Influence of the free water content on the dewaterability of sewage sludges

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Abstract Dewaterabilty of sewage depends on the physical water distribution. The various types of water in sewage sludge are mainly distinguished by type and intensity of their physical bonding to the solids. In a sewage sludge suspension different types of water can be distinguished. These are 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. Only free water can be separated during mechanical dewatering. It can be shown, that thermo-gravimteric measurement of the free water content leads to an exact prediction of full-scale dewatering results. Maximum dewatering results are reached by separating all free water during centrifugation. Furthermore on the basis of the drying curve an estimation of water binding energies can be achieved. The binding energy for free water is less than 0,28 kJ/kg water. The binding energy for bound water (sum of surface and intracellular water) is higher than 5 kJ/kg water.

Keywords Bound water; dewatering; characterisation; conditioning; free water; full-scale centrifuges; interstitial water; maximum dewatering result; sludge drying; water binding energy

Introduction

The dewatering result can be described by total solids concentration of the sludge cake and amount of conditioning agents. Achieved total solids concentration of the sludge cake depends on the distribution of water types in the sludge, since only the free water can be separated during mechanical dewatering (Kopp and Dichtl, 2000). 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 (Kopp and Dichtl, 1998).

The various types of water in sewage sludge are mainly distinguished by type and intensity of their physical bonding to the solids. 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. These are:

- 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.

Materials and methods

Thermo-gravimetric and dilatometric laboratory tests (Jones and Gortner, 1932; Smollen, 1987) are used for the measuring of water distribution. 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, 2000).

For thermo-gravimetric measurements the sludge sample is dried at constant conditions (air flow – 30 ml/min, temperature – 35°C). 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 differentiate the corresponding amounts of water, the sample is thickened in a laboratory beaker centrifuge at 1000 × g for 30 min before drying. The drying procedure must take place very slowly, because otherwise a distinction between the various types of water on the basis of the drying curve is not possible anymore, because of the high energy input.

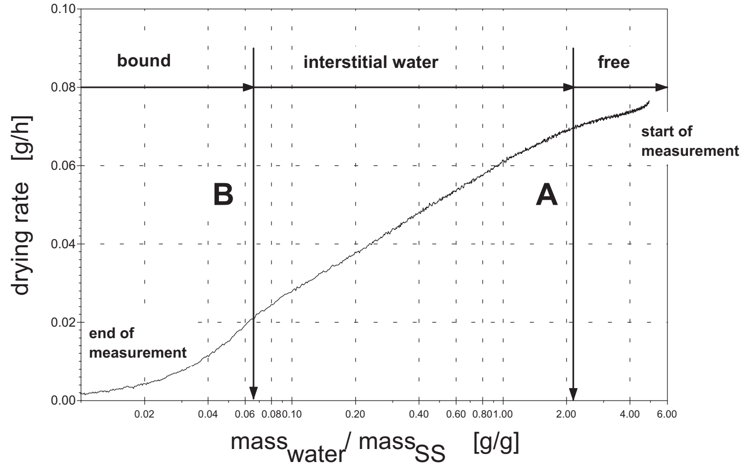

Figure 1 Drying curve of a digested sewage sludge for a logarithmic abscissa

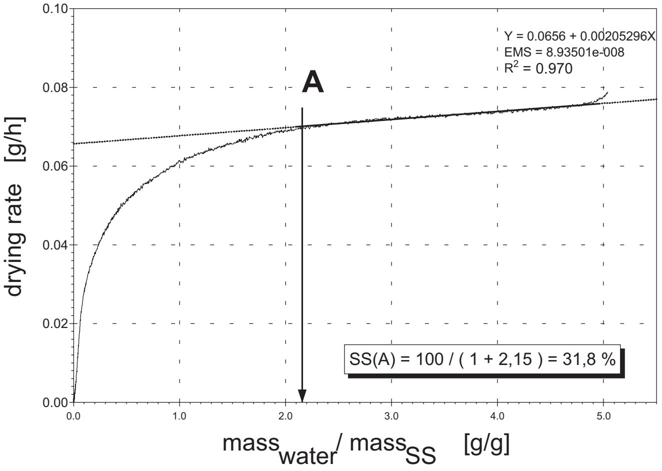

Figure 2 Drying curve of a digested sewage sludge for an arithmetic abscissa

Figure 1 shows the drying curve of a digested sewage sludge sample. Seen chronologically, the drying curve starts at the top right-hand corner with a high moisture content ($\text{mass}_{\text{water}}/\text{mass}_{\text{SS}}$) and ends when all water has dried from the sample. Two critical points A and 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, that means point A of the drying curve. Therefore it is useful to plot the drying curve with an arithmetic scale (Figure 2). 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 SS(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 (Smith and Vesilind, 1995). The measuring principle is based on the fact that the bonding forces are that 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. The amount of bound water corresponds to point B of the drying curve (Figure 1). 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.

Results and discussion

Prediction of full-scale dewatering results

The measurement depends on two conditions, air flow and temperature. A calibration of the drying instrument is necessary before an exact evaluation of the free water content can take place. After these a prediction of full-scale dewatering results is possible. Table 1 presents the water distribution, the polymer-demand, the solids content (SS) and the ignition loss (VSS) of 58 anaerobically and 15 aerobically digested sewage sludges.

Due to the present state of the art in science and technology, mechanical dewatering processes can only remove the free water content (w_{free}) from sludge. This water content is calculated with the drying instrument. The solids content in the sludge cake, which would exist after removal of the free water content, is derived as the parameter SS(A). The solids

Table 1 Water distribution for municipal sewage sludge

Sludge	SS [%]	VSS [%]	Polymer [g/kg]	SS_{dewat} [%]	SS(A) [%]	m(A) [g/g]	w_{free}* [%]	w_{inter}* [%]	w_{bound}* [%]
Anaerobically digested sludges (n = 58)									
Mean	**2.8**	**55**	**7.7**	**26.3**	**27.7**	**2.6**	**91.7**	**7.5**	**0.8**
Stand. deviation	0.8	5.0	2.8	4.4	4.1	0.5	1.7	1.6	1.3
Min	0.9	41	4.5	19.6	20.0	4.0	87.6	4.5	0.1
Max	5.9	68	13.3	37.5	37.7	1.7	94.9	11.6	1.3
Aerobically digested sludges (n = 15)									
Mean	**2.6**	**66**	**5.9**	**21.4**	**22.8**	**3.4**	**89.4**	**9.6**	**1.1**
Stand. deviation	0.5	5.3	2.6	3.6	3.3	0.7	2.3	2.2	0.4
Min	1.5	61	2.0	15.3	16.4	5.1	84.2	7.4	0.5
Max	5.5	78	10.0	26.7	27.0	2.7	91.7	13.9	2.0

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

content at point A – SS(A) is therefore the maximum solids content in the sludge cake, which can be achieved with mechanical dewatering. Figure 3 compares the SS(A) of digested sewage sludges calculated using the drying instrument (in other words, the SS after separating the free water content) with the dewatering results obtained with full-scale centrifuges and filter presses. The accuracy of the thermogravimetric measurement lies at about ± 1.5% SS, thus giving an exact prediction of the solids content after dewatering.

Calculation of the water binding energy

Since use of the terms for the various water fractions is not clearly defined, an allocation is consequently only possible according to the amount of energy binding the water to the solids. On the basis of the drying curve an estimation of water binding energies can be achieved, by assuming that the energy necessary for the drying process is the sum of energy of evaporation (E_E) and binding energy (E_B). Binding energies are the reason for the decrease of the drying rate during the drying process, that means that the difference between the drying rate of pure water to the measured drying rate corresponds to the amount of binding energy. Calculated binding energy at point A averages at 0.28 kJ/kg water (Figure 3). Determined binding energy was independent from the amount of free water, that means independent from mass ratio at point m(A).

$$E_B = \frac{(r_{H_2O} - r_{sludge})}{r_{sludge}} \cdot E_E \quad [\text{kJ / kg}]$$

E_B : binding energy [kJ/kg]
E_E : energy for evaporation = 2415 kJ/kg [kJ/kg]
r_{H2O} : drying rate of water [kg/h]
r_{sludge} : drying rate of sludge [kg/h]

At point B (Figure 1) the binding energy for the bound water (sum of surface and intracellular water) is higher than 5 kJ/kg water. In other words, up to 5 kJ/kg the interstitial water is bound by capillary forces. The theoretical size of the capillary pores is $3 \cdot 10^{-7}$ up to $6 \cdot 10^{-6}$ m (LAPLACE). The calculated water binding energy corresponds very well with results of Key (1972).

Influences on the water distribution

It is of great interest to determine the influences of different factors on the water fractions. The influence of polymer conditioning, the type of sludge and the volatile suspended solid content is published in Kopp and Dichtl (2000). Contrary to the expectation that the free

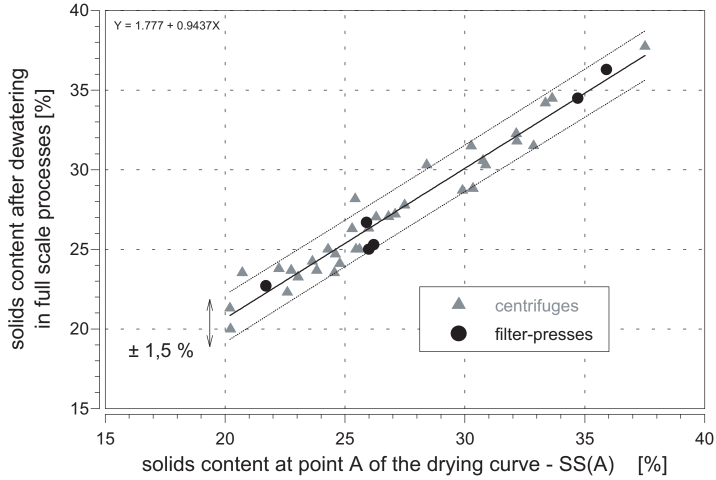

Figure 3 Correlation between SS(A) – solid content at point A of the drying curve in dependence of the solid contents after dewatering in full-scale centrifuges and filter presses

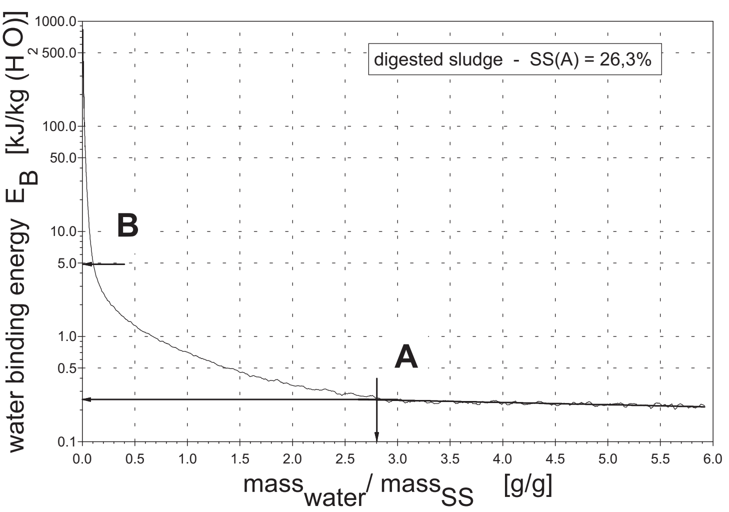

Figure 4 Water binding energy of an anaerobically digested sludge sample

water content should be the highest for an optimum polymer dosage, the free water content remained constant for all dosages. 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 maximum dewatering result achieved in full-scale centrifuges is independent of the polymer dosage and the polymer product.

Another important factor that affects sewage sludge dewaterability is the percentage of excess sludge in the total sludge mass. Usually primary sludges are easy to dewater. In contrast, excess sludges are difficult to dewater, since the percentage of free water is low. As the percentage of excess sludge in the total sludge mass increases, the amount of free water decreases, thus decreasing the quality of the dewatered product.

The volatile solids content represents the organic part of a sewage sludge and is the parameter most often used to characterise the dewaterability of sludge. The higher the amount of organic compounds in a sludge, the lower the density of the sludge particles. In addition, more water is bound, since the contact angle of organic particles is smaller than that of inorganic particles, thus binding more water by means of capillary forces. That means that sludges with a volatile suspended solid content (VSS) are in general more difficult to dewater. But it is not possible to predict the dewatering result of a sewage sludge by the volatile suspended solids content. Similar problems can be observed for other characterisation parameters, such as the particle size and the capillary suction time.

In this paper the main interest is to find out, how the digestion of sludges influences the free water content and the parameter SS(A). Therefore sludge was digested in several batch tests. Figure 5 shows the maximum dewatering result SS(A) and Figure 6 the polymer demand of a primary (PS), raw (RS) and excess sludge in dependence on the anaerobic digestion time. The excess sludge was digested both aerobically (ES-AE) and anaerobically (ES-AN).

During digestion the maximum dewatering result SS(A) decreases 2–3% SS. For the excess sludge no difference between aerobic and anaerobic digestion can be detected. Two contradictory effects can be observed. During digestion the amount of volatile solids decreases, this positively affects the dewatering result. On the other hand the particle size also decreases, which leads to an increase of interstitial water. The effect of particle size seems to be dominant.

The polymer demand increases during digestion. Especially the polymer demand of

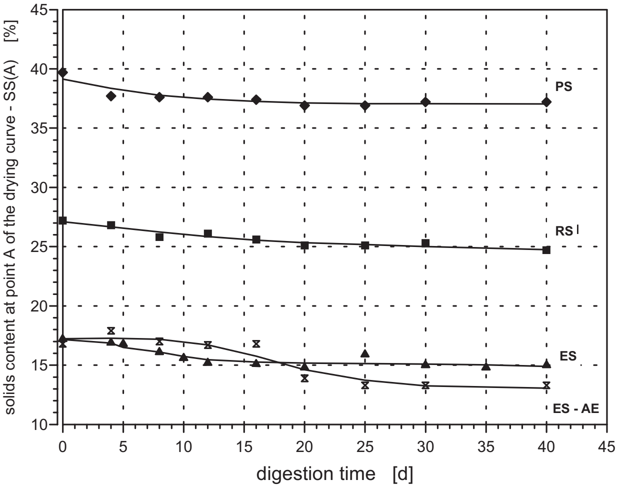

Figure 5 SS(A) in dependence on sludge digestion

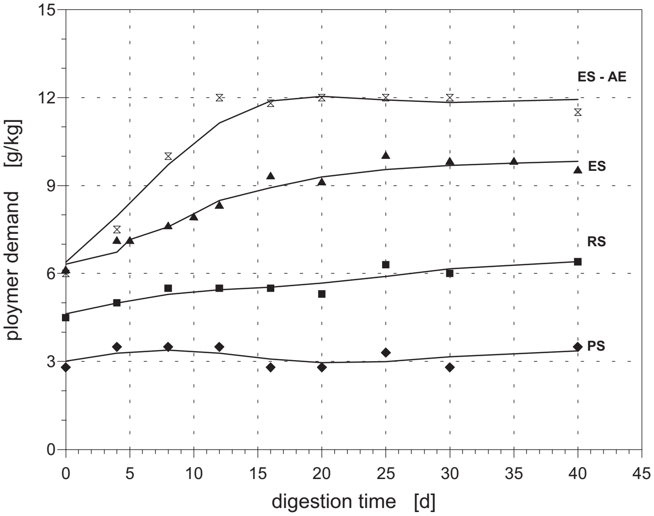

Figure 6 Polymer demand in dependence on sludge digestion

ES-AE is twice as high after aerobic digestion. A possible explanation for this result is the release of EPS (Kopp and Dichtl, 1998). Furthermore the influence of the type of sludge can be observed. The primary sludge achieves high dewatering results and the polymer demand is low. As the amount of excess sludge on the total sludge mass increases, the dewatering result decreases and the polymer demand increases.

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.

Four 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 dewatering results for full-scale centrifuges and filter presses.

The water binding energy is less than 0.28 kJ/kg water for the free water content and higher than 5 kJ/kg water for the bound water. Related to 3% SS of a sludge suspension the amount of free water is 85–95% and the amount of bound water is less than 1%.

The free water content does not depend on the polymer conditioning. But the influence of the amount of excess sludge to the total sludge mass is significant. During sludge digestion the maximum dewatering result SS(A) decreases 2–3% SS caused by the decrease of the particle size. Especially for excess sludges the polymer-demand increases during the digestion time.

Furthermore so far it is not possible, to replace the measuring of the water distribution by other individual parameters such as the volatile solids content, particle size and capillary suction time.

References

Jones, E.V., Gortner, R.A. (1932). Free and bound water in elastic and non-elastic gels, *J. Phys. Chem.*, **37**, 387.

Kopp, J. and Dichtl. N. (1998). *Influence of Surface Charge and Exoploysaccharides on the Conditioning Characteristics of Sewage Sludge*, Springer, 285–296.

Kopp, J. and Dichtl. N. (2000). Prediction of full-scale dewatering results by determining the water distribution of sewages sludges, *Wat. Sci. Tech.*, **42**(9), 141–149.

Keey, R.B. (1972). Drying Principles and Particles, Pergamon Press, London quoted in: Smollen, M. (1990), Evaluation of municipal sludge drying and dewatering with respect to sludge volume reduction, *Wat. Sci. Tech.***22**(12), 135–142.

Smith, J.K. and Vesilind, P.A. (1995). Dilatometric measurement of bound water in wastewater sludge, *Water Research*, 1995, **29**(12), S. 2621–2626.

Smollen, M. (1987). Categories of moisture and dewatering characteristics of sewage sludge, *Proceedings of the 4th World Filtration Congress, Ostend, Belgium*, 22–25.04.1987, 1435–1441.