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Rheological properties of different minerals and clay soils

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Abstract

Rheological properties of kaolinite, montmorillonite, ferralitic soil of the humid subtropics (Norfolk island, southwest of Oceania), alluvial clay soil of arid subtropics (Konya province, Turkey) and carbonate loess loam of Russian forest-steppe zone were determined. A parallel plate rheometer MCR-302 (Anton Paar, Austria) was used in order to conduct amplitude sweep test. Rheological properties allow to assess quantitatively structural bonds and estimate structural resistance to a mechanical impact. Measurements were carried out on samples previously pounded and capillary humidified during 24 hours. In the amplitude sweep method an analyzed sample was placed between two plates. The upper plate makes oscillating motions with gradually extending amplitude. Software of the device allows to receive several rheological parameters such as elastic modulus (G', Pa), viscosity modulus (G", Pa), linear viscoelasticity range (G'>>G"), and point of destruction of structure at which the elastic modulus becomes equal to the viscosity modulus (G'=G"- crossover). It was found out that in the elastic behavior at G '>> G " strength of structural links of kaolinite, alluvial clay soil and loess loam constituted one order of 10^5 Pa. Montmorillonit had a minimum strength - 10^4 Pa and ferrallitic soil of Norfolk island [has] - a maximum one -10^6 Pa. At the same time montmorillonite and ferralitic soil were characterized by the greatest plasticity. Destruction of their structure (G '= G") took place only in the cases when strain was reaching 11-12%. Destraction of the kaolinite structure happened at 5% of deformation and of the alluvial clay soil and loess loam - at 4.5%.

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Introduction

Solid phase of soil - is a polydisperse and polycomponent organomineral system consisting of primary and secondary products of mineral soil - secondary clay minerals, plant residues, their partial decomposition products, humus, salts and oxides (Gummatov and Pachepsky, 1991). It is known that structural characteristics and rheological properties of soils are correlated with the content of the soil solid phase elements of solid phase of soil: clay mineral composition, organic matter, salts, etc (Sokolov, 1973). Numerous studies (Khaydapova et al., 2013; Milanovskiy, 2009; Shein and Milanovskii, 2003; Markgraf et al., 2006) showed that the organic matter played the main role in the formation of the resistance of the soil structure to mechanical and water stresses. Clay minerals represent the most active part of a solid phase of soils to various interactions. Kaolinites and montmorillonites represent two groups of the most widespread minerals. These minerals differ from each other by lattice structure and respectively physical and rheological properties. Related to kaolinite group minerals have monolayer lattice with rigid interlayer connections and small interplanar spacing equal to 7.1Å. Montmorillonites are characterized by three layer lattice with movable connections between them and a wide interplanar spacing equal to 17.6 Å what allows

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these minerals to absorb a lot of water and other substances and to expand (Gorbunov, 1974). Therefore a dominance of this or that minerals in soil causes different physical and rheological behavior of soils. In this paper we have tried to evaluate the rheological properties of individual minerals - kaolinite, montmorillonite - and clay soils with a very low content of organic matter.

Material and Methods

The main objects of this study were minerals kaolinite Dutch and montmorillonite (bentonite clay, Turkmenistan, Oglandy), calcareous loess loam of a forest-steppe zone (Kursk region, Russia), agricultural alluvial calcareous soils (Calcic Fluvisols Oxyaquic, WRB, 2006) of the arid subtropical climate Konya Province (Çumra area, Turkie), and ferrallitic soil of the humid subtropics (island Norfolk, southwest of Oceania) (Ferrasols, WRB, 2006). The ferrasols of the humid subtropical climate were characterized by a high content of organic matter (OM). In order to neutralize the influence of OM agents on physical properties of the soils soil samples were treated by hydrogen peroxide which removed OM from them. For all soil samples particle size distribution, total carbon content, total surface area were determined: particle size distribution - by laser diffraction particle size on ANALYSETTE-22 (Germany), previously samples were dispersed ultrasonically (450-500 J • ml-1) with a Branson Sonifier250 (Branson, CT, USA) for 5 min, total carbon content - by analyzer AN-7529, the total surface area – by low-temperature nitrogen adsorption. Table 1 presents data of the humidity, content of organic matter (OM), total surface area and particle size distribution in the samples.

Table1. Soil properties

Objects	Depth, cm	Humidity, %	Total C content, %	Total surface area, S m²/g	Contents, (%/µm) <2	2-5	5-10	10-50	50-250	250-1250
Kaolinit		86.82	-	16,89	26,02	46,39	23,96	3,63	0,00	0,00
Montmorillonite		156.64	-	46,69	16,33	36,20	22,73	24,74	0,00	0,00
Fluvisols	10-20	75.26	1,00	78,17	41,18	21,66	16,65	16,22	1,57	2,72
Loess loam	140-150	57.58	0,51	23,27	18,91	20,61	14,69	45,40	0,35	0,04
Ferrasols	10-20	89.25	0,06	67,63	52,60	34,98	11,48	0,94	0,00	0,00

Mineralogical composition of the objects.

Mineralogical composition of the alluvial clay soil of the Konya Province (Çumra area, Turkey) was as follows: illite (59%), kaolinite and chloritic (30%). For humid subtropical ferrallitic soils the kaolinite content was predominant (Loze and Mate, 1998; Milanovskiy, 2009). Calcareous loess loam Kursk region contained minerals of montmorillonite-hydromica group with a predominance of montmorillonite (Gorbunov, 1974).

Kaolin is a clay mineral of 1:1 lattice type with steady interlayer distance of 0.7 nm and not extending lattice. Montmorillonite is a clay mineral of 2:1 lattice type with variable interlayers distance - from 1.0 to 1.75 nm (the mineral possesses an extending lattice). Illites is a clay mineral of 2:1 lattice type with not extending lattice (Gorbunov, 1974). Due to the different structure of the lattice the specific surface areas of these minerals determined by nitrogen adsorption at low temperature were different –16.9 m² / g – for kaolin, and 46 m² / g – for montmorillonite (Table 1). As a result the water absorption was different too: kaolin humidity 87% and montmorillonite one - at 157%.

Rheological measurements.

The study of rheological behavior of soil pastes was carried out on a modular rheometer MCR302 (Anton Paar, Austria) using a measuring system plate-plate PP25 by amplitude sweep test. Amplitude sweep tests were conducted in order to obtain information on the behavior of substrate and especialy its elastic part, the range of linear viscoelasticity marked as the area between the points of the parallel running curves elastic modulus G 'and the viscous modulus G " and their transition – crossover or deformation limit (γL). The elastic modulus in behavior of substance prevails to a deformation limit, after it the viscosity modulus of behavior of substance prevails (Mezger, 2011; Markgraf et al., 2006). For carrying out amplitude sweep tests the following parameters were chosen: a plate distance -2-3 mm, a rest period before the measurement - 15 s, deformation as logarithmic range from 0.001 to 100%, the frequency was set at a constant value of 0.5 Hz. During all tests a constant temperature of 20 °C regulated by a Peltier unit was given. Sample preparation: 3 g air-dry soil was placed in a small cylinder with a mesh bottom and filter paper, then it was lightly compacted and placed for a day on capillary saturation. After that the humidified sample was accurately moved on the bottom plate of a rheometer.

Results and Discussion

The ferrasols and fluvisols contain the greatest number of particles of the size <2 mkm (Figure 1). The montmorillonite differs from the kaolinite by the larger content of particles of the size 10-50 mkm. The loess loam is characterized by the greatest maintenance of particles of 10-50 microns in size. According to USDA classification system the kaolinit, the montmorillonit, and the loess loam can be characterized as silt loam, fluvisols – as silty clay, and ferrasols – as clay. Figure 2 shows the curves of the elastic modulus and viscosity modulus of kaolin and montmorillonite.

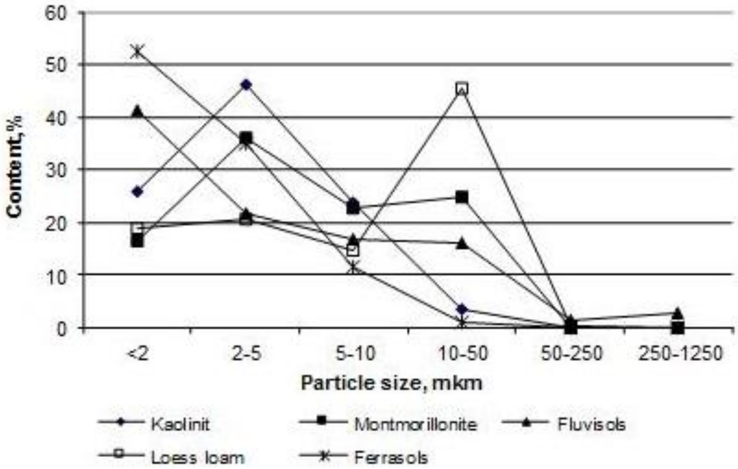

Figure 1. The texture of the investigated samples

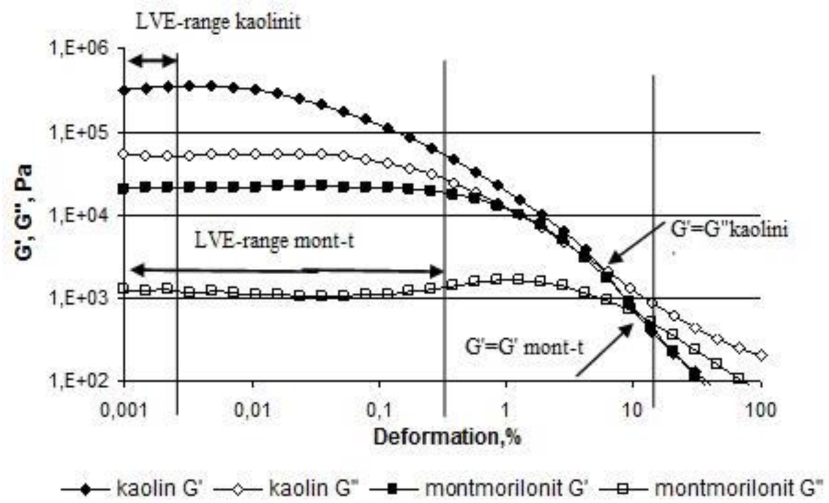

Figure 2. Amplitude sweep test of clay minerals: G' - elastic modulus, G" - viscosity modulus, LVE-range –linear viscoelastic range; G'=G" - crossover

The elastic modulus of the kaolin is close to those of the rest and makes up 10^5 Pa. Elastic modulus of montmorrilinite is much less - 10^4 Pa. The linear viscosity-elasticity range (LVE-range) of the kaolin extends to 0.01% of deformation, while of the montmorillonite - up to 0.5%. The crossover of elastic modulus G' and viscous modulus G" or deformation limit (γL) for the kaolin occurs at 5.35% of deformation, and for the montmorillonite - at 11,4%. Apparently the kaolin forms more stronger interparticle connections than the montmorillonite. Due to its stronger connections under load the kaolin quickly loses its elastic properties, destruction of its structure happens at 5.35% of deformation. The montmorrilonit with its weaker interparticle couplings possesses more plastic properties than the kaolinite, destruction of its structure occurs at larger values of deformation, namely at 11,4%. In comparison with the montmorillonite the behavior of the kaolin is characterized as friable: its stronger interparticle bonds collapse at smaller loadings. Plastic behavior of the montmorillonite allows it to maintain larger loadings, than kaolinite. Probably the more plastic behavior of the montmorrilonite is explained by a three-layer structure of lattice with mobile bonds which allows the mineral to swell, expand, and exhibit plastic properties.

Figure 3. shows the curves of the elastic modulus and viscosity modulus of the kaolinite, ferrasols and fluvisols.

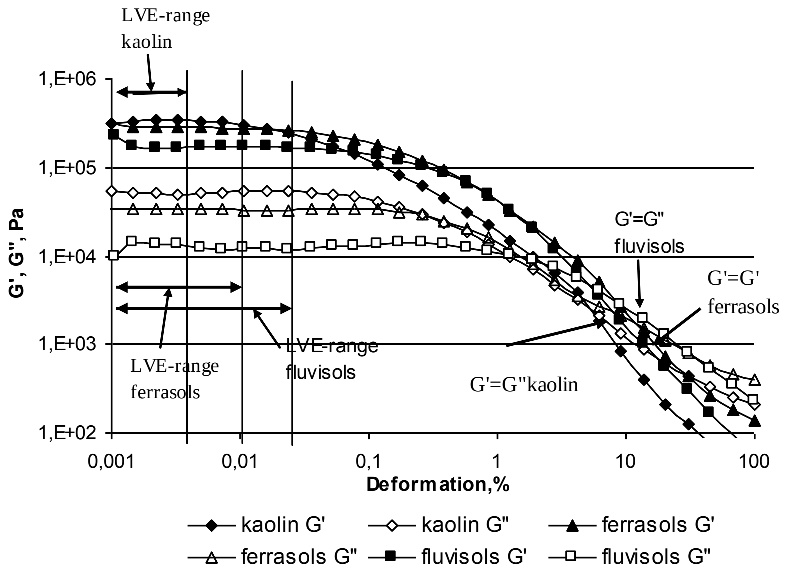

Figure 3. Amplitude sweep test of the kaolin, ferrasols and fluvisols: G' - elastic modulus, G" - viscosity modulus, LVE-range –linear viscoelastic range; G'=G" - crossover.

Kaolinite and non swelling minerals predominate in the mineralogical composition of these soils. As can be seen from the figure the compared curves lie very close to each other. The only difference is a larger value of the LVE-range in the case of the fluvisol. The ferrasols have greater plasticity, their crossover happens at 12% of deformation. This is probably due to their more fine texture.

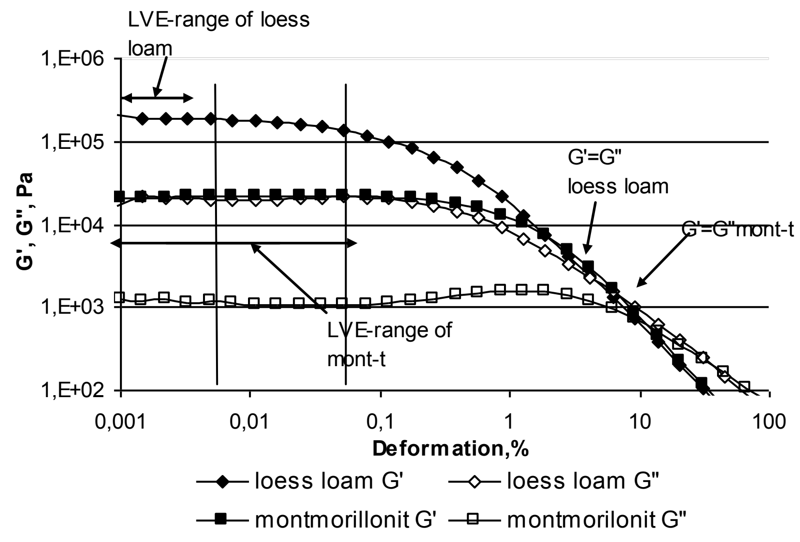

Figure 4. Amplitude sweep test of the loess loam and montmorrilonit: G' - elastic modulus, G" - viscosity modulus, LVE-range –linear viscoelastic range, G'=G" crossover.

Figure 4 shows the curves of the elastic modulus, viscosity modulus of the loess loam and montmorrilonit. As can be seen from the fig.4 the curves differ from each other. The loess loam elastic modulus considerably exceeds a montmorillonite elastic modulus at loading of the close to zero. But LVE-range of the loess loam is much less than that of the montmorillonite. Possibly it is linked with the high content of the silt fraction (10-50 mkm) and the lower content of the fine fractions (<2 mkm) in the loess loam that reduces elastic properties of the loess loam soil. The deformation limit (G'=G") of the loess loam structure happens at 4,35% deformation, but in the case of the montmorrilonit its occurs at 11,4 % deformation. Despite the high content of the montmorillonite in clay minerals composition of the loess loam his behavior differs from the behavior of the clear mineral.

Conclusion

- Thus, the soils in which the kaolinite and the nonswelling minerals prevail in the solid phase are characterized by rigid structural bonds and fragile behavior under loading, the soils which contain the montmorillonite or the swelling minerals among clay minerals are characterized by weak structural bonds and plastic behavior under loading.
- At the beginning of experiment elasticity modules in the studied pastes settle down in the following decreasing row: ferrasols > kaolinite > fluvisols> loess loam > montmorillonite. Such distribution of strength is probably connected with the mineralogical composition. The kaolinite, ferrasol, and fluvisol, which mainly consist of kaolinite and nonswelling minerals, form strong structural bond. The loess loam contain montmorillonite which causes weakening of the interparticle bonds.
- The fluvisols are characterized by the greatest resistance to external loading, its LVE-range is the largest among all studied samples and exceeds them approximately by 3 times.
- The deformation limits (G'=G") of the studied samples are distributed as follows: ferrasols> montmorrilonit> kaolin> fluvisol> loess loam.

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