Prediction of full-scale dewatering results of sewage sludges by the physical water distribution

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Abstract The dewaterabilty of sewage sludge can be described by the total solids concentration of the sludge cake and the polymer-demand for conditioning. The total solids concentration of the sludge cake depends on the physical water distribution. The various types of water in sewage sludge are mainly distinguished by the type and the intensity of their physical bonding to the solids. In a sewage sludge suspension four different types of water can be distinguished. These are the free water, which is not bound to the particles, the interstitial water, which is bound by capillary forces between the sludge flocs, the surface water, which is bound by adhesive forces and intracellular water. Only the share of free water can be separated during mechanical dewatering. It can be shown, that by thermo-gravimeteric measurement of the free water content, an exact prediction of full-scale dewatering results is possible. By separation of all free water during centrifugation the maximum dewatering result is reached. Polymer conditioning increases the velocity of the sludge water release, but the free water content is not influenced by this process. Furthermore it is not possible, to replace the measuring of the water distribution by other individual parameters such as ignition loss.

Keywords Sewage sludge dewatering; full scale centrifuges; maximum dewatering result; characterisation; polymer conditioning; free water; interstitial water; bound water; moisture content; drying rate; dilatometer

Introduction

Mechanical dewatering reduces the volume and the quantity of sludge that needs to be disposed of or to be treated subsequently. The dewatering result can be described by the total solids concentration of the sludge cake, the amount of conditioning agents and the specific energy consumption.

Achieved total solids concentration of the sludge cake depends on the distribution of water types in the sludge, since only the share of free water can be separated during mechanical dewatering. During conditioning the sludge coagulates because of the addition of cationic polymers for example and the release of water is accelerated. The polymer-demand is basically determined by the anionic surface charge of the sludge particles, the energy consumption depends on the dewatering machine itself and on the performance of the machine.

To predict the dewaterability of a sewage sludge it is necessary to measure the sludge water distribution, the free water content and to determine the polymer-demand. In this paper especially the method to measure the water distribution by thermo-gravimetric measurements will be presented.

The various types of water in sewage sludge are mainly distinguished by the type and the intensity of their physical bonding to the solids. The bonding forces counteract the steam pressure of the water molecules, thus decreasing the steam pressure (Lück, 1964), which means the higher the bonding forces, the lower the steam pressure. To explain this clearly the bonding forces can be understood as an attraction between the sludge particles and the adsorbed water molecules.

In a sewage sludge suspension, four different types of water can be distinguished according to their physical bonding to the sludge particles (see Figure 1). These are :

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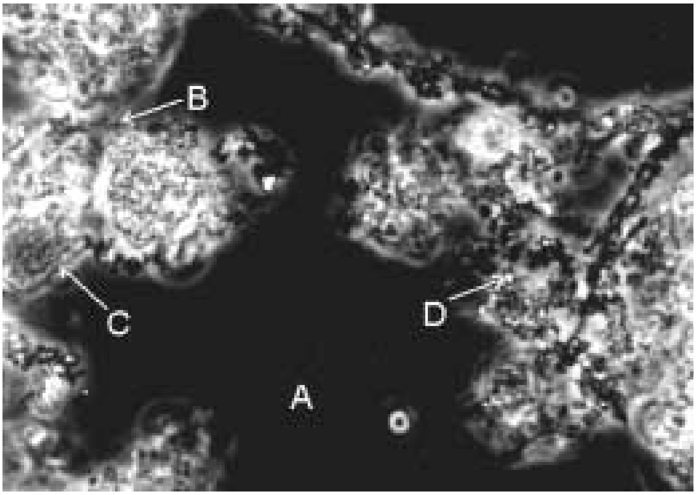

Figure 1 Water distribution in a sewage sludge floc

- free water, which is not bound to the particles
- interstitial water, which is bound by capillary forces between the sludge flocs
- surface water, which is bound by adhesive forces and
- intracellular water

The free water content represents the largest part in sewage sludge. The water moves freely between the individual sludge particles, is not adsorbed by them, not bound to them and is not influenced by capillary forces. This type of water can be separated mechanically, for example by centrifugal forces or filtration.

The interstitial water is kept in the interstice of the sludge particles and micro organisms in the sludge floc. This water is bound physically by active capillary forces.

The surface water covers the entire surface of the sludge particles in several layers of water molecules and is bound by adsorptive and adhesive forces. The surface water is physically bound to the particles and cannot move freely. Water, which is chemically bound in exopolymers, also is considered part of the surface water.

The intracellular water contains the water in cells and water of hydration. Intracellular water can only be determined together with the surface water and is often called bound water content (Smith *et al*., 1995).

Bound water is the smallest water content, has the strongest physical-chemical bonding to the particles and can only be removed thermally. It must be taken into account that the term "bound water" is not clearly defined and differs according to the used method of measuring (Schullert, 1998). In table 1 a survey of literature concerning the method to measure the water distribution and the term "bound water" is given.

Materials and method

For the measuring of water distribution thermo-gravimetric and dilatometric laboratory tests(Jones and Gortner, 1932; Smollen, 1987) are used. At the Technical University of Braunschweig those methods were adjusted and calibrated, so that a direct statement can be made concerning the maximum suspended solid content in the sludge cake after mechanical dewatering in centrifuges(Kopp and Dichtl, 1989a, 1999).

For thermo-gravimetric measurements the sludge sample is dried at constant conditions (air flow, temperature). The water distribution can be derived from the curve of the drying rate in dependence on the moisture content ($mass_{water}/mass_{SS}$) of the sample. In order to

Table 1 Survey of literature to measure the physical distribution of sludge water

Author	Methods	Results [g/gSS] or [%]	Definition of "bound water"
Jones/Gortner, 1932	Dilatometry samples: elastic and non-elastic gels	W_{bound} = 4.70 g/gSS (2% conc. of gel) W_{bound} = 0.70 g/gSS (32% ‘’)	water content, which does not freeze at 0°C
Heukelekian *et al.*, 1956 Katsiris *et al.*, 1987	Dilatometry activated sludge (Indicator: Petroleum)	W_{bound} = 90-380% of volatile solids in dependence of the volume index	Heukelekian *et al.*: water content, which does not freeze at 0°C Katsiris *et al.*: water content, which does not freeze at –20°C
Smith *et al.*, 1995	Dilatometry digested sludges (Indicator: hydraulic oil)	W_{bound} = 2.7 g/gSS (at -18°C, SS=0.28%) W_{bound} = 5.9 g/gSS (at -18°C, SS=1.27%) W_{bound} = 0.5 g/gSS (at -29°C, SS=0.28%) W_{bound} = 5.7 g/gSS (at -29°C, SS=1.27%)	water content, which does not freeze at 0°C
Vesilind *et al.*, 1994	Dilatometry digested sludge (Indicator: hydraulic oil)	W_{bound} = 5.0 ± 0.5 g/gSS	water content, which does not freeze at 0°C
Lee, 1995	Difference kaliometry (DSC), Filtration and Drying of excess sludge	W_{bound} = 6.70 g/gTR (Drying) W_{bound} = 3.85 g/gTR (Filtration)	sum of interstital, surface and intracellular water
Coackley *et al.*, 1957	Drying of different sludges with (15% SS)	<u>raw sludge:</u> free water W = 72-75% surface water W = 48-55% bound water W = 6-12% <u>primary sludge:</u> free water W = 74-76% surface water W = 44-48% bound water W = 7-11% <u>excess sludge:</u> free water W = 72% surface water W = 50% bound water W = 9%	bound water is the intracellular water free water is separated at the first critical drying point surface water is separated at the second critical drying point
Vesilind, 1979	Drying	free water floc water interstitial water bound water (no data)	bound water is the intracellular water
Robinson *et al.*, 1992	Dilatometry digested sludges	W_{bound} = 3.9 ± 0.4 g/gSS	sum of interstital, surface and chemical bound water
Tsang *et al.*, 1990	Drying digested and in dewatered sludges	W_{bound} = 0.2% of first water content of 61.5%	bound water remaines in sludge cake
Sato *et al.*, 1982	Drying alum sludges	W_{bound} = 0.3-1.1 g/gSS (≈16-27 vol.%)	bound water is separated at the second critical drying point
Herwijn *et al.*, 1992	Drying	no data	binding enthaphy >1kJ/kg
Smollen, 1987 1990	Vacuumfiltration, Drying at 30 u. 105°C excess and digested sludges	<u>excess sludge:</u> interstital water: W = 1.6-3.2 g/gSS bound water: W = 2.4-8.3 g/gSS chem. bound water: W = 0.7-1.4 g/gSS <u>digested sludge:</u> interstital water: W = 0.8-7.3 g/gSS bound water: W = 2.6-7.6 g/gSS chem. bound water:W = 0.3-0.9 g/gSS	interstitial water: evapoartes at 30°C bound water: evaporates at 105 °C chem. bound water: does not evaporates by drying
Kopp / Dichtl, 1999	Drying and Dilatometry	data see Table 2	bound water : sum of surface and intracellular water, measuring with dilatometer tests

differentiate the corresponding amounts of water, before drying the sample is thickened in a laboratory beaker centrifuge at 1000 × g for 30 min. The drying procedure must take place very slowly, because otherwise a distinction of the various types of water on the basis of the drying curve is not possible any more because of the high energy input.

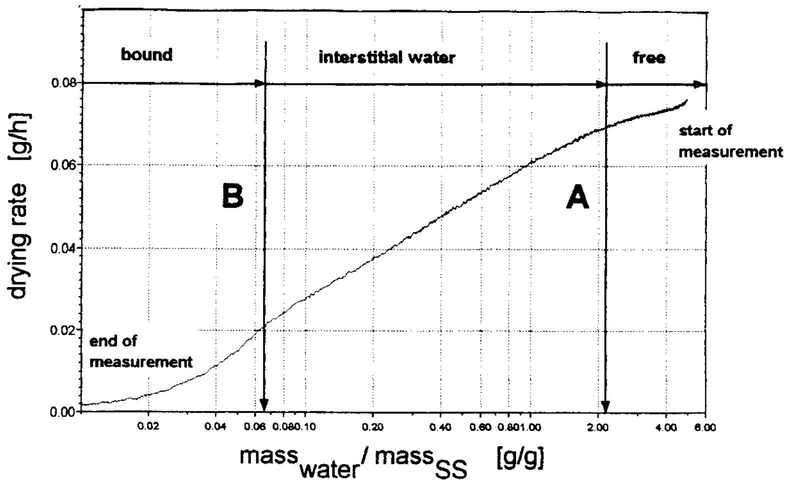

Figure 2 Drying curve of a digested sewage sludge for a logarithmic abscissa

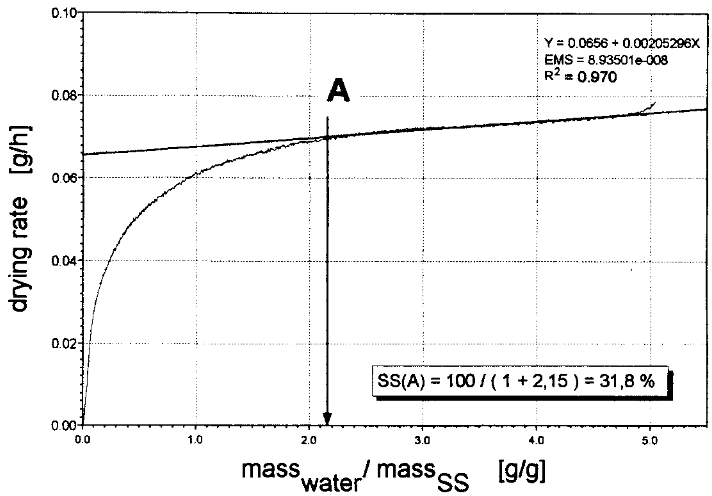

Figure 3 Drying curve of a digested sewage sludge for a arithmetic abscissa

Figure 2 shows the drying curve of a digested sewage sludge sample. Chronologically seen, the drying curve starts at the top right-hand corner with a high moisture content ($mass_{water}$/ $mass_{SS}$) and ends, when all water has dried from the sample. Two critical points A und B can be seen on the drying curve. Point A marks the end of the free water content and point B the end of the interstitial water.

The most interesting fact for mechanical dewatering is the exact determination of the free water content, which means point A of the drying curve. Therefore it is useful, to plot the drying curve with an arithmetic scale (Figure 3). As long as there is free water in the sludge sample, the drying rate is linear. Here the drying rate is described by the weight loss of the sludge for each time unit.

At point A the drying rate decreases, because of the capillary bonding of the interstitial water to the sludge, and the calculated tangent does not describe the curve anymore. The solid content of the sludge (TR_A) can be derived from the moisture content of the sample.

The amount of surface and intracellular water can be determined summarily as bound water content with dilatometric measurements (Vesilind and Martel, 1990). The measuring principle is based on the fact that the bonding forces are so strong, that bound water does not freeze at –25°C. The difference between the volume expansion of the frozen water content and the total water content of the sample determines the bound water content.

If one assumes that the difference between the free water content and the bound water is equivalent to the interstitial water, the water distribution can be determined. During our research work laboratory tests were carried out with digested sludge from various wastewater treatment plants.

The highly cation active polymer Zetag-87 (Allied Colloids) was used for the conditioning of the sewage sludge. Conditioning agent demand was determined in a series of experiments. An optimum polymer dosage is reached, when no electrostatic repulsive forces affect the sludge particles any more and the value of the zetapotential in the centrate lies between –3 and ±0 mV. The zetapotential was measured electrophoretically (Malvern Zetamaster) in the centrate water, which was diluted to a specific electrical conductivity of 0.5 mS/cm. As additional dewatering parameters, particle size distribution, capillary flow time and the surface charge of the sludge were determined. The polymer-demand is basically determined by the anionic surface charge of the sludge particles and the amount of exopolysaccharides (Kopp and Dichtl, 1998b).

Results and discussion

Calibration of the thermogravimetric-measurement

The measurement depends on the two conditions air flow und temperature, so that for an exact evaluation of the free water content, a calibration must take place. Figure 4 shows the dependence on the conditions for the moisture content (A). Temperature has a linear influence on the steam pressure and on the distribution of water. At high air flow the influence on the results decreases. Since the measurings are time-consuming *E. Coli* bacteria were used, because these samples can be reproduced in constant quality.

For the exact determination of the free water content, calibration is inevitable, even if that is very time-consuming. For the calibration of the thermo-gravimetric measuring instrument mono-disperse silica particles were measured. According to the model of Batel (Batel, 1961) and Schubert/Pietsch (Schubert *et al.*, 1967) the interstitial water content and the bound water content can be calculated. The advantage in using mono-disperse particles is, that all variables for the calculation are known. The contact angle of silica comes to 60–70°, at natural bulking a porosity of 40% and a coordination number of 8 can be expected. 0.1 μm was assumed for the strength of the adsortive layer. Figure 5 shows the results of the model calculation and the measured values for five particle sizes. It can be observed that the values agree very well with the more exact model calculation of Schubert/Pietsch.

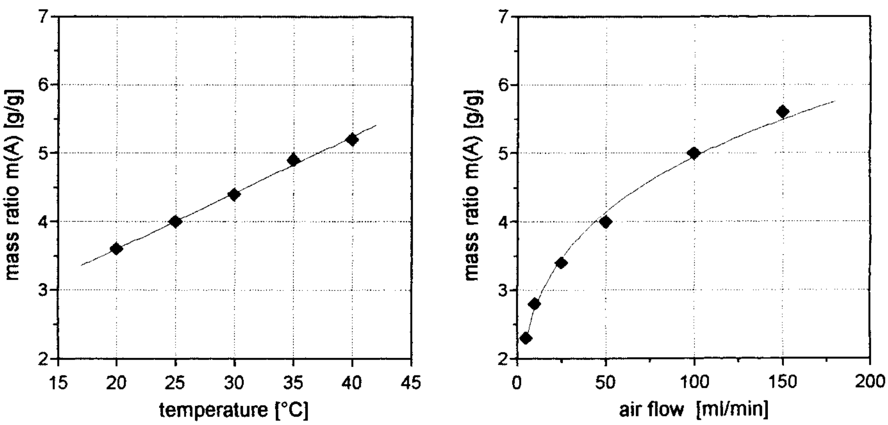

Figure 4 Dependence of the drying curve on laboratory conditions

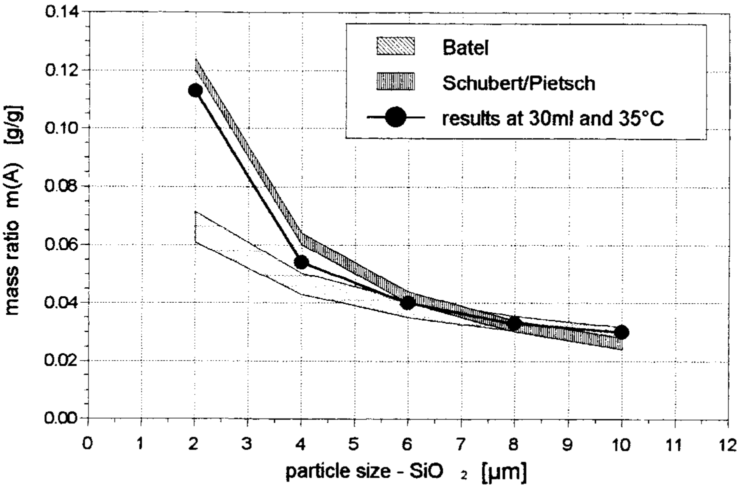

Figure 5 Calibration of the measuring system with the help of standard particles

Table 2 Water distribution for municipal sewage sludge

Sample	SS [%]	VSS [%]	Poly* [g/kg]	SS_A [%]	w_{bound}** [%]	W_{inter}** [%]	W_{free}** [%]
Excess sludge 1	2.46	68	10.0	20.0	0.8	11.6	87.6
Excess sludge 2	1.53	61	2.5	26.3	1.0	7.7	91.3
Primary sludge	3.77	64	4.5	37.0	0.5	4.8	94.7
Raw sludge	3.72	63	6.5	27.8	0.6	7.5	91.9
Digested sludge 1	4.28	55	7.5	25.0	0.7	8.6	90.7
Digested sludge 2	4.59	52	5.8	31.8	0.9	5.7	93.4

*= Polymer-demand for Zetag-87

**= the percentage values are related to 3% SS of the sludge suspensions

Prediction of full-scale dewatering results

Table 2 examplarily presents the water distribution, the polymer-demand, the solids content (SS) and the ignition loss (VSS) of four sewage sludges. According to the state of the art in science and technology only the free water content (w_{free}) can be removed during mechanical dewatering processes. This water content is calculated with thermo-gravimetric measurement instruments. The solids content in the sludge cake, which would exist after removal of the free water content, is derived as a parameter (SS_A). The solid content at point A (SSA) is therefore the maximum solid content in the sludge cake, which can be achieved with mechanical dewatering. The content of interstitial water (w_{inter}) in the end determines the dewaterability, because this water content remains in the sludge cake after the dewatering process. For sewage sludges the interstitial water content amounts to approximately 4–13%. Regarding the mechanical dewatering process the bound water content (w_{bound}) measured with dilatometric tests is of minor importance. On the one hand this water content always remains in the sludge cake but on the other hand it is very small. The values lie at about 1% SS.

Figure 6 contrasts the SS_A of 33 digested sewage sludges, which means SS after separating the free water content, with the dewatering results obtained with full scale centrifuges. The accuracy of the thermo-gravimetric measurement lies at about ±1% SS, thus giving an exact prediction of the solid content after dewatering.

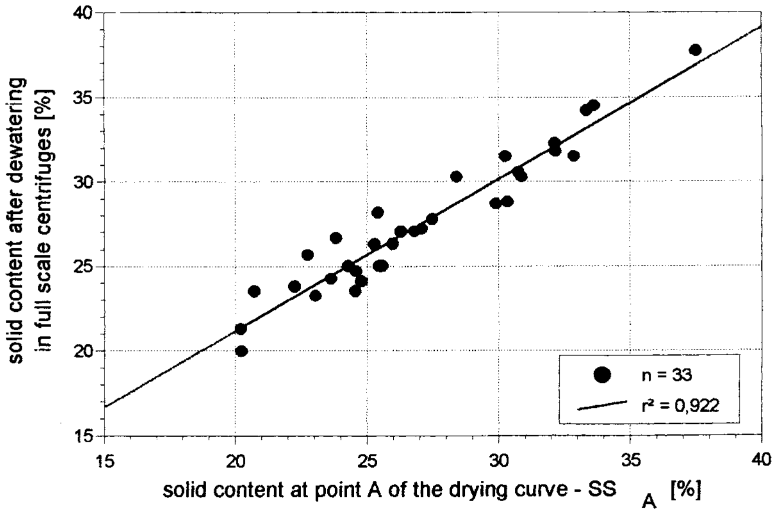

Figure 6 Correlation between SS_A solid content at point A of the drying curve in dependence of the solid contents after dewatering in full scale centrifuges

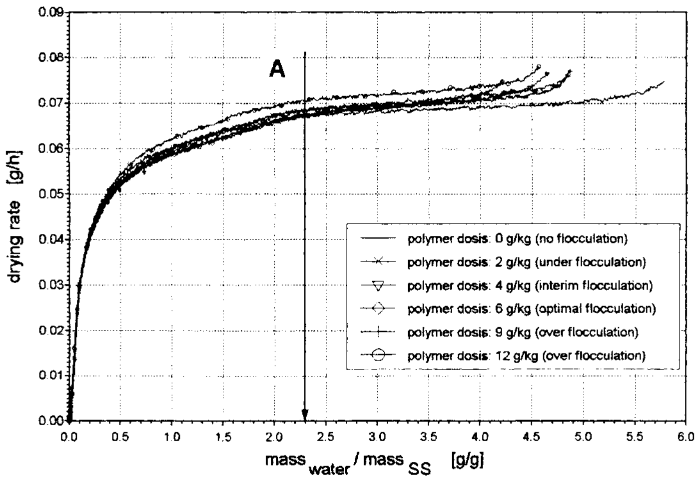

Figure 7 Influence of polymer conditioning on the drying curve

Influences on the water distribution

Now the main interest is to find out what influences the water distribution. Therefore the influence of the polymer dosage on the water distribution was examined for various digested sewage sludges and various polymers. Figure 7 shows the drying curves for various polymer dosages of one digested sludge. For these tests high under- und over-flocculation was used as well as an optimum polymer dosage for the conditioning. Contrary to the expectation that the free water content should be the highest for an optimum polymer dosage, the free water content remained constant during all measurings. This effect was confirmed during the tests with other sludges and polymer products. A possible explanation for this result is that the interstitial water is bound in the flocs and during conditioning flocs are combined in larger agglomerates, thus increasing the velocity of the sludge water release. In the final analysis the dewatering result achieved in full scale centrifuges is independent from the polymer dosage and the polymer product. The retention time of the sludge in the centrifuge however is so short, that optimum dewatering results can only be reached at an optimum velocity of the water release from the sludge.

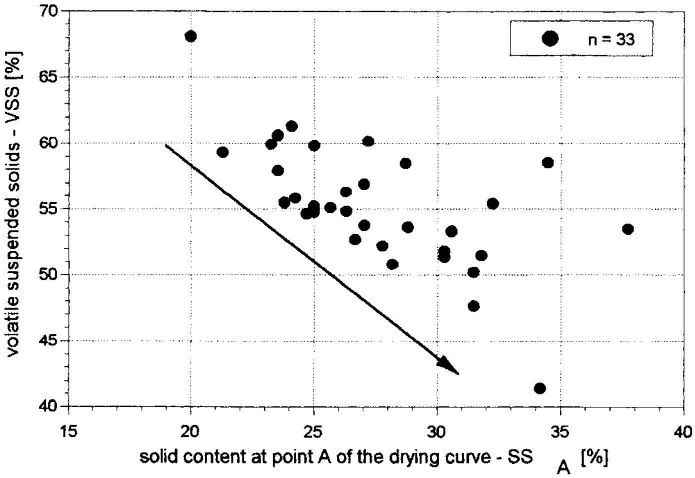

Figure 8 Dependency of the achievable dewatering results SS_A on the volatile suspended solids

It must be noted that a separation degree of 100% of the sludge particles is assumed for the TRA values. When operating full scale centrifuges as classifiers, higher solid contents in the sludge cake are achieved at the expense of a high polution of the centrate with organic particles.

The volatile solids content is the parameter of sludge characterisation most often used for describing the dewaterability of sludge. The higher the amount of organic compounds of a sludge, the lower the density of the sludge particles ($\rho_{organic} \approx 1.0$ g/cm^3; $\rho_{inorganic} \approx 2.3$ g/cm^3). Also, more water is bound, since the contact angle of organic particles is smaller than that of inorganic particles, thus binding more water with capillary forces. This means that sludges with a high ignition loss are in general more difficult to dewater. Figure 8 describes the solid content after separation of the free water content (SS_A) in dependence on the volatile solid content. It can be seen in Figure 8 that there is a tendency that the achievable dewatering result increases with decreasing volatile solid content. Nevertheless the measuring values are so scattered that the dewatering result of a sludge cannot be derived from the volatile suspended solids content. Similar problems can be observed for other characterisation parameters, such as the amount of colloids.

Conclusions

In order to be able to judge the dewaterability of a sewage sludge, two methods of measuring the water distribution were presented. With the help of experiments it is possible to determine the polymer demand of a sludge. To do this, the polymer dosage is increased until the zeta potential in the centrate is close to the iso-electric point.

Three types of water can be distinguished in a sewage sludge by measurement. The free water content is not bound to the sludge particles and can be separated by a mechanical dewatering process. The interstitial and bound water content (surface and intracellular water) remain in the sludge cake after the dewatering process.

The measuring system for the thermo-gravimetric determination of the water distribution of sewage sludges, adjusted and calibrated at the Technical University of Braunschweig makes it possible to predict the maximum possible dewatering results for full scale centrifuges.

The free water content is not influenced by polymer conditioning. Furthermore, it is so far not possible to replace the measuring of the water distribution by other individual parameters such as the volatile solid content.

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