RSC Advances

PAPER

Cite this: RSC Adv., 2016, 6, 9725

Effect of back mixing on thin-layer drying characteristics of sewage sludge by the appropriate foaming pretreatment

Lijun Zhao,[ab] Zhaohui Yang,*[ab] Jing Huang,[ab] Jingwu Yan[ab] and Rui Xu[ab]

Received 21st October 2015
Accepted 4th January 2016

DOI: 10.1039/c5ra21987f

www.rsc.org/advances

Herein, we report the creative combination of foaming and back mixing. Back mixing was simulated by the addition of dried foamed sludge (DFS) to raw sludge. Different ratios of (DFS + CaO), DFS shape and dosing sequence were investigated on the influence of sludge foamability and drying efficiency. Experimental results indicate that back mixing has positive effects on sludge foaming and sludge foam stability. Moreover, CaO is still dominant in the sludge foam. The best addition ratio is 10 g DFS + 10 g CaO for 1 kg of fresh sludge with an optimal dosing sequence of first CaO followed by DFS after 5 min. In addition, foam-mat drying for dewatered sludge is not greatly subjected to the DFS shape. During foam-mat drying, a high drying rate appears at a high foam density (>0.70 g cm^{-3}). The foamed sludge of 0.80 g cm^{-3} has the fastest drying speed at 30 °C, whereas the best drying density is 0.90 g cm^{-3} at 50 °C. Moreover, the drying rates of foamed sludge were higher when the temperature was increased from 30 °C to 50 °C. In addition, mathematical modelling results demonstrate that the Logistic model is the most adequate model to describe the entire convective drying of thin layer sludge under the best drying density both at 30 °C and at 50 °C.

1. Introduction

Nowadays, with the rapid urbanization and stringent environmental regulations, sewage treatment has caused a significant increase in the annual sewage sludge production.[1] Because of its high water content (generally over 70–80%),[2] sludge management has become a severe challenge due to its final treatment and disposal. In general, sludge drying is an essential step to further reduce the water content of dewatered sludge.

It is well known that thermal drying is a common and established method to eliminate water in sewage sludge by delivering energy to the system.[3] Compared with thermal drying, lime drying is also widely applied due to its simple operation, low cost, and because it is mostly odor-free.[3–5] Furthermore, solar drying,[6,7] bio-drying[8,9] and fry-drying[10] have also been paid more attention by many researchers in recent decades. Nonetheless, there are still some limitations of these drying processes such as large energy consumption, expensive facilities[5] and longer average time-consumption.[11,12] Hence, innovative drying methods for sewage sludge need to be further developed.

Foam-mat drying shows promise as an effective and novel technology to realize the fast drying of dewatered sludge. Currently, this process is popular and successful, especially in the food industries.[13–15] Liquids or semi-liquids are mechanically whipped to form stable foams with open structures and large surface areas, with the aim to facilitate moisture evaporation and moisture movement by capillarity in liquid films.[16] The foam-mat drying process is characterized by lower drying temperatures and short drying times, especially for sticky and viscous materials.[17] As dewatered sludge is highly viscous and sticky, the combined use of foaming pretreatment and thermal drying seems to be a new route to reinforce the drying rate of dewatered sludge. In this way, our previous studies have found that proper amounts of CaO could make dewatered sludge foam by stirring and the optimal dosage of CaO is 2.0 wt% relative to the total weight of dewatered sludge in wet basis.[17,18] However, there are still two inevitable problems. On the one hand, the dosage of CaO is practically large during this foaming process. On the other hand, the reuse of subsequent DFS appears to be the main priority. DFS is pathogen-free, easily compressed and significantly saves the calorific value of sludge after foam-mat drying.

To the best of our knowledge, back mixing is a common and important process for sludge drying, which is mainly used to improve the initial sludge texture structure through the backflow of dried material.[19] The sludge texture reinforcement leads to an increase of sludge-bed porosity,[20] which exhibits significant influence on sludge drying. Leonard[20] *et al.* revealed that back mixing plays a positive role on the drying kinetics of sewage sludge through the enhancement of the area available for heat and mass transfer. It was also found that the back

[a]College of Environmental Science and Engineering, Hunan University, Changsha 410082, China. E-mail: yzh@hnu.edu.cn; Fax: +86-731-88822829; Tel: +86-731-88822829

[b]Key Laboratory of Environmental Biology and Pollution Control, Hunan University, Ministry of Education, Changsha 410082, China

mixing of dried sludge can improve the mixing effect of the paddle dryer to effectively alleviate the unfavorable lumpy phase effect.[21] Moreover, solid particles in the sludge foam system improve the foam stability, because the particles could bridge gas bubbles in close contact and increase the viscosity of the sludge.[22] Thus, based on the abovementioned factors, the creative combination of foaming and back mixing is a feasible option to further study the effect of back mixing on foaming and drying of dewatered sludge. At the same time, this process also decreases the dosage of CaO. In addition, mathematical modelling of thin layer drying is essential for optimum management of the operating parameters and prediction of performance of the drying system.[23]

The objective of this study is to focus on investigating the effects of different parameters on the foamability and drying efficiency of dewatered sludge, including different ratios of DFS and CaO, DFS shape and dosing sequence. Moreover, different temperatures (30 °C and 50 °C) were selected to analyze their effect on the sludge drying efficiency. Moreover, several thin-layer drying models were also employed to simulate the entire convective drying of dewatered sewage under the optimal conditions, in order to provide more convenient and detailed information for the practical application of this method.

2. Materials and methods

2.1. Materials

Fresh sludge was collected after mechanical dewatering with cationic polymeric flocculants as conditioner from a local wastewater treatment plant (WWTP) in Changsha, China. Approximate 150 000 m^3 of wastewater is treated there on a daily basis though an Anoxic-Anaerobic-Carrousel process. The main characteristics of the dewatered sludge are listed in Table 1. Considering its organic constituents, the dewatered sludge must be stored at 4 °C before each experiment, and the corresponding experiments should be completed in a relatively short time.

The initial amount of dewatered sludge used in every experiment was 1 kg. By the sole feeding of 20 g CaO, the dewatered sludge was mechanically whipped to form foamed sludge. DFS was attained by drying the foamed sludge at 0.70 g cm^{-3} to a constant weight at 105 °C. Then, two types of dried sludge (DS) were prepared, A and B. A, powdered DFS (PDFS), was obtained by grinding DFS into fine powder (FP) and filtering it from a mesh sieve at the size of 60 items. B, lumpy DFS (LDFS), was a product with a random shape without any physical and chemical treatment. Moreover, all other reagents used were of analytical grade, and the water used in experiment was ultrapure water (UPW).

Table 1 The characteristics of the dewatered sludge

Dewatered sludge		Solvent phase of sludge suspension	
Moisture content (wet basis %)	86 ± 1	pH	7.81
Volatile solid (dry basis %)	54.2	Surface tension (mN m^{-1})	70.5
Density (g cm^{-3})	1.02	Protein (mg L^{-1})	51.33

2.2. Sludge foaming

Foam formation occurred by whipping the dewatered sludge with the addition of different ratios of DFS and CaO using a cement mortar mixer (JJ-5, JIANYI, China) at 140 ± 5 rpm. Moreover, different sludge densities were obtained by controlling the whipping time. Sludge density was determined by the mean ratio of the measured weight using one conical measuring cylinder with the full-loaded water weight of 206.6 g. In this process, the sludge transfer must be more careful to avoid destroying the foam structure and to ensure that there are no voids while filling the foamed sludge into the conical measuring cylinder.

Back mixing was simulated by adding increasing quantities of DFS to the fresh sludge. DFS is regarded as a substitute for CaO, but the total mass of DFS and CaO was constant, namely, 20 g. Different ratios were designed as follows: 0 g DFS + 20 g CaO, 5 g DFS + 15 g CaO, 7.5 g DFS + 12.5 g CaO, 10 g DFS + 10 g CaO, 12.5 g DFS + 7.5 g CaO, 15 g DFS + 5 g CaO, and 20 g DFS + 0 g CaO. According to the observation of density change, the foaming speed of the dewatered sludge was analyzed and compared regarding the different addition ratios of DFS and CaO. Then, the optimum addition ratio was established through the foaming speed. Next, under the optimal mixing ratio, the effects of the DFS shape and dosing sequence were also studied on sludge foaming and drying characteristics.

2.3. Drying characteristics of foamed sludge

Drying of foamed sludge was performed in a drying oven (150 L) with the air temperatures of 30 °C and 50 °C, the relative humidity of 20% and superficial air velocity of 0.2 m s^{-1}. Prior to each test, the drying oven was thermally stabilized by passing hot air at the pre-set temperature for 30 min. In the drying process, every 10.00 g sludge sample was poured in a Petri dish (60 mm diameter and 12 mm height) and the density was determined from the thickness of the sludge foam mat. Moisture loss from the samples within the time interval of 20 min was determined by weighing the dish outside the drying oven using an electronic balance (±0.01). Moreover, the moisture content (MC) of sludge was determined by the mass loss after drying at 105 °C to a constant weight. During the drying procedure, the moisture content of the samples was calculated according to their initial value and the mass loss at every interval. To analyze the influence of back mixing on the foam-mat drying characteristics of the sludge, drying curves and the drying rate curves were plotted to evaluate the evaporation rate at any given moisture content on dry basis.

In our experiments, the optimum addition ratio was chosen from the abovementioned ratios to further study the drying behavior of the foamed sludge. The addition ratio of 0 g DFS + 20 g CaO was used as the control group. Moreover, the various densities of foamed sludge also affected its drying. 0.70 g cm^{-3} was chosen as the key density, given that the foamed sludge at 0.70 g cm^{-3} has the best drying performance by the addition of

20 g CaO.[18] Moreover, considering the economic benefit and easy operation, three foam densities were studied, including 0.70 g cm^{-3}, 0.80 g cm^{-3}, and 0.90 g cm^{-3}. Herein, fresh sludge was taken as a reference. In addition, the influence of drying temperature on sludge drying was also studied.

2.4. Preparation and characterization of the sludge suspension

The sludge suspension was prepared by blending the foamed sludge with distilled water in the mass ratio of 1 : 2 and mechanically stirring for 240 min. Then, the supernatant was obtained by separating the sludge suspension at the rotational speed of 10 000 rpm for 10 min in a centrifuge (Allegra 25R, Beckman Coulter, USA). The properties of the sludge suspension were mainly characterized by determining the nature of the supernatant, including pH, surface tension and protein content.

The surface tension and pH of the sludge suspension samples were measured using a surface tensiometer (JZ-200A, Chengde, Chinese) and pH-meter (PB-10, Sartorius, Germany), respectively. Then, the supernatant obtained was further filtered through a mixed cellulose ester membrane with 0.22 μm micropores to separate any residual biomass and thus eliminate interferences to the protein determination. Protein content was determined using the Coomassie Brilliant Blue (CBB) method with bovine serum albumin (BSA) as the standard.

2.5. Mathematical modelling of drying curves

The moisture content values obtained from the drying experiments were converted into the moisture ratio (MR). The dimensionless MR was calculated using eqn (1):

$$\mathrm{MR} = \frac{M_t - M_e}{M_0 - M_e} \tag{1}$$

where M_t, M_e and M_0 are the moisture content at a given time, equilibrium moisture content and initial moisture content, respectively. The values of M_e are relatively small compared to those of M_t or M_0, and the error involved in the simplification is negligible,[24] thus moisture ratio was calculated as follows:

$$\mathrm{MR} = \frac{M_t}{M_0} \tag{2}$$

The experimental results of moisture ratio *versus* drying time were fitted to five different drying kinetics models using nonlinear regression *via* the Origin Pro10.0 software. The coefficient of correlation (γ) was the primary criterion to select the best equation, and mean squared deviation (χ^2) was used to determine the suitability of the fit.

3. Results and discussion

3.1. Effect of addition ratios on sludge foam density and stability

3.1.1. Sludge foam density. In general, foamability can be evaluated by the measurement of foam density. During mechanical blending, more air enters into the foam to form lower foam density when the stirring time is increased. The effects of stirring time and the adding ratio (DFS + CaO) on the sludge foam density are illustrated in Fig. 1.

As the stirring time increased, the sludge density began to decrease. However, its variation trend was different with the addition ratios of DFS + CaO. It was observed that when the addition ratios were 20 g DFS + 0 g CaO and 15 g DFS + 5 g CaO, the sludge density first briefly decreased to approximately 0.95 g cm^{-3} and 0.97 g cm^{-3} in 20 min, respectively, then continued to increase even beyond the initial density of fresh sludge. The subsequent increase in foam density may be mainly attributed to the increase in the viscosity of the mixture due to excess DFS, which possibly exceeds the limiting value in order to prevent the entry of more air. However, once increasing doses of CaO are added, the sludge foamability can be also strengthened to different degrees. This implies that CaO may be dominating in the admixture of CaO and DFS during sludge foaming.

As shown in Fig. 1, for the control group (0 g DFS + 20 g CaO), the sludge indeed has a better foamability. The final density of sludge could decrease to approximately 0.55 g cm^{-3} after 140 min. However, compared with the control group, the sludge foamability weakened at the addition ratio of 12.5 g DFS + 7.5 g CaO. The sludge density only reached 0.75 g cm^{-3} after 140 min and the foaming speed also obviously slowed down. However, it was amazing that the dewatered sludge could significantly foam in the case of these ratios, including 10 g DFS + 10 g CaO, 7.5 g DFS + 12.5 g CaO and 5 g DFS + 15 g CaO. After 140 min, the lowest foam density decreased to 0.36, 0.27, 0.24 g cm^{-3}. Furthermore, the foaming speed tended to be faster than that of the control group. As the best drying density of the control group,[18] 0.70 g cm^{-3} was chosen as the key discussion point, with the aim to easily highlight the positive effect of back mixing on foaming. By analyzing the experimental data, it was found that the sludge density can almost reach 0.70 g cm^{-3} after around 40 minutes. Compared with the control group, the stirring time required to achieve the density of 0.70 g cm^{-3} is shortened by around 42%. This suggests that a proper amount

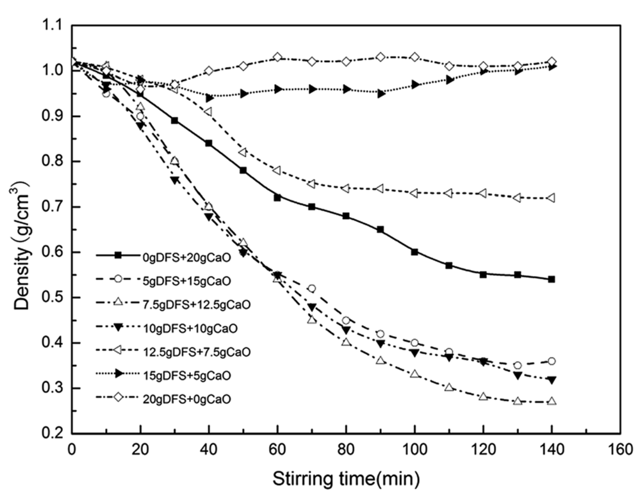

Fig. 1 Effect of stirring time and addition ratios (DFS + CaO) on the sludge foam density (dosing sequence: synchronous addition of DFS and CaO before stirring; DFS shape: PDFS).

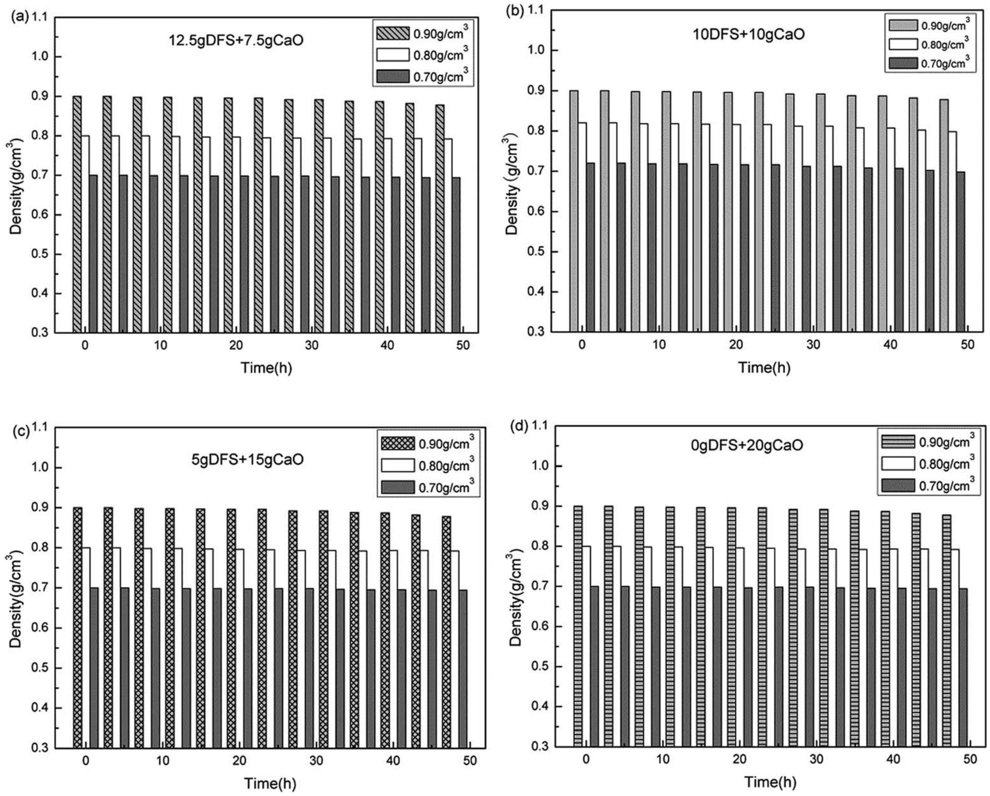

Fig. 2 Variation of sludge foam density over time at different initial densities under the different addition ratios (DFS + CaO) (dosing sequence: synchronous addition of DFS and CaO before stirring; DFS shape: PDFS).

of backmixed DFS exerts a positive effect on sludge foaming. Moreover, it was also observed that the foaming speed is a little faster than that of other two ratios when the addition ratio is 10 g DFS + 10 g CaO. Considering the economic and energy consumption, the adding ratio of 10 g DFS + 10 g CaO was chosen as the optimal addition ratio in conclusion.

3.1.2. Sludge foam stability. During the foam-mat drying process, the key factor is the generation of stable foam, which does not collapse during feeding and deposition in the drying system. Foam stability is usually evaluated by the measurement of density variation over a specified time. Practically, foams that do not collapse for at least one hour are considered stable.[25]

According to our experimental results, the stability of foamed sludge with different initial densities was studied by determining the variations of density every 4 h. As shown in Fig. 2, the densities of sludge foam at different initial densities, *i.e.* 0.90, 0.80, and 0.70 g cm^{-3}, had few variations after standing for 48 h for different addition ratios (DFS + CaO). This phenomenon suggests that the sludge foam is stable enough for foam-mat drying under different densities. It is generally acknowledged that solid particles can be considered as a stabilizer to help stabilize the foam.[22,26] Thus, the back mixing of DFS may play a positive role on the sludge foam stability in order to gain better sludge foamability.

3.2. Effect of dosing sequence and DFS shape

The effect of the dosing sequence of DFS and CaO on sludge foaming and the drying rate is illustrated in Fig. 3. In preliminary repeated experiments, it was found that the dewatered sludge foamed after approximately 5 min only when CaO was added. Hence, 5 minutes was chosen as the critical point for the different dosing sequences. Although the sludge foamed well under the different dosing sequences, there are some differences in the foaming speed, as shown in Fig. 3(a). When CaO was first added before stirring, the foaming speed of sludge tended to be faster. This phenomenon demonstrates that CaO is a key constituent in the admixture of CaO and DFS during sludge foaming. Furthermore, in the case of the dosing sequence of CaO, then DFS after 5 min, the foaming speed was the fastest. From this result, it can be concluded that a proper amount of DFS has positive effects on sludge foaming with CaO and may play an important role in foam stabilization as a stabilizer due to solid particles.

In order to further shed light on the effect of dosing sequence, the influence on the drying rate for the sludge foam was also investigated, and 50 °C was chosen as the drying temperature. The result showed that different dosing sequences have a great effect on the drying rate for the foamed sludge at different densities. Combining Fig. 3(b) with Fig. 3(d), it can be found that when CaO was added before stirring, the optimal drying rate appeared at the higher foam density, namely, 0.80 g cm^{-3} or 0.90 g cm^{-3}, no matter when DFS was added. However, the drying rate for the foam sludge at 0.70 g cm^{-3} was abnormally lower than that of the control group. This finding may result from the subsequent increase in the viscosity with the increase of the stirring time. Moreover, when DFS was added prior to CaO, the drying rate for the sludge foam at 0.70 g cm^{-3}, 0.80 g cm^{-3}, and

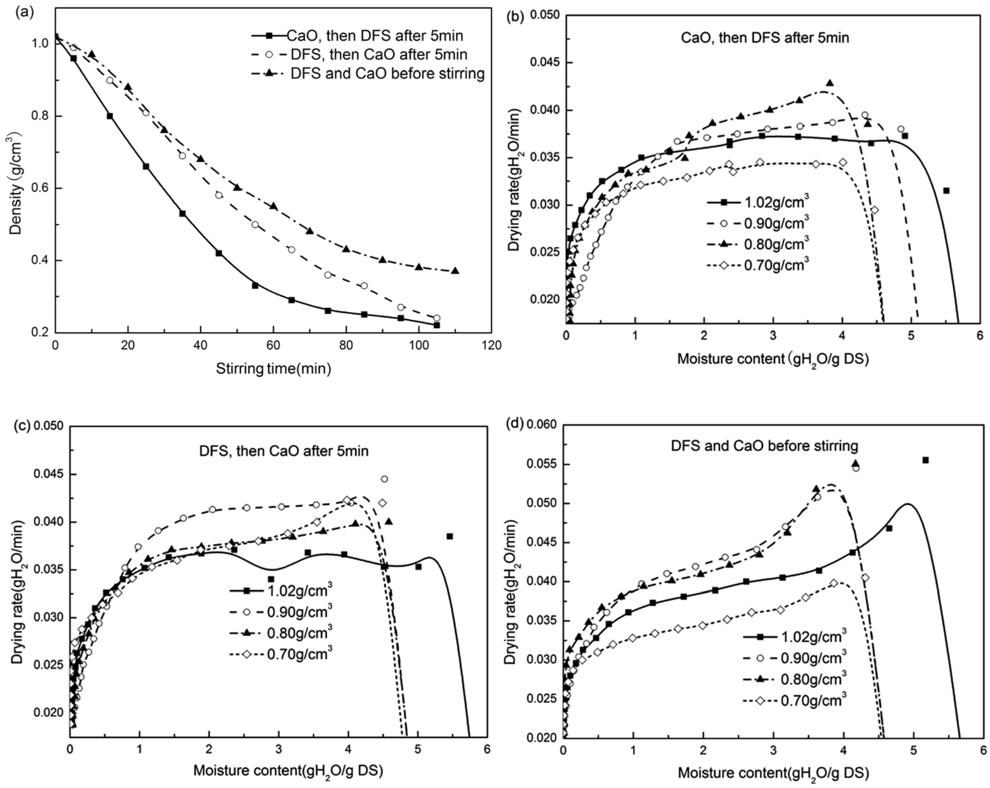

Fig. 3 (a) Effect of different dosing sequences on the sludge foam density; and (b)–(d) effect of different dosing sequences on the drying rate of sludge foam at different densities (the mass ratio of DFS to CaO is 10 g DFS + 10 g CaO; DFS shape: PDFS; and drying temperature: 50 °C).

0.90 g cm^{-3} was faster than that of the control group, which is similar with the previous experiment result.[17,18] The fastest drying speed for the sludge foam still appeared at the higher foam density, *i.e.* 0.90 g cm^{-3}. In summary, first CaO and then DFS after 5 min, is considered as the best dosing sequence in terms of the fastest foaming speed and best drying density.

In addition to the dosing sequence, DFS shape also affects sludge foaming and the drying rates, as shown in Fig. 4. Comparatively, there was no significant difference in sludge foaming, as observed in Fig. 4(a), regardless of LDFS or PDFS. However, as the LDFS was added, the fastest sludge foam drying rate was at the lowest foam density (0.70 g cm^{-3}), as observed in Fig. 4(b). This is almost the same as the previous conclusion with direct addition of 20 g CaO. However, LDFS is still the priority due to easy operation in the practical application, although the foaming time required to attain the best drying density seems to be a little longer than that by adding the PDFS. That is to say, the foam-mat drying for dewatered sludge is not greatly dependent on the DFS shape.

3.3. Drying characteristics of foamed sludge

3.3.1. Drying curve. The influence of the addition ratio (DFS + CaO), foam density and drying temperature on the drying characteristics of sludge foam-mats was studied. Fig. 5(a)–(d) describe the drying curves of foamed sludge at different initial densities and drying temperatures by the foaming pretreatment using the admixture of 10 g DFS + 10 g CaO and 20 g CaO alone. From Fig. 5(a) and (b), it can be seen that when the foamed sludge was dried at 30°, the moisture content, which averaged 5.29 g H_2O/g DS at the beginning, was sharply reduced to 1.04, 1.03 and 2.09 g H_2O/g DS for the initial foam densities of 0.90, 0.80 and 0.70 g cm^{-3}, respectively, after drying for 440 min. Comparatively, foamed sludge at 0.80 g cm^{-3} has the fastest drying speed during the back mixing operation of DFS. However, the moisture content of foamed sludge at 0.90 g cm^{-3} was reduced the fastest at 50 °C. These outcomes are not in agreement with the previous experimental result that lower density (0.70 g cm^{-3}) foam is available for the easier and faster diffusion of water to shorten the drying time by the direct addition of 20 g CaO, as illustrated in Fig. 5(c) and (d). This phenomenon is possibly due to the fact that DFS adsorbed at the surface of sludge can increase the porous structure of the sludge foam and the viscosity of foamed sludge, thus hindering more air into the sludge.

Moreover, from Fig. 5(a)–(d), it is clear that the drying temperature appears to be an important parameter that influences the process time and moisture content of dewatered sludge. As the drying temperature increased to 50 °C, the sludge foam at different densities almost reached the drying equilibrium after 440 min. The drying time required for reducing the moisture content to about 1.0 g H_2O/g DS was approximately 180 min, which is shorter by approximately 60% than that at 30 °C. Overall, the higher temperature results in a shorter drying time.

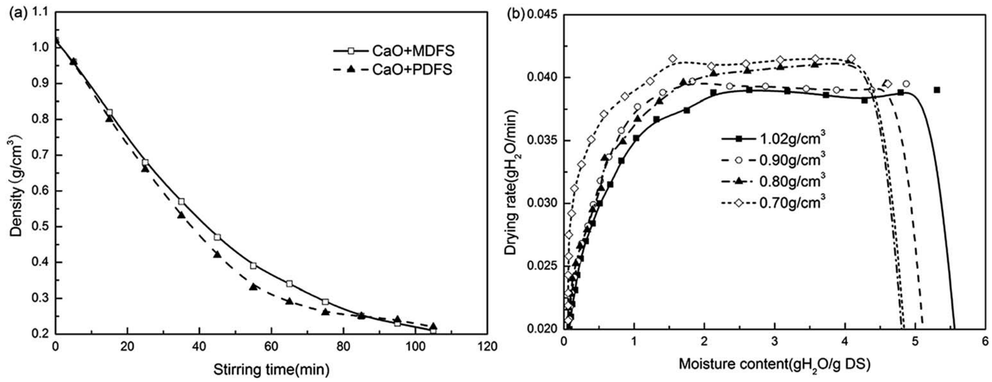

Fig. 4 (a) Effect of DFS shape on the sludge foam density; (b) effect of DFS shape on the drying rate of sludge foam at different densities (the mass ratio of DFS to CaO is 10 g DFS + 10 g CaO; dosing sequence: CaO, then DFS after 5 min; drying temperature: 50 °C).

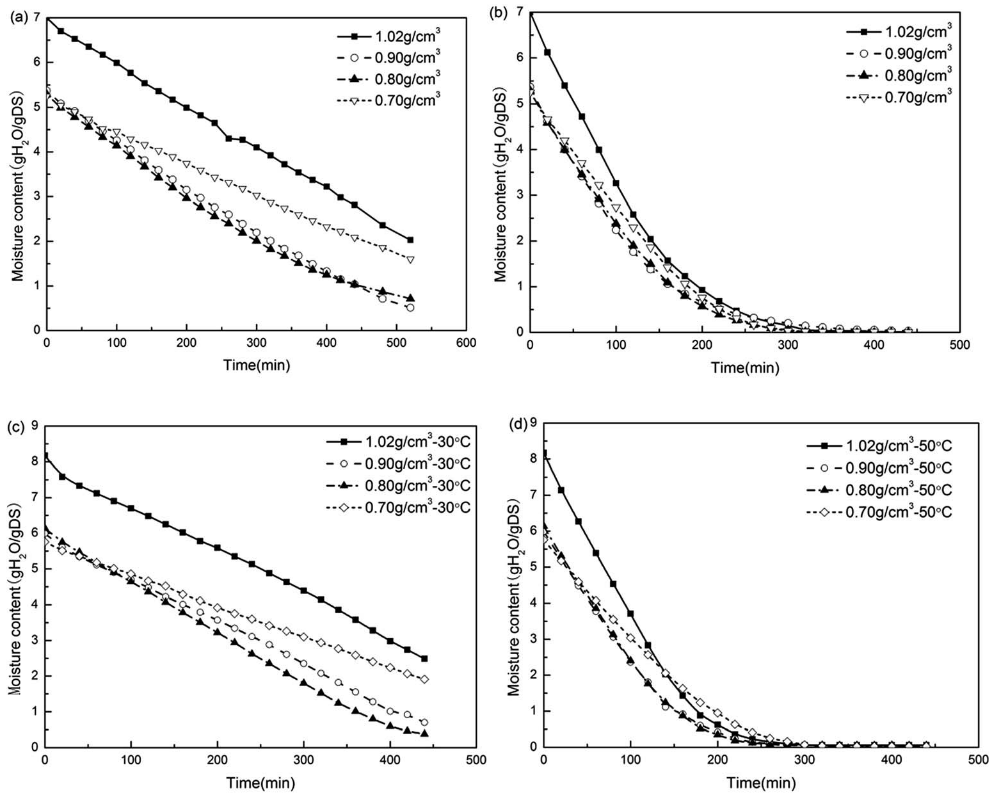

Fig. 5 Drying curves of sludge foam mats at different addition ratios (DFS : CaO) and drying temperatures: (a) 10 g DFS + 10 g CaO, 30 °C; (b) 10 g DFS + 10 g CaO, 50 °C; (c) 20 g CaO, 30 °C; and (d) 20 g CaO, 50 °C (1.02 g cm^{-3} was the density of dewatered sludge without the foaming process; and 0.90 g cm^{-3}, 0.80 g cm^{-3} and 0.70 g cm^{-3} were the densities of the foamed sludge).

3.3.2. Drying rate curve. As presented in Fig. 6(a)–(d), thermal drying of each sludge sample comprised a heat up period at the early stage of drying and then a falling rate stage. The short constant rate period disappeared because of the added DFS, which is entirely consistent with the conclusion observed by Leonard[20] *et al.* Moreover, thin-layer drying of foamed sludge took place primarily in the falling rate period for both temperatures. In the heat up period, the drying rates rapidly increased to the peak value as the moisture content of the foamed sludge decreased from the initial moisture content to approximately 5.0 g H_2O/g DS and 4.5 g H_2O/g DS at 30 °C and 50 °C, respectively. Thereafter, the drying rates decreased with a decrease in moisture content, which signaled the beginning of the falling rate period. The falling rate period could be divided into two stages according to the change in the drying rate curves. The loss of free water occurs in the first falling rate stage.[14] Otherwise, the variation range of the moisture content is different from the drying temperature in this stage. The moisture content ranges from 4.5 g H_2O/g DS to 1.0 g H_2O/g DS at 50 °C, whereas it declines from 5.0 g H_2O/g DS to the value below 1.0 g H_2O/g DS at 30 °C. At

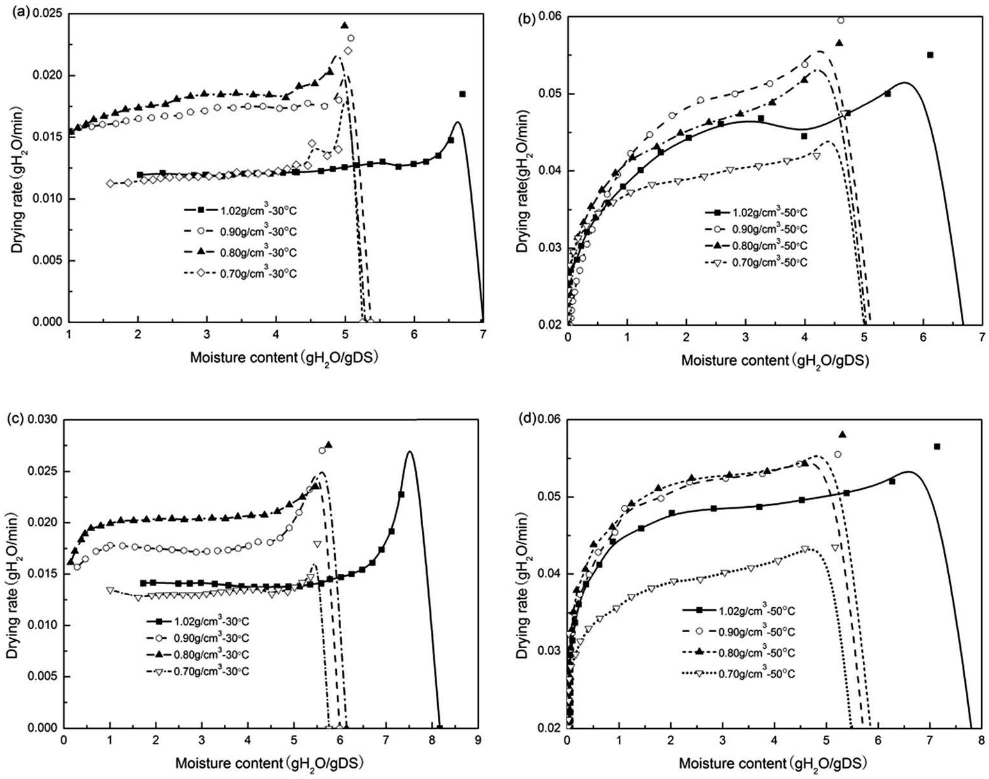

Fig. 6 Relationship between drying rate and drying time of sludge foam-mats at different addition ratios and drying temperatures: (a) 10 g DFS + 10 g CaO, 30 °C; (b) 10 g DFS + 10 g CaO, 50 °C; (c) 20 g CaO, 30 °C; and (d) 20 g CaO, 50 °C (1.02 g cm^{-3} was the density of dewatered sludge without the foaming process; 0.90 g cm^{-3}, 0.80 g cm^{-3} and 0.70 g cm^{-3} were the densities of the foamed sludge).

moisture contents below 1.0 g H_2O/g DS, the decrease in drying rate was sharp, which indicates that drying was in the second falling rate stage. Furthermore, a very low drying rate occurred in the second falling rate stage, which is probably because smaller amounts of free water is available[14] and the crust phenomenon is formed on the surface of the sludge.[27]

The densities of foamed sludge also play an important role on internal mass transfer rates. For both temperatures (30 °C and 50 °C), the foamed sludge of 0.80 g cm^{-3} has the fastest drying speed at 30 °C, whereas the best drying density is 0.90 g cm^{-3} at 50 °C. The reason for this may be that the added DFS enhances the skeleton-built role of CaO and improves the void space, which is helpful for the diffusion of water, thus shortening the drying time. Except for the foam density, the drying temperature also affects the drying rates. The drying rates of foamed sludge were higher when the sludge drying was performed at a higher drying temperature, as can be seen in Fig. 6(a)–(d).

3.4. Properties analysis of foamed sludge

As shown in Fig. 7, compared with the raw dewatered sludge, the initial moisture content of sludge foam under various densities fell by approximately 2–3% when DFS and CaO were added at the mass ratio of 10 g DFS + 10 g CaO. This is mainly dependent on the lime hydration reaction and the interaction between DFS and water within the sludge. Moreover, added CaO and DFS can create a strong alkaline environment and sludge can be solubilized to release the inner water held inside the floc and cell structure. In addition, the alkaline environment can accelerate sludge hydrolysis and release sludge inner organic matter.[28] When the density was below 0.90 g cm^{-3}, the pH of the sludge foam was higher than 12. Under this high pH, the protein content of the sludge foam is over 6 times higher than that of raw dewatered sludge. Previously, many researchers have pointed out that protein may play an important role in sludge foaming.[18,29] This explains why the admixture of DFS and CaO can make the sludge foam.

Moreover, the alkaline environment can reduce the surface tension and thus display surface activity.[30] Low surface tension is essential for both foam formation and stability, which makes the foam easier to form and maintain a large interfacial area. According to Fig. 7, the surface tension of sludge foam at 0.90 g cm^{-3}, 0.80 g cm^{-3}, and 0.70 g cm^{-3} was 65.77 mN m^{-1}, 67.30 mN m^{-1} and 63.60 mN m^{-1}, respectively. Compared to the raw sludge, the reduction in the surface tension of the foamed sludge at 0.90 g cm^{-3}, 0.80 g cm^{-3}, and 0.70 g cm^{-3} was 14.10%, 12.11% and 16.94%, respectively. From the abovementioned results, there was no significant difference for the surface tension of the sludge foam at the three different densities. This may imply that surface tension lowering is necessary, but not sufficient.[18]

3.5. Modelling of drying curves

Regression analysis was done for the five thin-layer drying models, which related the drying time and moisture ratio for

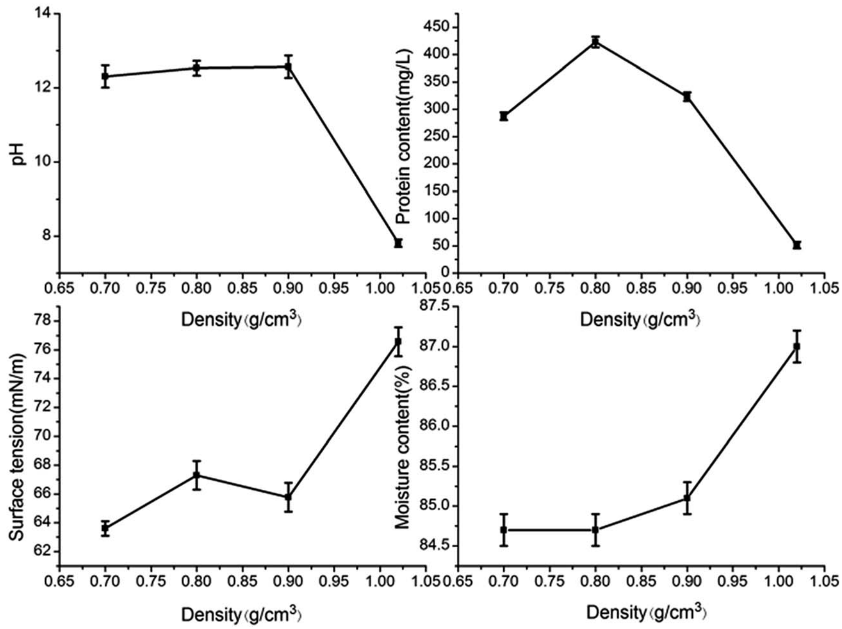

Fig. 7 Effects of back mixing on the protein content, surface tension and pH of the solvent phase of the sludge suspension and the initial moisture content of the sludge foam at different densities (the mass ratio of DFS to CaO is 10 g DFS + 10 g CaO; DFS shape: PDFS; dosing sequence: CaO, then DFS after 5 min).

Table 2 Parameters specific to each model (30 °C, 0.80 g cm^{-3}; 50 °C, 0.90 g cm^{-3})

Model name	Model equation	Temperature	Parameter	γ^2	χ^2
Logistic[31]	$y = A_{2+}\dfrac{A_1 - A_2}{1+\left(\dfrac{x}{x_0}\right)^p}$	30 °C	A_1: 0.99307, A_2: −11.61132, x_0: 3307.42178, p: 72 191	0.99906	2.04×10^{-5}
		50 °C	A_1: 0.99303, A_2: −0.50504, x_0: 348.35857, p: 00 292	0.99887	1.21×10^{-4}
Asymptotic[32]	$y = a - bcA^x$	30 °C	a: −408.6026, b: 9.65556, c: 1	0.95548	9.72×10^{-4}
		50 °C	a: −173.55328, b: 174.62566, c: 0.99999	0.99069	1.00×10^{-3}
Exponential[33]	$y = y_0 + A\exp(R_0x)$	30 °C	y_0: 1.1772, A: −0.16987, R_0: 0.00272	0.99747	5.52×10^{-5}
		50 °C	y_0: 8.78497, A: 7.72387, R_0: 0.00028	0.99108	9.60×10^{-4}
Parabola[34]	$y = A + Bx + Cx^2$	30 °C	A: 0.997664, B: -2.68×10^{-4}, C: -1.38169×10^{-6}	0.99905	2.04×10^{-5}
		50 °C	A: 1.05984, B: -2.15×10^{-3}, C: -3.57×10^{-7}	0.99112	9.56×10^{-4}
Two-parameter exponential[35]	$y = ab^x$	30 °C	a: 1.06476, b: 0.99887	0.91905	1.77×10^{-3}
		50 °C	a: 1.17087, b: 0.99612	0.91612	9.02×10^{-3}

the given temperature (30 °C and 50 °C) to the best drying density.[31–35] The model coefficients are shown in Table 2 with their values for the coefficients of correlation and mean square of the deviation values. The acceptability of the model is based on the highest value for γ^2 and the lowest value for χ^2. It can be observed from Table 2 that the most appropriate model to describe the drying kinetics of thin-layer sludge foam is the Logistic model at both 30 °C and at 50 °C. When the drying temperature was 30 °C and the foam density was 0.80 g cm^{-3}, the values of γ^2 and χ^2 were 0.99906 and 2.04×10^{-5}, respectively. For the sludge foam of 0.90 g cm^{-3}, when the drying temperature was 50 °C, the values of γ^2 and χ^2 were 0.99887 and 1.21×10^{-4}, respectively.

4. Conclusion

As part of the sludge foam-mat drying process, back mixing has the potential to reduce the amount of CaO in order to save more energy in the practical application. The result showed that the optimal addition ratio of DFS to CaO is 10 g DFS + 10 g CaO, which makes the dosage of CaO reduced by 50%. Moreover, a proper amount of DFS used for back mixing has positive effects on sludge foaming and the sludge foam stability. The best dosing sequence is that of CaO, then DFS after 5 min. CaO is still dominant in the sludge foaming during the back mixing operation. Furthermore, foaming and foam-mat drying for dewatered sludge are not greatly dependent on the DFS shape. During the foaming progress, CaO and DFS can create a strong alkaline environment (pH > 12) through the interaction with the inner water of dewatered sludge. Under this condition, the protein content increases by over 6 times higher than that of raw dewatered sludge and the surface tension decreases, regardless of the small amplitude in variation. These changes may lead to sludge foaming.

Thin-layer drying of foamed sludge took place primarily in the falling rate period for both temperatures (30 °C and 50 °C). During the foam-mat drying, with the temperature increase, the best drying rate appears at the higher foam density. The sludge foam of 0.80 g cm^{-3} has the fastest drying speed at 30 °C, whereas the best drying density is 0.90 g cm^{-3} at 50 °C. Moreover, the drying rates of foamed sludge are higher when the sludge drying is performed at higher drying temperatures.

Among the five models investigated in this study, the Logistic model is the best-fit model for the intermittent drying of thin-layer sludge foam under the best drying density both at 30 °C and at 50 °C since it produces the highest correlation coefficient (γ^2) and lowest statistical indicator, chi-square (χ^2).

Acknowledgements

This project was supported by the National Natural Science Foundation of China (grant numbers: 51378189, 51578223 and 51521006) for the financial supports.

References

1 A. Kelessidis and A. S. Stasinakis, *Waste Manage.*, 2012, **32**, 1186–1195.
2 L. Houdková, J. Boráň, V. Ucekaj, T. Elsäßer and P. Stehlík, *Appl. Therm. Eng.*, 2008, **28**, 2083–2088.
3 L. Bennamoun, P. Arlabosse and A. Léonard, *Renewable Sustainable Energy Rev.*, 2013, **28**, 29–43.
4 W. Xu, J. Xu, J. Liu, H. Li, B. Cao, X. Huang and G. Li, *J. Cleaner Prod.*, 2014, **83**, 286–293.
5 B. M. Cieślik, J. Namieśnik and P. Konieczka, *J. Cleaner Prod.*, 2014, **90**, 1–15.
6 A. A. El-Sebaii and S. M. Shalaby, *Renewable Sustainable Energy Rev.*, 2012, **16**, 37–43.
7 V. L. Mathioudakis, A. G. Kapagiannidis, E. Athanasoulia, V. I. Diamantis, P. Melidis and A. Aivasidis, *Desalination*, 2009, **248**, 733–739.
8 L. Cai, D. Gao, T. B. Chen, H. T. Liu, G. D. Zheng and Q. W. Yang, *Bioresour. Technol.*, 2012, **117**, 13–19.
9 L. Zhao, W. M. Gu, P. J. He and L. M. Shao, *Water Res.*, 2010, **44**, 6144–6152.
10 C. Peregrina, V. Rudolph, D. Lecomte and P. Arlabosse, *J. Environ. Manage.*, 2008, **86**, 246–261.
11 L. Bennamoun, *Renewable Sustainable Energy Rev.*, 2012, **16**, 1061–1073.
12 L. Zhao, W. M. Gu, P. J. He and L. M. Shao, *Water Res.*, 2011, **45**, 2322–2330.
13 C. C. W. A. Abd Karim, *Food Chem.*, 1999, **64**, 337–343.
14 R. Thuwapanichayanan, S. Prachayawarakorn and S. Soponronnarit, *J. Food Eng.*, 2008, **86**, 573–583.
15 C. L. Hii, C. L. Law, M. Cloke and S. Suzannah, *Biosystems Eng.*, 2009, **102**, 153–161.
16 C. K. Sankat and F. Castaigne, *LWT–Food Sci. Technol.*, 2004, **37**, 517–525.
17 H.-L. Wang, Z.-H. Yang, J. Huang, L.-K. Wang, C.-L. Gou, J.-W. Yan and J. Yang, *Water Sci. Technol.*, 2014, **69**, 1859.
18 J. Huang, Z.-H. Yang, G.-M. Zeng, H.-L. Wang, J.-W. Yan, H.-Y. Xu and C.-L. Gou, *Water Res.*, 2015, **68**, 667–679.
19 Y. Huron, T. Salmon, M. Crine, G. Blandin and A. Léonard, *Asia-Pac. J. Chem. Eng.*, 2010, **5**, 909–914.
20 A. Leonard, E. Meneses, E. le Trong, T. Salmon, P. Marchot, D. Toye and M. Crine, *Water Res.*, 2008, **42**, 2671–2677.
21 W. Deng and Y. Su, *J. Environ. Sci.*, 2014, **26**, 1523–1529.
22 S. I. Karakashev, O. Ozdemir, M. A. Hampton and A. V. Nguyen, *Colloids Surf., A*, 2011, **382**, 132–138.
23 J. Vaxelaire and P. Cezac, *Water Res.*, 2004, **38**, 2214–2229.
24 M. Aghbashlo, M. H. Kianmehr and A. Arabhosseini, *Energy Convers. Manage.*, 2009, **50**, 1348–1355.
25 G. E.-P. Eduardo, J. Vernon-Cartera, C. I. Beristainb and H. Romero-Tehuitzila, *Food Res. Int.*, 2001, **34**, 587–598.
26 T. Horozov, *Curr. Opin. Colloid Interface Sci.*, 2008, **13**, 134–140.
27 J. Vaxelair, J. M. Bongiovanni, P. Mousques and J. R. Puiggali, *Water Res.*, 2000, **34**, 4318–4323.
28 H. Li, Y. Jin, R. Mahar, Z. Wang and Y. Nie, *Bioresour. Technol.*, 2008, **99**, 5140–5144.
29 J. C. Germain and J. M. Aguilera, *Food Struct.*, 2014, **1**, 55–70.
30 D. Zhao, K. Miyanaga and Y. Tanji, *Biochem. Eng. J.*, 2011, **56**, 241–246.
31 A. Khanchi, C. L. Jones, B. Sharma, R. L. Huhnke, P. Weckler and N. O. Maness, *Biomass Bioenergy*, 2013, **58**, 128–135.
32 D. Jain and P. B. Pathare, *Biosysems Eng.*, 2004, **89**, 289–296.
33 N. A. Akgun and I. Doymaz, *J. Food Eng.*, 2005, **68**, 455–461.
34 A. R. Celma, F. Cuadros and F. López-Rodríguez, *Food Bioprod. Process.*, 2012, **90**, 224–234.
35 M. S. Rahman, C. Perera and C. Thebaudb, *Food Res. Int.*, 1997, **30**, 485–491.