Mechanical disintegration of sewage sludge

G. Lehne, A. Müller and J. Schwedes

Institute of Mechanical Process Engineering, Post Box 3329, Technical University of Braunschweig, D–38023 Braunschweig, Germany

Abstract Mechanical disintegration can be used for an accelerated and improved anaerobic digestion of excess sludge. The hydrolysis is the limiting step of this process. Mechanical disintegration can be used to disrupt the cell walls and to cause the release of the organic material from the cells. Particle size analysis describes the size reduction but is not suitable for characterising the release of the organic material and the cell disruption. Two biochemical methods were developed for these phenomena. One of the parameters provides information about the disruption of micro-organisms, the other one gives information about the release of organic material.

Different ultrasonic homogenizers, a high pressure homogenizer and stirred ball mills were used for disintegration experiments using various parameters. The influences of a mechanical disintegration on the particle size and of the energy intensity on the disintegration were investigated. Further investigations had to detect the influence of the solid content on the disintegration results. For sludge with a higher solid content better results in terms of energy consumption could be achieved. An optimum of the bead diameter and the stress intensity in stirred ball mills could be detected. A comparison of the results of different methods of sludge disintegration shows that the investigated ultrasonic homogenizers are inferior to a high pressure homogenizer and a stirred ball mill in terms of energy consumption.

Keywords Anaerobic digestion; cell-disruption; mechanical disintegration; excess sludge; disintegration devices

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Introduction

There are three major ideas for the application of a mechanical disintegration of sewage sludge. One is to detect the possibilities of using the organic material of the disintegrated sewage sludge as a hydrogen-ion-source for the denitrification process. For the denitrification process easily available organic material is essential as a hydrogen-ion-source. If the incoming amount of such material for a waste water treatment plant is too low, additional easily available organic material has to be added for the denitrification. The disintegrated excess sludge can be used as a substitute for expensive hydrogen-ion-sources like acetate or methanol (Kunz, 1993, 1996).

A second application is that use of a mechanical disintegration for reduction of bulking and foaming in a water treatment process. For that application a size reduction of the larger flocs and a break up of the filamentous structures is more important than the cell disruption. For that reason the energy consumption is much less than for cell disruption. The mechanical disintegration can be used for solving problems with bulking and foaming in the aerobic and in the anaerobic tank as well (Müller, 1999, 2000). The third aim is to make the organic material of the excess sludge available for the degradation in an anaerobic process (Müller, 1996; Tiehm *et al.*, 1997; Grüning *et al.*, 1999). Digestion is a common method to improve the dewaterability of excess sludge and to reduce the amount of sludge that has to be disposed of. The digestion process is characterised by hydraulic retention times of more than 20 days under anaerobic conditions. These high retention times cause digesters of high volume. Because of the high building costs of digesters it is advantageous to decrease the digestion times and thereby to reduce the necessary volume of the digester.

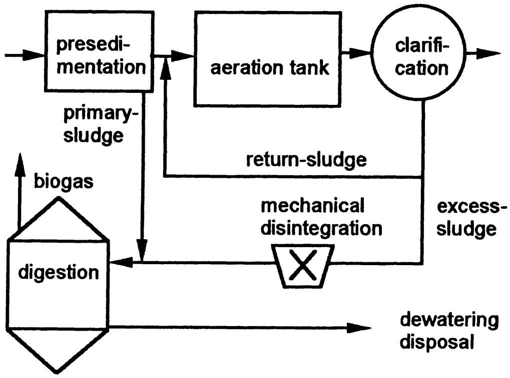

Figure 1 Flow sheet of a waste water treatment plant with mechanical disintegration of excess sludge

Excess sludge contains up to 70% of bacteria. The hydrolysis of these bacteria limits the speed of the whole anaerobic process. Especially facultative anaerobic bacteria are not affected by the anaerobic degradation process. The degree of degradation of the organic material that can be achieved is mostly under 40%. It is beneficial to increase the degree of degradation of the organic material. That reduces the amount of digested sludge that has to be disposed of and enlarges the quantity of produced biogas. Therefore again an improved hydrolysis is important.

For a waste water treatment plant only the excess sludge has to be treated by mechanical disintegration. The primary sludge contains substances that are mostly easy to hydrolyse. There would be no benefit from using a mechanical disintegration for the primary sludge. The disintegrated excess sludge can be digested together with the primary sludge as shown in Figure 1.

A high release of organic material and a high degree of disintegration in combination with an economical energy consumption are essential for the beneficial use of mechanical disintegration to improve the anaerobic digestion. The energy consumption is directly related to the operating expenses of the disintegration device. Other cost factors are the investment cost, labour cost and the service life of the disintegration device.

Materials and methods

The sewage sludges of two municipal waste water treatment plants with a size of 60,000 and 120,000 population equivalents and a sludge age of 13 days in both plants were used for the investigations. A third sludge with a sludge age of 3 days from a plant with 100,000 population equivalents was used. An ultrasonic homogenizer UPC 200 (Dr. Hielscher GmbH) was used for batch disintegration experiments. An ultrasonic homogenizer UIP 500 (Dr. Hielscher GmbH) with a sonotrode with a length of 65 mm was used in continuous flow experiments. The third ultrasonic homogenizer was a Labsonic L (B. Braun). All 3 ultrasonic homogenizers work with an operating frequency of 200 kHz.

Besides using ultrasound, investigations with a stirred ball mill and glass grinding beads (Netzsch LME 4) and a high-pressure homogenizer (APV Gaulin lab 60) were carried out (Müller, 1996; Lehne *et al.*, 1998). A laser diffraction sensor Helos (Sympatec) was used for measuring particle size distributions. Two different biochemical methods were used to measure the degree of disintegration (Müller *et al.*, 1998). The degree of disintegration DR_O is determined by the measured specific oxygen consumption OC_m of the treated sewage sludge in relation to the specific oxygen consumption OC_u of the untreated sewage sludge. The specific oxygen consumption is directly related to the metabolism of aerobic micro-organisms. If all bacteria of the sewage sludge are disrupted the specific oxygen consumption of the treated sludge is zero and the degrees of disintegration DR_O reaches 100%.

$$DR_O = [1 - (OC_m / OC_u)] \cdot 100\% \qquad (1)$$

The second degree of disintegration uses the chemical oxygen demand of a sewage sludge and describes the release of organic material originated by the mechanical cell disruption. A maximum chemical oxygen demand COD_a using alkaline hydrolysis has to be determined for the degree of disintegration measured by COD release. In addition the COD of the treated sludge COD_m and the COD of the untreated sludge COD_O have to be measured.

$$DR_{COD} = [(COD_m - COD_0) / (COD_a - COD_0)] \cdot 100\% \qquad (2)$$

The specific energy for the disintegration process provides information about the necessary energy input to achieve a certain degree of disintegration. The definition of the specific energy is the energy input in relation to the treated solid mass. The energy input is determined by the power P of the ultrasonic homogenizer and the retention time t_r. The treated solid mass can be detected by measuring the treated volume V_P and the solid content SS.

$$E_{spec} = [(P \cdot t_r) / (SS \cdot V_P)] \qquad (3)$$

For the anaerobic treatment continuous and batch experiments were used. The batch experiments were carried out in 1 litre bodies. An inoculum of 200 ml of adapted anaerobic sludge was used with 600 ml of excess sludge. The gas was collected and daily measured volumetrically. Laboratory scale digesters with 20 litres volume and an immobilisation were used for the continuous experiments.

Results

Particle size analysis

As is common for other comminution processes the disintegration of sewage sludge can be described by particle size analysis. An increase of the energy input leads to a decrease of the particle size as shown in Figure 2. Simultaneously the degree of disintegration increases. The major change in particle size takes place with low energy input of under 3,000 kJ/kg, where floc size reduction is the major effect.

The particle size of the sludge is an unsuitable parameter to describe the release of organic material or the cell disruption. With increasing energy consumption only minor changes in the particle size take place. With high specific energies an increased release of organic material can be detected and a significant cell disintegration occurs. Because of that the particle size is only used as an additional parameter for excess sludge disintegration. The degrees of disintegration DR_O and DR_{COD} are more suitable to describe the release of organic material and the cell disruption.

Degree of disintegration

Two biochemical methods are used to describe the disintegration of sewage sludge. The degree of disintegration DR_O to the limit of E_{spec} = 3,000 kJ/kg is approximately DR_O = 10%. In Figure 2 the area of cross hatch marks the area of **floc size reduction.** This area is characterised by an intense particle size reduction. On the other hand the degree of disintegration remains very low. The release of organic components to the sludge water is accordingly poor. With such a low release of organic material no significant improvement of the degradation in the anaerobic process is possible. The particle size reduction may lead to an improved mass transfer, but the effect for the anaerobic process stays small. Degradation experiments with sludge of low degrees of disintegration showed no significant improvement of the degradation results compared with untreated sludge.

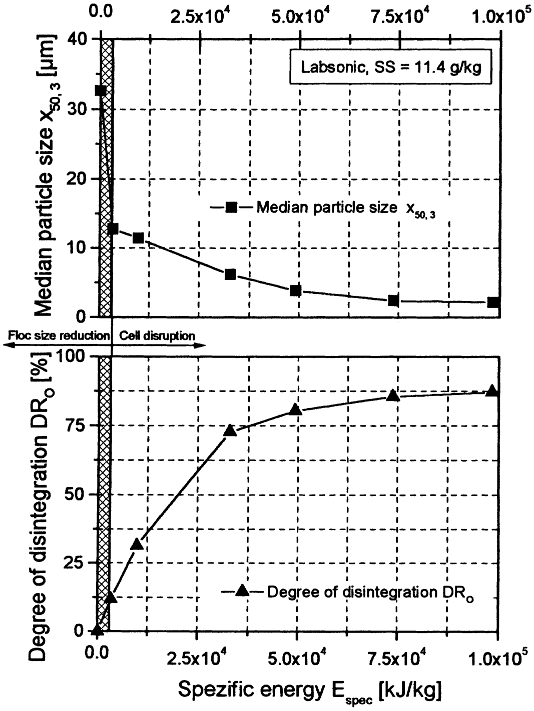

Figure 2 Degrees of disintegration and particle size for an ultrasonic disintegration

For sludge with degrees of **disintegration** higher than DR_O = 10% the release of organic components reaches higher values and the particle size changes less than for values under DR_O = 10% (Figure 2). The released organic material is easily degradable. The increased release of organic material leads to improved degradation results. For an improved anaerobic digestion such high degrees of disintegration are essential. The degree of disintegration measured by the oxygen consumption DR_O can reach values from 0 up to 100%. Using mechanical disintegration with very low specific energy can result in an increased oxygen consumption of the treated sludge in comparison with the untreated sludge. The enhancement can reach up to 10%. That effect can be explained by focusing on the particle size. A high decrease in particle size takes already place for low energy inputs. Because of that decrease the microorganisms from inside the sludge flocs are exposed to the surface of the floc fragments and have a better access to the oxygen. The oxygen consumption increases. If this effect is stronger than the decreases of the oxygen consumption by cell disruption, the degree of disintegration DR_O can reach values below 0%.

The maximum value of the degree of disintegration measured by COD release, DR_{COD}, is determined by the reference method for the maximal COD release. The alkaline total fusion of the sludge leads to a higher release of organic material than the mechanical disintegration. The exact ratio depends on the conditions for the alkaline total fusion. With a hold up time of 10 min, a temperature of 90°C and a 1:1 mixture of sludge and 1-molar NaOH approximately twice as much organic material is released by the alkaline hydrolysis in comparison with the mechanical disintegration. Therefore the degree of disintegration, DR_{COD}, reaches only maximum values of approximately 50%. Figure 3 shows results for the disintegration of excess sludge with various disintegration devices.

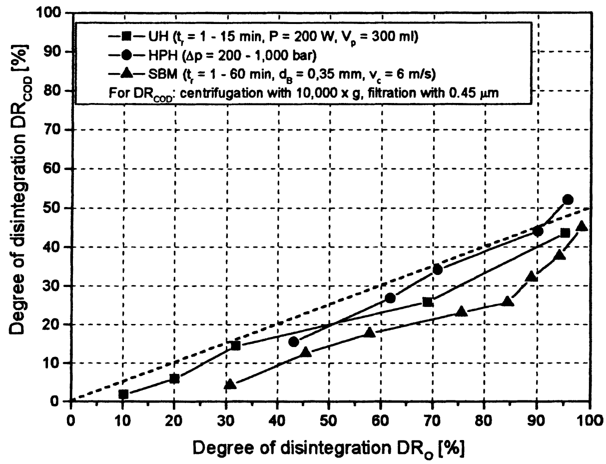

Figure 3 Influence of the solid content on the energy consumption of an ultrasonic homogenizer

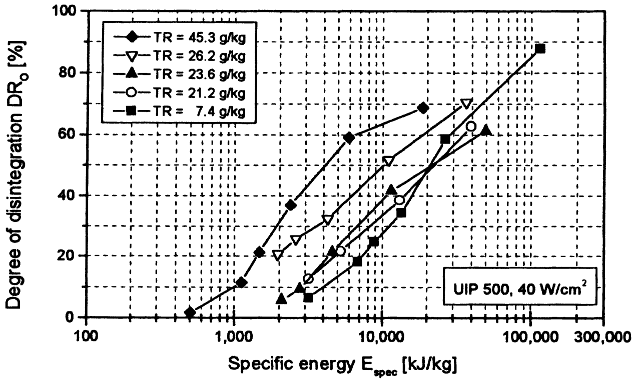

Figure 4 Influence of the bead diameter of a stirred ball mill on the disintegration results

Solid content of the disintegrated sludge

A major factor of the disintegration of excess sludge is the solid content of the sludge. For a common standard excess sludge the content of suspended solids SS is approximately SS = 5–10 g/kg. The solid content can be up to 600 g/kg after thickening. A mechanical treatment prior to the thickening would affect the thickening. Therefore it is important to know if mechanical disintegration of thickened sludge shows advantages.

Figure 4 shows results from a continuous flow experiment using the ultrasonic homogenizer UIP 500. The solid content was varied between 7.4 and 45.3 g/kg. The sludge with the highest solid content showed the disintegration results with the lowest specific energy consumption. The decrease of specific energy with increasing solid content makes use of the mechanical disintegration for thickened sludge more profitable.

According results could be found for the stirred ball mill and the high pressure homogenizer. Less specific energy is necessary to reach a certain disintegration result if the solid content of the sludge is higher. That means a mechanical disintegration is advantageous especially after the thickening process.

Operational parameters of stirred ball mills

The **bead diameter** is one of the major operational parameters of a stirred ball mill. The influence of the bead diameter on the specific energy to reach a certain degree of disintegration is shown in Figure 5. With decreasing bead diameter less energy is necessary to reach a

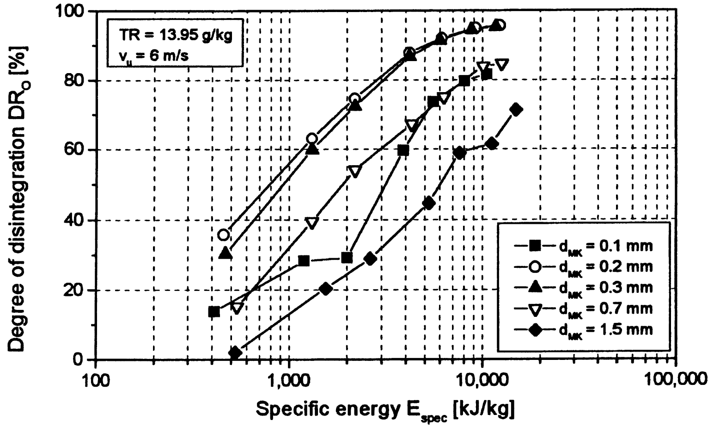

Figure 5 shows disruption results for constant solid content SS and circumferential velocity v_c. An optimum for the stress intensity can be detected for both specific energies. With the same specific energy a higher degree of disintegration can be achieved. Operating stirred ball mills with an optimum stress intensity reduces the energy cost.

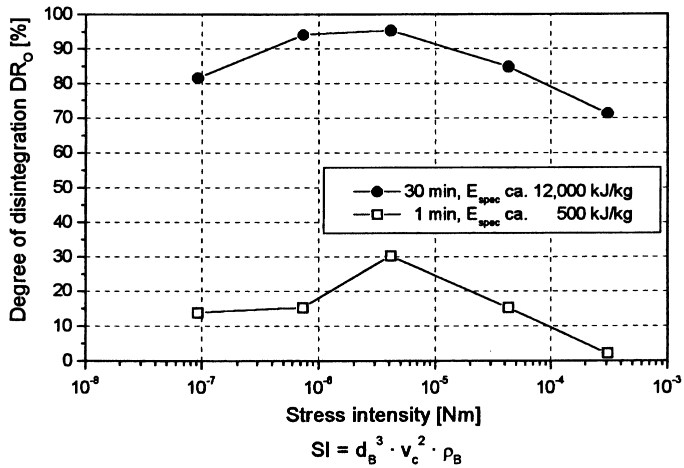

Figure 6 Influence of stress intensity on degree of disintegration for two specific energies

certain degree of disintegration. At a bead diameter of 0.2 mm a minimum of the specific energy is reached. For the smaller beads of 0.1 mm an increasing specific energy has been detected. These beads are too small and have not enough kinetic energy to cause a cell disruption at every bead-bead or bead-wall contact.

The specific energy input for the comminution process can be seen as a product of the number of stress events and the specific energy that is consumed at a single stress event, the **stress intensity**. The kinetic energy of the grinding beads determines the stress intensity of the grinding beads in a stirred ball mill. For that reason the following equation can be taken as a measure for the stress intensity.

$$SI = d_B^3 \cdot v_c^2 \cdot \rho_B \qquad (4)$$

If the stress intensity is too low to disrupt cells at every stress event, energy is consumed but not every stress event causes cell disruption. If the stress intensity is too high, a cell disruption takes place but too much energy is consumed for the single stress event. In both cases more energy than necessary is consumed for the disruption process. To reduce the specific

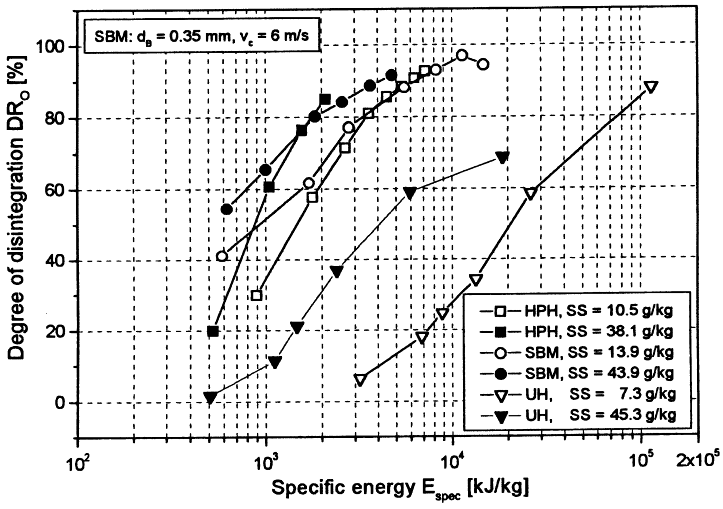

Figure 7 Comparison of different disintegration methods

energy it is important to operate the stirred ball mill with grinding beads of the optimal stress intensity. If the stress intensity is higher than this optimum the number of disrupted cells is directly related to the number of stress events. The number of stress events in a stirred ball mill increases with decreasing grinding bead diameter and increasing circumferential velocity. To keep the number of stress events high it is beneficial to use smaller grinding beads.

Energy consumption of different disintegration methods

Figure 7 shows disintegration results for a high pressure homogenizer, a stirred ball mill and an ultrasonic homogenizer. With an increasing specific energy higher degrees of disintegration are achieved. All three disintegration devices show better results for thickened sludge. The stirred ball mill and the high pressure homogenizer achieves high degrees of disintegration at relatively low specific energies. The ultrasonic homogenizer UIP 500 consumes more energy even for a high solid content (Figure 7). These results could be enhanced by a further improvement of the energy intensity and the shape of the sonotrode. The used ultrasonic homogenizers and sonotrodes were not optimised for the sewage sludge disintegration. Further investigations are essential to optimise the energy consumption of all disintegration devices because the impact of the specific energy on the operation cost of the whole process is high.

Operation experience

Disintegration using a stirred ball mill can be adapted to sludge properties by changing operation parameters such as grinding bead size and material, the circumferential velocity or the retention time. Stirred ball mills are proven devices under harsh conditions. For the continuous operation of a stirred ball mill the grinding beads have to be separated from the product. Mostly this separation is realised by a frictional gap or a sieve cartridge. A solution is the separation of the grinding beads by centrifugal forces. For the high pressure homogenizer the higher solid content leads to higher wear of the homogenising valve and operation problems for the pump. However, high pressure homogenizers show advantageous disruption results. They are proven technology for cell disruption and available with a flow up to 40 m^3/h. The development of new ultrasonic homogenizers can lead to decreasing specific energies for comparable degrees of disintegration. Nevertheless the use of an ultrasonic homogenizer with a higher specific energy consumption can be advantageous, because they are easy to integrate in an existing waste water treatment plant and in existing pipes mostly without additional baffles. The risk to block up an ultrasonic homogenizer with sludge solids is small.

Conclusion

The mechanical disintegration of excess sludge is a possibility to improve the degradation results in an anaerobic process. The disintegration can be monitored by using the degrees of disintegration DR_O and DR_{COD}. An increase of the solid content is beneficial for the specific energy to reach the same disintegration results. For stirred ball mills, there exists an optimum of the bead diameter at low values. The stress intensity is a parameter characterising the kinetic energy of the grinding beads. Operating stirred ball mills with an optimum stress intensity reduces the energy cost. Comparing experiments for different disintegration devices shows benefits for stirred ball mills and high pressure homogenizers in terms of the specific energy.

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List of symbols

u		untreated
COD	mg/l	chemical oxygen demand
COD_m	mg/l	COD of the treated sludge
COD_a	mg/l	COD after alkaline total fusion
COD_O	mg/l	COD of the untreated sludge
d_B	mm	bead diameter
DR_{COD}	%	degree of disruption measured by COD release
DR_O	%	degree of disruption measured by oxygen consumption
E_{spec}	kJ/kg	specific energy for disintegration
HPH		high pressure homogenizer
OC	mg/l · min	oxygen consumption
OC_m	mg/l · min	oxygen consumption of the treated sludge
OC_u	mg/l · min	oxygen consumption of the untreated sludge
P	W	power
SBM		stirred ball mill
SS	g/kg	suspended solid content
t_r	min	retention time
UH		ultrasonic homogenizer
v_c	m/s	circumferential velocity
V_P	m^3	volume of the sample
WAS		waste activated sludge