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Effect of Water on the Rheological Properties of Typical Chernozem in Kursk Oblast

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Abstract—The rheological properties of typical chernozem were investigated by the amplitude sweep test on an MCR-302 rheometer (Anton Paar, Austria) for three water contents: maximum swelling, the liquid limit, and capillary rupture. A method is proposed for determining the water content of capillary rupture on an analyzer by using the curves for soil drying at constant temperature, determined simultaneously with the water content. Comparison of rheological soil characteristics at different soil humidity has shown that variations in the forms of soil water cause changes in the rheological soil behavior from viscous to elastic—brittle.

Keywords: soil physics, structure, rheology, amplitude sweep, drying curves

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INTRODUCTION

Evaluation of the stability of soil structure is very important under climate change conditions. Today, the rheological approach for solving this problem is widely used in soil science [4, 8, 11–13, 15], because the main property of soil structure—resistance to different loads—can be characterized on its basis.

Rheological properties of soils are a function of the surface properties of the solid soil phase. They are determined by the mineralogical composition, soil dispersion, and qualitative composition and amount of organic matter, and they are responsible for the stability, degradation, and formation of soil structure. The strength of bonds between soil particles mainly depends on the amount of water. The aim of this work was to reveal the interrelation between (1) the rheological behavior of soils at different water contents and (2) their physical properties and organic matter content.

Recent new-generation instruments have made it possible to significantly expand the number and accuracy of physically substantiated rheological parameters. They can be used to determine the interaction between particles and predict the behavior of soil microstructures under different loads. In particular, methods based on the oscillating parallel plates of an MCR-302 rheometer are used and recommended by some investigators as most suitable for analyzing the rheological behavior of soils [11, 12, 14], in particular, in the viscoelastic range prior to transition to the viscous flow state.

Soil water plays a leading role in the formation of soil structure. Study of the soil drying kinetics may provide information on the interaction patterns between water and the solid soil phase. The possibility of determining the transformation of one form of water into another from the kinetic characteristics of the evaporation rate was pointed out in [3]. Drying has been divided into the period of its stable rate and constant temperature of dried material and the period of the decreasing rate and variable temperature of the material [2, 5, 7, 9]. The moisture content during the transition between the two periods is determined as critical. Materials with different types of moisture bonds yield different shapes of drying curves. The period of the constant rate is characterized by a stable drying rate and constant temperature of the material, while in the period of the decreasing rate, the drying rate drops and the temperature of the material rises. The temperature curves make it possible to determine the relationship between water and material, in particular, capillary and adsorption water [7].

MATERIALS AND METHODS

The objects of the investigation are the top (0- to 10-cm) layers of typical chernozems of Kursk oblast (postlithogenic humus-accumulative chernozems and mycelium-migration carbonate-containing medium-sized thick heavy-loamy agrochernozems on loesslike loams according to the 2004 classification, or Voronic chernozem pachic according to the WRB 2006) under various conditions of land use: croplands, an adjacent shelter belt, long-term fallow, forest massif (oak forest), and unmown steppe. The cropland and forest shelter belt planted on old arable land in 1967 are

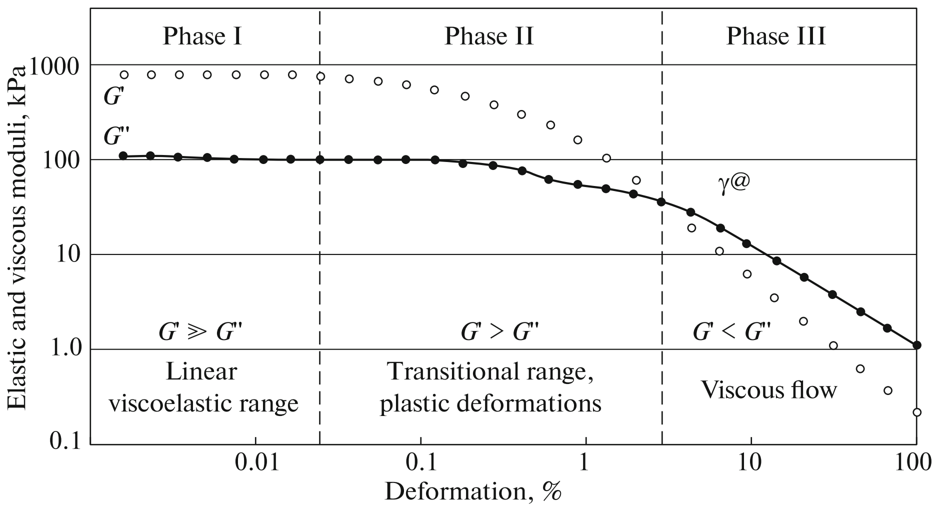

Fig. 1. Elastic modulus (*G*') and viscous modulus (*G*") of virgin chernozem for water content of liquid limit.

located in the area of the Petrinsk Experimental Station of the Dokuchaev Soil Science Institute; the fallow land (plowed twice a year since 1947), the oak forest, and steppe belong to the Alekhin Central Chernozemic Natural Biosphere Reserve.

We determined the total carbon content by dry digestion on an AN-7529 M analyzer and granulometric composition by laser diffraction of the particle size on an Analysette 22 Comfort device (Germany) after ultrasonic dispersion of the sample. The drying curves were analyzed with an MX-50 moisture analyzer (Japan), whose work is based on the principles of thermography [9]. The rheological parameters were determined by the amplitude sweep method in the oscillation mode on an MCR-302 modular rheometer with a parallel-plate measuring system (Anton Paar, Austria) [11, 12, 14].

The structure or rheological properties of soils were characterized by the following parameters (Fig. 1): (1) the elastic modulus (*G*'), which determines the initial binding strength between particles at the start of the experiment at the lowest amplitudes; (2) at low amplitudes (phase I) in the linear viscoelastic range, the elasticity (*G*') and viscosity (*G*') curves have a range of constant values in the form of a plateau parallel to the *x* axis; its presence and range testify to the stability of structural relationships in these soils under particular loads; (3) the range between the initial decreasing points of the curves and their intersection is the transitional range of plastic deformations (phase II)—in this range, the substance acts as a plastic body; (4) the intersection point of the moduli (phase III) or the equality of the elastic (*G*') and viscous (*G*") moduli indicates the transition of the sample from the viscoelastic to the viscous state; this is the range of fracture of the elastic component of the soil; (5) the integrated zone *Z* (phases I and II) characterizes the total value of the elastic and plastic behavior prior to the intersection point of the moduli.

We used the following technical conditions of the test: the distance between plates (*h*) was about 2–4 mm, the plate diameter was 2.5 cm, the shear deformation (γ) was 0.001–100%, the angular frequency (*f*) was 0.5 Hz, the number of measuring points was 30, and the sample temperature was maintained by Peltier units at a constant level of 20°C. The rheological soil properties were determined for the water content of maximum capillary saturation, of the liquid limit, and of capillary rupture.

Soil paste was prepared from air-dried soil, which was triturated with a rubber pestle and sieved through a 0.25-mm sieve. For the rheological test for the water content of maximum swelling, the soil was capillary-saturated for 24 h; for tests for the water content of the liquid limit, the soil was brought to this state by addition of water and control by a Vasil'ev drop cone [1]. The obtained paste was put into a plastic Petri dish 3 cm in diameter and left in a desiccator saturated with water vapor for 24 h for structuring.

The water content of capillary rupture was determined from the temperature–moisture and drying rate–moisture curves. The drying rate was measured on an MX-50 (Japan) moisture analyzer at the constant temperature of 60°C. The soil mass was recorded every minute synchronously with the temperature using a Termokhron recorder placed in the middle of the dried sample. The bend points of the temperature and drying curves between the ranges of the constant rate (constant temperature) and decreasing (increasing) temperature were taken as the range of water content of capillary rupture [9]. It was determined according to the period of soil drying to the bend point of the curve; after that, the sample was accurately placed on the plate of the rheometer.

Table 1. Total carbon content and particle-size composition of soils

Type of land use	C, %	Content (%) of fractions with diameter (mm)						Physical clay content, %
		<0.001	0.001–0.005	0.005–0.01	0.01–0.05	0.05–0.25	>0.25	
Steppe	6.8	5.4	23.0	14.1	51.6	4.9	0.9	42.5
Oak forest	6.5	9.0	32.3	16.2	41.7	0.7	0.0	57.5
Forest shelter belt	5.8	5.8	18.6	12.0	31.8	30.0	1.8	36.4
Plow land	3.3	8.1	27.9	13.4	31.7	7.5	11.4	49.4
Fallow	3.0	9.7	30.1	13.4	45.9	0.9	0.0	53.2

RESULTS AND DISCUSSION

The types of land use involving the objects of study affect the soil organic matter content (Table 1). The highest carbon content is typical of soils of the steppe plot, oak forest, and forest shelter belt. Its amount in the soils of the long-term fallow and plow land is almost two times lower. This is explained by the intensive mineralization of organic matter in cultivated soils, characterized by a modified oxidation–reduction potential and hydrothermal regime [6, 10].

The particle-size analysis showed that the coarse silt fraction predominates in all variants. The physical clay content in humified soils is the highest under the oak forest and the lowest under the forest shelter belt. The studied chernozem is characterized by heavy loamy (oak forest, plow land, and fallow land) and medium loamy (steppe and forest shelter belt) particle-size composition according to the Kachinskii classification. By international classification, it is assigned to loamy and silty-loamy soils.

The experimental drying curves (Fig. 2) correspond to those described in [7]. Their critical values (Wc_1 and Wc_2) were determined from the temperature–drying rate curves. The water content Wc_1 corresponds to the bend point on the drying rate and temperature curves at the transition from the range of decreasing to constant values. This indicates that free water was replaced by capillary water. The Wc_2 value corresponds to the bend point at the transition from the constant drying to the decreasing range or from the constant to rising temperature and is the boundary between capillary and film water (Table 2). The water contents were determined by intersection of the tangent lines drawn by the majority of points of the specified areas.

Capillary water evaporates in the range of the constant drying rate and constant temperature [3]. It corresponds to the range from Wc_1 to Wc_2 (%). The greatest area of constant drying rate of soils under the steppe plot, oak forest, and forest shelter belt testifies their higher organic matter content. During the transition from the area of constant rate to decreasing drying rate or from the area of constant to increasing temperature, capillary water is replaced by film water. This is probably the range of water content of capillary rupture.

The data on the soil rheological properties for various water contents are given in Table 3.

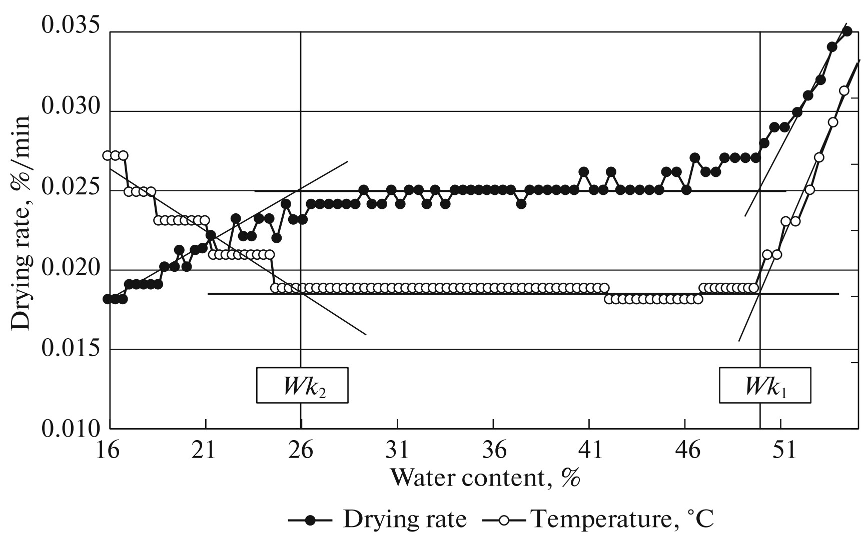

Fig. 2. Temperature curve and drying rate curve with example of soils under forest shelter belt.

Table 2. Water values at critical points of drying curves and soil temperature (Wc_1 is replacement of free water by capillary, and Wc_2 is replacement of capillary water by film water), %

Type of cropland	Wc_1	Wc_2	Wc_1-Wc_2
Steppe	53	26	27
Oak forest	56	25	30
Forest shelter belt	50	26	23
Plow land	38	18	19
Fallow	38	18	19

Table 3. Water content in samples from humic horizons, %

Type of cropland	Water content of the maximum swelling	Liquid limit	Water content of capillary rupture
Steppe	84	55	23
Oak forest	73	50	25
Forest shelter belt	75	52	27
Plow land	64	40	18
Fallow	57	36	19

Each soil of the agricultural lands was characterized by the elastic modulus, linear viscoelastic range, the intersection point ofthe elastic and viscous moduli ($G' = G''$), and the integrated zone Z (calculated by the rheometer software).

The binding strength between particles or the elastic modulus (Fig. 3a) in the linear viscoelastic range is two to three times smaller for the water content of maximum swelling when compared to the water content of the liquid limit. It is obvious that the free water content in soil paste is high for the water content of maximum swelling, so the distance between particles is the greatest and the bonds between them are weak. A drop in water content to the liquid limit (about 1.5 times) probably results in appearance of capillary forces, which cause a two- to threefold increase in cohesion of particles (Table 3). Soil drying from the liquid limit to the water content of capillary rupture (about a twofold drop) results in 1- to 19-fold strengthening of bonds. It is the highest in the samples from the plow land and long-term fallow land, which is obviously related to smaller content of organic matter. The direct contact between soil particles favors the formation of strong bonds.

The distribution patterns of elastic moduli for the variants of land use at the initial point are similar for the water content of maximum swelling and of the liquid point. With respect to binding strength, the types of land use can be arranged in the following series: long-term fallow and plow land > forest shelter belt > oak forest > unmowed steppe. For the water content of capillary rupture, the series of agricultural lands with respect to the decrease in strength of bonds between particles is as follows: fallow land, plow land, steppe, oak forest, and forest shelter belt. The interparticle bonds of soils rich in organic matter are weaker compared to soils with a small OM content.

The linear viscoelastic range or the range of viscoelastic behavior for the water content of maximum swelling is highest in the steppe soil and lowest under the fallow land (Fig. 3b). With respect to the water content of the liquid limit, the samples are divided into two groups: (i) soils of the steppe plot, oak forest, and forest shelter belt and (ii) soils of the plow land and fallow land. This distribution of the linear viscoelastic range corresponds to the distribution of organic matter. For the moisture content of capillary rupture, the range of viscoelastic behavior significantly decreases: it is smallest for the steppe, plow land, and fallow land and somewhat higher for the oak forest and forest shelter belt. For the water content of capillary rupture, the plastic soil behavior gives way to elastic–brittle. The smaller range of the viscoelastic state testifies that this amount of water pertains to the range of aggregate formation.

The deformation value is determined as the intersection point of the elasticity and viscosity moduli (Fig. 3c). When it is exceeded, the soil becomes viscous. The viscosity rate is greater in soils with the water moisture content of maximum swelling compared to soils with the water content of the liquid limit or capillary rupture. When the water content is high, soils are more plastic and soil particles can move with respect to each other. For a low water content, the bonds between particles are stronger, the rheological behavior of the soil paste becomes more brittle, and the bonds are more quickly disrupted under load. The greatest plasticity (or the range of viscoelastic structure) is typical of soils rich in organic matter with the water content of maximum swelling and the liquid limit. For the water content of capillary rupture, the deformation at the intersection point of the moduli is the highest in the soil under the oak forest and the lowest for the fallow land.

The integrated zone Z can be used as an integral parameter of viscoelastic soil behavior [12, 13]. It characterizes the total value of the elastic and viscoelastic (plastic) behavior prior to the transitions to the range of viscous state. The higher is the integral of Z, the more plastic is the soil state.

The values of the integral zone Z (Fig. 3d) strongly differ at the three ranges of water amount. For the water content of the maximum swelling, this range is rather great and results in the following series of the kinds of land use: unmowed steppe > oak forest = forest shelter belt > plow land > long-term fallow land. The range of viscoelastic behavior becomes 3–5 times smaller, when water content is at the liquid limit, and 5–10 times smaller for the water content of capillary rupture. The shift range of soil particles relative to each other probably becomes considerably smaller as a

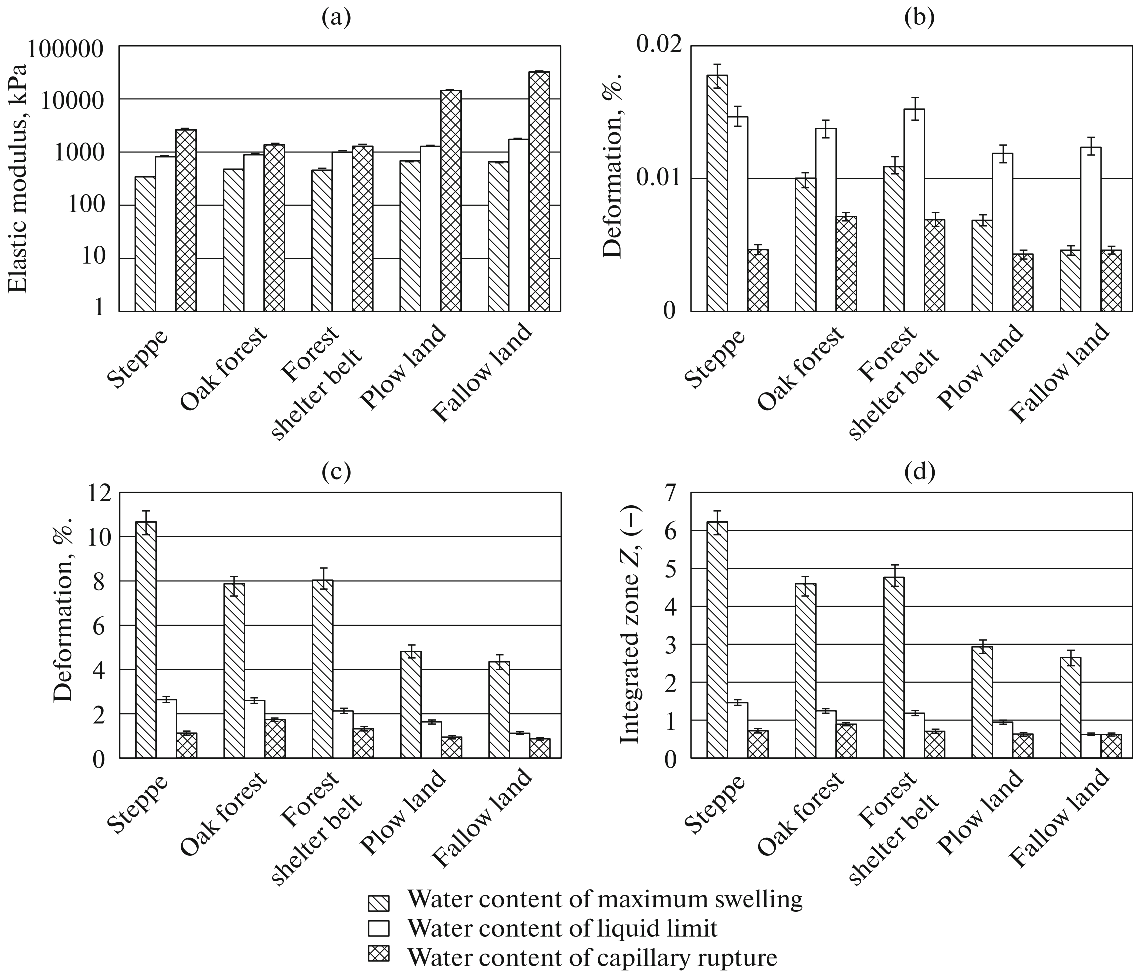

Fig. 3. Rheological parameters of investigated objects for different water contents: (a) elastic modulus at the linear viscoelastic range, (b) linear viscoelastic range, (c) intersection point of elastic and viscous moduli, (d) integrated zone *Z*.

result of forming capillary bonds. The distribution pattern of values of the zone *Z* for soils with water content of the liquid limit in different variants of land use corresponds to that for the water content of the maximum swelling and is in general determined by the amount of organic matter. Nevertheless, for the moisture content of capillary rupture, the integral zone is the greatest in soils under the oak forest and the lowest under the fallow land. The qualitative composition of organic matter under the oak forest is probably responsible for the higher soil structure resistance to loads. It can be concluded that organic matter favors an increase in the range of viscoelastic behavior of soils.

Therefore, the rheological parameters determined for different water contents show that rheological soil behavior strongly depends on it. The lower the amount of water, the stronger the bonds between particles. The range of plastic behavior becomes considerably smaller during the transition from the water content of maximum swelling to the amount of water of the liquid limit and capillary rupture. The bends of the drying curves at a constant temperature and its synchronous determination show the limits of the content of capillary water during the transition from free to capillary and from capillary to film (water content of capillary rupture) moisture. The highest amount of capillary water is typical of soils with a high organic matter content. For the water content of the maximum swelling, the strength of bonds between particles is the smallest (340–740 kPa), and the soil state is close to liquid; for the water content at the liquid limit, the bond between particles becomes two to three times stronger (885–1212 kPa), and the soil state becomes plastic; and for the water content of capillary rupture, interparticle bonds become about 3–50 times stronger (7790–36700 kPa), and soil state becomes elastic–brittle.

CONCLUSIONS

• The rheological parameters of typical chernozem under various types of land use were investigated by the amplitude sweep test on an MCR-302 rheometer (Anton Paar, Austria) for different water contents. The range of soil plastic behavior becomes significantly smaller during the transition from the water content of maximum swelling to the amount of water of the liquid limit and capillary rupture.

• In the humidity rupture of capillaries, soil paste is characterized by the greatest strength of interparticle cohesion and the most brittle behavior. This probably explains why the water content of aggregate formation corresponds to the amount of water of capillary rupture.

• A method is proposed for determining the water content of capillary rupture from the soil drying curves on a moisture analyzer at a constant temperature, which is detected parallel to water content.

• Comparison of soil rheological characteristics for different water contents has shown that variations in the forms of soil water cause changes in the rheological behavior of soils from viscous to elastic–brittle. For the water content of maximum swelling, the strength of bonds (or elastic modulus) is not high (340–740 kPa) and soil behavior is very plastic and close to viscous; for the water content of the liquid limit, the bonds become stronger (885–1212 kPa),and soil behavior is plastic; and for humidity rupture of capillaries, interparticle cohesion increases about 3–50 times (7790–36 700 kPa) and the soil state becomes elastic-brittle.

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