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GENERAL BIOLOGY

The Mechanism of Influence of the Organic Matter on the Soil Structure and Mechanical Properties

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The conventional model of soil suggests that soil is a biologically inert system composed of the solid, liquid, and gaseous phases, as well as soil organisms [1]. Soil solid phase predominates; it includes particles of different sizes, from macroscopic to colloid particles. The mineral, organic, and organomineral particles constitute soil colloids [2, 3].

It has been experimentally demonstrated [4] that colloid particles coagulate on the big particles. Tyulin has subsequently developed a concept of the film–gels covering the large soil particles [5].

The fact that, in soils, the colloid component exists as gels on the surface of large particles stems from the physical and chemical nature of colloids and causes no doubt. It has been recently demonstrated that the fractal clusters of supermolecules of the humic substance form the basis of soil gels [6], and the humic gel (humic matrix) is built up of the humic substances.

Since soil gels cover the macroparticle surface, large particles are probably bound to each other via the soil organomineral gels. At the same time, the gels ensure functional interaction between the soil components; hence, they are the backbone element.

Nevertheless, there is only a few of the direct experimental evidence suggesting the crucial role of soil gel in organization of the soil structure; therefore, studies of this kind are of great interest.

The structural and mechanical properties of the systems on the basis of gels are among the most important ones that characterize these systems [7, 8]. Even the name "gel" (from the Latin congelo) suggests their solid-phase status.

The structural and mechanical properties of soils were earlier analyzed [9]; nevertheless modern equipment and a combination of various methods used to follow the processes of soil structure disruption would provide much more information.

The objective of this study was to gain a deeper insight into the structural soil organization and to clarify the role and location of gels in soil. We have analyzed the structural and mechanical properties of soils with different contents of the organic matter (OM), as well as changes in soil gel in response to a mechanical impact.

Soil samples were taken from the humus-accumulative horizon of typical heavy loam chernozem maintained under the artificial long fallow for 60 years (Alekhin Central Chernozem Reserve).

The intact soil samples were compared with the samples of soil from where most of the organic matter (OM) was removed. The OM content was 3.98 and 0.85%, respectively.

To remove OM, we used a technique of OM combustion by means of hydrogen peroxide [10]. OM was removed in two stages. First, 100 mL of 1% hydrogen peroxide solution was poured on a 60-g sample of air-dried soil. When an intense release of carbon dioxide is stopped, hydrogen peroxide was evaporated on a sand bath. Afterwards, a 30% hydrogen peroxide solution was poured on the same soil sample and evaporation continued on the sand bath.

To study the rheological characteristics, the soil samples were prepared as follows: 3 g of soil, which was ground and sieved through a 1-mm sieve, was placed into a plastic tube 2.5-cm in diameter with a permeable mesh bottom, where the soil was capillary wetted for a day. The moist soil was carefully (without disturbance of integrity) laid out by means of a piston on the platform of the measuring device. Rheological parameters of the soil pastes were determined using the amplitude sweep technique and a modular MCR-302 rheometer (Anton Paar, Austria).[1] The oscillating technique performed on the parallel platform of MCR rheometer has been used by several authors to deter-

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mine the mechanical soil behavior [11, 12]. The following parameters were determined: the modulus of elasticity (G', Pa), loss modulus (G'', Pa), and intersection point of modulus ($G' = G''$). The distance between two platforms is 3 mm during measurement. The number of measured points is 30. The measurement time of a point is 15 s. The frequency is 0.5 Hz.

Modulus of elasticity is a measure of strain energy retained by a sample during a shear. After a shear, this energy acts as a driving force for the process of recovery. The materials that retain completely the applied strain energy are capable of the absolutely reversible deformation. Thus, the modulus of elasticity is a characteristic of the material elasticity [13].

The loss modulus or viscosity is a measure of the strain energy that is expended and lost by a sample during a shear process. This energy is consumed to change the structure of the material, i.e., during movement between the molecules, particles, and other components of the structure, such as groups, aggregates, and “domains.” A waste of energy is characteristic of the materials that demonstrate irreversible deformation, and the loss modulus is indicative of viscous behavior of these materials [13].

To study the structural changes in soil that occur in response to a mechanical impact, it was necessary to make a fixation of these changes in soil samples. For this purpose, we used an HBDV-II+PRO rotation Brookfield viscometer (Brookfield, United States). Soil sample was placed between two parallel planes located at a distance of 3 mm from each other; one of the two planes (the upper one) was rotated at a speed corresponding to the degree of soil disruption as determined on a MCR-302 rheometer (Anton Paar, Austria). The lower plane was the bottom of a thin-walled metal container. A soil sample was treated at this rotational speed for 3 min; afterwards, liquid nitrogen was poured into the container to cause rapid freezing of the soil sample. Various techniques, including sublimation dryer, are used to remove water from a frozen sample so that the fixed structure remained unaffected [14]. However, cryoextraction proved to be a much simpler and rapid method that does not require elaborate equipment [15].

The frozen sample was placed into a beaker containing a large (about hundredfold) excess of acetone to be kept at the melting acetone temperature (–95°C) for 1.5–2 h until it reached 0°C and more. Below ice melting temperature, acetone absorbs water from the frozen soil solution. Soil samples were withdrawn and dried at 40°C to remove the remaining acetone. Intact (unaffected) soil samples were treated similarly, except that rotation of the upper of two planes was excluded.

Preliminary experiments with wet soil aggregates have demonstrated that the technique used for water removal caused no shrinkage of a soil sample.

The sample surfaces contacting with the parallel metal planes were examined using a JEOL-6060A scanning electron microscope (JEOL, Japan) with a tungsten cathode.

Before examination, the samples were covered with platinum using a JFC-1600 device (JEOL, Japan).

Figure 1 shows the results of rheological analysis of the OM-containing chernozem samples and of the same samples after OM removal.

It can be seen that, after OM removal from soil paste by hydrogen peroxide, it is almost in unaffected state; i.e., when deformation tends to zero (0.01%), the modulus of elasticity G' or the strength of structural bonds increases as compared to the OM-containing sample. The structural disruption, i.e., the moment when the modulus of elasticity becomes equal to viscosity, occurs at a 6.2% deformation in the OM-containing chernozem and at a 4.17% deformation in chernozem without OM.

Thus, after OM removal from chernozem, the bond strength between the structural elements (particles) grows up, but elasticity of the structure decreases: it is destroyed at a lower deformation.

To gain insight into the process, we have examined the microstructure of the intact wet soil samples before and after OM removal (Fig. 2). Micrograph analysis demonstrates that, after OM removal, the samples contain numerous small aggregates and mineral particles (see the photo, the right part) that are absent in the OM-containing samples (the left part of the photo). Since handling of the samples did not include any processes that could disrupt large structural elements down to the small ones, we assume that these particles are released due to OM removal. In the intact OM-containing chernozem, they were invisible within the humus matrix, while OM removal released them and made accessible for observation. These data are in accordance with the concept that the organic humus gels covering the large soil particles and binding them are reinforced (filled) with small mineral particles.

We studied also the morphology of the OM-containing chernozem exposed and unexposed to a mechanical impact, with disrupted and unaffected gel structures. The mechanical impact leads to disruption of a soil sample: its solid gel structure is transformed into the fluid-like gel structure. Comparison of the electron microscopic images (Fig. 3, the right and left parts) suggests that, in the samples with disrupted soil structure, the soil gels emerge on the sample surfaces contacting with the metal planes. They appear on the surface in amounts large enough to hide the big soil particles. This enables us to conclude that, in response to mechanical impact on the OM-containing samples of chernozem, the gels are squeezed out from the areas where they support soil structure to appear on the surface of a sample. Hence, disruption of the OM-con-

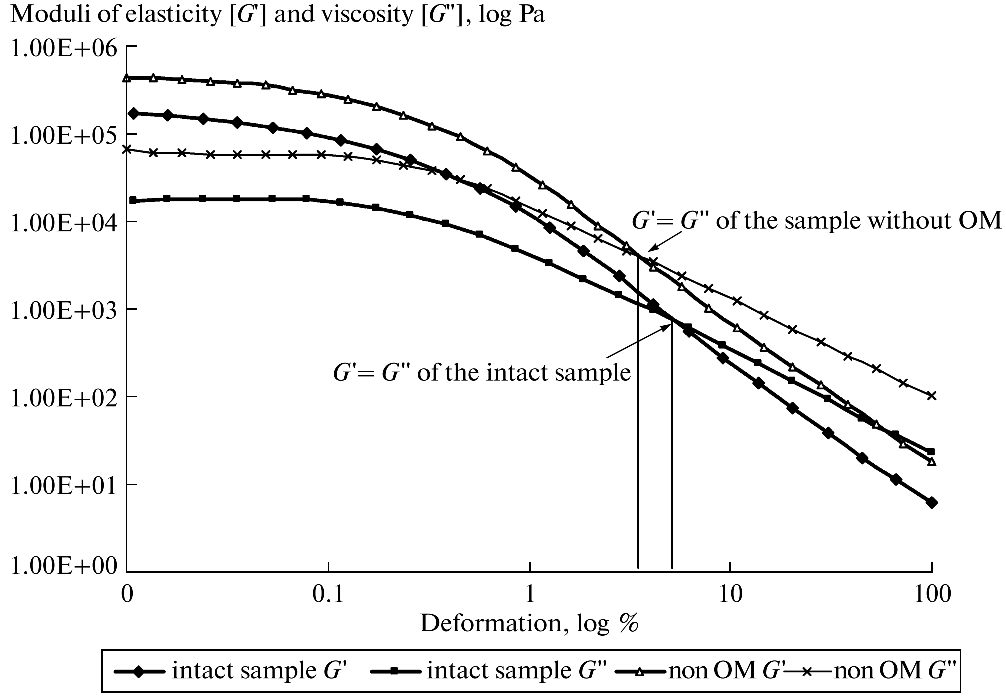

Fig. 1. The moduli of elasticity (*G*') and viscosity (*G*'') versus chernozem deformation before and after OM removal.

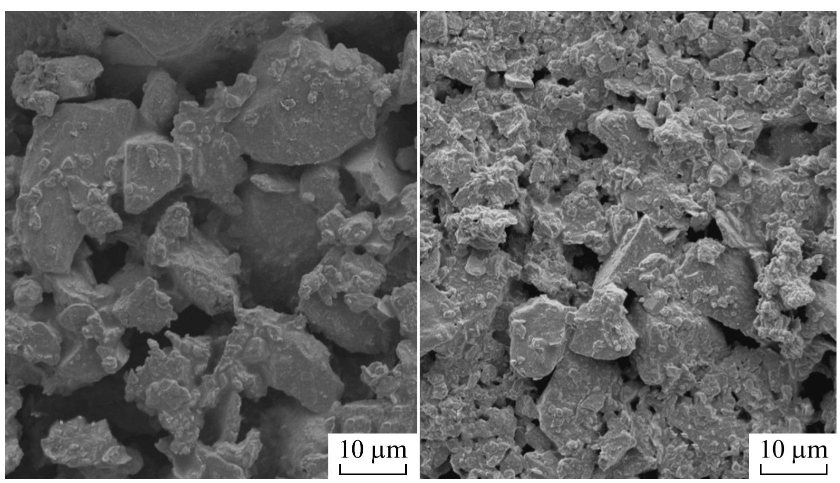

Fig. 2. Electron micrographs of the intact chernozem (the left part) and chernozem after OM removal (the right part).

taining soil structure leads to a removal of a portion of the organic mineral gels from the sites where soil particles interact to secure the uniform system.

If the humic matrix forms the basis of soil gels and support the gel strength, as well as the entire soil structure, the pattern described above should be characteristic of only the OM-containing soil samples. Small mineral particles are not expected to be displaced during structural disruption in the soil samples without OM.

This suggestion was verified using electron microscopic examination of the OM-deprived chernozem samples before and after disruption of soil structure by a mechanical impact (Fig. 4, the left and right parts, respectively).

The micrographs of chernozem that contains no OM were obtained before and after sample rotation to compare the states of intact and disrupted structures, respectively. It has been found out that sample rotation leads to a particle orientation. However, unlike the OM-containing chernozem, rotation caused no release of the organic mineral gels or small particles in the samples with removed OM.

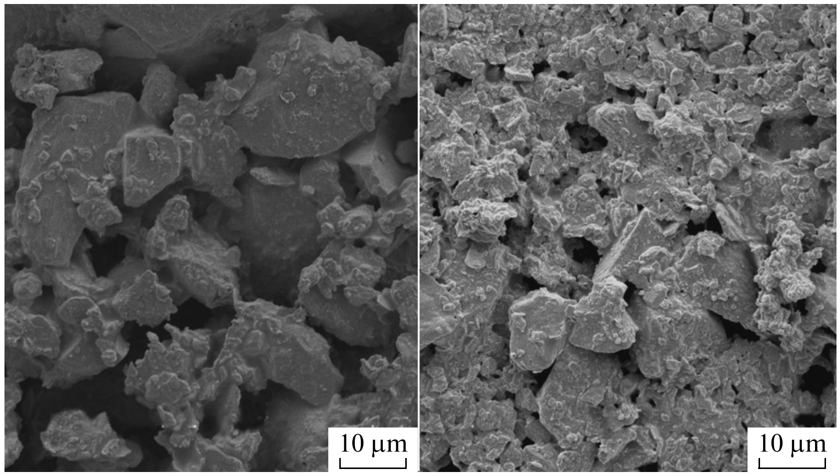

Fig. 3. Electron micrographs of the intact chernozem with unaffected structure (the left part) and chernozem with disrupted structure (the right part).

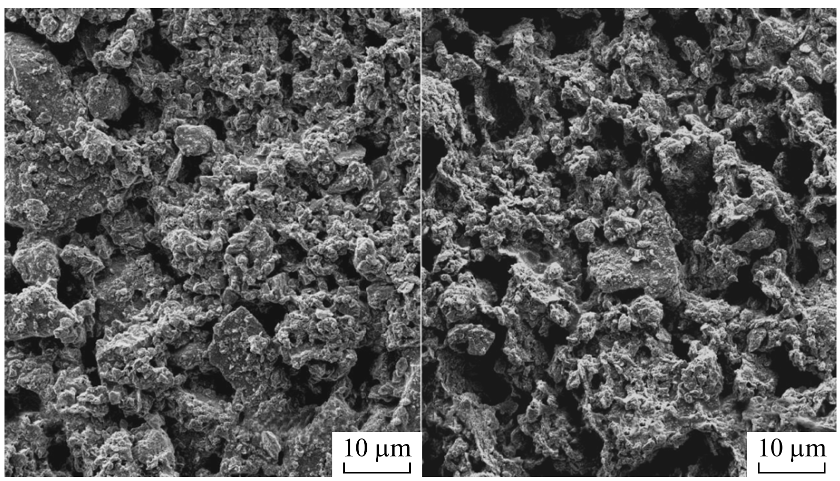

Fig. 4. Electron micrographs of chernozem after OM removal: with unaffected structure (the left part) and with disrupted structure (the right part).

Our data suggest that the number of direct contacts between the mineral particles increases after OM removal from soil samples. This leads to a higher structural strength and a loss of elasticity, which is usually supported due to the humic gels that cover and bind soil particles.

All these changes can be considered on a model of two porous sintered plates that are pressed to each other and rotate relative to each other. If the mineral particles in a large amount of the grease are placed between these plates, then, during rotation, the lubricant will be squeezed out to pass through the porous plates onto their outer surface. A small amount of the lubricant enters the pores between particles rather than passes through the plates. In the absence of abundant lubrication, the structural strength enhances, while the elasticity decreases.

Thus, our data confirm that the soil gels on the basis of humic substances are covering and binding together the soil particles and therefore, soil gels represent the main factor that determines formation of the soil structure.

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