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Relationship between soil rheological properties and water retention curves

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Abstract. The interdependence between the rheological properties and the water retention curve was determined on the example of typical chernozems of Kursk region. The strength of the aggregates of humus horizons of a virgin chernozem, an arable chernozem, and aggregates of Bca horizon in a wide range of water content was investigated by the conical Rebinder’s plastometer. It was shown that the strength of the aggregates depends on water content. The dependence of aggregates strength on moisture is exponential. Comparison of virgin and arable soils revealed a positive effect of organic matter on the structural state of the soil. At high water content, aggregates of the virgin soil are more stable than aggregates of the arable soil and ones of the lower horizons Bca. In air-dry conditions, the strength of aggregates from the arable soil significantly exceeds the aggregates’ strength from the virgin soil, which indicates degradation processes in the arable soil, a decrease of organic matter content leads to an increase of interparticle interaction and an increase in a block-like structure. These experimentally obtained data confirmed the existence of a close relationship between logarithm’s values of the soil moisture full potentials’ moduli and the strength of soil aggregates and the presence of an appropriate linear regression dependence. Voronin’s structural-functional concept is confirmed by the fact that hydrophysical, mechanical and rheological properties of soils are functions of the soil structure.

1. Introduction
Voronin’s structural-functional concept suggested that the hydrophysical, mechanical and rheological properties of soils are functions of the soil structure since they are caused by both the curvature of the interface between the solid part and liquid and gaseous parts. The definition of A.D. Voronin [1] soil structure as the physical structure of soil matter, due to the size, shape, quantitative ratio, nature of a relationship of elementary soil particles and aggregates consisting of them, allows to discover the causes of the formation of structural and physical properties of soil and identify ways to change them in a given direction. Nature of a relationship of soil particles and their strength is an integral expression of all properties of the soil structure components. Tensile strength of soil aggregates is a very sensitive indicator of soil structural stability [2, 3]. The tensile strength is defined as the force per unit area required to break soil aggregates into smaller particles [2]. The methods of soil rheology as a science about deformations, the quality of structural bonds, and their strength are most suitable for obtaining quantitative patterns of behaviour of soil structures depending on the soil moisture content and the water retention curve. The goal of this work was to identify the relationship of the rheological behaviour of the soil with the water retention curve.

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2. Objects
The objects of the study were typical chernozems of Kursk region (Russia), according WRB - Haplic Chernozems (Pachic). Location GPS coordinates of the virgin chernozem is 51°34'19.6"N 36°05'37.3"E and the arable chernozem is 51°36'120"N 036°13’393"E. Aggregates of 3-5 mm size of the humus horizons of the virgin chernozem under steppe vegetation (A1) and the arable chernozem (A arable) and the bottom Bca horizon with carbonates have been investigated.

3. Methods
Texture was determined by the pipette sedimentation method [4], the organic matter (OM) – by the express analyzer AN-7529 [5], the data are presented in table 1.

| C\(^a\),% | Content (%) of texture (mm) |
|---|---|---|---|---|---|---|---|
| A1 Steppe | 6.8 | 5.4 | 23.0 | 14.1 | 51.6 | 4.9 | 0.9 | 42.5 |
| A Arable land | 3.3 | 8.1 | 27.9 | 13.4 | 31.7 | 7.5 | 11.4 | 49.4 |
| Horizon Bca | 1.7 | 8.3 | 26.5 | 14.5 | 50.5 | 0.2 | 0.0 | 49.3 |

\(^a\)C - total carbon

The organic matter content in the arable soil is approximately two times lower than in a virgin soil. According to the USDA classification texture is silt loam. Strength of the aggregates was determined by a Rebinder’s conical plastometer [5, 6]. Aggregates were pre-capillary moistened on a ceramic tile within 24 hours. Moisture of aggregates after daily capillary moistening will be called capillary moisture capacity (CM) below. After determining the strength of the wetted aggregates, the aggregates were placed on a glass surface for drying at room temperature. Strength and moisture of the aggregates were determined every 15 minutes of drying. Determination was carried out in ten-fold repetition. A strength calculation was performed according to the Rebinder’s formula:

\[ P = \frac{K F}{h^2} \]

where \( P \) –strength of aggregate, kg/cm\(^2\); \( F \) – load, kg; \( h \) - average diameter of the aggregate, cm; K-coefficient 1.108, corresponding to the opening angle of the 30\(^\circ\) cone. The coefficient K-1.108 corresponds with the surface of the area of the cone that comes into contact with the material during viscous and plastic behaviour. For elastic-fragile state, Rebinder proposed to calculate the coefficient based on the projection of the circle area at the base of the cone, in this case our calculations showed a coefficient equal to 4.4 [5]. Variability within the replicates was presented as a confidence interval with a significance level of 0.05. Calculations and figures were done using Microsoft Excel 2010.

Determination of the transition moment from the plastic behaviour of soil aggregates to the brittle fracture during their drying was carried out by the inflection point of the curve of the dependence of the drying temperature of a soil sample on moisture. This moisture corresponds to the capillary rupture moisture [7]. The water retention curves were obtained by centrifuging in Smagin’s modification [8].

4. Results
Figure 1 shows the curves of the dependence of the aggregates’ strength on water content (A) and (B) an enlarged scale of the lower part of the curves. As can be seen, all curves are functions of the exponential form with a quite high value of determination coefficient close to 1 (figure 1, (A)).
Figure 1. The dependence of the aggregates’ strength on the water content – (A); (B) - an increased scale of the lower part of the curves.

The largest amount of moisture was absorbed by the aggregates of a virgin chernozem, and they also have greater strength in the area of high water content, unlike the aggregates of the arable field and the Bca horizon (B). Aggregates of the arable chernozem at high moisture are less stable than aggregates of virgin chernozem, due to significantly lower OM content. Aggregates of Bca horizon at high moisture are characterized by the least stability. Obviously, in the condition of high moisture content, the organic matter of the virgin chernozem keeps soil particles in a bound state, providing significant water resistance, while the arable chernozem due to a 50% loss of organic matter is no longer capable of ensuring the same stability. A sharp bend of the curve of the virgin chernozem is observed in the water content range of 25%, arable land and Bca horizon - 18% moisture. This moisture corresponds to the moisture of the rupture of the capillary connection [7]. The existence of such excesses in increasing the strength of clays depending on moisture was noted by Sokolov and Osipov [9]. They associated them with the various effects of water on the strength of clays. In the range of moisture content from capillary moisture capacity to the capillary rupture moisture, the strength increases gradually, the nature of the dependence is linear. The structure simultaneously has coagulative type caused by long-range forces. When the moisture becomes less than the moisture of rupture of the capillary bonds, the interparticle interaction occurs through residual thin capillaries or water film. Under these conditions, the interparticle interaction becomes greater in the arable soil with a lower OM content and the curve of strength versus moisture is steeper than in virgin chernozem. With further reduction of moisture, there is a sharp increase in strength, the system gradually moves from coagulation to condensation type of structure. When drying to about 4% moisture, the maximum hardening of the structure occurs, contacts in such systems are mainly due to ion-electrostatic bonds. The strength of the arable aggregates in air-dry condition reaches 21 kg / cm², while in the aggregates of the virgin chernozem it is 15 kg / cm². The decrease in the OM content causes a stronger hardening in the dry state and the formation of a blocky structure. A similar pattern was noted by Hector Causarano [10] for the clay soil, with organic matter varying from 1.3 to 10.4%, large organic matter content appeared to strengthen wet soil aggregates and weaken dry ones. There is a slight increase in strength in the aggregates of the carbonate horizon. This is probably due to the carbonates which cause the formation of microaggregates with highly porous structure. This fact confirms the positive effect of soil liming.

Thus, there is an obvious connection between the strength of the soil structure and different moisture content. In this regard, we tried to establish the dependence of the strength of the structure with the water retention curve. In order to compare the water retention curves with the strength curves, the average of

\[
\begin{align*}
\text{y} &= 18,874e^{0.12x}, \quad R^2 = 0.9812 \\
\text{y} &= 43,835e^{0.198x}, \quad R^2 = 0.9732 \\
\text{y} &= 10,677e^{0.168x}, \quad R^2 = 0.9161
\end{align*}
\]

...
10 replicates of strength values of the aggregates kg/cm² were transferred to log of centimeters of water column (pF) and plotted combined strength graphs and WRC (figure 2).

As can be seen, the strength curves of the aggregates lay very close to the WRC. This suggests that the hydrophysical and rheological properties of soils are subject to the same laws and depend on the moisture content in the soil. These experimentally obtained data confirmed the existence of a close relationship between logarithm’s values of the soil moisture full potentials and logarithm’s values of the strength of soil aggregates and the presence of an appropriate linear regression dependence (figure 3.).

5. Conclusions
For the first time, a close regression relationship was established between the potential of soil moisture and the strength of aggregates. Thus, Voronin’s structural-functional concept is confirmed by the fact that hydrophysical, mechanical and rheological properties of soils are functions of the soil structure.

A study of the strength of the aggregates in a wide range of moisture showed the strength of the aggregates depends on the moisture content and it is an exponential dependence. Comparison of virgin and arable soils has revealed a double positive effect of organic matter on the structural state of the soil: 1) at high moisture, aggregates of the virgin soil are more stable than aggregates of arable, 2) in the air-dry condition, the strength of aggregates of the arable soil greatly exceeds the strength of
aggregates of the virgin soil. This suggests degradation processes in the arable soil, where a decrease of the OM content has led to an increase of interparticle interaction and an increase in the blocky soil structure. The low strength of the Bca aggregates in the dry state shows a positive structuring effect of CaCO₃, which forms the porous structure of the soil.

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