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Surface shear resistance of soils on the micro- to mesoscale

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A b s t r a c t. The effect of soil matric potential, bulk density and organic carbon content on soil shear strength in sandy soils was determined. Relatively new method was applied for measuring surface shear resistance, where sandpaper was adapted as a shear media between soil and vertical load, within top 2 mm of soil. Mohr circles were used to determine shear strength parameters: angle of friction and adhesion. Soil shear resistance increased with increasing content of organic carbon. Air dry state of soil samples resulted in the smallest resistance to shearing in comparison with the range of water content applied. The effect of bulk density on soil shear strength depended on water content and was distinct for higher range of vertical loads.

K e y w o r d s: surface shear resistance, shear strength parameters, shear test device, soil matric potential

INTRODUCTION

Shear strength of a soil is often considered as the best soil property in predicting critical shear stress which must be exceeded before soil particles begin to move (Leonard and Richard, 2004). Relationships between mechanical soil resistance expressed by shear strength and different soil erosion incidents like: rill formation (Knapen *et al*., 2006; Torri *et al*., 1987a; 1987b), sheet flow (Luk and Hamilton, 1986) or splash erosion (Kuhn *et al*., 2003; Nearing and Bradford, 1985) were described by many scientists. Referring to Leonard and Richard (2004) it is important to link the shear strength of a soil to some of its measurable properties *eg* organic matter content, bulk density or texture which further could be linked with agricultural practices applied and soil type. It is furthermore essential to also relate the scale and the size of the soil samples to the resolution needed to obtain an appropriate answer.

Soil strength, especially in sandy soils, is often at first approximated by bulk density (Horn and Baumgartl, 2002) and water content (Dexter, 1988). It decreases with decreasing bulk density and increasing water content as a result of changes in proportions between water-filled and air-filled pores. It is known that the strength required to deform soil also depends on the grain size distribution, content of organic matter and pore water pressure (Horn *et al.*, 1995). Higher menisci forces due to decreasing matric water potential result in increased cohesion what may increase bulk density and shear strength (Baumgartl and Horn, 1991). Stability of soil (as described by the ability to retain its structural form despite external forces) is positively correlated with organic carbon content (Kay *et al.*, 1994; Rachman *et al*., 2003). In sandy soils devoided of colloidal clay particles, humus works as a cementing substance improving soil structure, increasing specific surface area and sorption of cations. Increased content of organic matter and in particular of carbohydrates, lignin subunits, and fatty acids increases mechanical soil parameters such as angle of internal friction and cohesion (Horn and Baumgartl, 2002). These two parameters are therefore responsible for shear strength of a particular soil and can be derived by the Mohr-Coulomb equation from the Mohr circles (Pisarczyk, 2005).

Many different shear test devices were applied for measuring the shear strength, including direct shear apparatus, shear vane or cone penetrometers. Some of them can be used in laboratory only, others directly in field. However, as suggested Zhang *et al.* (2001) they do not measure shear resistance at a soil surface and consequently cannot sufficiently explain erosion processes. Collis-George *et al.* (1993) at first proposed a resin plate method for measuring

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strength close to soil surface. This method is easy, inexpensive, quick and the results are reproducible. However, the determination of the shear plane included some difficulties. Additionally an influence of the tension upon the results was noticed because tension cracks appeared. The next attempt to measure surface shear strength was made by Zhang *et al.* (2001). This method is easy to apply, cheap, but based on the applied small vertical stresses. Its sensitivity is a major benefit especially for very thin layer strength measurements. It only requires a box covered with sandpaper at the bottom as a shear media between soil and applied load which will be added in the box. The authors achieved statistically significant, repetitive results, while they investigated shear stress as affected by bulk density and water content of soil. It seems necessary to check further capabilities of the device for searching the influence of organic carbon content or soil structure on shearing.

Regarding the facts mentioned above, the aim of this study was to investigate surface shearing resistance of bulk soil using the specific shear device proposed by Zhang *et al.* (2001), in order to determine the influence of water content, soil matric potential, organic carbon content, bulk density and soil structure upon surface shear resistance of soils from two fields prone to wind erosion.

MATERIALS AND METHODS

The samples were obtained from two different fields in Goldelund, situated 25 km SW from Flensburg and 25 km NE from Husum in the Niedere Geest NW Germany. The first field (GM) is located 1.5 km NW, the second site (GS) is located 0.7 km SE from Goldelund village. Both fields are used for forage maize monocropping for dairy cow husbandry with application of conventional tilllage. Between April and May the fields are ploughed, harrowed and maize is sown. Harvests are carried on at the turn of September and October, followed by a winter fallow. Soil stability is a decisive factor for the reduction of *eg* wind erosion risk in the Sandergeest of Schleswig-Holstein. With Podzol as a dominating soil type and a sandy texture the topsoil is characterized by a high erodibility. Topsoil stability is mainly determined by soil organic matter, soil moisture content and matric potential. Regarding the criteria: texture (medium sized fine sand), management (conventional ploughing) and crop species (maize) the site can be referred to as vulnerable towards wind erosion, especially during dry springs and erosive winds from E to NE direction. Main properties of soil materials are shown in Table 1. The GM was characterized as Gleyic Podzol soil type, with 0° slope and 5 m a.s.l. The GS was identified as Stagnic Cambisol, with 1° slope, situated 15 m a.s.l.

For the measurements disturbed GS soil material and both undisturbed and disturbed GM material were used. Undisturbed soil cores of GM were obtained from topsoil layer (2-5 cm depth) and from subsoil layer (depth of 55-58 cm) in steel cylinders (10 cm diameter, 3 cm height), while disturbed soil material was collected in buckets from both sampled horizons of GM and from one GS horizon (Table 1).

The soil samples, after saturation, were dehydrated at different suctions from the range: 30 to 500 hPa (equal to the soil matric potential from -30 to -500 hPa, respectively) as shown in Table 2. Dehydration at pore water pressures of -30 hPa and -60 hPa was carried out on especially prepared sand beds for 5 and 10 days, respectively. Dehydration at -150 hPa (3 weeks), -300 hPa (about 3-4 weeks) and -500 hPa (4 weeks) was carried on ceramic plates. The air dry samples, used for the measurements in the shear device, were prepared by drying in an oven at 40°C for 48 h. The samples of field water content did not require preparation. After collection they were kept, in air-tight plastic bags to preserve their properties and then, after 2-7 days, were taken for the measurements in the shear device.

In order to compare soil with different bulk densities the disturbed samples with a defined: small (1.20 g cm^{-3}) and higher (1.40 g cm^{-3}) bulk densities were prepared and dehydrated to -30 and -300 hPa. Detailed specification of the samples is shown in Table 2.

For the measurement of surface shear resistance a shear device described by Zhang *et al.* (2001) was used with a few modifications (Fig. 1). On the bottom face of the plastic box (for adding vertical load on soil sample) of diameter of 6.8 cm a piece of sandpaper (grain size 80) was stuck with stiffening glue to simulate the interlocks between aggregates or particles within top 2 mm of the soil. It was used as a shear medium.

Vertical stress was applied at five levels: 2, 5, 8, 10, and 20 hPa. To achieve the desired values of normal stress on the soil surface, loads were imposed, approximated adequately by 0.075 for 2, 0.187 for 5, 0.299 for 8, 0.373 for 10 and 0.746 kg for 20 hPa. Horizontal force was applied through a loop of string over two chain wheels by adding water into

T a b l e 1. General characteristic of the investigated soil horizons

Field name	Horizon	Depth (cm)	Grain size distribution (%, dia in mm)		$C_{org.}$ (%)
			<0.002	0.002-2	
GM	Aep	0-35	1	99	7.2
	Go-Bs	55-65	1	99	1.2
GS	rAp	0-32	8	92	2.4

T a b l e 2. Outline of the measurements

Type of soil material	GM topsoil		GM subsoil		GS topsoil
Undisturbed	-30 -60 -150 -300 -500 air dry field moist		-30 -300		
Disturbed	dB_1 -30 -300	dB_2 -30 -300	dB_1 -30 -300	dB_2 -30 -300	dB_1 -30

dB_1, dB_2 – bulk densities of 1.2 and 1.4 g cm^{-3}, respectively; -30÷-500 hPa – soil matric potential.

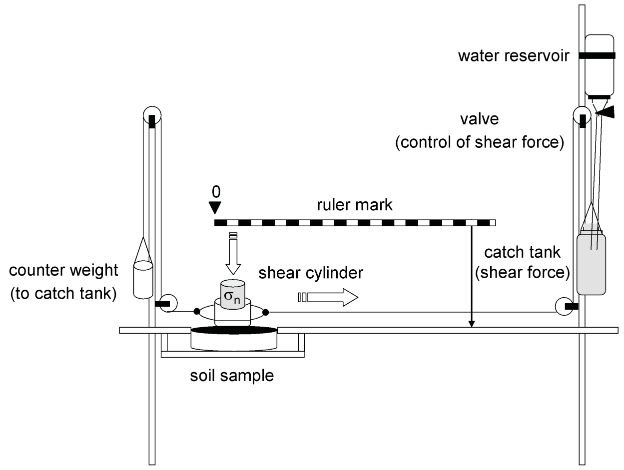


Fig. 1. Schematic representation of shear device (σ_n – normal stress applied to the soil surface).

a bottle, which was connected with the loop. Flow of water was 140 g min^{-1} in order to slowly increase the load under a given constant shear rate. When the shear box moved at least 10 mm, water valve was closed to stop water supply and water in the bottle was weighed. Additionally, the time of movement was measured. The shear stress, under the applied vertical load, was calculated from the weight of water divided by the area of the shear box. Three replicates for one vertical load were used to determine the shear stress in each type of soil cores using separate samples. The same sample could not be used twice for the measurement, because of irreversible damage of the sample structure, caused by shearing. To calculate the shear strength, a modified Mohr-Coulomb equation was applied:

$$\tau = c_a + \sigma_n \tan \varphi, \qquad (1)$$

where: τ – soil shear strength (hPa), c_a – adhesion between sandpaper and soil (hPa), σ_n – normal stress applied on the soil surface (hPa), φ – surface angle of internal friction (°).

Statistical analysis of the results was done using confidence tests by the one way analysis of variance ANOVA. The means were compared by the ANOVA LSD.

RESULTS

The determination of the shear strength as a function of matric potential, bulk density, and soil structure defined as undisturbed or homogenized reveals, especially under very small normal stresses applied, an interesting behaviour, which also shows the applicability of the very sensitive apparatus for surface shear analysis.

The complete dataset of undisturbed GM topsoil is summed up in Table 3. Water content and bulk density of these samples represents Table 4. Shear stress was well related to the applied normal stress in each type of samples, with coefficient of linearity not lower then 0.98. It can be seen that a decrease in matric potential does not result in a significant change in the shear stress while an increase in normal stress results in higher shear stress values (Fig. 2) (data about significance not shown). With increasing stress applied (20 hPa) a slight decline in the shear stress occurs with decreasing matric potential. Air dried samples were least of all resistant to almost every load (Table 4). These samples had always the smallest values of shear stress, which ranged from 9.98 hPa under 2 hPa of vertical stress to 27.03 hPa under vertical stress of 20 hPa. In subsoil material at two matric potentials: -30 and -300 hPa, influence of water content on shear stress differed with applied vertical stress. For vertical loads 5, 10, and 20 hPa, the values of shear stress were higher for matric potential equal to -30 hPa, while for the applied stresses: 2 and 8 hPa higher values of shear stress were achieved at matric potential -300 hPa (Fig. 3).

T a b l e 3. Shear stress (hPa) of undisturbed GM topsoil material under different vertical stresses (σ) and soil matric potentials, additionally angle of internal friction (φ), coefficients of linearity (R^2) and adhesion (c_a) as a function of matric potential

σ (hPa)	Soil matric potential (hPa)						
	-30	-60	field moist	-150	-300	-500	air dry
2	12.19 (0.68)*	11.37 (0.59)	10.01 (1.00)	11.27 (0.45)	11.26 (0.45)	12.46 (0.77)	9.98 (0.90)
5	15.29 (1.46)	14.58 (0.80)	13.72 (1.18)	14.77 (0.83)	13.14 (0.67)	14.05 (0.19)	13.92 (0.30)
8	17.60 (0.98)	18.29 (1.05)	17.47 (0.89)	17.62 (1.29)	16.89 (1.11)	18.08 (0.25)	16.24 (0.86)
10	18.52 (0.62)	19.06 (1.46)	18.56 (1.05)	18.92 (0.32)	19.47 (1.67)	19.69 (0.83)	17.44 (0.76)
20	30.66 (0.56)	30.92 (1.06)	28.67 (1.70)	29.98 (0.58)	28.69 (1.98)	28.45 (1.53)	27.03 (0.10)
R^2	0.986	0.995	0.994	0.997	0.994	0.993	0.994
φ (°)	45.56	47.19	45.53	45.77	44.82	42.31	42.62
c_a (hPa)	9.68	9.13	8.52	9.27	8.94	10.35	8.64

*sd.

T a b l e 4. Water content and bulk density of undisturbed samples for GM

Soil matric potential (hPa)	Bulk density (g cm^{-3})	Water content (%, vol.)
Topsoil (2-5 cm)		
-30	1.18	36.9
-60	1.20	33.9
-150	1.24	22.8
-300	1.22	22.3
-500	1.25	21.8
air dry	1.16	1.8
field moist	1.26	31.3
Subsoil (55-58 cm)		
-30	1.29	29.3
-300	1.44	18.7

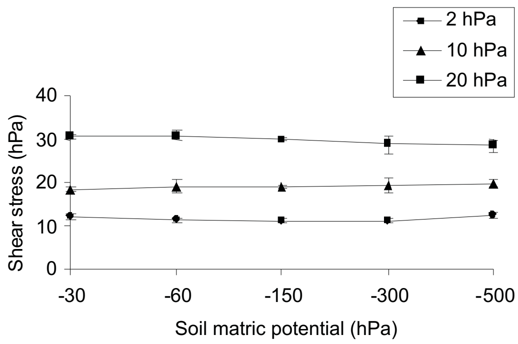


Fig. 2. Shear stress in undisturbed GM topsoil samples for different soil matric potentials and under different vertical loads applied (2, 10, and 20 hPa).

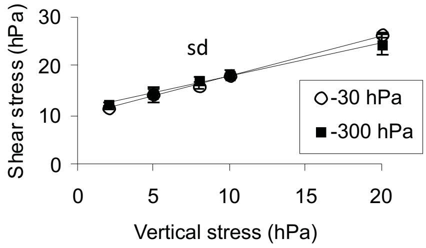


Fig. 3. Shear stress as a function of vertical stress. Undisturbed GM subsoil: predried at -30 hPa (adhesion c_a= 9.83 hPa, angle of internal friction φ=39.29°) and at -300 hPa (c_a= 11.12 hPa, φ= 34.20°); sd – significant difference at p<0.05 between matric potentials.

Comparison between topsoil and subsoil undisturbed material at a given matric potential value showed significantly different shear resistance after dehydration at -30 hPa for vertical loads of 8 and 20 hPa. The topsoil material was more resistant against any kind of deformation than those from the subsoil (Fig. 4). However, the differences in shear resistance are insignificant between subsoil and topsoil material after dehydration at -300 hPa.

For disturbed samples the effect of bulk density on shear resistance could be proofed. Bulk densities and water contents are gathered in Table 5. The significant effect of bulk density on soil shear stress was found for GM topsoil material at matric potential of -30 hPa. Samples with smaller bulk density had higher shear stress at the same normal stress as compared with higher bulk density (Fig. 5a), while these differences are not so clear at -300 hPa (Fig. 5b). The same relationship was found in subsoil (Fig. 6). However, in subsoil the influence of bulk density after dehydration at -300 hPa was clearer but again insignificant (Fig. 6b). At small normal stresses (2, 5, 8 hPa) higher values of shear resistance were found in samples with higher bulk density. But it changed for loads of 10 hPa and 20 hPa where samples with smaller bulk density had higher values of shear stress.

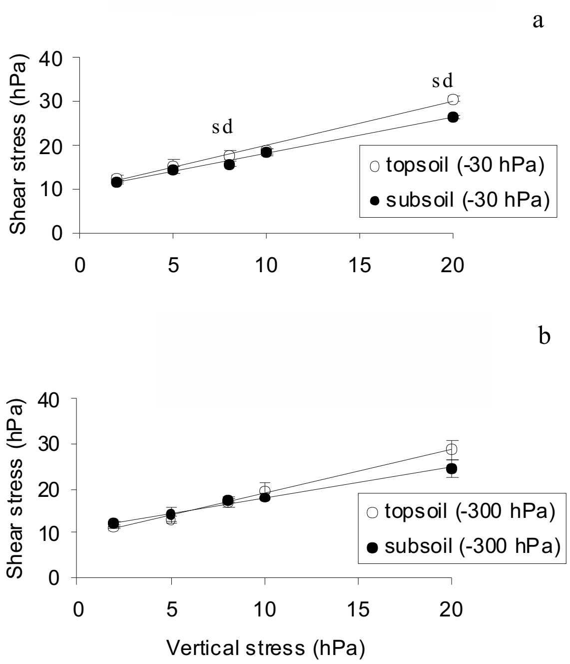
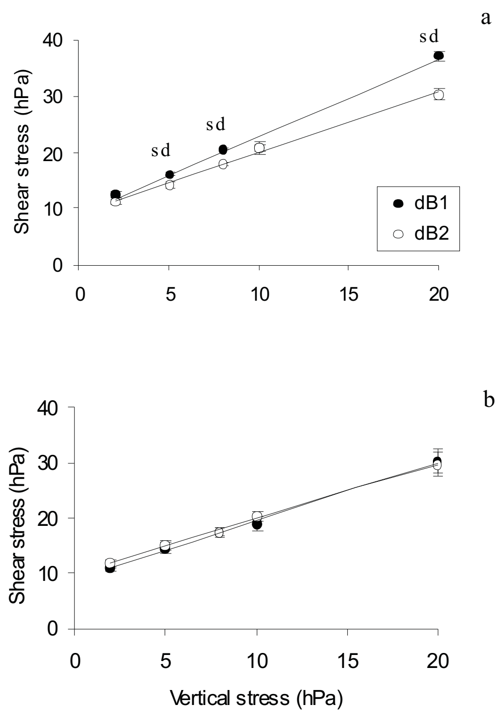


Fig. 4. Shear stress as a function of vertical stress. Comparison of undisturbed GM topsoil and subsoil at the same matric potential: a – -30, b – -300 hPa; sd – significant difference at p<0.05 between topsoil and subsoil.

T a b l e 5. Water content at different soil matric potential and bulk density of disturbed samples

Field	Soil matric potential (hPa)	Bulk density (g cm^{-3})	Water content (%, vol.)
GM topsoil	-30	1.27	35.77
		1.45	35.63
	-300	1.25	24.17
		1.46	25.12
GM subsoil	-30	1.24	32.50
		1.48	24.18
	-300	1.24	18.94
		1.44	17.04
GS topsoil	-30	1.20	32.51



Shear stress as a function of vertical stress for disturbed GM with different bulk densities (dB1≅1.2 g cm^{-3}, dB2≅1.4 g cm^{-3}) atric potential values: a – -30, b – -300 hPa; sd – significant nce at p<0.05 between bulk densities.

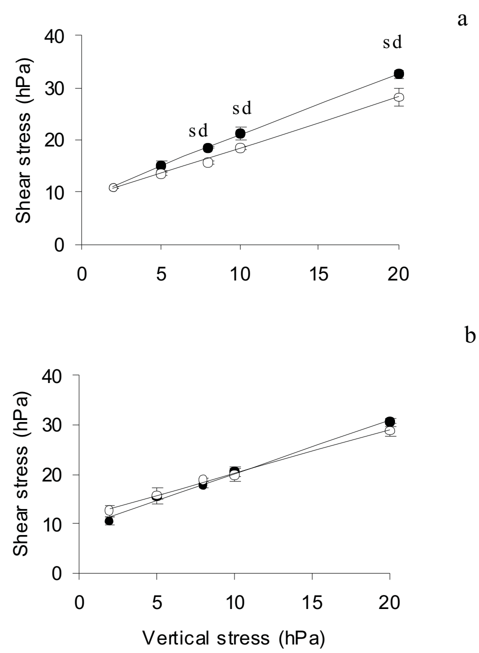


Fig. 6. Shear stress as a function of normal (vertical) stress in GM subsoil with different bulk densities and matric potentials: a – -30, b – -300 hPa. Explanations as in Fig. 5.

Between both sampling sites in Goldelund (GM and GS), there were slight differences in the absolute values of shear strength. However, GS soil material showed smaller resistance to the applied force (not shown).

According to the Mohr-Coulomb failure line theory, the angle of friction and adhesion were calculated. Correlation between angle of friction (φ) and matric potential for the undisturbed topsoil samples is shown in Fig. 7. The values of φ ranged from 42.3 to 47.2°. The highest value had the samples after dehydration at -60 hPa while the smallest at -500 hPa and air dry (42.3 and 42.6°, respectively). In the case of disturbed soil material, samples with higher bulk density had lower values of angle of internal friction at the same matric potential (-30 hPa). However, it was not confirmed in undisturbed soil material, which had the smallest bulk densities and the smallest values of angle of friction, too (Fig. 8a). It is further noteworthy that comparison between GM topsoil, GM subsoil and topsoil from GS at a given bulk density shows that the highest value of the angle of internal friction had GM topsoil while in GS the angle of internal friction achieved the smallest values (Fig. 8a).

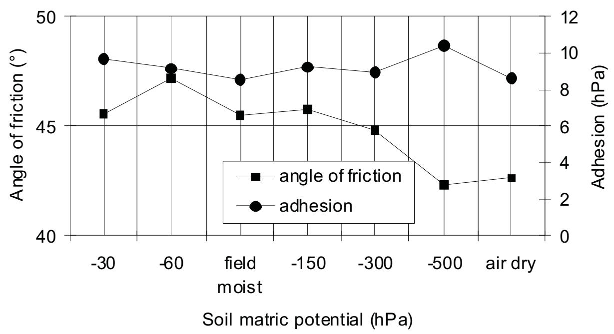


Fig. 7. Correlation between angle of friction and adhesion for undisturbed GM topsoil material at different soil matric potential.

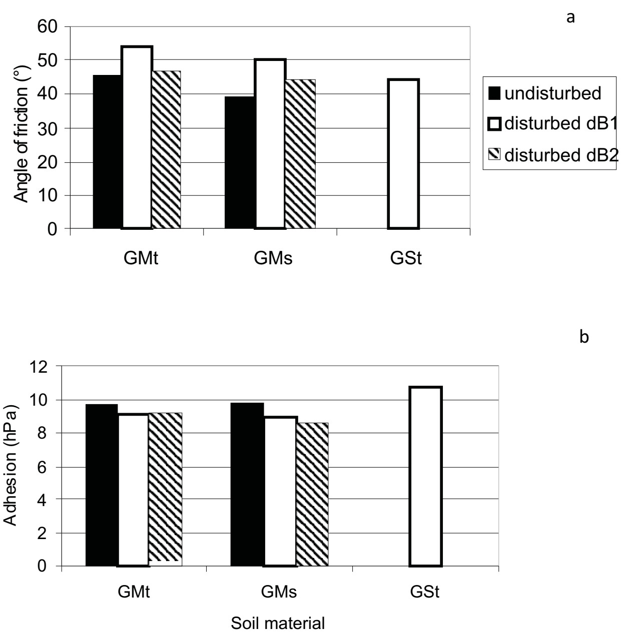


Fig. 8. Angle of internal friction (a) and adhesion (b) in undisturbed and disturbed soil with small (dB1≅1.2 g cm^{-3}) and higher (dB2≅1.4 g cm^{-3}) bulk density, collected from different fields (GMt-GM topsoil; GMs-GM subsoil; GSt-GS topsoil) and at the same matric potential (-30 hPa).

As to adhesion, in undisturbed soil cores its values ranged between 8.52 hPa in field moist samples and 10.35 hPa at a matric potential of -500 hPa (Fig. 7). The samples with higher bulk density had lower adhesion except for GM topsoil where adhesion was slightly higher for higher bulk density at the same matric potential (-30 hPa). Topsoil from GS was characterized by the highest value of adhesion in comparison with GM topsoil and subsoil prepared with similar bulk densities. This correlation is shown in Fig. 8b.

DISCUSSION

Soil shear resistance varies greatly among soil types, soil treatments or climatic factors. It is among others generally higher in soil horizons with increasing aggregation, more negative matric potential, higher organic carbon content, and higher clay content dependently on the clay mineralogical composition. The matric potential and the dissolved organic carbon are the main factors affecting the shear strength, especially in the sandy soils. Often the biological activity results in a 'strong' fixation of single aggregates via extracellular polysaccharide acids (EPS) (Alami *et al.*, 2000), which can be proofed also by the comparison of data for undisturbed and homogenized soil samples.

Rasiah *et al.* (1992), found that clay and organic matter contents explained more than 80% of variability in soil stability which, however, is furthermore varied if the topsoil is compared with the soil layer even below within the first 10 cm depth. Topsoil samples usually had higher shear strength than subsoil ones and that can be related to differences in between organic carbon content which was much higher in topsoil than in subsoil material (Table 1). Le Bissonnais and Arrouays (1997) state that soil erodibility generally increases as organic carbon content decreases. Kay *et al.* (1994) and Rachman *et al.* (2003), confirm that a significant correlation exists between the decline in soil stability and decline in organic carbon content. It can also be proofed by the differences in shear strength in samples from GS and GM. Soil collected from GM was more resistant to applied vertical loads. That was undoubtedly connected with higher organic carbon content, as the grain size distribution was similar. The fact, that the differences were only slight could be attributed to the local variation in the composition of the organic carbon and the binding forces between single particles.

The effect of the water content while determining the influence of organic carbon on shearing resistance needs to be underlined. More clear differences between topsoil and subsoil have always been found in samples subjected to smaller dehydration (comparison between -30 and -300 hPa in GM) irrespective of soil structure (disturbed, undisturbed). Interaction of humus and water might lead to cementation of organic particles and result in increase of soil resistance to shearing.

Soil strength as connected with soil shear resistance is highly sensitive to soil matric potential (Bradford *et al.*, 1992). Without any doubt the initial moisture content greatly influences detachment and transport of particles and erosion what is inseparably connected with shear strength (Govers and Loch, 1993; Le Bissonnais *et al.*, 1994). In our study, water influenced shearing resistance of soil nonlinearly. The smallest moisture content in air dry samples explains their small resistance to shearing. On the other hand, in samples with the highest amount of water: 36.9% (soil matric potential -30 hPa) there was a high number of coarse pores filled with water what could result in a decline of shearing resistance. But the opposite is true: increasing water content increases the pores with water menisci and thus the neutral stresses according to the effective stress equation of Bishop *et al.*(1960). Collis-George *et al.* (1993) using resin plate method found a similar relationship between soil moisture content and shear strength of a soil like it is presented in this paper in the range of suctions 14, 23 and 230 hPa. They investigated homogeneous material and they observed that the shear strength at failure increased as a matric potential became more negative to a peak value and then started to decline. Semmel *et al.* (1990) found that intensive drying of soil decreases its strength because with decreasing water content also the water filled pore area gets smaller and therefore also the component of the neutral stress on the effective stress (Horn and Baumgartl, 1999).

Theoretically soil shear strength should increase with increasing bulk density because of a higher number of contact points between the single particles per volume (Baumgartl and Horn, 1991). However, as it was proofed by our measurements, that the effect of interparticle fixation by organic acids in combination with the matric potential *ie* neutral stress effect exceeded that one of the bulk density. As it was shown by our data, soil samples with smaller bulk density values were more resistant than those with higher values. It is confirmed by the results of Zhang *et al.* (2001) and Rachman *et al.* (2003), who found that soil shear resistance might decrease with increasing bulk density. At a matric potential of -30 hPa (where the coarse pores are still water-filled), soil with a smaller bulk density has larger diameter of capillary between particles which results in a greater portion of the neutral stress on total stress and can therefore also stick particles together. However, at more negative matric potential (-300 hPa) the differences between shear strength at different bulk density values practically did not appear. This can be explained as follows: after dehydration at -300 hPa, only medium and fine pores (diameter < 10 μm) are still water saturated, which also results in a prevented particle movement. Under those conditions the sensitivity of the surface shear device is too small in order to quantify the effect of contact points on soil strength.

It remains an open question how far the grain size of the sandpaper overestimates or vanishes these obtained trends. The selection of the sandpaper coarseness must exceed the coarsest particles in order to fully mobilize the shear resistance between the single particles but does not only slide on top of the thin soil layer. This recommendation is obviously only a rule of thumb, which for more detailed and more intense or frequent measurements can be further specified.

CONCLUSIONS

1. Increase of organic carbon content resulted in an increase of shear strength in the soils.
2. Dehydration of soil results in an increase in soil shear strength up to a peak value, which can be explained by the effect of the neutral stress on the effective stress and which, after exceeding a texture and structure dependent peak value, declines again.
3. Bulk density influenced adhesion and angle of internal friction. However, common effect of matric potential and organic acids exceeded the one of bulk density.
4. The characteristic of sandpaper (size and density of sand) was important, especially when the magnitude of adhesion and angle of internal friction were investigated. The selection of a proper sandpaper to a given soil characteristic should be a point of further studies. Improper sandpaper may cause sliding of shear media over the soil sample and may lead to determination of 'sliding shear stress' which is smaller than the peak stress.
5. The measurement device is sensitive to soil strength parameters, especially in the range of small values of normal stress, what indicates in the microscale the existence of interparticle and/or organo-mineralic bondings.
6. This method of measurement of surface shear resistance can be easily applied for determining the effects of organic carbon content on soil shear strength.

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