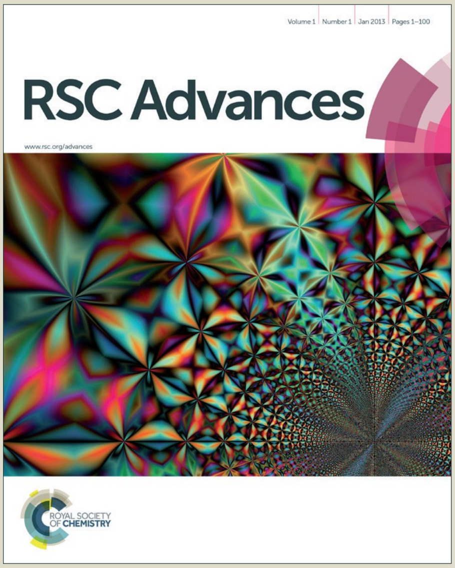
# RSC Advances



ROYAL SOCIETY
OF CHEMISTRY

www.rsc.org/advances

# 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]

## Abstract

A creative combination of foaming and back mixing was made in our work. Back mixing was simulated by adding the dried and foamed sludge (DFS) to the raw sludge. Different ratios of (DFS+ CaO), DFS shape and the dosing sequence were investigated on the influence of sludge foamability and drying efficiency. Experimental results indicated that back mixing has positive effects on the sludge foaming and the sludge foam stability. CaO is still dominant in the sludge foaming. The best adding ratio is (10gDFS+10gCaO) for 1kg of fresh sludge, with an optimal dosing sequence of first CaO followed by DFS after 5 min. Additionally, the foam-mat drying for dewatered sludge is not greatly subjected to the DFS shape. During the foam-mat drying, the higher drying rate appears at the higher foam density (>0.70 g/cm$^3$). The foamed sludge of 0.80 g/cm$^3$ has the fastest drying speed at 30℃ while the best drying density is 0.90 g/cm$^3$ at 50℃. And the drying rates of foamed sludge were higher with the temperature increased from 30℃ to 50℃. Besides, the mathematical modelling results demonstrated that the Logistic model is the most adequate model in describing the whole convective drying of thin layer sludge under the best drying density both at 30℃ and at 50℃.

## [1]Keywords

Dewatered sludge; Back mixing; Foaming; Drying characteristics; Mathematical modelling

## 1. Introduction

---

a College of Environmental Science and Engineering, Hunan University, Changsha 410082, China

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

*Corresponding author: E-mail: yzh@hnu.edu.cn

Tel.: +86-0731-88822829; Fax: +86-0731-88822829.

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

It is well known that thermal drying is a common and mature 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 simple operation, low cost, and mostly odor-free.[3-5] Besides, solar drying, [6,7] bio-drying [8,9] and fry-drying[10] also have 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] So, innovative drying methods of sewage sludge need to be further developed.

Foam-mat drying shows promise as an effective and novel technology to realize the fast drying of the dewatered sludge. Currently, this process has been popular and successful, especially in food industries. [13-15] Liquid or semi-liquid is mechanically whipped to form stable foams with open structure and large surface area, aimed to facilitate moisture evaporation and the moisture movement of capillarity in the liquid films.[16] Foam-mat drying process is characterized as lower drying temperatures and shorter drying times, especially for sticky and viscous materials. [17] As the dewatered sludge is highly viscous and sticky, the joint use of foaming pretreatment and thermal drying seems to be a new routine to reinforce the drying rate of dewatered sludge. In this way, our previous studies have found that proper amounts of CaO could make the dewatered sludge foamed by stirring; the optimal dosage of CaO is 2.0wt% relative to the total weight of dewatered sludge in wet basis.[17,18] However, there are still two inevitable problems. On one hand, the dosage of CaO is practically larger 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 greatly 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 the sludge drying, which is mainly used to improve the initial sludge texture structure through backflow of dried material.[19] The sludge texture reinforcement leads to an increase of sludge-bed porosity,[20] thus exhibiting a significant influence on the sludge drying. Leonard [20] et al. revealed that back mixing plays a positive role on the drying kinetics of sewage sludge through an enhancement of the area available for heat and mass transfer. It was also found that back mixing of dried sludge can improve the mixing effect of the paddle dryer to effectively alleviate the unfavorable effect of lumpy phase. [21] Moreover, the solid particles in the sludge foam system improved the foam stability, because the particles could bridge gas bubbles in close contact, and increased the viscosity of sludge. [22] Thus, based on these above, a creative combination of foaming and back mixing was 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 declines the dosage of CaO. In addition, mathematical modelling of thin layer drying is essential for optimum management of operating parameters and prediction of performance of the drying system. [23]

The objective of this paper was to focus on investigating effects of different parameters on foamability and drying efficiency of dewatered sludge, including different ratios of DFS and CaO, DFS shape and dosing sequence. And different temperatures (30℃, 50℃) were selected to analyze its effect on the sludge drying efficiency. Meanwhile, several thin-layer drying models were also employed to simulate the whole convective drying of dewatered sewage under the optimal conditions, so as to provide more convenience and detailed information for the practical application of this method.

## 2. Materials and methods

### 2.1. Materials

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

The initial amount of dewatered sludge used was 1kg in every experiment. By the sole feeding of 20g CaO, the dewatered sludge was mechanically whipped to form the foamed sludge. DFS was attained through drying the foamed sludge at 0.70g/$cm^3$ to constant weight at 105 ℃. Then two types of dried sludge (DS) were prepared, respectively called A and B. A, powdered DFS (PDFS), was obtained though gridding DFS into fine powder (FP) and filtering it from a mesh sieve at the size of 60 items. B, lumpish DFS (LDFS), was a product in a random shape without any physical and chemical treatment of DFS. Meanwhile, all other reagents used were analytical reagent, and the experimental water was ultrapure water(UPW).

### 2.2. Sludge foaming

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

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

### 2.3. Drying characteristics of foamed sludge

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

In our experiments, the optimum adding ratio was chosen from the above-mentioned ones to further study the drying behavior of the foamed sludge. The adding ratio of 0gDFS+20gCaO, was used as the control group. Meanwhile, various densities of foamed sludge also affected its drying. 0.70g/cm$^3$ was chosen as a key density, given that the foamed sludge at 0.70g/cm$^3$ have the best drying performance by the addition of 20g CaO.[18] Also considering economic benefit and easy operation, three foam densities were studied, including 0.70g/cm$^3$, 0.80g/cm$^3$, 0.90g/cm$^3$. Herein, the fresh sludge was taken as a reference. Otherwise, the influence of drying temperature on the sludge drying was also studied.

### 2.4. Preparation and characterization of the sludge suspension

Preparation of the sludge suspension was made 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 10000 rpm for 10 min in the centrifuge (Allegra 25R, Beckman Coulter, USA). Properties of the sludge suspension were mainly represented by determining the nature of the supernatant, including pH, surface tension and the protein content.

Surface tension and pH of the sludge suspension samples were measured by surface tensiometer (JZ-200A, Chengde, Chinese) and pH-meter (PB-10, Sartorius, Germany), respectively. Then the supernatant obtained was further filtered through the mixed cellulose esters membrane with 0.22 μm micropores to separate any residual biomass, eliminating the disturbance to the protein determination. Protein content was determined by the Coomassie Brilliant Blue (CBB) method with bovine serum albumin (BSA) as 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 Eq. (1):

$$\mathrm{MR} = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

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

$$\mathrm{MR} = \frac{M_t}{M_0} \quad (2)$$

Experimental results of moisture ratio versus drying time were fitted to five different drying kinetics models, using nonlinear regression through Origin Pro10.0 software. The coefficient of correlation (γ) was a primary criterion for selecting the best equation and mean squared deviation ($\chi^2$) were used to determine 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

Generally, the foamability can be evaluated through the measurement of the foam density. During mechanical blending, more air entered into the foam to form lower foam density with the stirring time increased. 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 decline. However, its variation trend was different with the adding ratios of (DFS+ CaO). It was observed that when adding ratios were 20g DFS+ 0gCaO and 15gDFS+ 5gCaO, the sludge density first briefly declined to around 0.95 g/cm$^3$ and 0.97 g/cm$^3$ in 20min respectively, then continued to rise even beyond the initial density of fresh sludge.

The succedent increase in foam density may be mainly attributed to an increase of the viscosity of the mixture due to excess DFS, which possibly exceeds the limiting value so as to prevent the entry of more air. However, once adding the increasing doses of CaO, the sludge foamability can be also strengthened to different degrees. This implied that CaO may be dominating in the admixture of CaO and DFS during the sludge foaming.

As shown in Fig1, for the control group (0gDFS+20gCaO), the sludge indeed has a better foamability. The final density of sludge could be declined to about 0.55 g/cm$^3$ after 140min. Yet, compared with the control group, the sludge foamability weakened at the adding ratio of 12.5gDFS+7.5gCaO. The sludge density only reached 0.75 g/cm$^3$ after 140min 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, including10gDFS+10gCaO, 7.5gDFS+12.5gCaO and 5gDFS+15gCaO. After 140min the lowest foam density decreased to 0.36, 0.27, 0.24 g/cm$^3$, respectively. What's more, 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 a key discussion point, aiming at easily highlighting positive effect of back mixing on foaming by comparison. By analyzing the experimental data, it was found that the sludge density can almost reach 0.70 g/cm$^3$ after about 40 minutes. Compared with the control group, the stirring time required to achieving the density of 0.70 g/cm$^3$ would be shortened by around 42%. This suggested that a proper amount of backmixed DFS exerts a positive effect on sludge foaming. Besides, it was also observed that the foaming speed is a little faster than that of other two ratios when the adding ratio is 10gDFS+10gCaO. Considering the economic and energy consumption, the adding ratio of (10gDFS+10gCaO) was chosen as the optimal addition ratio in conclusion.

### 3.1.2. Sludge foam stability

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

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

### 3.2. Effect of dosing sequence and DFS shape

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

In order to further throw light upon the effect of dosing sequence, the influence on the drying rate for the sludge foam was also investigated. 50℃ 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. Combined Fig.3 (b) with Fig.3 (d), it can be found that when CaO was added before stirring, the optimal drying rate both 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 of the viscosity with the increase of the stirring time. Besides, when DFS was added prior to CaO, the drying rate for the sludge foam at 0.70 g/cm$^3$, 0.80 g/cm$^3$, 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$^3$. To sum up, first CaO and then DFS after 5min, was considered as the best dosing sequence in terms of the fastest foaming speed and the best drying density.

In addition to the dosing sequence, DFS shape also affects the sludge foaming and the drying rates, as shown in Fig.4. Comparatively, there was no significant difference in sludge foaming in Fig.4 (a), regardless of LDFS or PDFS. However, as the LDFS was added, the fastest drying rate of sludge foam was at the lowest foam density (0.70 g/cm$^3$) in Fig.4 (b). This almost stays the same as the previous conclusion with direct addition of 20g CaO. Yet, the 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 influences of adding ratio (DFS+ CaO), foam density and drying temperature on the drying characteristics of sludge foam-mats were studied. Fig.5(a)-(d) describes the drying curves of foamed sludge at the different initial densities and drying temperatures by the foaming pretreatment using the admixture of (10gDFS+10gCaO) and solely feeding of 20g CaO. From Fig.5(a) and Fig.5(b), it can be seen that when the foamed sludge was dried at 30℃, their moisture content ,averaging 5.29 $gH_2O/gDS$ at the beginning, was sharply reduced to 1.04, 1.03 and 2.09 $gH_2O/gDS$ for the initial foam densities of 0.90, 0.80 and 0.70 $g/cm^3$ after drying for 440 min, respectively. 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℃. 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 direct addition of 20g CaO, illustrated in Fig.5 (c) and Fig.5 (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 in the meantime, thus hindering more air into the sludge.

Besides, from Fig.5 (a)-(d), it is clear that the drying temperature appears to be an important parameter influencing the process time and moisture content of the dewatered sludge. As the drying temperature increased to 50℃, sludge foams at the different densities almost reached the drying equilibrium after 440min. And the drying time required for reducing their moisture content to about 1.0 $gH_2O/gDS$ was approximately 180 min, shorter by approximately 60% than that at 30℃. Overall, the higher temperature results in a shorter drying time.

### 3.3.2. Drying rate curve

Presented in Fig.6 (a)-(d), thermal drying of each sludge sample comprised of a heat up period at the early stage of drying and then the falling rate stage. A short constant rate period disappeared because of the added DFS. This is entirely consistent with the conclusion observed by Leonard [20] et al. And 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 foamed sludge decreased from the initial moisture content to approximately 5.0 $gH_2O/gDS$, 4.5 $gH_2O/gDS$, respectively in 30℃ and 50℃. Thereafter, the drying rates decreased with decreasing moisture content, signaling 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 $gH_2O/gDS$ to 1.0 $gH_2O/gDS$ in 50℃ while it declines from 5.0 $gH_2O/gDS$ to the value below 1.0 $gH_2O/gDS$ in 30℃. At moisture contents below 1.0 $gH_2O/gDS$, a decrease in drying rate was sharper, indicating that the drying was in the second falling rate stage. Afterwards, the very low drying rate occurred in the second falling rate stage, 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 the internal mass transfer rates. For both temperatures(30℃,50℃), the foamed sludge of 0.80 $g/cm^3$ has the fastest drying speed at 30℃ while the best drying density is 0.90 $g/cm^3$ at 50℃. The reason 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 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 usually fell by about 2%-3% when adding DFS and CaO at the mass ratio of (10gDFS+10gCaO). This is mainly dependent on the lime hydration reaction and the interaction between DFS and water within the sludge. And added CaO and DFS can create a strong alkaline environment and sludge can be solubilized to release the inner water held inside floc and cell structure. Meanwhile, the alkaline environment can accelerate sludge hydrolysis and release sludge inner organic matters. [28] As the density was below 0.90 g/cm$^3$, pH of the sludge foam was beyond 12. Under this higher pH, 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 on sludge foaming. [18,29] This explains why the admixture of DFS and CaO can make the sludge foaming.

Besides, alkaline environment can reduce the surface tension and obtain the surface activity. [30] Low surface tension is essential for both foam formation and stability, which makes the foam easier to form and maintain large interfacial area. According to Fig.7, the surface tension of sludge foam at 0.90 g/cm$^3$, 0.80 g/cm$^3$, 0.70 g/cm$^3$, was 65.77mN/m, 67.30mN/m and 63.60mN/m, 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$^3$, 0.70 g/cm$^3$ was 14.10%, 12.11% and 16.94%, respectively. From these above-mentioned results, there was no significant difference for the surface tension of the sludge foam at three different densities. This may imply that surface tension lowering is necessary, but not sufficient. [18]

### 3.5. Modelling of drying curves

The regression analysis was done for the five thin-layer drying models relating the drying time and moisture ratio for the given temperature (30 ºC, 50 ºC) at the best drying density, respectively.[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 $\gamma^2$ and the lowest for $\chi^2$. It can be observed from Table 2 that the most appropriate model in describing the drying kinetics of thin-layer sludge foam was both the Logistic model at 30 ºC and at 50 ºC. When the drying temperature was 30 ºC and the foam density was 0.80g/cm$^3$, the values of $\gamma^2$ and $\chi^2$ were 0.99906 and $2.04\times10^{-5}$, respectively. For the sludge foam of 0.90 g/cm$^3$, as the drying temperature was 50 ºC, the values of $\gamma^2$ and $\chi^2$ were 0.99887 and $1.21\times10^{-4}$, respectively.

## 4. Conclusion

As a part of the sludge foam-mat drying process, back mixing has the potential to reduce the amount of CaO so as to save more energy in the practical application. The result showed that the optimal adding ratio of DFS to CaO is (10gDFS+10gCaO), which makes the dosage of CaO reduced by 50%. Moreover, a proper amount of DFS used for back mixing has positive effects on the sludge foaming and the sludge foam stability. The best dosing sequence is that of CaO, then DFS after 5min. CaO is still dominant in the sludge foaming during the back mixing operation. Furthermore, foaming and the foam-mat drying for dewatered sludge is 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 declines regardless of a small amplitude variation. These changes may lead to the sludge foaming.

Thin-layer drying of foamed sludge took place primarily in the falling rate period for both temperatures (30℃, 50℃). During the foam-mat drying, with the temperature increasing, 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℃ while the best drying density is 0.90 g/cm$^3$ at 50℃. Besides, 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℃ and at 50℃ as it produces the highest correlation coefficient($\gamma^2$) and lowest the statistical indicators chi-square($\chi^2$).

## Acknowledgments

This project was supported by 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, *Renew. Sust. Energ. Rev*, 2013, **28**, 29-43.
4. W. Xu, J. Xu, J. Liu, H. Li, B. Cao, X. Huang and G. Li, *J. Clean. Prod*., 2014, **83**, 286-293.
5. B. M. Cieślik, J. Namieśnik and P. Konieczka, *J.Clean. Prod*., 2014, **90**, 1-15.
6. A. A. El-Sebaii and S. M. Shalaby, *Renew. Sust. Energ. 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, *Renew. Sust. Energ. 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, *Biosysems .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-Pacific 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, *Energ. Convers. Manage.*, 2009, **50**, 1348-1355.

25. G. E.-P. Eduardo J. Vernon-Cartera, César I. Beristainb, Hipólito Romero-Tehuitzila, *Food Res. Int.*, 2001, **34**, 587-598.

26. T. Horozov, *Curr. Opin. Colloid. In.*, 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.

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 Bioproduct. Process.*, 2012, **90**, 224-234.

35. M. S. Rahman, C. Perera and C. Thebaudb, *Food Res. Int.*, 1997, **30**, 485-491.

All figures in my paper are shown as follows:

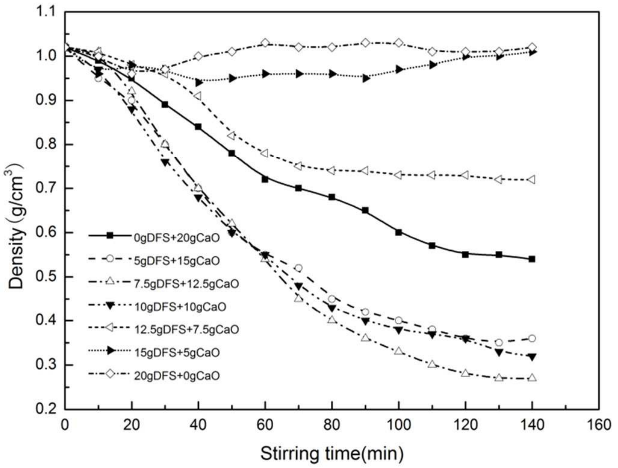


Fig.1. Effect of stirring time and adding ratios (DFS+ CaO) on the sludge foam density. (Dosing sequence: synchronous addition of DFS and CaO before stirring; DFS shape: PDFS)

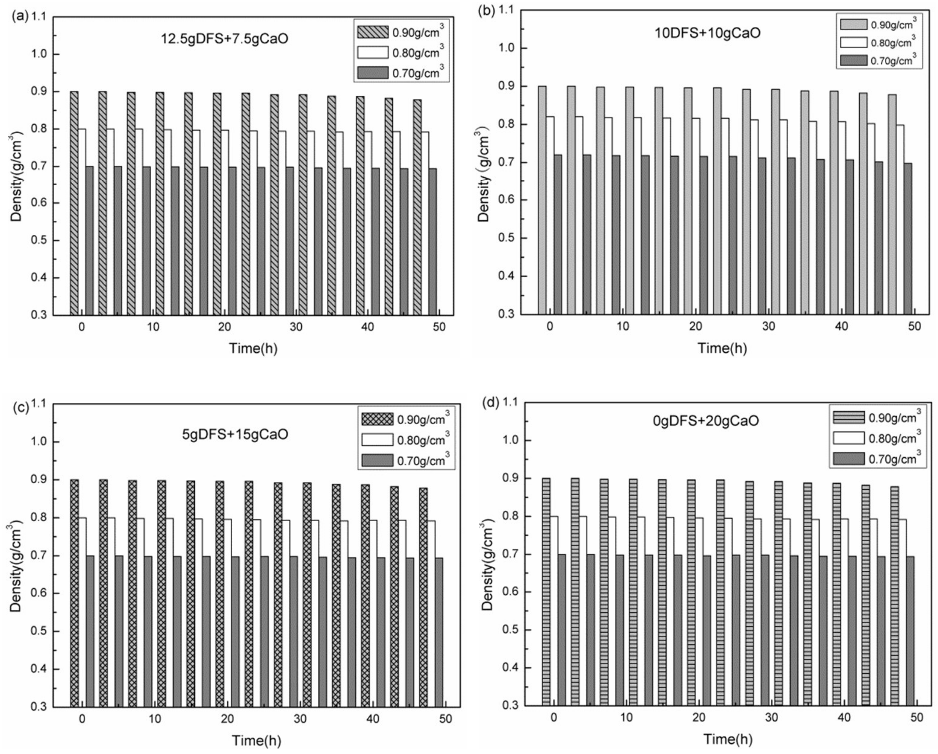


Fig.2. Variation of sludge foam density over time at the different initial densities under the different adding ratios(DFS+ CaO). (Dosing sequence: synchronous addition of DFS and CaO before stirring; DFS shape: PDFS)

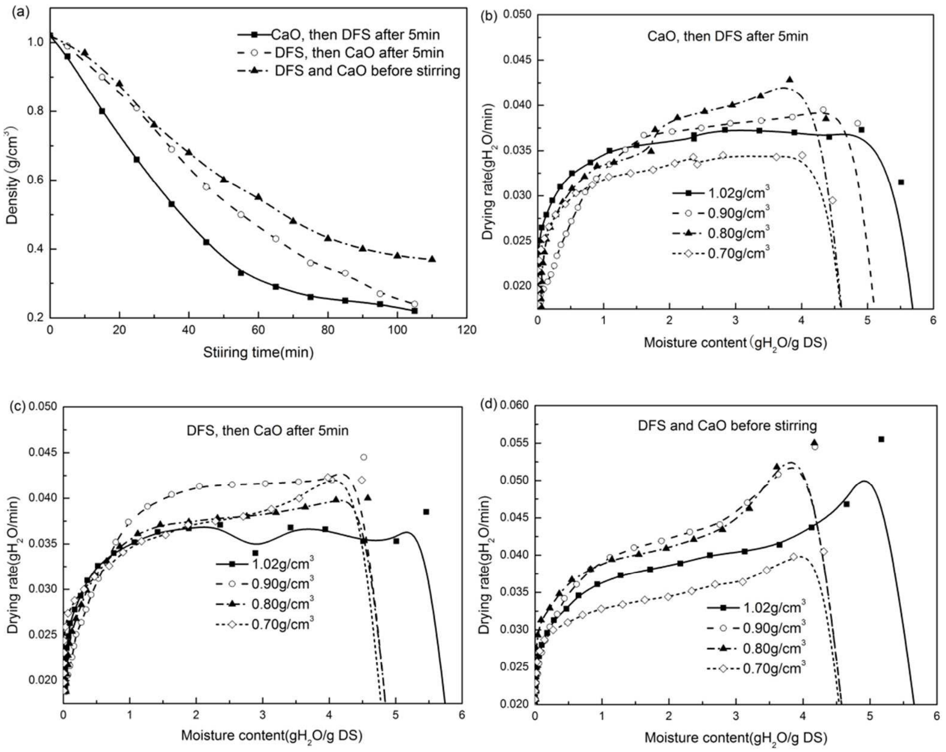


Fig.3-(a) Effect of different dosing sequences on the sludge foam density;

(b)- (d) Effect of different dosing sequences on the drying rate of sludge foam at the different densities (The mass ratio of DFS to CaO is 10gDFS+10gCaO; DFS shape: PDFS; Drying temperature:50℃)

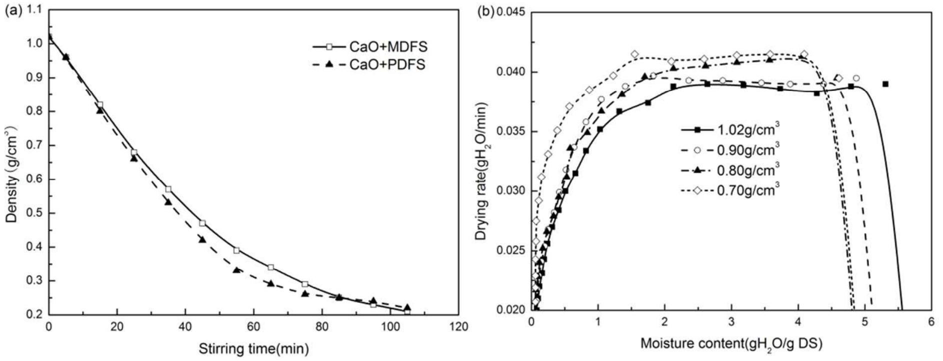


Fig.4- (a) Effect of DFS shape on the sludge foam density;

(b) Effect of DFS shape on the drying rate of sludge foam at the different densities. (The mass ratio of DFS to CaO is 10gDFS+10gCaO; Dosing sequence: CaO, then DFS after 5min; Drying temperature:50℃)

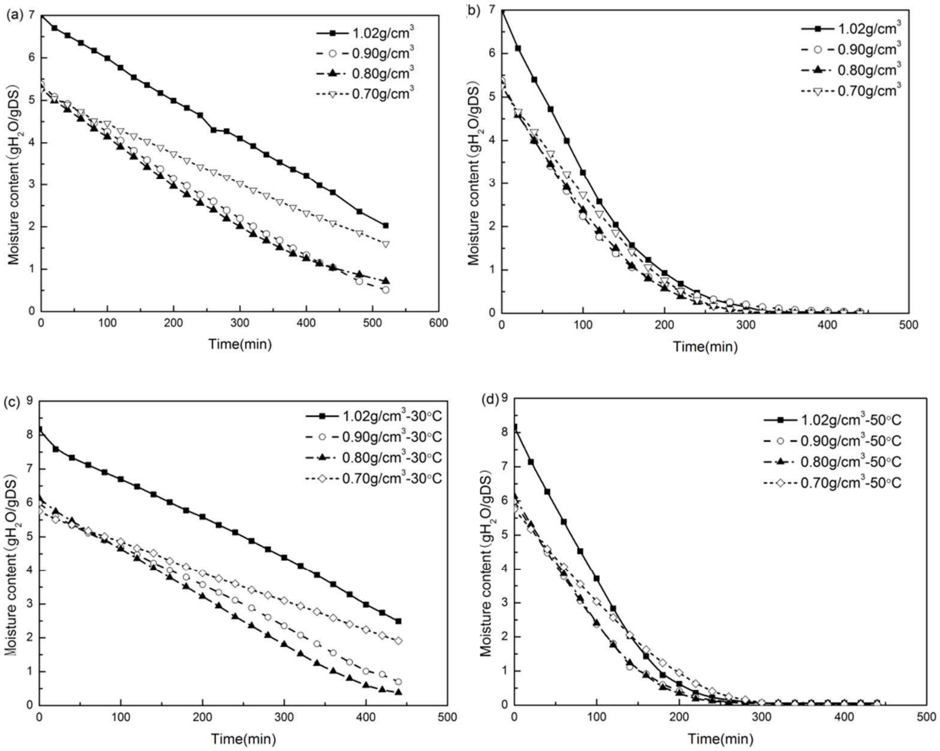


Fig.5. Drying curves of sludge foam mats at different addition ratios (DFS: CaO) and drying temperatures:(a) 10gDFS+10gCaO , 30℃; (b) 10gDFS+10gCaO, 50℃; (c)20gCaO, 30℃; (d) 20gCaO, 50℃. (1.02 g/cm$^3$ was the density of dewatered sludge without foaming process; 0.90 g/cm$^3$, 0.80 g/cm$^3$and 0.70 g/cm$^3$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

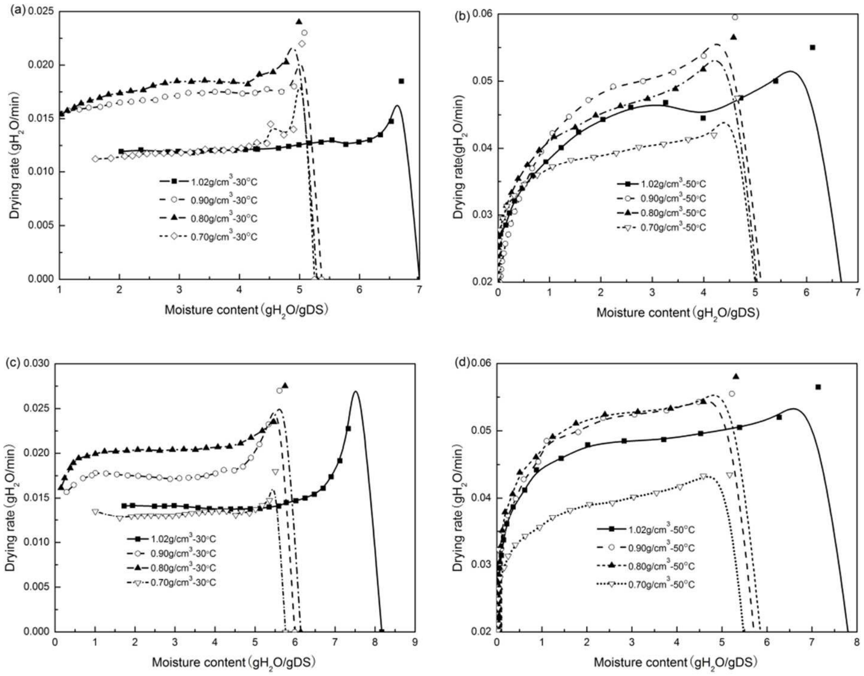


Fig.6. Relationship between drying rate and drying time of sludge foam-mats at different addition ratios and drying temperatures:(a)10gDFS+10gCaO,30℃;(b)10gDFS+10gCaO,50℃;(c)20gCaO,30℃; (d) 20gCaO,50℃. (1.02 g/cm$^3$ was the density of dewatered sludge without foaming process; 0.90 g/cm$^3$, 0.80 g/cm$^3$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

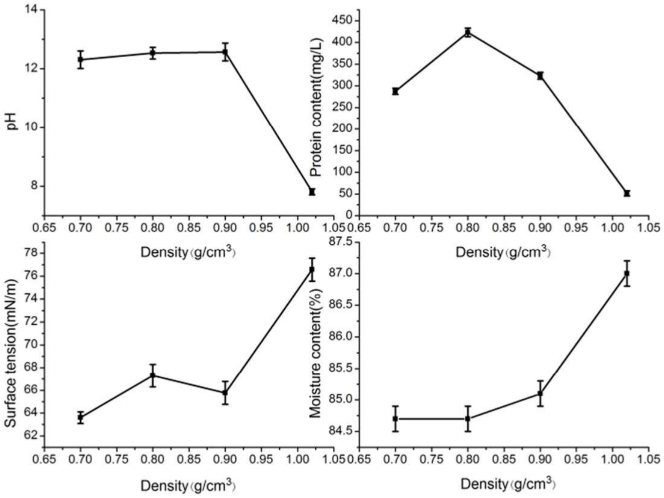


Fig.7. Effects of back mixing on the protein content, surface tension and pH of the solvent phase of sludge suspension and the initial moisture content of the sludge foam at the different densities. (The mass ratio of DFS to CaO is 10gDFS+10gCaO; DFS shape: PDFS; Dosing sequence: CaO, then DFS after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

All tables in my paper are shown as follows:

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) | 70.5 |
| Density(g/cm$^3$) | 1.02 | Protein (mg/L) | 51.33 |

Table 2 Parameters specific to each model (30 ºC, 0.80 g/cm$^3$; 50ºC, 0.90 g/cm$^3$)

| Model name | Model Equation | Temperature | Parameter | γ2 | χ2 |
|---|---|---|---|---|---|
| Logistic[31] | $y=A_{2+}\dfrac{A_1-A_2}{1+\left(\frac{x}{x_0}\right)^p}$ | 30℃ | $A_1$:0.99307 $A_2$:-11.61132<br>$x_0$:3307.42178 $p$:72191 | 0.99906 | $2.04\times10^{-5}$ |
| | | 50℃ | $A_1$:0.99303 $A_2$:-0.50504<br>$x_0$:348.35857 $p$:00292 | 0.99887 | $1.21\times10^{-4}$ |
| Asymptotic[32] | $y=a-bcA^x$ | 30℃ | $a$:-408.6026 $b$:9.65556<br>$c$:1 | 0.95548 | $9.72\times10^{-4}$ |
| | | 50℃ | $a$:-173.55328 $b$:174.62566<br>$c$:0.99999 | 0.99069 | $1.00\times10^{-3}$ |
| Exponential[33] | $y=y_0+Aexp(R_0x)$ | 30℃ | $y_0$:1.1772 $A$:-0.16987<br>$R_0$:0.00272 | 0.99747 | $5.52\times10^{-5}$ |
| | | 50℃ | $y_0$:8.78497 $A$:7.72387<br>$R_0$:0.00028 | 0.99108 | $9.60\times10^{-4}$ |
| Parabola[34] | $y=A+Bx+Cx^2$ | 30℃ | $A$:0.997664 $B$:$-2.68\times10^{-4}$<br>$C$:$-1.38169\times10^{-6}$ | 0.99905 | $2.04\times10^{-5}$ |
| | | 50℃ | $A$:1.05984 $B$:$-2.15\times10^{-3}$<br>$C$:$-3.57\times10^{-7}$ | 0.99112 | $9.56\times10^{-4}$ |
| Two-parameter Exponential[35] | $y=ab^x$ | 30℃ | $a$:1.06476 $b$:0.99887 | 0.91905 | $1.77\times10^{-3}$ |
| | | 50℃ | $a$:1.17087 $b$:0.99612 | 0.91612 | $9.02\times10^{-3}$ |