, yield point) for all horizons of the investigated soils. After that, at the state G'<G" microstructural collapse occurs and a viscous character of behavior prevails [1].

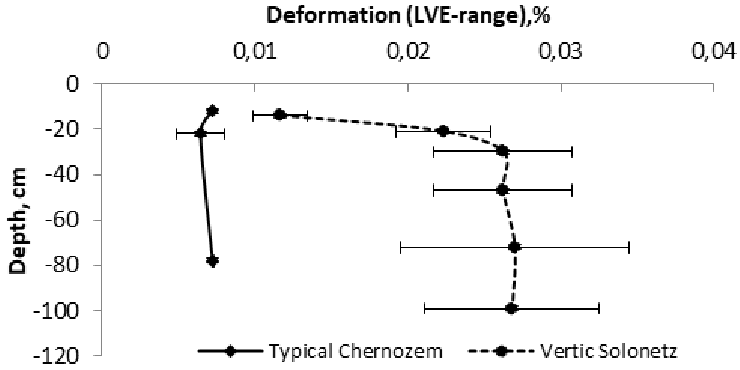

Figure 3. Linear viscoelastic range (LVE-range).

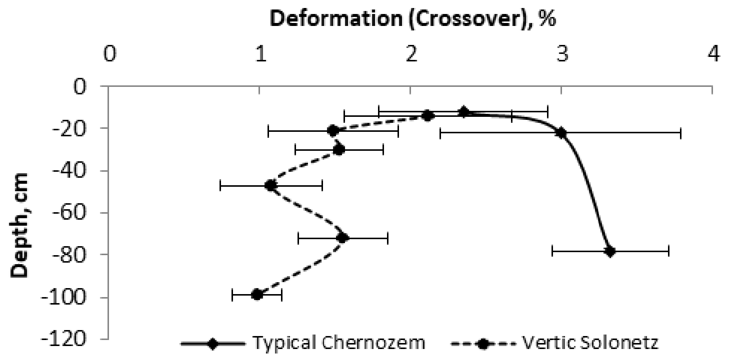

Figure 4. The deformation at the Crossover point.

The deformation value at the Crossover point (G' = G") of the Vertic Solonetz is considerably smaller than Typical Chernozem. This is evidence that the Vertic Solonetz has faster transition to a viscous state with increasing of stress than Typical Chernozem. In the Vertic Solonetz, the largest Crossover value is in the upper humus horizon which related to the high organic matter content and provides a stable structure [3, 6]. The decrease of Crossover values down the profile is probably related to an increase of exchangeable sodium percentage (ESP). This is agree with the data of Markgraf et al. [5] who noted that in the case of natural saline-sodic conditions Integral z decreases with an increase of ESP.

4. Conclusions

Rheological properties of the undisturbed Vertic Solonetz of Voronezh Oblast and Typical Chernozem of Kursk Oblast are investigated.

The storage modulus of the Vertic Solonetz, as an indicator of the strength of the soil structure, is significantly less than the Typical Chernozem. We assume that this is due to the high silt fraction content (> 40–55%) and the predominance of smectite minerals in them, which leads to the formation of weak inter-particle bonds caused by the expanding crystal lattice and the greater amount of absorbed moisture. Additionally, the weakening of bonds in the Vertic Solonetz is caused by high alkalinity (pH_{H2O} 8.5–9.3), the presence of exchange sodium (> 30%), low total salt concentration in soil solution (electrical conductivity of soil saturated extract was 1.7–3.4 dS m^{-1} and the formation of a wide double electric layer, that do not allow the particles to form close contacts and facilitate a soil dispersion. The profile of the Vertic Solonetz is differentiated by storage modulus values. The lowest values of storage modulus are observed in humus horizons of the Vertic Solonetz with organic matter content of 3.65–3.75% that increases the water absorption and prevents the formation of close contacts. The increase of the salt concentration at the depth of 47 cm (67% ESP; 3.44 dS m^{-1}) led to the compression of the double electric layer and resulting in the increase of the storage modulus at the depth of 40–60 cm.

The value of linear viscoelastic range of the Vertic Solonetz significantly exceeds the Typical Chernozem. Heavy texture of the Vertic Solonetz provides increasing LVE-range. Perhaps it can be assumed that Ca contributes to an increase of the LVE-range in the lower horizon. Ca ions cause aggregation of soil particles and strengthen the soil structure.

The deformation value of the intersection of moduli curves (G' = G") of the Vertic Solonetz is considerably smaller than the Typical Chernozem. This is evidence that the Vertic Solonetz has faster transition to a viscous state with increasing of stress than Typical Chernozem. This is also evidenced by the sharper slope of the storage modulus curve of the Vertic Solonetz. This soil shows low resistance to stress, at low deformations it passes to viscous behavior. Such behavior is caused by smectite mineralogical composition of the clay fraction and dispersing influence of salts.

Acknowledgments
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References

[1] Markgraf W, Horn R and Peth S 2006 An approach to rheometry in soil mechanics – structural changes in bentonite, clayey and silty soils *Soil Tillage Res.* **91** 1–14
[2] Baumgarten W and Horn R 2013 Assessing soil degradation by using a scale-spanning soil mechanical approach: a review *Adv. Geoecol.* **42** 1–61
[3] Khaydapova D D, Chestnova V V, Shein E V and Milanovskiy E Yu 2016 Rheological properties of typical chernozems (Kursk Oblast) under different land use *Eurasian Soil Sci.* **49** 890–97
[4] Manucharov A C and Abrukova V V 1983 Structural-mechanical properties of a sod-podzolic soil *Pochvovedenie* **4** 64–73 (in Russian)
[5] Markgraf W, Moreno F and Horn R 2012 Quantification of microstructural changes in salorthidic fluvaquents using rheological and particale charge techniques *Vadose Zone J.* **11** 1–11
[6] Markgraf W, Watts C W, Whalley W R, Hrkac T and Horn R 2012 Influence of organic matter on rheological properties of soil *Appl. Clay Sci.* **64** 25–33
[7] Mezger T 2014 *The rheology handbook for users of rotational and oscillatory rheometers* (Hanover: Vincentz Network)
[8] Klyueva V V and Khaydapova D D 2017 Rheological properties of natural and disturbed structure samples of soddy-podzolic and agro soddy-podzolic soil *Dokuchaev Soil Bull.* **89** 21–35 (in Russian)
[9] IUSS Working Group WRB 2015 *World Reference Base for Soil Resources 2014, update 2015, International soil classification system for naming soils and creating legends for soil maps* (World Soil Resources Reports No. 106) (Rome: FAO)
[10] Chizhikova N P 2000 Relationship between spatial distribution of soil mineralogical composition and soil cover patterns *Modern problems of soil science* (Moscow: Dokuchaev Soil Science Institute) pp 182–96 (in Russian)
[11] Chizhikova N P, Khitrov N B and Cheverdin Yu I 2011 Evolution of clay material due to solonetz process in the humus horizon of chernozems *Proc. Int. Conf. "100 years Bulgarian Soil Sci."* part 1 (Sofia) pp 216–9
[12] Shein E V, Milanovskiy E Yu, Khaydapova D D, Pozdnaykov A I , Tugai Z N, Pochatkova T N and Dembovetzkiy A V 2017 *Workshop on the physics of the solid phase of soils* (Moscow: Buki Vedi) (in Russian)
[13] *Handbook for laboratory methods investigation of ionic-salt composition of neutral and alkaline mineral soils* 1990 (Moscow: Dokuchaev Soil Science Institute) (in Russian)
[14] Ghezzehei T A and Or D 2001 Rheological properties of wet soils and clays under steady and oscillatory stress *Soil Sci. Soc. Am. J.* **65** 624–37
[15] Khaydapova D, Milanovskiy E and Shein E 2015 Rheological properties of different minerals and clay soils *Eurasian Soil Sci.* **4** 198–202
[16] Kawecka-Radomska M, Tomczyńska-Mleko M, Muszyńskic S, Wesołowska-Trojanowska M and Mleko S 2017 Viscoelastic properties of soil with different ammonium nitrate addition *Eurasian Soil Sci.* **50** 1450–4