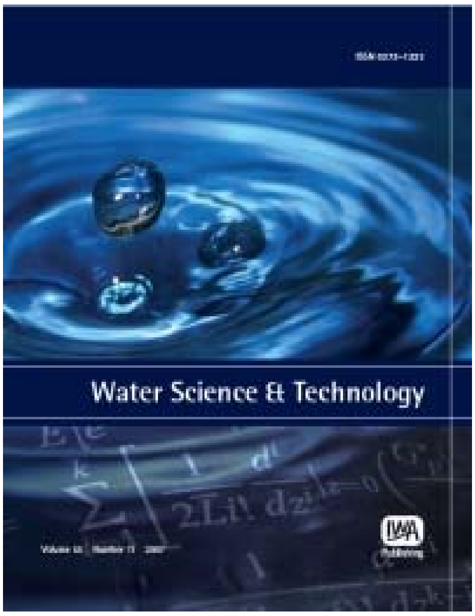
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The thin-layer drying characteristics of sewage sludge by the appropriate foaming pretreatment

Hui-Ling Wang, Zhao-Hui Yang, Jing Huang, Li-Ke Wang, Cheng-Liu Gou, Jing-Wu Yan and Jian Yang

ABSTRACT

As dewatered sludge is highly viscous and sticky, the combination of foaming pretreatment and drying process seems to be an alternative method to improve the drying performance of dewatered sludge. In this study, CaO addition followed by mechanical whipping was employed for foaming the dewatered sludge. It was found that the foams were stable and the diameters of bubbles mainly ranged from 0.1 to 0.3 mm. The drying experiments were carried out in a drying oven in the convective mode. The results indicated that foamed sludge at 0.70 g/cm^3 had the best drying performance at each level of temperature, which could save 35–45% drying time to reach 20% moisture content compared with the non-foamed sludge. The drying rate of foamed sludge at 0.70 g/cm^3 was improved with the increasing of drying temperature. The impact of sample thickness on drying rate was not obvious when the sample thickness increased from 2 to 8 mm. Different mathematical models were used for the simulation of foamed sludge drying curves. The Wang and Singh model represented the drying characteristics better than other models with coefficient of determination values over 0.99.

Key words | dewatered sludge, drying characteristics, foaming pretreatment, foam stability, mathematical models

Hui-Ling Wang
Zhao-Hui Yang (corresponding author)
Jing Huang
Li-Ke Wang
Cheng-Liu Gou
Jing-Wu Yan
College of Environmental Science and Engineering,
Hunan University,
Changsha 410082,
China
and
Key Laboratory of Environmental Biology and Pollution Control,
Hunan University,
Ministry of Education,
Changsha 410082,
China
E-mail: *yzh@hnu.edu.cn*

Jian Yang
The Quality Supervision and Management Station of Civil Air Defense Engineering of Changsha City,
Hunan Province, 29 Fuhua Road,
Changsha 410013,
China

INTRODUCTION

Sewage sludge, with rich nutrient and high moisture content, is produced as a by-product during the wastewater treatment process (Mathioudakis *et al.* 2009). The production of sludge from wastewater treatment plants (WWTPs) has been continuously increasing in China for several years because of the rapid urbanization process and the stringent environmental regulation.

Considering the reduction of sludge quantity and volume, water separation has become the principal goal in the sludge treatment (Alexandros & Athanasios 2012). In practice, several mechanical dewatering techniques like belt and filter pressing have been widely used in WWTPs. However, these processes lead to dewatered sludge with moisture content of more than 75% (Mathioudakis *et al.* 2009). These values cannot meet the demands of sludge ultimate disposal, and then the remaining moisture needs to be removed by extended dewatering.

Thermal drying is an efficient method to make a thorough dehydration of sludge, although in most cases it is not cost-effective or environmentally friendly due to the consumption of a non-renewable energy resource (Carlos *et al.* 2008). For the purpose of energy saving, many studies have been conducted about the use of renewable energy for sludge drying.

Solar drying allows the moisture content of sludge to reach approximately 10% using free solar energy (Lyes 2012). Bio-drying, aiming at removing water from bio-wastes, has been developed in recent years. The main advantage of bio-drying is that the heat generated during the aerobic degradation of organic substances could be used to evaporate water (Zhao *et al.* 2011). However, the drying performances of these systems are dissatisfactory. An average time of 10–25 days is needed to make the moisture content of sludge attain 30% (Ido & Markus 2006; Zhao *et al.* 2011; Lyes 2012). Some methods are still needed to improve the efficiency of sludge drying.

Foam-mat drying is a process by which a liquid or semi-liquid is whipped by various means to form a stable foam, and then dehydrated by evaporation of water (Ratti & Kudra 2006). Drying of foamed materials has long been recognized

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as a method to process hard-to-dry materials with heat sensitive, sticky and viscous behaviors (Rajkumar *et al.* 2007). This technology has been widely applied to the industries of food and pharmaceuticals (Rajkumar *et al.* 2007; Eduardo & Gilberto 2001) because of some distinct features such as lower drying temperature, shorter drying time and the possibility of retaining volatiles that otherwise would be lost during drying of non-foamed materials. As the dewatered sludge is highly viscous and sticky, the combination of foaming pretreatment and drying process seems to be an alternative method to improve the drying performance of dewatered sludge. However, there are few reports about the application of foaming pretreatment in dewatered sludge drying.

The materials used to form foams should contain foaming agents, which contribute to the formation and stability of the foam structure (Ratti & Kudra 2006). Based on the combination of foaming pretreatment and sludge drying process, the problem is raised on the source of foaming agents. Our team had found that the addition of CaO in dewatered sludge could disrupt microorganism cells and release the inner organic materials of sludge (Kim *et al.* 2010; Guan *et al.* 2012). Then the inner organic materials could provide an intrinsic source for a foaming agent. Meanwhile, the addition of CaO at concentration of 2 wt% resulted in the highest foaming rate of sludge at an optimum whipping time. On the basis of these, the objectives of this study were to: (1) evaluate the foam stability and analyze the mechanisms resulting in the stability of sludge foam; (2) investigate the optimum condition of foamed sludge for thin-layer drying and evaluate the drying characteristics of foamed sludge; (3) determine the suitable mathematical modeling of drying curves for foamed sludge.

MATERIAL AND METHODS

Material

The dewatered sewage sludge was obtained from a local municipal WWTP in Changsha, China. This plant treats 150,000 m^3/d of wastewater (almost all domestic sewage) using the oxidation ditch process. Sludge was dewatered by belt filter presses with addition of cationic flocculating agents. The moisture content of dewatered sludge was 84.0%, and the density was 1.05 g/cm^3.

Foam formation

The foam formation was conducted by whipping the dewatered sludge with 2.0 wt% dosages of CaO. All the processes were carried out using a cement mortar mixer (JJ-5, Jianyi, China) at 62 ± 5 rpm. 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. And the sludge density was controlled by managing the duration of whipping. The sludge transferring was performed carefully to avoid destroying the foam structure and to ensure that there were no voids while filling the foamed sludge into the conical measuring cylinders.

Image analysis

After whipping, the foamed sludge samples were photographed by camera for various initial foam densities. Image analysis software (ImagePro Plus 6.0, Media Cybernetic, MD, USA) was used to quantify the foam characteristics such as bubble diameter. Each pixel of a digital photo was assigned a value of gray intensity. The threshold-based segmentation technique was employed to distinguish the bubble from the solid with an appropriate gray-level threshold. A binary image was then generated. The pixels with gray levels above the selected threshold were assigned as bubble, which appeared as a transparent color in the binary image. With an assumption of spherical shape, a bubble diameter was estimated from the known bubble area. The bubble area was determined by counting the number of pixels filled in the specified space.

Foam-mat drying

In this study, a drying oven (150 L) was used as experimental equipment. It consisted of a heating control system, shutters, trays, fans and measurement instruments. The temperature, humidity and air flow velocity were continuously monitored and controlled during the whole experiment.

The first stage in the drying experiments focused on the influence of sludge density on foamed sludge drying. Samples of 10.00 g of foamed sludge were poured into Petri dishes (60 mm diameter and 12 mm height). Drying experiments were conducted at 40 and 50 °C. The relative humidity was 20% and drying air velocity was 0.2–0.4 m/s. Prior to drying, the drying oven was thermally stabilized by passing hot air at a pre-set temperature for 30 min. Moisture losses from the samples with a time interval of 20 min were measured by weighing the dish outside the drying oven using an electronic balance (±0.01). Meanwhile, the moisture content of sludge was determined by the mass loss after drying at 105 °C for 2 h.

In follow-up drying experiments, the studies focused on the influence of drying temperature and sample thickness on foamed sludge drying. Foamed sludge samples were poured into Petri dishes. The dishes were placed into the drying oven at different drying temperatures of 40, 50 and 60 °C, and the sample thicknesses of 2, 5 and 8 mm. All the other drying conditions and data processing methods were as mentioned above.

Mathematical modeling 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 Equation (1):

$$\mathrm{MR} = M_{\mathrm{t}}/M_{\mathrm{O}} \tag{1}$$

where M_{t} and M_{O} are the moisture content at a given time and the initial moisture content, respectively.

Experimental results of MR versus drying time were fitted to six semi-theoretical models, which are widely used to describe the kinetics in the drying process. Non-linear regression techniques were used to obtain the specific constants in each of the selected models, using Origin Pro 8.0 software based on the Levenberg–Marquardt method (Nalan & Ibrahim 2005; Celma *et al.* 2007).

The coefficient of determination (γ^2) and reduced chi-square (χ^2) were calculated to evaluate the fitting of a model to experimental data. The higher values of γ^2 and the lower values of χ^2 were chosen for goodness of fit (Nalan & Ibrahim 2005; Celma *et al.* 2007). These parameters can be calculated as Equations (2)–(3):

$$\gamma^2 = \sum_{i=1}^{N} \frac{\left(\mathrm{MR}_{\mathrm{pre},i} - \overline{\mathrm{MR}_{\exp,i}}\right)}{\left(\mathrm{MR}_{\exp,i} - \overline{\mathrm{MR}_{\exp,i}}\right)^2} \tag{2}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(\mathrm{MR}_{\exp,i} - \mathrm{MR}_{\mathrm{pre},i}\right)^2}{N - z} \tag{3}$$

where N is the number of data values and z is the number of constants.

RESULTS AND DISCUSSION

Sludge foam stability

Foam-mat drying depends on the generation of stable foam. The stability is required prior to drying, so as to not collapse during feeding and deposition in the drying system (Ratti & Kudra 2006). Foam stability is usually assessed by measurement of density variation over a specified time. Practically, foams that do not collapse for least 1 hour are considered stable (Eduardo & Gilberto 2001). In this paper, the stability of sludge foam in different initial densities was studied by determining the variations of density every 12 h. Results showed that the densities of foamed sludge at different

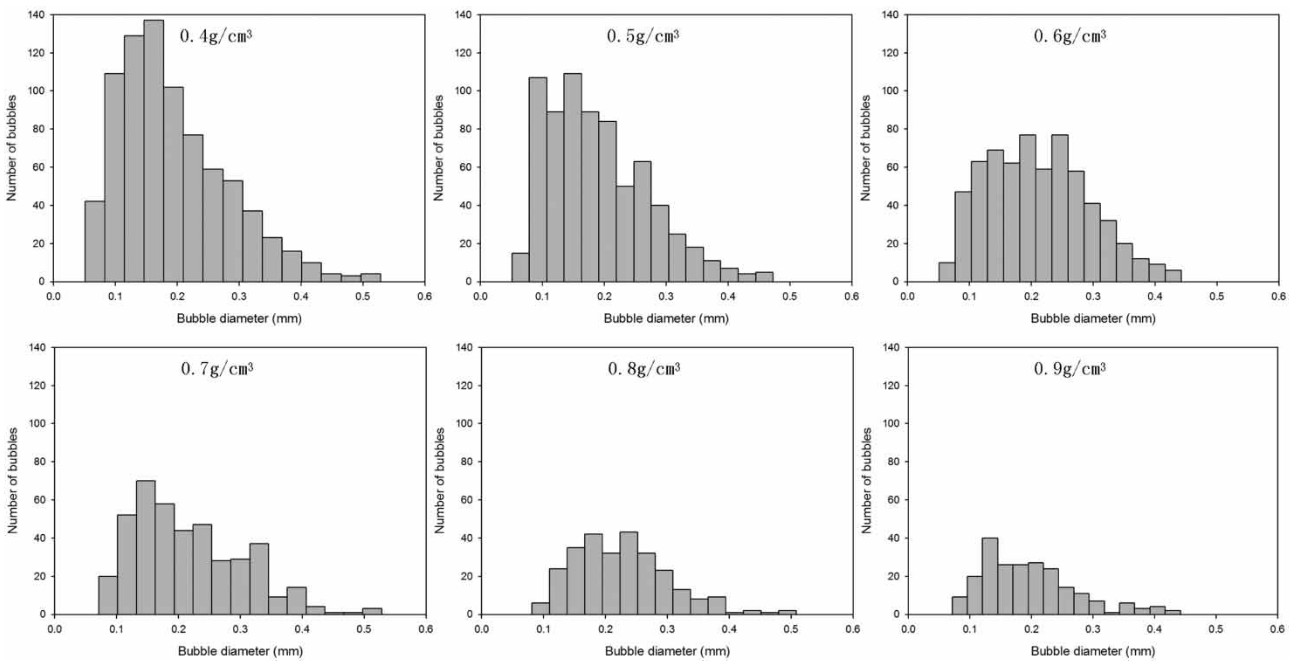

Figure 1 | Bubble diameter distribution at different sludge densities (0.90–0.40 g/cm^3 were the densities of foamed sludge).

initial densities had few variations after standing for 48 h. This phenomenon indicated that the sludge foam was stable enough for foam-mat drying.

Generally, bubble size and numbers are considered to be important factors of foam stability (Stoyan *et al.* 2011). Figure 1 shows the bubble size distributions. It was observed that the total number of bubbles of samples with lower sludge densities was larger than those at higher sludge densities. However, the bubble size distributions were insignificantly different amongst the samples with higher and lower densities. The bubble diameters mainly ranged from 0.1 to 0.3 mm.

Unlike big bubbles, foams with small bubbles were always highly stable. The homogeneous bubble size distributions in a foam structure could lead to stability of foam because of balanced forces at the interface (Ratti & Kudra 2006). Moreover, as a three-phase foam system, 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 (Stoyan *et al.* 2011).

Drying curves of foamed sludge at different drying conditions

Figure 2 shows the changes of moisture content versus drying time of sludge samples with different initial density at various temperatures. Seen from Figure 2(a) and (b), the foamed sludge took less time to approach the equilibrium moisture content than the non-foamed sludge. However, a lower density of sludge foam does not always imply a shorter drying time in the same drying condition. According to Figure 2, the foamed sludge at 0.70 g/cm^3 had the best drying performance at every temperature. On the one hand, the shorter drying time primarily results from the larger surface area exposed to drying air; on the other

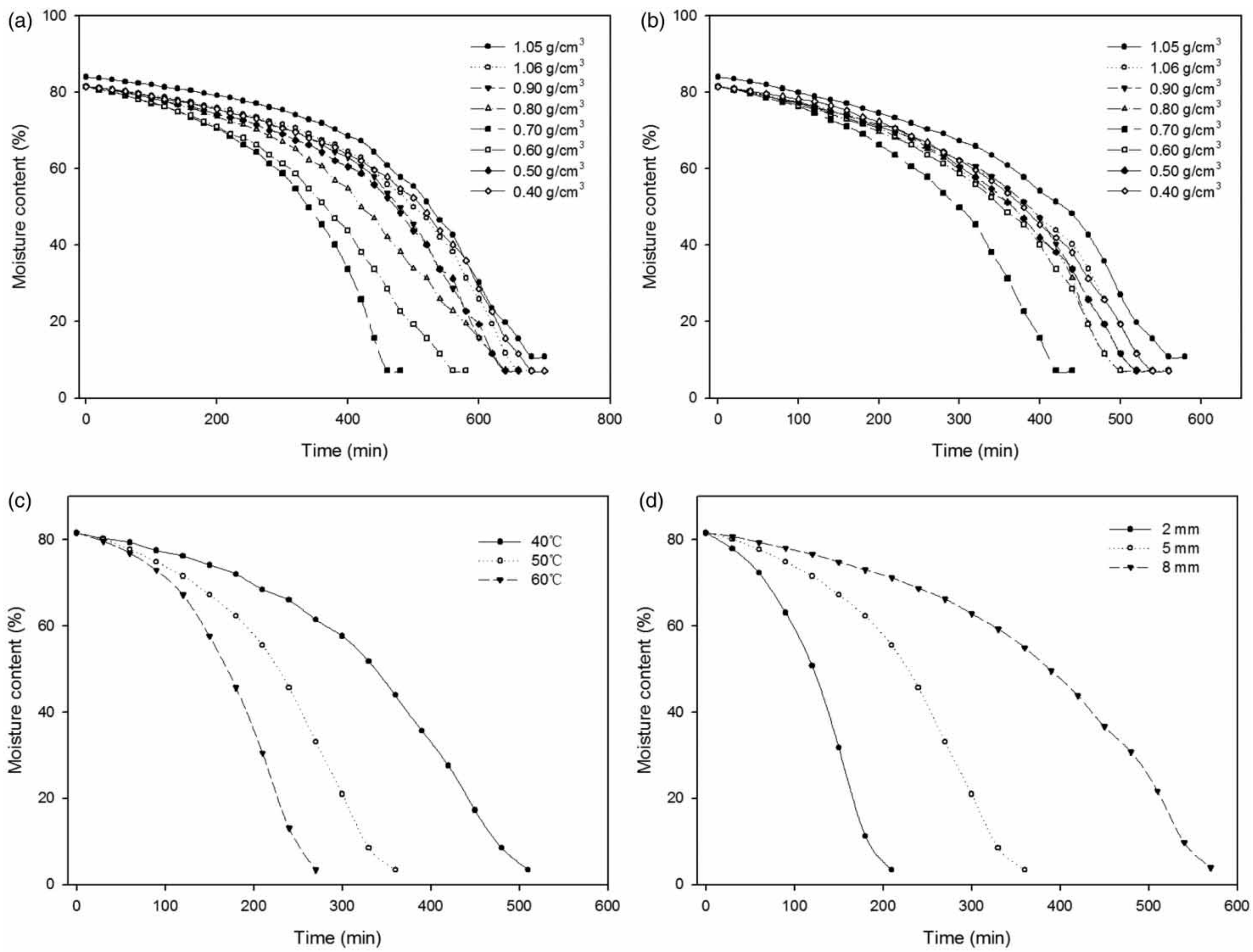

Figure 2 | Drying curves of sludge at different drying condition: (a) 40 °C; (b) 50 °C; (c) 5 mm, 0.7 g/cm^3; (d) 50 °C, 0.7 g/cm^3 (1.05 g/cm^3 was the density of dewatered sludge without foaming process; 1.06 g/cm^3 was the density of dewatered sludge with CaO addition but whipping; 0.90–0.40 g/cm^3 were the densities of foamed sludge).

hand, the lower thermal conductivity of foams, compared liquids, seems to be a negative effect on heat transfer. Thus the drying performance will not be improved by foaming infinitely (Ratti & Kudra 2006).

The experiments of drying temperature and sample thickness were conducted at the density of 0.70 g/cm^3. Figure 2(c) shows that the total drying time required for attaining the equilibrium moisture content was successively reduced with the increasing of drying temperature. This was because higher drying temperature offered more energy to the drying system at the same time. Meanwhile, higher drying temperature enabled the moisture to shift to vapor and enhanced the vapor pressure of the air passing through the foamed sludge to carry more moisture out (Zhao *et al.* 2010).

The changes of moisture content versus drying time of foamed sludge samples at different sample thicknesses are presented in Figure 2(d). The total drying time required for attaining the equilibrium moisture content increased with the increasing of sample thickness. Compared to the thinner sludge samples, with the increasing of sample thickness, the masses of sludge became larger. Then, longer drying time and more energy were needed to obtain lower moisture content.

Drying rates of foamed sludge at different drying conditions

Usually, two main types of water within the sludge are considered: the free water which is not influenced by the solid particles and the bound water whose properties are modified due to the presence of the solid (Vaxelaire & Cezac 2004). The drying rate curve describes the evolution of the evaporation flux versus moisture content

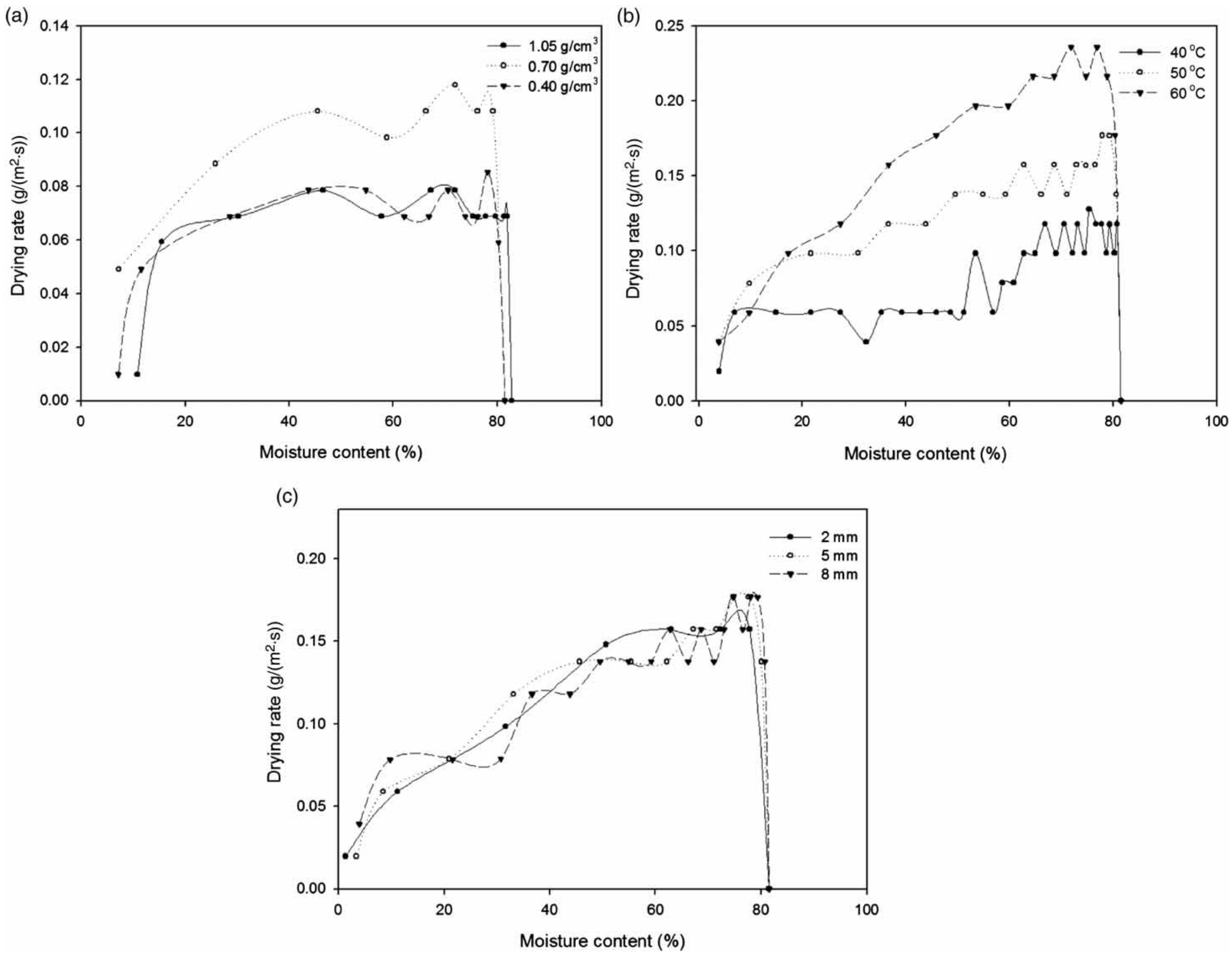

Figure 3 | Drying rate curves of sludge at different drying conditions: (a) 40 °C, 10 g; (b) 8 mm, 0.70 g/cm^3; (c) 50 °C, 0.70 g/cm^3 (1.05 g/cm^3 was the density of dewatered sludge without foaming process; 0.70 and 0.40 g/cm^3 were the densities of foamed sludge).

Table 1 | Curve fitting criteria for the thin layer models (50 °C, 0.70 g/cm^3)

Model name	Model	Thickness (mm)	Model constants	γ^2	χ^2
Lewis (Celma & Cuadros 2012)	$MR = \exp(-kt)$	2	$k = 0.01179$	0.96144	5.2925×10^{-3}
		5	$k = 0.00612$	0.94532	6.6700×10^{-3}
		8	$k = 0.00353$	0.94442	5.9100×10^{-3}
Page (Karaaslan & Tuncer 2008)	$MR = \exp(-kt^{a})$	2	$k = 0.00113$, $a = 1.50684$	0.99643	4.9050×10^{-4}
		5	$k = 0.00033$, $a = 1.55457$	0.99375	7.6290×10^{-4}
		8	$k = 0.00021$, $a = 1.49357$	0.99050	8.1010×10^{-4}
Henderson and Pabis (Roberts *et al.* 2008)	$MR = a\exp(-kt)$	2	$k = 0.01249$, $a = 1.06828$	0.96254	5.1400×10^{-3}
		5	$k = 0.00671$, $a = 1.10207$	0.95446	5.5600×10^{-3}
		8	$k = 0.00390$, $a = 1.10255$	0.95597	4.6800×10^{-3}
Modified Henderson and Pabis (Demir *et al.* 2007)	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$	2	$k = 0.00516$, $g = 0.00516$, $h = 0.00459$, $a = 4.53970$, $b = 4.53970$, $c = -8.04713$	0.97895	2.8900×10^{-3}
		5	$k = 0.00209$, $g = 0.00208$, $h = 0.00174$, $a = 4.54493$, $b = 4.54494$, $c = -8.05114$	0.98999	1.2200×10^{-3}
		8	$k = 0.00093$, $g = 0.00094$, $h = 0.00069$, $a = 3.90774$, $b = 3.90772$, $c = -6.79447$	0.99755	2.6040×10^{-4}
Logarithmic (Nalan & Ibrahim 2005)	$MR = a\exp(-kt) + b$	2	$k = 0.00801$, $a = 1.26581$, $b = -0.23296$	0.98783	1.6700×10^{-3}
		5	$k = 0.00330$, $a = 1.50266$, $b = -0.46361$	0.99207	9.6717×10^{-4}
		8	$k = 0.00146$, $a = 1.80681$, $b = -0.78538$	0.99781	2.3250×10^{-4}
Wang and Singh (Celma & Cuadros 2012)	$MR = 1 + at + bt^2$	2	$a = -0.00844$, $b = 1.7539 \times 10^{-5}$	0.99623	4.1734×10^{-4}
		5	$a = -0.00428$, $b = 4.1613 \times 10^{-6}$	0.99406	3.2464×10^{-4}
		8	$a = -0.00241$, $b = 1.1577 \times 10^{-6}$	0.99811	2.0067×10^{-4}

and is always employed to classify the moisture in the sludge.

As shown in Figure 3(a), three representative densities of sludge were selected. Meanwhile, the constant period of the foamed sludge at 0.70 g/cm^3 was significantly different from the others, and extended to a wider range of moisture content. Usually, the constant rate period typically corresponds to the loss of free water at the surface of the material (Vaxelaire & Cezac 2004), and alkali pretreatment could disrupt the microorganism cell and change the water molecules–organic matter bonding. Therefore, the best drying performance of foamed sludge at 0.70 g/cm^3 might result from not only the larger surface area exposed to drying air, but also from the alkaline pretreatment weakening the water retention capacity of sludge, and changing more water from bound type into free type.

As shown in Figure 3(b) and 3(c), the values of drying rate increased rapidly when drying temperature rose from 40 to 60 °C. And the constant rate period narrowed with the increasing temperature. The reasons for this phenomenon may be that the constant rate period mainly depended on the external conditions, including drying temperature, velocity and humidity. However, drying rates were improved with the increase of sludge sample thickness in the early stages of drying, and then the effect of sample thickness on drying rate was not obvious in the following drying stages.

Modeling of drying curves

An efficient modeling of drying curves could be used to perform an accurate estimate of the MR of foamed sludge at any time during the whole drying process (Demir *et al*. 2007). In particular, empirical and semi-theoretical thin-layer drying models, which only consider the external resistance to moisture transfer between the sludge sample, are most widely used. (Celma & Cuadros 2012).

So a wide set of empirical and semi-theoretical thin-layer drying models were examined in the present paper to describe the drying curves of foamed sludge at different sample thicknesses. Results of the statistical computing are summarized in Table 1.

According to this perspective, a simple model leading to the highest value for γ^2 and the lowest for χ^2 for all sample thicknesses was selected. This way, the Wang and Singh model was found to best represent the drying behaviour. The values of γ^2 were over 0.99 along the whole sample thickness range. The values of χ^2 were between 2.0067×10^{-4} and 4.1734×10^{-4}.

CONCLUSIONS

Addition of CaO at concentration of 2 wt% could produce foamed sludge at an optimum whipping time, and the foams were stable. The diameters of bubbles mainly ranged from 0.1 to 0.3 mm. This homogeneous distribution of bubble size in a foam structure could lead to the stability of foam because of balanced forces at the interface. Foaming pretreatment had positive effect on the drying behavior of dewatered sludge. At each level of temperature, the foamed sludge at 0.70 g/cm^3 exhibited the best drying performance, which mainly derived from its long constant rate period. The drying rates of foamed sludge at 0.70 g/cm^3 were improved with the increasing of drying temperature. However, the effect of sample thickness on drying rate was not obvious when the sample thickness increased from 2 to 8 mm. The mathematical modeling of the thin-layer drying process of foamed sludge at 0.70 g/cm^3 was developed in this paper, using a nonlinear regression method. The Wang and Singh model was found to best represent the drying behavior, while the values of γ^2 were over 0.99 along the whole sample thickness range.

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