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CONVECTIVE DRYING OF SAWDUST/SLUDGE MIXTURES IN A FIXED BED: THE EFFECT OF SLUDGE ORIGIN

J. Li*, L. Fraikin, T. Salmon, D. Toye, A. Léonard

Laboratory of Chemical Engineering, Department of Applied Chemistry, University of Liège

B6c, Allée de la chimie, Sart Tilman, Liège, 4000, Belgium

**Corresponding author: Tel.:+32 4 36 63 51 3, E-mail: jie.li@ulg.ac.be*

Abstract: Sludges collected from Oupeye WWTP (MS=80%), Grosses Battes WWTP (MS=85.5%), and Embourg WWTP (MS=88%) in Belgium and presenting different properties were used. The influence of the sawdust/sludge ratio on convective drying was investigated in a fixed bed. X-ray tomography was used to assess changes in volume, exchange surface and void fraction. Results showed that the average drying rates were 0.062 (Oupeye), 0.079 g/s (Grosses Battes) and 0.042 g/s (Embourg) respectively, using raw sludges. For sawdust/sludge mixtures with the mass ratio of 4/6, the average drying rates of sludges were improved (Oupeye: 0.092 g/s, Grosses Battes: 0.106 g/s, Embourg: 0.049 g/s).

Keywords: sewage sludge, sawdust, mixing, drying kinetics, pasty, X-ray tomography

INTRODUCTION

The treatment of wastewater from domestic activities generates large amounts of sludge [1]. As a result of strict regulations, the amount of residual treatment sludge has also increased and became a serious environmental problem [2]. Due to environmental and economic considerations, the reduction and reuse of this waste are nowadays needed. Thermal drying is one of the technologies available for processing of dewatered solids produced at municipal wastewater treatment plants (WWTPs) [3-5].

Because of the soft and pasty form of the sludge, thermal drying can be difficult when using technologies requiring an extrusion of feed. Due to poor rigidity of sludge, the developed exchange area is rather small, also giving low drying rates. In this work sawdust addition was proposed as a way of reinforcing the texture of soft and pasty sludge, which are difficult to be dried. Reinforcing the texture of sludge can increase the drying rate and decrease the drying time, and then the heat energy supply and operation cost will be reduced significantly. Besides the improvement of drying kinetics, sawdust also brings organic matter which is useful for further gasification or combustion processes. Sawdust is produced in large amount by the forest industry and also needs safe disposal solutions [6]. Normally, the application of sawdust is in the manufacture of compressed biofuels or for making compressed wood boards [7], but new applications should be explored. A mixing machine will be added to the typical industrial sludge drying setup which consists of a belt dryer and sludge extruder. Sawdust/sludge mixtures are extruded and then dried in the belt dryer. The investment cost will slightly increase because of the addition of the mixing machine. However, as mentioned above the operation cost will be reduced significantly because the reduction of the drying time, altogether the overall cost will be reduced.

Furthermore, sludges are heterogeneous mixtures of microorganisms, mineral particles, colloids, organic polymers and cations, whose composition varies considerably depending on sample origin [8]. Their drying behavior may strongly vary from one sludge sample to another and sawdust addition may have a different influence on the drying behavior.

Within this context, the present work aims to determine the effect of sawdust addition operation on sludges coming from different WWTPs which have different properties. X-ray tomography, a non-destructive imaging technique, is used to follow the 3D characteristics of the bed during the course of drying (volume, exchange surface, void fraction...).

MATERIAL AND METHOD

Material

Sludges were collected after the mechanical dewatering step in three WWTPs located near University of Liège. The initial moisture contents were determined according to standard methods [9]. Before drying, the sludges are stored at a temperature of 4 °C, the way to keep drying properties the same during storage [10]. Table 1 gives some physical and chemical characteristics of the used sludges. The sludge from Embourg has higher moisture content and it is pastier than the sludges from Grosses Battes and Oupeye.

Pine sawdust was collected from a wood pellet factory ('Industrie du bois', Vielsalm, Belgium) and the initial moisture content (wet basis) was around 30%. Table 2 gives the size distribution of the used sawdust.

Table 1. Characteristics of the used sludges.

Sample	Sludge origin	Equivalent population*	Effluent	Dewatering	Initial moisture content (wet basis)
Sludge 1	WWTP of Oupeye, Liège, Belgium	446500	Domestic	Centrifuge	80.0%
Sludge 2	WWTP of Grosses Battes, Liège, Belgium	59040	Domestic	Belt filter	85.5%
Sludge 3	WWTP of Embourg, Chaudfontaine, Belgium	27000	Domestic	Belt filter	88.0%

*Equivalent population (EH) corresponds to an average daily discharge of 180 L of effluent with a load of 90 g of MES, 60 g of BOD5, 135 g of COD, 9.9 g of total nitrogen, and 2 g of total phosphorus.

Table 2. Characteristics of the used sawdust.

Diameter	<0.6 mm	0.6–1.7 mm	1.7–5 mm
Mass percent (%)	20.14%	45.03%	34.83%

In this paper, the drying behavior of several samples was tested: the original sludge, the mixed sludge (the original sludge after mixing without sawdust) and some mixtures (the original sludge after mixing with sawdust). A kitchen machine (KM1000, PROline) with a beater was used to prepare the mixed sludge and the mixtures. The mass ratios (expressed on a dry matter basis for both the sludge and sawdust) of sawdust/sludge were 1/9, 2/8, 3/7 and 4/6. Sludge and sawdust were mixed during 30 s at 40 rpm because longer mixing time and higher mixing velocity will decrease the rigidity of sludge extrudates and drying rate. The same protocol was used to mix the original sludge without any sawdust addition. The samples were then extruded through a disk with circular dies of 12 mm before drying, forming a bed of extrudates on the dryer perforated grid. The initial mass of the bed of extrudates was fixed at 500 g in all experiments.

Pilot-scale dryer

The drying experiments were carried out in a discontinuous pilot-scale dryer reproducing most of the operating conditions prevailing in a full-scale continuous belt dryer, as shown in Fig. 1. A fan (a) draws in ambient air and then the air is heated up to the required temperature by a set of electrical resistances (b). If needed, the air is humidified just after heating by adding vapor from a vapor generator. Hot air flows through the bed of sludge extrudates (c), which lies on a perforated grid (d) linked to scales (e). The inner diameter of the sample holder is 160 mm. Three operating parameters may be controlled: air temperature, superficial velocity, and humidity. In this study, the temperature was 80 °C, with air velocity fixed at 2 m/s. No additional air humidification was carried out. During the whole study, the ambient air humidity was close to 0.004 $kg_{water}/kg_{dry\ air}$. For the drying experiments, the sample was continuously weighed during the drying test until the weight reached constant and its mass was recorded every 10 s.

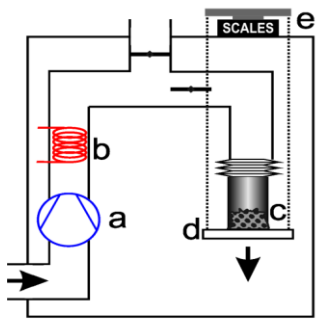


Fig. 1. Convective pilot-scale dryer.

Mechanic properties

A LS series advanced, single column, universal testing machine (AMETEK Lloyd Instruments Ltd, UK) was used to determine mechanic properties of sludges and sawdust/sludge mixtures. A self-defined compression test was performed for different samples. The steps are: at first press samples to a limit position with a ball, then hold at a fixed time and finally withdraw. In all our compression test experiments, the limit position is 10 mm below sample surfaces, the moving speed is 1 mm/s and the holding time is 60 s. The rate of withdraw is 1 mm/s and in the end the ball returns to the starting position. The diameter of the ball is 30 mm.

X-ray tomography

The X-ray tomographic device used in this paper was a high-energy X-ray tomography, first presented by Toye et al. [11]. The generator is a Baltograph CS450A (Balteau NDT, Belgium), which may be operated between 30 and 420 kV. The X-ray source is an oil-cooled, bipolar TSD420/0 tube (Comet and Balteau NDT), whose intensity may be varied between 2 and 8 mA depending on the voltage used. A lead collimator produces a 1 mm thick fan beam. The detector is an X-Scan 0.4f2-512-HE manufactured by Detection Technology (Finland). This detector consists of a linear array of 1280 photodiodes each coupled with a $CdWO_4$ scintillator. The mechanical rig designed by Pro Actis, Belgium, consists of two parts, a source–detector arm and a rotating table on which the object to be scanned is fixed. This arm is embedded in a carriage that slides on two vertical high precision machined rails. The rig allows vertical movement up to 3780 mm, keeping verticality and horizontality errors within 1 mm. The maximum diameter of the sample that can be tested is 0.45 m.

The extrudates bed to be scanned is put on the turntable whose rotation is obtained by a synchronous motor equipped with a frequency validator which is supervised by the data acquisition system. Once the sample is put on the turntable, projections of several slices of the bed are recorded around 360°. Reconstruction of the cross sections was obtained by a classical linear back-projection algorithm adapted to the fan beam geometry implemented in the Fourier domain. Three-dimensional images were obtained by stacking 2D reconstructed sections.

In our experiments, the energy of the source was 420 kV and 3.5 mA, the pixel size of the image was 0.36 mm and the distance between two slices was 2.2 mm.

Image analysis

Gray-level images provided by X-ray tomography are formed by two phases: the pore space at low gray levels (dark pixels) and sludge extrudates at high gray levels (bright pixels). A circular mask corresponding to the inner diameter of the drying chamber was first constructed to isolate the sludge bed from the background. Then binarization, i.e. assigning the value 1 to pixels belonging to the solid and the value 0 to the pixel belonging to the voids, was performed following Otsu's method [12].

The bed volume was the total volume of the volume-of-interest (VOI) and the calculation method was simply the total number of voxels of (solid and space) in the VOI timed the voxel volume.

The total exchange surface was calculated by the total perimeter of the air/solid interface in 2D images, i.e. the pixel edges shared by void and solid pixels, timed the distance between two slices.

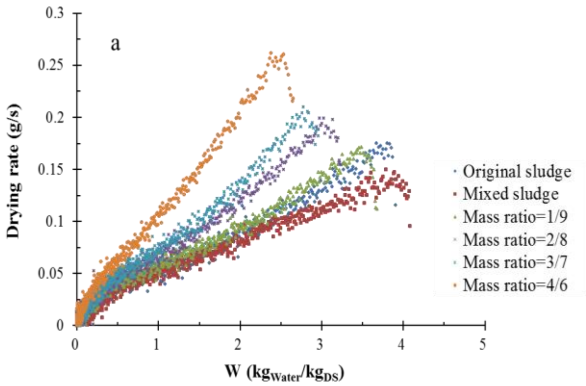
The void fraction was determined by dividing the number of pixels corresponding to the void space by the total number of pixels of VOI (void +solid).

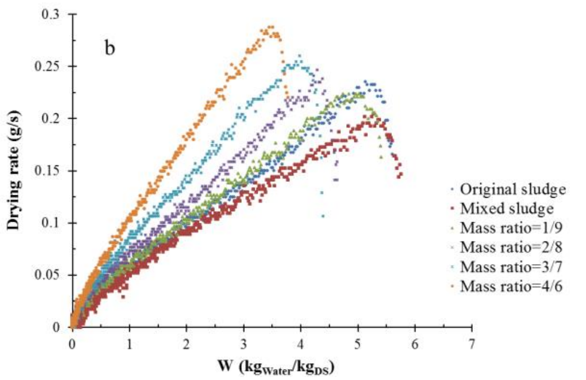
All these operations were implemented in Matlab (Matworks), using the image analysis toolbox version 6.0.

RESULTS AND DISCUSSION

Drying kinetics

The influence of the mixing step (no mixing against 30 s at 40 rpm) and of the sawdust/sludge ratio (1/9, 2/8, 3/7 and 4/6 on a dry basis) has been investigated. Fig. 2 shows the drying rate vs. moisture content for the three sludges. As shown in previous work [13, 14], the drying rate is lower for the sludge after the mixing step and the addition of sawdust allows to recover the drying rate and even to go higher. It is worth to mention that the drying rate of the sludge from Emboug is significantly lower than the sludge from Ouyeye and Grosses Battes, even though the initial moisture content is higher. Moreover, with the same ratio of sawdust addition, the drying rate of mixture with the sludge from Embourg remains lower than the mixture with the sludge from Ouyeye or Grosses Battes.





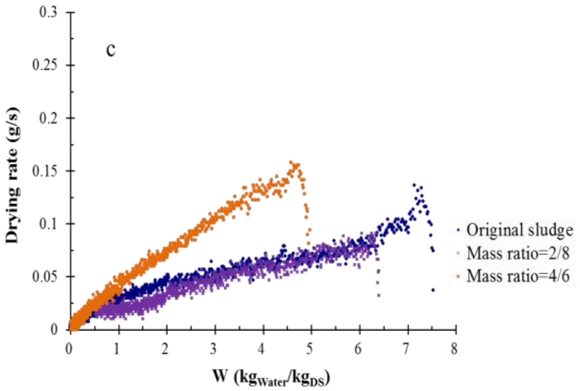


Fig. 2. Drying rate vs. moisture content. (a) Oupeye WWTP. (b) Grosses Battes WWTP. (c) Embourg WWTP.

In order to compare the drying kinetics of different samples, some drying characteristics including the total amount of sludge, total amount of evaporated water, normalized amount of water, drying time, average drying rate and normalized drying rate are shown in Table 3.

As mentioned above, the initial mass of the bed of extrudates was fixed at 500 g. So with higher sawdust addition the total amount of sludge and evaporated water both decrease. However, the drying time also varies. By dividing the drying rate by the drying time, the average drying rate is obtained and then the normalized drying rate can be obtained by taking the average drying rate of the original sludge as a base. The results showed the average drying rates were 0.062 (Oupeye), 0.079 g/s (Grosses Battes) and 0.042 g/s (Embourg) respectively, using raw sludges. This means the pastiest sludge in these three sludges has the lowest drying rate.

Table 3. Drying characteristics of sludges and sawdust/sludge mixtures.

Sludge origin	Sample	Total amount of sludge (g)	Total amount of evaporated water (g)	Normalized amount of water	*Drying time 95%DS (s)	Average drying rate (g/s)	Normalized drying rate
Oupeye	Original sludge	500	398	1.000	6370	0.062	1.000
	Mixed sludge	500	402	1.009	7280	0.055	0.883
	Mass ratio=1/9	485	393	0.988	6030	0.065	1.043
	Mass ratio=2/8	467	382	0.960	5440	0.070	1.124
	Mass ratio=3/7	445	374	0.939	5280	0.071	1.133
	Mass ratio=4/6	420	363	0.912	3940	0.092	1.475
Grosses Battes	Original sludge	500	424	1.000	5370	0.079	1.000
	Mixed sludge	500	426	1.005	7130	0.060	0.759
	Mass ratio=1/9	489	422	0.995	5970	0.071	0.899
	Mass ratio=2/8	475	411	0.969	4770	0.086	1.089
	Mass ratio=3/7	459	407	0.960	4280	0.095	1.203
	Mass ratio=4/6	439	395	0.932	3720	0.106	1.342
Embourg	Original sludge	500	441	1.000	10490	0.042	1.000
	Mass ratio=2/8	479	433	0.980	13060	0.033	0.787
	Mass ratio=4/6	449	416	0.943	8510	0.049	1.162

*Drying time 95%DS: The drying time that the dry solid content (DS) reaches to 95%.

Moreover, for the sludge from Embourg the positive impact of sawdust addition is weaker. The normalized drying rate increases to 1.124 for Oupeye and 1.089 for Grosses Battes but decreases to 0.787 for Embourg when the mass ratio of 2/8 was used. The normalized drying rate increases to 1.475 for Ouyeye, 1.342 for Grosses Battes, and 1.162 for Embourg when the mass ratio of 4/6 was used. Sawdust addition is benefit for the drying rate of three sludges which have different moisture content and pasty degree. However, more sawdust should be added into this pastiest sludge.

Mechanical properties

The mechanical properties were tested by using the universal testing machine mentioned above and the results of the load vs. extension from preload are shown in Fig. 3. There are three periods in each curve and the change laws are approximate. First, the load increases because the ball presses the sample until it reaches 10 mm below the surface. Then the load decreases slowly. This is because the ball holds in this position and the elasticity of the sample causes relaxation. At last, when the ball withdraws the load decreases fast. Moreover, there are some negative values of the load when the ball is out of the sample. This is due to the viscosity of the sample. From Fig. 3 we can see the values of the load for three different sludges are different and the sawdust addition also changes the value of the load.

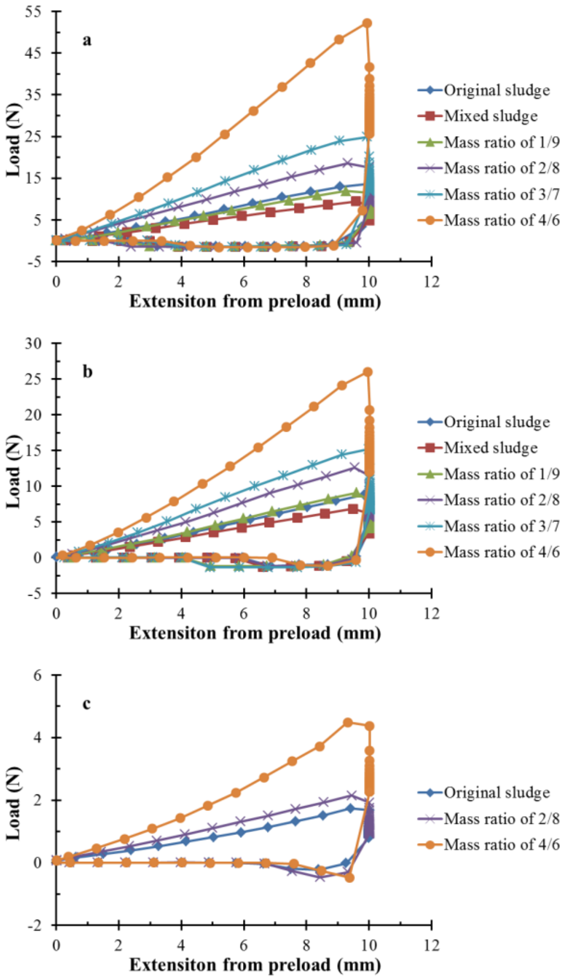


Fig. 3. Load vs. extension from preload. (a) Oupeye WWTP. (b) Grosses Battes WWTP. (c) Embourg WWTP.

Fig.4 gives the maximum load vs. ratio of sawdust/sludge for the three sludges. The maximum load of each sample in this figure is the average value of four repeated experiments. In fact, the maximum compression load represents the rigidity of the sample [15, 16]. The bigger value of the maximum compression load means the higher rigidity and large deformability, which can keep the sample shape better. With lower rigidity and small deformability, the extrudates cannot keep the sample shape and are easier to stick together in the sample bed. From Fig. 4 we can see that the maximum load of the original sludge from Oupeye is the biggest and from Embourg is the smallest. Comparing with the initial moisture content of sludges, it is obvious that higher moisture content of sludge decreases the rigidity and causes smaller deformability. Moreover, the maximum load decreases after the mixing step and increases with increasing the addition of sawdust. This means the mixing step decreases the rigidity and the sawdust addition increases the rigidity. For the sludges from Oupeye and Grosses Battes, the exponential curve fitting was used for the results of the maximum load of the mixed sludge and sawdust/sludge mixtures. The fitting results are shown in Fig. 4 and the correlation coefficients are 0.9944 (Oupeye) and 0.9756 (Grosses Battes) respectively.

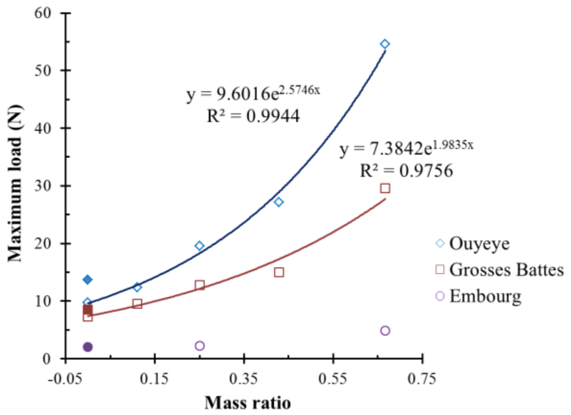


Fig. 4. Maximum load vs. ratio of sawdust/sludge. The solid symbols are the original sludges and the hollow symbols are the mixed sludges and sawdust/sludge mixtures.

2D cross-sections

By using X-ray tomography and the image analysis, 2D cross-sections and 3D images can be obtained, as shown in a previous work [17]. Fig. 5 shows the 2D cross-sections of the original sludge, the mixture of the mass ratio of 4/6 before drying for the three sludges. The positions of these 2D cross-sections are all 8.8 mm from the sample bottom. In these images the black part are the solid and the white part are the void. For the original sludge of Oupeye which has smallest initial moisture content in the three sludges, the extrudates are good columnar shapes and the void is big. However, for the original sludge of Grosses Battes which has higher initial moisture content than Oupeye, the shapes of extrudates become less regular and the void becomes smaller. For the original sludge of Embourg which has the highest initial moisture content in the three sludges, the extrudates are gelatinous shapes and the void is very small. Moreover, the sawdust addition has significant influence on the 2D cross-sections. By comparing the Fig. 5(a) and 5(b), for the sludge of Oupeye, with the sawdust addition (mass ratio=4/6), the diameter and length of extrudates both become smaller and more granules appear. By comparing the Fig. 5(e) and 5(f), for the sludge of Oupeye, with the sawdust addition (mass ratio=4/6), the extrudates separate and the void becomes obvious.

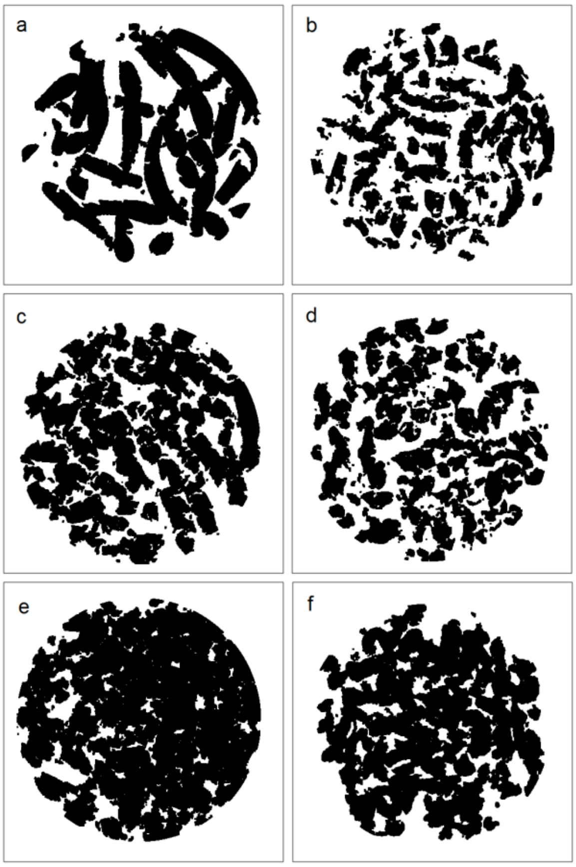


Fig. 5. 2D cross-sections of the sample bed before drying. (a) Oupeye, original sludge. (b) Oupeye, mixture of a mass ratio of 4/6. (c) Grosses Battes, original sludge. (d) Grosses Battes, mixture of a mass ratio of 4/6. (e) Embourg, original sludge. (f) Embourg, mixture of a mass ratio of 4/6.

As mentioned above, the void of the bed of different samples changes significantly. In order to investigate it in detail, the results of the initial void fraction of all sample beds are shown in Fig. 6. The initial void fraction of the original sludge from Oupeye is the biggest and from Embourg is the smallest. Moreover, the void fraction decreases after the mixing step and increases with increasing the addition of sawdust. For the sludges from Oupeye and Grosses Battes, the linear curve fitting was used for the results of the initial void fraction of the mixed sludge and sawdust/sludge mixtures. The fitting results are shown in Fig. 6 and the correlation coefficients are 0.7537 (Oupeye) and 0.7822 (Grosses Battes) respectively.

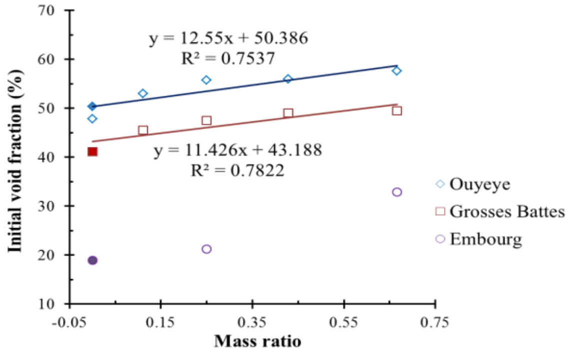


Fig. 6. Initial void fraction vs. ratio of sawdust/sludge. The solid symbols are the original sludges and the hollow symbols are the mixed sludges and sawdust/sludge mixtures.

Bed volume and total exchange surface

Besides the void fraction, the bed volume and total exchange surface can be obtained by image analysis as well. The results of the bed volume vs. ratio of sawdust/sludge of three sludges before and after drying are shown in Fig. 7. Among the three sludges, the initial bed volume of the original sludge from Oupeye is the biggest and from Embourg is the smallest. As mentioned above, the reason is that the pastier sludge is not easy to keep form and the extrudates stick together because of small rigidity. The initial bed volume slightly decreases after the mixing step. However, the initial and final bed volumes both significantly increase with the increased sawdust addition. For the sludge from Oupeye and Grosses Battes, the linear curve fitting was used for the results of the initial and final bed volumes of the mixed sludge and sawdust/sludge mixtures. The fitting results are shown in Fig. 7 and the correlation coefficients are 0.9893 (Oupeye, wet), 0.9712 (Oupeye, dry), 0.871 (Grosses Battes, wet), and 0.8965 (Grosses Battes) respectively.

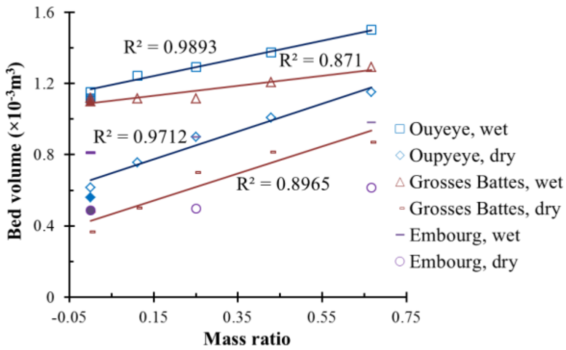


Fig. 7. Bed volume vs. ratio of sawdust/sludge. The solid symbols are the original sludges and the hollow symbols are the mixed sludges and sawdust/sludge mixtures.

The results of the total exchange surface vs. ratio of sawdust/sludge of two sludges before and after drying are shown in Fig. 8. It is worthy to mention that among the three sludges, the initial bed volume of the original sludge from Grosses Battes is the biggest and from Embourg is the smallest. This result is in accordance with the result of the drying rate of three original sludges. The possible reasons are as follows: Higher moisture content leads to the phenomenon that the extrudates stick together and this decreases the surface. Lower moisture content creates big columnar extruates and this decreases the surface. The initial total exchange surface decreases when plays the mixing step but significantly increases with the increased sawdust addition. For the sludges from Oupeye and Grosses Battes, the linear curve fitting was used for the results of the initial and final total exchange surfaces of the mixed sludge and sawdust/sludge mixtures. The fitting results are shown in Fig. 8 and the correlation coefficients are 0.9753 (Oupeye, wet), 0.9902 (Oupeye, dry), 0.985 (Grosses Battes, wet), and 0.9796 (Grosses Battes) respectively.

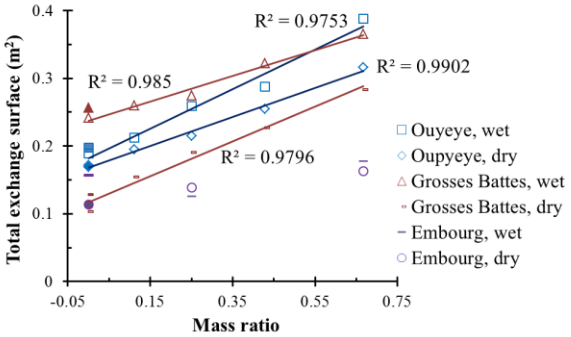


Fig. 8. Total exchange surface vs. ratio of sawdust/sludge. The solid symbols are the original sludges and the hollow symbols are the mixed sludges and sawdust/sludge mixtures.

In accordance with the convective drying theory [18], three periods can be identified in our drying experiments: the very short preheating period, the very short constant rate period and the long falling rate period. The falling rate period also can be divided into the first decreasing zone and second decreasing zone. In the constant rate period and the first decreasing zone of the falling rate period, the drying rate is related to the total exchange surface. In order to further explore their relationship, the values of the maximum drying rate and total exchange surface of all samples in our experiments are summaried and the results are represented in Fig. 9. The maximum drying rate appears in the constant rate period. During this period, the total exchange surface keeps constant and is equal to the initial total exchange surface. The maximum drying rate has a good linear increase relationship with the initial total exchange surface (the correlation coefficient is 0.8904), even for different sludge origins. Hence, increase of the initial total exchange surface is an effective method to increase the drying rate of sludge. This also convinces that sawdust addition is a positive mean for sludge drying because of the increase of the initial exchange surface.

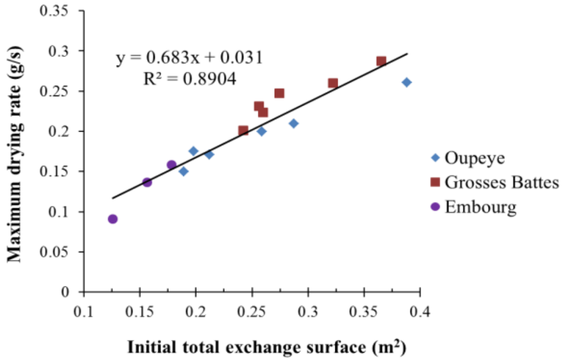


Fig. 9. Maximum drying rate vs. initial total exchange surface.

CONCLUSIONS

This work investigated the effect of sludge origin on the convective drying of sawdust/sludge. Three sludges which come from Oupeye WWTP (MS=80%), Grosses Battes WWTP (MS=85.5%), and Embourg WWTP (MS=88%) were used in our experiments. The sludge is pastier when the moisture content is higher. The influence of the mixing step (no mixing against 30 s at 40 rpm) and the sawdust/sludge ratio (1/9, 2/8, 3/7 and 4/6 on a dry basis) have been investigated. Drying experiments were carried out in a convective pilot-scale dryer.

Mechanical property test showed that the rigidity of the original sludge from Oupeye is the biggest and from Embourg is the smallest. Big rigidity causes the good columnar shapes of extrudates, big initial void fraction and initial bed volume. On contrary, small rigidity leads to gelatinous shapes, small initial void fraction and initial bed volume. It is worthy to mention that among the three sludges, the initial total exchange surface of the original sludge from Grosses Battes is the biggest and from Embourg is the smallest. The possible reasons are: Higher moisture content leads to the phenomenon that the extrudates stick together and this decreases the surface. Lower moisture content creates big columnar extruates and this decreases the surface.

The mixing step has a negative impact, the rigidity, initial bed volume, total exchange surface, and drying rate all decrease. However, the sawdust addition has a positive impact, the rigidity, void fraction, initial bed volume, total exchange surface and drying rate all increase with increasing the addition of sawdust for three sludge. For the sludge from Embourg the positive impact of sawdust addition is weaker. The normalized drying rate increases to 1.475 for Ouyeye, 1.342 for Grosses Battes, and 1.162 for Embourg when the mass ratio of 4/6 was used, so more sawdust should be added into this pastiest sludge. Increase of the initial total exchange surface is an effective method to increase the drying rate of sludge.

Further work will be done in order to characterize the structure of the samples during drying. The behaviour of these samples during pyrolysis using thermo gravimetric analysis will also be investigated.

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