The Relationship of Rheological Parameters and Erodibility of Soils

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Abstract: Aggregation, texture, organic matter content and permeability are the major factors controlling the soil's inherent susceptibility to erosion. Rheological measurements of concentrated suspensions can provide information on particle-particle interaction, the colloidal stability and structure of suspensions. Field samples from the experimental farm of Szent Istvan University (Hungary), and model samples of artificial complexes were investigated. Beside general laboratory analyses (soil organic matter content, $CaCO_3$ content, CEC), rheology was applied to investigate the microaggregate stability of the samples. The thixotropic low curve character and the evaluation of pseudoplastic flow curves indicated close relationships between strength and stability of the physical network and the composition of the particles. The stability and resilience of the aggregate structure was significantly higher in the presence of $CaCO_3$. Clay content and the amount and composition of organic matter also had an effect on attractive energy and separation distance between particles.

Rheology proved to be a useful tool to investigate the influence of changing soil properties (such as soil organic matter content, $CaCO_3$ content, CEC) on aggregate stability. Separation of particles is a key process in erosion. We suggest that quantitative rheological parameters should be included in the methods used to predict erodibility for erosion models.
Keywords: erodibility, rheology, aggregate stability, Hungary

1 Introduction and objectives

Hungary is located in the Carpathian basin. A huge portion of our agricultural soils developed on calcareous loess, a favorable parent material for formation of fertile soils. Historically chernozems have been considered very good soils in their natural conditions. Most of the loess derived Chernozem soils of Hungary have been cultivated for several centuries, however observing and monitoring soil quality is a recent activity there as in most countries. Unfortunately, almost the entire area of Chernozems in the country have experienced erosion and/or structural degradation. The objective of the paper is to report the relationship of rheological measurements to other measures of soil properties related to erodibility.

2 Experimental materials and methodology

Study area and samples: Samples were collected from the experimental farm of Szent Istvan University, Hungary located on the "North Plain Alluvial Fan", a small geographical area of the "North Hungarian Hills". Soils of the farm developed mainly on Pleistocene calcareous loess, and represent Calcic Chernozems, according to WRB (FAO, 1998) and Calciustolls, according to Soil Taxonomy (Soil Survey Staff, 1996), with different histories of erosion and structural degradation. Laboratory data of two representative profiles are given in Table 1 and Table 2. Table 1 gives the laboratory data for a representative profile in a plateau position with a very deep, dark, A horizon. The ploughed layer does not show the ideal "once upon a time" Chernozem crumble, but an angular blocky structure that is compacted and hard when dry. Table 2. gives the laboratory data for a representative profile in a middle slope position on an interfluve surface. The A horizon is truncated. Its structure is platy on top and strong prismatic in the lower part. It is very compacted and hard, roots penetrate only between ped surfaces of the prisms (Fig.1.). The samples from this horizon are indicated as "degraded A" in the figures and the following text. Samples from the A horizon of the plateau profile were used and indicated as reference “non degraded A” in the figures and the following text. In addition to natural soil samples, model samples were studied to determine the influence of added Ca salt and clay. The compositions of the model preparations are in Tables 3 and 4.

Table 1 Laboratory data of representative profile in plateau position

Genetic layer	Depth (cm)	pH H_2O	SOM (%)	$CaCO_3$ (%)	CEC (cmol/kg)	B %	% Sand 2—0.05 mm	% Clay <0.002 mm	Texture FAO	BD (g • cm^{-3})
Ap	0—40	6.1	2.9	0.0	29	59	37	36	CL	1.4
A	40—60	6.9	2.6	0.0	27	60	36	37	CL	1.3
B	60—90	7.1	0.9	0.0	19	92	37	33	CL	1.3
Ck	90—130	8.1	0.4	26.0	14	100	41	34	CL	1.2

Table 2 Laboratory data of representative profile in middle slope position

Genetic layer	Depth (cm)	pH H_2O	SOM (%)	$CaCO_3$ (%)	CEC (cmol/kg)	B %	% Sand 2—0.05 mm	% Clay <0.002 mm	Texture FAO	BD (g • cm^{-}
Ap	0—40	6.1	2.6	0	28	58	34	32	CL	1.5
B	40—70	6.9	1.6	0	30	60	35	37	CL	1.3
Ck	70—120	7.1	0.5	16	18	92	34	31.9	CL	1.3

Table 3 Data of model samples used for studying the influence Ca^{++} on rheological properties

Sample	pH (H_2O)	SOM(%)	$CaCO_3$ (%)	CEC (cmol/kg)	% Clay<0.002 mm
	7.1	4.19	0	38	38

Ca^{++} added: 0, 0.25, 0.5, 1, 2 mM/liter suspension

Table 4 Data of model samples used for studying the influence of clay on rheological properties

Sample	Diameter	CEC (cmol/kg)	SOM%
sand	0,2—2 mm	2,9	0,3
montmorillonite	1μm	79,6	0
2% montmorillonite + sand	nd	9,2	nd
5% montmorillonite + sand	nd	15	nd
10 % montmorillonite +sand	nd	17,1	nd

nd-not determined

Fig. 1 Compacted, strong prismatic, A horizon of the truncated, structurally degraded Chernozem soil in the middle slope position

Laboratory methods: Air-dried soil samples were ground to pass a 2 mm sieve before chemical analyses. Soil organic matter (SOM) content of the soil samples was measured by the Walkly and Black procedure (Nelson and Sommers, 1982). The cation exchange capacities of the bulk soil samples were measured by the modified Melich method ($BaCl_2$) (Buzas, 1988). Particle size distribution was determined by the pipette method (Klute *et al.*, 1986). $CaCO_3$ content was determined by the Scheibler volumetric method (Buzas, 1988).

Rheological study: Concentrated suspensions of soil and model samples were investigated by rheological methods using the Haake Rotovisco RV20, CV100 apparatus and Rheometer RS150 device over the shear rate range 0 to 100 1/s at $25\pm0.1^{o}C$. Thixotropic hysteresis loops were obtained by measuring the non-equilibrium shear stress in CR (controlled rate) ramp measurements as the shear rate was first increased (up curves) then decreased (down curves) in a standard way. The evaluation of pseudoplastic flow curves was done according to the classical Bingham model ($\tau = \tau_B + \eta_{pl}\, d\gamma/dt$, where τ is the shear stress, τ_B is the yield value, η_{pl} is the plastic viscosity and $d\gamma/dt$ is the shear rate). This results in a yield value (τ_B) by extrapolation of the linear part of the flow curve back to zero shear rate. (Barnes *et al.*,1989, Tombacz *et al.*,1990). This rheological parameter is related to the strength of the physical network built up from particles.

3 Results

The flow curves of samples from the degraded Calciustoll are given in Fig.2. The general feature of the curves are typical for moderately adhesive systems, sensitive to deformation (Barnes *et al.*,1989). The curves maxima represent the highest shear stress that the soil particle network can tolerate. The strength of the particle network is characterized by the area of the thixotropic loop between the up and down curves.

The flow curves of the four horizons show great differences. The up curve of the non degraded A horizon with relatively high organic matter content gave high yield stress suggesting that strength between particles could tolerate the shear at low shear rates. However, the bounding between the particles seems to break suddenly at higher shear rates and practically no recovery of the particle network appears during the measurement. The behavior of the sample from the degraded A horizon with very compacted structure was obviously different even though the chemical composition is very similar to the non-degraded sample. The characteristics of the up curve indicate decreased strengths of bounding between particles. The sudden breakdown and no recovery is similar to the non-degraded A horizon. The rheological behavior of the B horizon gave similar curves to the degraded A above it(similar yield stress, sudden breakdown at similar shear rate, no recovery). The particle network of the C horizon showed less tolerance to shear stress. The breakdown is less but starts at lower shear rate. No recovery of the aggregation was observed in this horizon either. Recovery was expected, because of the high $CaCO_3$ content of the sample. The secondary $CaCO_3$ crystals may coat the aggregates modifying the aggregation characteristics. This influence is different from the case when Ca ions are in adsorbed form on the colloid surfaces.

The simple influence of Ca ion concentration was studied on model samples by increasing the amount of Ca^{++} added to a non calcareous soil sample. Results are given in Figure 3. The original sample shows shear thinning rheological character. The samples with increasing amounts of Ca^{++} added show increasing strength in particle network. The evaluation of pseudoplastic flow curves according to the classical Bingham model results in yield value (τ_B) by extrapolation of the linear part of the flow curve back to zero shear rate (Barnes *et al.*,1989, Tombacz *et al.*,1990). This rheological parameter bears a relation to the strength of physical network built up from particles. The energy required to separate particles can be calculated from Bingham yield value for well-defined particle network (shape, size and spatial arrangement of particles need to be known) assuming a relevant model (Firth&Hunter, 1976). Soil suspensions are heterogeneous mixtures of multiparticulate solid phase. The data needed for this calculation are not defined for soil particles even in model suspensions. However, the appearance of an increasing trend of definite yield values indicates the strengthening of soil structure due to the Ca-bond formation in aggregates.

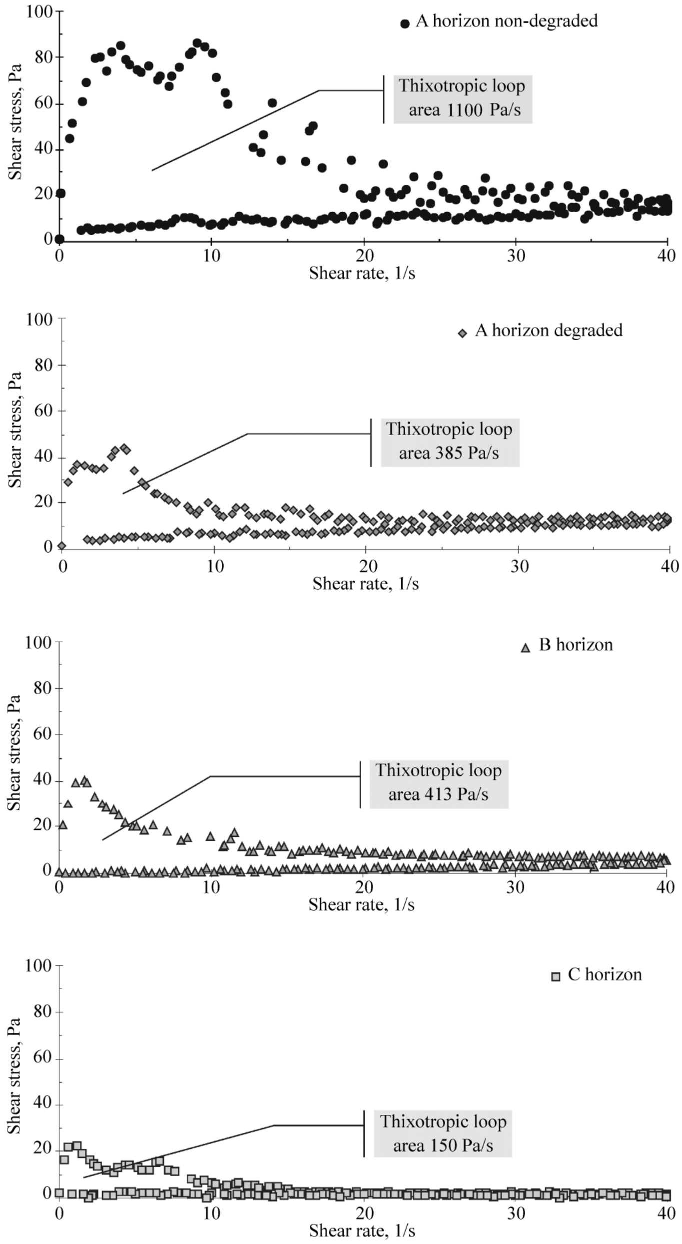

Fig. 2 Flow curves of samples from the horizons of the degraded Calciustoll (Concentration of the suspension 64—66 g/100g)

A similar hardening of structure forming in the suspensions of sand-clay model mixtures can be observed in Fig. 4. Small amounts of montmorillonite increased the bonding strength between particles. Besides the higher tolerance of the initial shear stress (up curve) an important observation is that particle network developed by the addition of the clay can recover during the measurement since down curves run higher and higher as clay content increases.

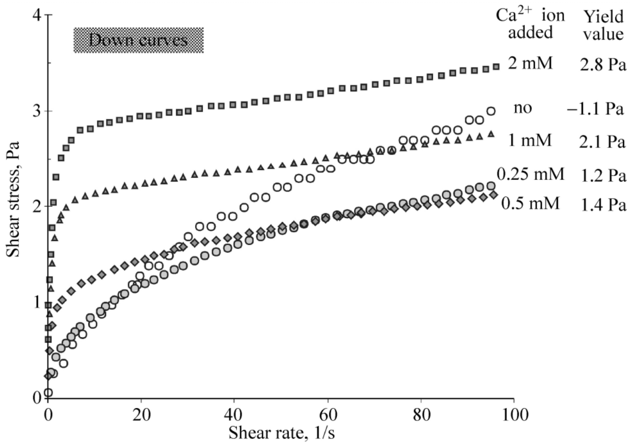

Fig. 3 Flow curves of model samples with added Ca^{++} (Concentration of the suspension 38g/100g)

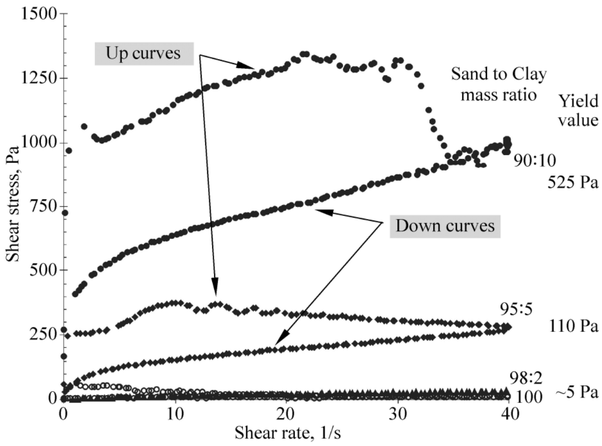

Fig. 4 Flow curves of model samples with added clay. (Concentration of the suspension 52—79g/100g)

4 Conclusions

Rheology proved to be a useful tool to investigate the influence of soil properties (such as soil organic matter content, $CaCO_3$ content, clay content) on aggregate stability. The rheological parameters have direct relation to attractive energy and separation distance between particles. Soil organic matter is believed to be important in the development of favorable structure. In addition to the influence of chemical and physical attractions the genesis of particle network and good structure is related to biological environment of the soil. Our experience is that most cultivated Chernozems that originally had good structure are degraded in the ploughed layer and are subject to erosion. Our rheological measurements support the observation that aggregation that is determined by organic matter is very sensitive to disturbance. The rheological investigations indicated no recovery of the broken particle network during the measurement. Circumstances and the time factor are different in field conditions. However observations in agricultural environments is similar, the degraded aggregation of the Chernozem soils indicate no recovery under cultivated conditions. In soils where clays and oxides are the major binding agents dramatic degradation of the ploughed layer is seldom observed. Rheology studies of model samples with increasing clay content supported the hypothesis that clay is strengthening the particle-particle attraction. It was also noted that the broken particle network can partially recover after the stress is relieved.

The experiments with the model samples with added Ca^{++} also indicated increasing strength of the particle network with the addition of Ca^{++} . The results of our measurements suggest that rheological parameters have close relationships with soil properties that are controlling factors in the susceptibility to erosion. Extended studies are planned to investigate the usefulness of quantitative rheological parameters in estimating erodibility for use in erosion prediction models.

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