

## Characterization of salt- and surfactant-containing sandy soil extracts by laser light methods

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**A b s t r a c t.** The aim of this work was to study how different salt and surfactant solutions influence the particle size distribution and colloidal stability of sandy soil extracts. Particle size distribution was investigated by the laser diffraction method. Extracts were made from the soil – before and after removing its organic content – with solutions of NaCl or CaCl<sub>2</sub> and one cationic and two anionic surfactants. The surfactants influence the particle size distribution of the soil. Due to the use of the NaCl and surfactant mixtures after removal of organic content, the particle sizes increased compared to the extract of the soil. Colloidal stability was investigated by the laser Doppler electrophoresis method resulting in a zeta potential between -5.63 and -23.7 mV, showing that the extracts were rather instable. Static equilibrium experiments with sodium dodecyl sulphate on sandy soil resulted in an L-type of isotherm with three steps, indicating the formation of more surface layers. Comparison of the adsorption isotherm and the measurements of particle size distribution demonstrated that the particle size changes comparably with the formation of the different layers. The zeta potential of the equilibrated solution reached the region of instability and stability when the initial concentration of sodium dodecyl sulphate was near its critical micelle concentration.

**K e y w o r d s:** adsorption, laser diffraction, particle size distribution, soil extract, surfactants

### INTRODUCTION

The particle size distribution (also called grain size distribution or texture) is one of the most important characteristics of soils. Currently, laser diffraction (LD) is increasingly used for particle size distribution (PSD) analysis of sediments and soils. The technique can be very precise and offers advantages of speed and cost over many other methods when used to analyse mixtures of sand, silt,

and clay. There is no standard procedure for determination of soil PSD by the LD method (Arriaga *et al.*, 2006); therefore, data are given in volume percentage. Commonly used methods for determination of PSD (pipette, aerometer *etc.*) are based on Stokes law and results are expressed in mass percentage. LD has the advantage that small samples can be analyzed accurately, which cannot be carried out by the pipette method (Cooper *et al.*, 1984). The LD method is suitable to investigate also soil suspensions and soil extracts prepared by different methods (Ryżak and Bieganowski, 2010; 2011). Laser diffraction equipment can be used for measurement of particle size in a rather wide range (0.01-3000 µm), *ie* also in the colloid region. The stability of colloidal solutions can be studied by measurement of electrokinetic (zeta) potential. The alteration in zeta potential is well in agreement with the alteration in physical stability. Minimum zeta potential greater than |60| mV and greater than |30| mV is required for excellent and good physical stability, respectively (Malvern Instruments, 2007a). Freitas and Müller (1998) have found that a potential around |25| mV is just below the critical value; however, in principle, it can still be sufficient for a stable system in combination with the sterically stabilizing effect. Stability of solution affects the sedimentation, adsorption, aggregation, and transportation of contaminants in soils. Better stability means further transport.

The soil solution is a colloidal system containing inorganic (clay minerals) and organic (humic substances) constituents. Humic substances (HS) are special and important components of natural organic matter (NOM) present

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in soil, water, and other geological deposits. Since HS molecules consist of an elongated hydrophobic portion with more anionic (carboxylate) groups, these compounds have amphiphilic character and therefore they can be considered as natural surfactants (Tombácz *et al.*, 1988; Wandruszka, 2000). This character makes them able to form micelles; however, the critical micelle concentration (cmc) of humic acid was estimated to be as high as 10 g l<sup>-1</sup> (Tschapek and Wasowski, 1984). Humic substances are present in natural waters at lower concentration levels (5–100 mg l<sup>-1</sup>) when aggregates can be formed. These are referred to as *pseudomicelles* having a hydrophobic interior and a more hydrophilic surface. The hydrophobic moiety in the centre of these aggregates leads to enhanced dissolution ('solubilization') of non-polar contaminants like PAH (Földényi *et al.*, 2013; Senesi, 1993; Wandruszka, 2000). This property of HS can be applied under controlled conditions in remediation of contaminated sites (Nègre *et al.*, 2008) while under natural conditions the same process can lead to mobilization of pollutants (Földényi *et al.*, 2013).

Adsorption is the most important process that plays a role in the retention of pollutants in the bulk phase of soil. The composition and properties of the soil solution (pH and the nature of electrolytes) are important factors influencing the sorption of different ions and molecules by soil components (Barrow, 1993; Ertli *et al.*, 2004). The adsorption of ions affects the charge and electrokinetic potential of colloidal particles, hence their dispersion-flocculation behaviour. This can have important consequences on soil structural stability, colloid mobility in soils, and groundwater aquifers, as well as suspended sediment features in surface waters (Kretzschmar *et al.*, 1993; McCarthy and Zachara, 1989).

Since processes of pollutant adsorption play a special role in the field of environmental research, there is an increasing demand for investigations of the effect of different chemicals in soil suspensions (Kovács *et al.*, 2004) and extracts. Adsorption processes have determinative importance for chemicals entering the environment. Materials dissolved or suspended in groundwater can self-influence the PSD of soil and the transport of chemicals (Haque and Freed, 1975; Wilson, 1991).

The role of surface-active agents produced by the chemical industry is to dissolve non- or barely water-soluble materials as well as to form stable emulsion or extract; consequently, this type of compounds is likely to be very harmful to the environment. Surfactants in soil may promote the dissolution of different materials; therefore, the transport of contaminants can be faster. This is the case of formation of agents that keep pesticides in the liquid phase and lead to solubilization of barely water-soluble compounds (Földényi *et al.*, 2013; Senesi, 1993). Surfactants can adsorb on the soil surface in more layers (Czinkota *et al.*, 2002); however, there is a contrary process called peptization (Buscall and Ottewill, 1985), wherein

these compounds disperse the organic matter content of soil and afterward create a stable colloidal solution (Czinkota *et al.*, 2002).

The soil texture and thus the shape of the PSD curve is a very important sign of other soil properties like hydraulic conductivity, adsorption capacity, *etc.* If the curve is gently sloping, the hydraulic conductivity of the investigated formation is lower; however, it is more compactable. If the curve is steep, the soil contains a considerable amount of same-sized particles. This means higher hydraulic conductivity and less compactness. Smaller particles can achieve longer distances than larger particles in the soil solution, while they transport adsorbed contaminants. Even the presence of a small fraction of fine particles influences hydraulic conductivity of some porous formations and the possibility of contaminant transport. PSD data can be used for modelling of transport processes (Kovács *et al.*, 2004). Particle size distribution influences the specific surface area of materials and hence the adsorption capacity of the adsorbent (Bänninger *et al.*, 2006).

Our aim was to study how different salt and surfactant solutions influence the particle size distribution and colloidal stability of soil extracts (obtained after centrifugation and filtration). PSD is usually studied in the absence of soil organic matter, but in this case, natural conditions cannot be modelled. Sandy soil was chosen for our investigations because it contains relatively high amounts of soluble humic substances (mostly fulvic acids) at any pH values.

The influence of the composition of any solution on the PSD of soil extracts has not been studied by other researchers yet; however, it can be very important due to the alteration of various soil properties. Our investigations focused on the role of anionic and cationic surfactants (solutes) in the soil extracts. Three different surface-active materials were selected:

- sodium dodecyl sulphate (SDS), which is used most frequently as a detergent in cosmetics;
- sodium diisopropyl naphthalenesulfonate (Supragil WP), a forming agent in pesticide formulations in agriculture;
- and cetyl trimethyl ammonium bromide (CTAB, also known as Cetrimide), an industrial forming agent.

Sodium dodecyl sulphate, which can be used also for soil remediation (Khalladi *et al.*, 2009), and Supragil WP represent the anionic, while CTAB is the cationic type of surfactants. The structure of surfactants is shown in Fig. 1.

PSDs of the extracts were investigated by the laser diffraction method, which is a special application for the investigation of soil texture and is applicable in a wide range of particle size. Colloidal stability of the extracts was studied by the laser Doppler electrophoresis method measuring the zeta potential.

Since humic substances exhibit similar behaviour to surfactants (Tombácz *et al.*, 1988; Wandruszka, 2000), the investigated compounds and HS can form mixed micelles resulting in alteration of the PSD curve and in the stability

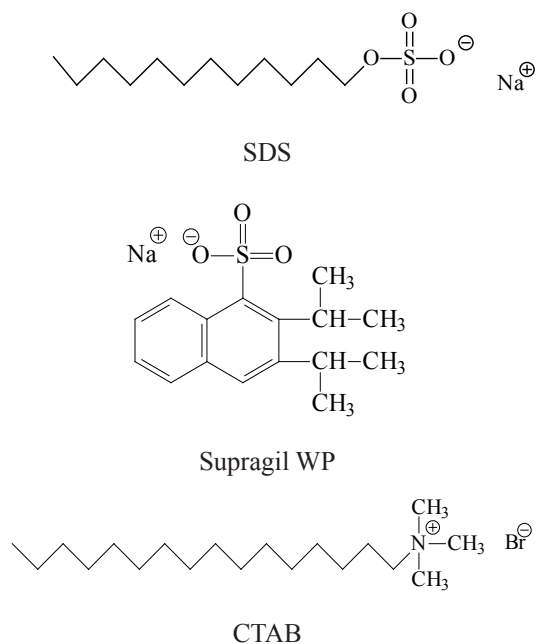


Fig. 1. Structure of the surfactants used.

of the colloidal system. Therefore, we intended to make a detailed comparison between the adsorption isotherm generated on the soil and the PSD of the equilibrated soil extracts. For this aim, the surfactant having the most significant effect on changing the particle size distribution was chosen.

#### MATERIALS AND METHODS

The sandy soil sample was obtained from the upper 30 cm layer of the soil in Dabrony, Hungary. Air-dried samples were prepared by grinding in a ball mill for one hour and then sieving under 0.5 mm particle size. Relevant properties of the studied sandy soil are as follows: specific surface area: 3.85 m<sup>2</sup> g<sup>-1</sup>; pH: 5.88; TOC (total organic carbon content): 16 mg C g<sup>-1</sup> soil; main minerals: 9.9% albite, 3.6% chlorite, 4.8% mica, 3.8% microcline, 55.3% quartz, and 18.2% smectite.

Supragil WP originated from RHODIA Geronazzo (Milan, Italy), while CTAB and SDS were obtained from Reanal Chemical Co. (Budapest, Hungary).

Hydrogen peroxide, CaCl<sub>2</sub>, and NaCl salts were purchased from Reanal Chemical Co. Chloroform (for gas chromatography application) was obtained from Spektrum 3D Ltd (Debrecen, Hungary).

For laser diffraction measurements, different sand extracts were prepared using the following treating solutions in distilled water:

- 0 – distilled water,
- NaCl – 0.1 mol l<sup>-1</sup>,
- CaCl<sub>2</sub> – 0.01 mol l<sup>-1</sup> CaCl<sub>2</sub>,
- Supragil – 0.1 g l<sup>-1</sup> Supragil WP,
- Supragil/NaCl – 0.1 g l<sup>-1</sup> Supragil WP and 0.1 mol l<sup>-1</sup> NaCl,

- CTAB – 0.1 g l<sup>-1</sup> CTAB,
- CTAB/NaCl – 0.1 g l<sup>-1</sup> CTAB in 0.1 mol l<sup>-1</sup> NaCl solution,
- SDS – 0.1 g l<sup>-1</sup> SDS,
- SDS/NaCl – 0.1 g l<sup>-1</sup> SDS in 0.1 mol l<sup>-1</sup> NaCl,
- SDS/CaCl<sub>2</sub> – 0.1 g l<sup>-1</sup> SDS in 0.01 mol l<sup>-1</sup> CaCl<sub>2</sub>.

The soil extracts were prepared as follows:

A extracts: 5 g soil was shaken with 0.05 l of the above-described solutions for 30 min, centrifuged at 1046 g for 30 min with a Hettich Universal 32 centrifuge, and allowed to stay overnight at room temperature. The samples were filtered for coarse particles on filter paper and the extracts were analyzed.

B extracts: Sandy soil was treated with 30 % hydrogen peroxide (until churning of the suspension stopped); then the sample was dried in order to remove the organic content of the soil. The material obtained was suspended in different treating solutions and prepared for LD measurements as described for the A extracts.

The measurements of PSD of the soil extracts were performed by a Mastersizer 2000 (Malvern Instruments) laser diffraction analyser. For measurements, the SM dispersion unit was used: 80-100 ml of distilled water was filled in the unit and stirred at 1 200 r.p.m. After background measurements, the sample extract was given into the unit until the obscuration reached 8-10%. For calculation of the PSD, a refractive index of 1.544 (Silica, Quartz) and an adsorption index of 0 were used (Malvern Instruments, 2007b) for sand, and a refractive index of water *ie* 1.330, was used for the dispersant. The PSDs were characterized by the volume-based frequency curve or by the volume mean diameters (D) of the particles.

The measurements were carried out with three replicates.

The zeta potential of the A and B soil extracts was determined and the extracts made with different concentrations of SDS (0.1-1 000 mg l<sup>-1</sup> solutions for adsorption experiments) were filtered through a 0.45 mm membrane and measured by a ZetaSizer Nano ZS (Malvern) device. Measurements were carried out at 25°C with capillary cuvette and the Smoluchowski equation was used for the calculation (Cieřla *et al.*, 2011). The measurements were carried out with three replicates.

Adsorption of SDS dissolved in the 0.01 mol l<sup>-1</sup> CaCl<sub>2</sub> solution was investigated on sandy soil by static equilibrium experiments at 25°C in triplicate runs. Exactly known amounts of the soil (7 g) were weighed and left to stand in 5 ml 0.01 mol l<sup>-1</sup> CaCl<sub>2</sub> for 24 hours. 65 ml of SDS solution (from 10 to 1 000 mg l<sup>-1</sup>) was added to the suspensions; the flasks were then shaken (150 min<sup>-1</sup>) for one hour and left to stand overnight for equilibration. Equilibrium phases were separated by centrifugation (at 1 046 g for 30 min) and then by filtration.

The concentration of SDS in the supernatant liquid was determined by two-phase titration described elsewhere (Patzkó, 1996). Cationic surface-active agents can be titrated

by anionic surfactants and vice versa. The concentration of SDS was analyzed in a shaking graduated cylinder in the presence of the methylene blue indicator. The samples were titrated by a 0.001 mol l<sup>-1</sup> CTAB solution until methylene blue colour disappeared in the organic (chloroform) phase. The equilibrium concentration was determined by the calibration curve (from 0 to 1000 mg l<sup>-1</sup>) and the specific adsorbed amount ( $q$ , mg SDS g<sup>-1</sup> soil) was calculated by the following equation:

$$q = \frac{(c_0 - c)V}{m}, \quad (1)$$

where:  $V$  is the volume of the equilibrium solution (0.070 l),  $c_0$  is the initial and  $c$  is the equilibrium concentration of the investigated compound (mg l<sup>-1</sup>), and  $m$  is the weighed amount of the air dry soil (g).

The isotherm was fitted by Eq. (2) as suggested by Czinkota *et al.* (2002):

$$q = \sum_{i=1}^s \left\{ \frac{q_{Ti} K_i (c - b_i + |c - b_i|)^{n_i}}{2^{n_i} + K_i (c - b_i + |c - b_i|)^{n_i}} \right\}, \quad (2)$$

where:  $s$  – the number of steps of the isotherm,  $q_{Ti}$  – adsorption capacity,  $K_i$  – equilibrium constant,  $b_i$  – critical concentration limit,  $n_i$  – average degree of association – all assigned to the  $i$ th step of the curve.

The PSD of the equilibrated systems (similar to soil extracts) was also investigated by the laser diffraction method described above. All the measurements were carried out with three replicates.

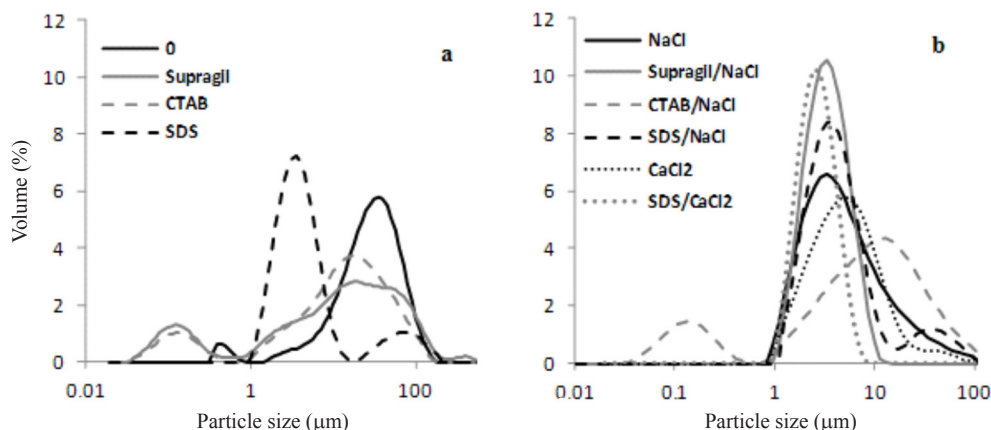
## RESULTS AND DISCUSSION

The laser diffraction method was used for the measurement of PSD of soil extracts. The PSD of the A extracts without salt showed bimodal distributions (Fig. 2a).

Surfactants (Supragil, CTAB and SDS) influenced the PSD; the ratio of particles between 1 and 200  $\mu\text{m}$  decreased in all three cases compared to the simple water

extract (0). Supragil and CTAB showed a similar effect: the gently sloping curve indicated a low percent of very small particles ( $\varnothing \leq 1 \mu\text{m}$ ) but a higher amount of particles occupied the 1-200  $\mu\text{m}$  of the particle size range. The PSD was most significantly shifted to smaller particle sizes in the SDS extract. Addition of surfactants affects the hydraulic conductivity of porous media like soils. The interaction can be very different depending on the surfactant and soil characteristics, the surfactant concentration, and the influence of ionic strength. Allred and Brown (1994) investigated the hydraulic conductivity changes of Daugherty (USA) sand treated with different nonionic, anionic, and cationic type surfactants. They have found that in the case of an anionic surfactant (the concentration of the surfactant was 0.5 mol kg<sup>-1</sup>), eg SDS, the hydraulic conductivity decreased significantly, and the SDS caused a high dispersion ratio of the particles. On the other hand, they found that when two different cationic surfactants were applied, the hydraulic conductivity decreased also significantly but the particle mobility was not affected compared to the untreated soil. Mohamed (2014) investigated the interaction between ethanediyl-1,2-bis (dimethyldodecylammonium chloride) as a cationic surfactant and sandy soil. It was found that, due to a hydraulic conductivity decrease, the mean weight diameter of the soil increased. In the process of mobilization of small particles from soils, the hydraulic conductivity change is very important, but the PSD cannot be predicted when only this parameter is taken into account.

The added solution electrolytes affect also the hydraulic conductivity and, consequently, the dispersion rate and the average size of the investigated soil extracts. In our case, at the 0.1 mol l<sup>-1</sup> concentration of NaCl in the surfactant solutions (NaCl, Supragil/NaCl, CTAB/NaCl and SDS/NaCl), the PSD and the volume mean diameter changed significantly in two cases (NaCl and Supragil/NaCl) compared to samples treated without NaCl. The PSD can be seen in Fig. 2b, and the volume mean diameters ( $D_1$ ) of the soil A extracts are summarized in Table 1. The PSD of



**Fig. 2.** PSD of sandy soil A extracts treated with a surfactant dissolved in: a – water or in 0.1 mol l<sup>-1</sup> NaCl, b – 0.01 mol l<sup>-1</sup> CaCl<sub>2</sub> solutions.

**Table 1.** Volume mean diameters of extracts prepared by different solutions before ( $D_1$ ) and after ( $D_2$ )  $H_2O_2$  treatment of sandy soil

Solution	Extract ( $\mu\text{m}$ )	
	A ( $D_1$ )	B ( $D_2$ )
0	37.44	0.61
NaCl	8.90	3.89
$\text{CaCl}_2$	14.49	63.85
Supragil	31.60	3.84
Supragil/NaCl	3.94	38.14
CTAB	23.10	10.29
CTAB/NaCl	15.87	27.61
SDS	14.43	11.98
SDS/NaCl	9.14	68.10
SDS/ $\text{CaCl}_2$	4.02	82.07

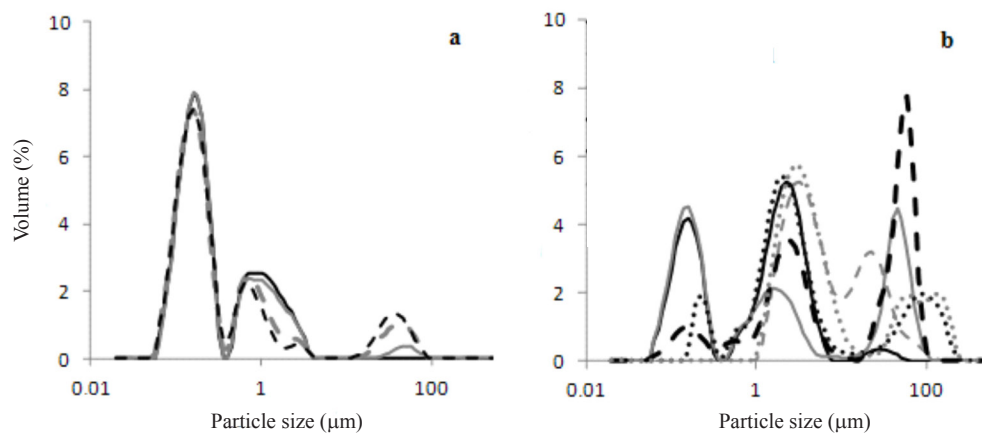
CTAB and CTAB/NaCl as well as SDS and SDS/NaCl is almost the same as when the surfactant dissolved only in water was used for the treatment (*ie* without NaCl). In the case of anionic surfactants (Supragil/NaCl and SDS/NaCl), the average particle size was under  $10 \mu\text{m}$ , similar as for salted water (NaCl). At the  $0.01 \text{ mol l}^{-1}$  concentration of  $\text{CaCl}_2$  for the treatment ( $\text{CaCl}_2$  extract), the PSD obtained is very similar to the NaCl extract with lower shifting to higher particle sizes. At the application of the electrolyte together with SDS (SDS/ $\text{CaCl}_2$ ), a similar effect was observed to that for the Supragil/NaCl and SDS/NaCl extracts *ie* the average size decreased below  $10 \mu\text{m}$ .

The organic materials were removed from the sand before the preparation of the B extracts to investigate the influence of the organic matter on immobilization of soil particles. After removing the organic materials, the

treatment without electrolytes resulted in very similar PSDs of the different extracts (0, Supragil, CTAB, and SDS in Fig. 3a).

When the treatment was carried out in the presence of electrolytes (Fig. 3b), the PSDs changed significantly compared to the A extracts (Fig. 2b). In the case of samples 0, NaCl, Supragil, CTAB and SDS, the particle size ( $D_2$  data in Table 1) was shifted to smaller values after the organic matter was removed. If the treating solutions contained electrolytes and surface-active materials together, an increasing tendency of particle size was observed compared to the particle size of the Supragil/NaCl, CTAB/NaCl, SDS/NaCl, and SDS/ $\text{CaCl}_2$  in the A and B extracts ( $D_1$  and  $D_2$  data in Table 2). Increasing particle size was also found when  $\text{CaCl}_2$  was used alone for the treatment. The increase in particle size was remarkable when anionic surfactants were used (Supragil/NaCl, SDS/NaCl, and SDS/ $\text{CaCl}_2$ ); the values were higher than for the extract with water (0) in the A extract. In the absence of organic matter, the investigated surfactant together with salt promoted the formation of aggregates (flocculation) and not dispersion. The experiments demonstrated that both surfactants and NaCl used separately promote the dispersion of smaller inorganic particles but they can repeal this effect when used together.

Since zeta potential ( $\zeta$ ) gives valuable information about the colloidal stability of the system, the A and B soil extracts were studied in this aspect. It was found that these extracts were mostly unstable (Table 2). The smallest stability was obtained between the A extracts when NaCl was used alone for the preparation of the extract ( $\zeta_1$  data in Table 2). Considering the surfactant-containing samples, it can be seen that, in the presence of electrolytes, the instability of the system is very similar to that of the extract made with pure water (a decreasing tendency can be observed in  $\zeta_1$  data but the standard deviation of the data ranged between 0.99 and 3.80). The rather high ionic strength may cause phase separation in the HS containing system (Tombácz



**Fig. 3.** PSD of sandy soil B extracts treated with a surfactant dissolved in: a – water or in  $0.1 \text{ mol l}^{-1}$  NaCl, b –  $0.01 \text{ mol l}^{-1}$   $\text{CaCl}_2$  solutions. Explanations as in Fig. 2.

**Table 2.** Zeta potential of A and B sandy soil extracts

Solution	Extract ( $\mu\text{m}$ )	
	A ( $\zeta_1$ )*	B ( $\zeta_2$ )*
0	-16.6	-15.9
NaCl	-9.37	-6.2
CaCl <sub>2</sub>	-13.2	-12.3
Supragil	-18.2	-13.4
Supragil/NaCl	-15.4	-8.2
CTAB	-12.2	-11.1
CTAB/NaCl	-11.2	-8.81
SDS	-23.7	-13.6
SDS/NaCl	-16.5	-5.63
SDS/CaCl <sub>2</sub>	-22.7	-6.81

\*Standard deviation.

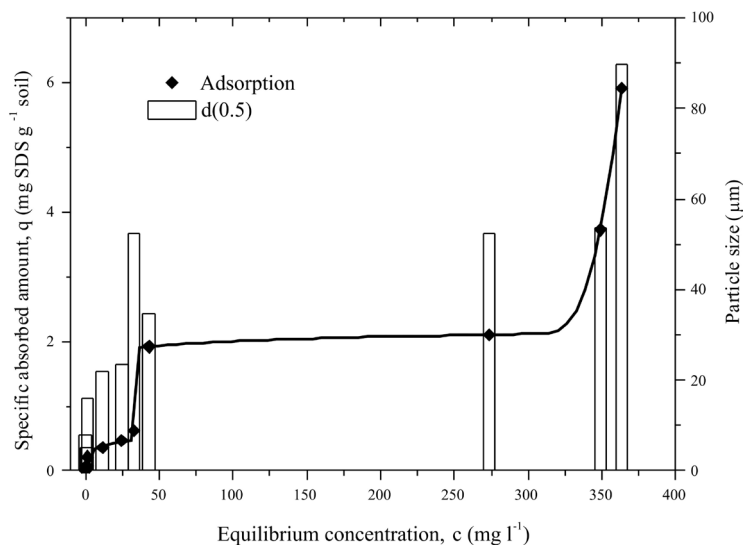
*et al.*, 2001) at the surfactant concentration applied. SDS and the SDS/CaCl<sub>2</sub> extracts resulted in the highest stability compared to the other solutions. In all cases of the B extracts, the zeta potential ( $\zeta_2$  data in Table 2) decreased compared to the A extracts, especially significant changes were observed in the extract containing SDS.

Since the PSD curves of the investigated surfactants indicated that SDS might cause the most significant environmental impact, adsorption studies were carried out with this compound. SDS was dissolved in a 0.01 mol l<sup>-1</sup> CaCl<sub>2</sub> solution and the concentration as well as the PSD was determined in the liquid phase after equilibration with sandy soil (see Materials and methods). In order to clarify

the relationship between the adsorption of the surfactant and the particle sizes measured in the extracts, the results are shown in the same figure (Fig. 4). In Table 3, the initial (applied) and equilibrium (measured) concentration of SDS are described.

The adsorption curve has three steps and, according to the shape of its initial part, it can be classified as a Langmuir type (L-type) of the isotherm indicating that the solute and the water molecules do not compete with each other to the active sites (Giles *et al.*, 1960). This first step can be explained by hydrophobic interaction between the solute and the hydrocarbon (due to HS) as well as siloxane (due to quartz) chains forming hydrophobic binding sites on the surface (Johnston and Tombácz, 2002; Majzik and Tombácz, 2007). According to the work of Czinkota *et al.* (2002), further steps of an isotherm must be the result of associates either formed in the solution and adsorbed afterwards or formed by the molecules adsorbed. In this case, the so-called multilayer adsorption occurs. Since SDS being an anionic surfactant and humic substances having also amphiphilic character are present, the adsorption process needs more detailed discussion where the PSD investigations will be taken also into account (Fig. 4, Table 3).

The specific adsorbed amount ( $q$ ) increased suddenly above a 32 mg l<sup>-1</sup> equilibrium concentration ( $c$ ) when also the particle size became significantly larger. These results were obtained when 100 mg l<sup>-1</sup> ( $c_0$ ) SDS was used for equilibration (Table 3). The critical micelle concentration (CMC) of SDS determined in 0.01 mol l<sup>-1</sup> CaCl<sub>2</sub> (Sebestyén, 2008) is just equal to this particular initial concentration when the second step of the isotherm is started. In this case, not only single molecules but also micelles of the surfactant can be adsorbed on the soil, resulting in more negative charge repelling the dissociated carboxylic groups of HS on the surface. This repulsing effect leads to solubilization



**Fig. 4.** Adsorption isotherm of SDS on sandy soil and d(0.5) mean particle size determined in the equilibrated liquid phase.

**Table 3.** Initial ( $c_0$ , applied) and equilibrium ( $c$ , measured) concentration of SDS during the adsorption experiment

$c_0$	SDS concentration (mg l <sup>-1</sup> )									
	0	10	25	50	75	100	250	500	750	1000
$c$	0	0.72	1.44	11.5	24.5	32.7	42.8	274	349	363

of humic substances that are able to form also micelles; thus, big aggregates can be obtained above the 350 mg l<sup>-1</sup> equilibrium concentration of SDS (when  $c_0$  is above 750 mg l<sup>-1</sup>, Table 3), and the third step of the isotherm is evolving.

The  $\zeta$  of sandy soil extracts obtained with different initial concentrations of SDS solutions are as follows: -20.8 mV (0.1 mg l<sup>-1</sup>); -19.5 mV (1 mg l<sup>-1</sup>); -23.7 mV (100 mg l<sup>-1</sup>); and -46.6 mV (1000 mg l<sup>-1</sup>). Comparison of these results to the PSD measurements (Fig. 4) as well as to the  $\zeta$  values of extracts made by SDS showed that the zeta potential of equilibrated solution reached the limit between instability and stability (-23.7 mV) when the initial concentration was close to CMC (100 mg l<sup>-1</sup>), which proved to be of special value considering the newly formed surface.

In our surfactant-containing system, either homogenous micelles (SDS-SDS, HS-HS) or mixed micelles (SDS-HS) can be formed (Tombácz *et al.*, 1988) due to the solubilization process (Földényi *et al.*, 2013; Senesi, 1993), which is caused here by the anionic surfactant. Mixed micelles are the result of interaction between the hydrophobic moieties of the surfactant and that of HS. These associates also contribute to the increased particle size measured in the equilibrated system during adsorption (Fig. 4). Since the homogenous micelles of a surfactant have higher CMC when also mixed associates can be formed (Nylander *et al.*, 2006), it can be pointed out that the third step of the isotherm starts above this higher value ( $c > 300$  mg l<sup>-1</sup>, Fig. 4).

#### CONCLUSIONS

1. According to the results of particle size distribution measurements of sandy soil extracts, it can be pointed out that the surfactants significantly influenced the particle size distribution.

2. Without electrolytes, peptization of organic material was especially enhanced by sodium dodecyl sulphate, which is used widely as a detergent.

3. The experiments demonstrated that both surfactants and sodium chloride used separately promote the dispersion of smaller inorganic particles but they can repeal this effect when used together.

4. In the absence of organic matter, the investigated surfactant treatment resulted in very similar PSDs when electrolytes were not used.

5. In the absence of organic matter, the investigated surfactant together with the salt promoted the formation of aggregates (flocculation) and not the dispersion.

6. The resulted in adsorption of sodium dodecyl sulphate on sandy soil showed an isotherm curve with three steps and, according to the shape of its initial part. It was classified as a Langmuir type (L-type) of the isotherm.

7. Comparison of the adsorption isotherm and the particle size distribution data for sodium dodecyl sulphate revealed significant changes in the isotherm as well as in the particle size distribution at similar values of initial concentration.

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