Drying characteristics of sewage sludge pre-conditioned by CaO and sawdust under low-temperature drying conditions

Author(s): Zhang, Qunli; Wang, Baozhong; Xing, Yuhao; Wang, Gang; Zhang, Xinchao; Lü, Xiaoshu

Title: Drying characteristics of sewage sludge pre-conditioned by CaO and sawdust under low-temperature drying conditions

Year: 2024

Version: Accepted manuscript

Please cite the original version:

Zhang, Q., Wang, B., Xing, Y., Wang, G., Zhang, X. & Lü, X. (2024). Drying characteristics of sewage sludge pre-conditioned by CaO and sawdust under low-temperature drying conditions. *Environmental Technology*. https://doi.org/10.1080/09593330.2024.2330474

Drying characteristics of sewage sludge pre-conditioned by CaO and sawdust under low-temperature drying conditions

Qunli Zhang[a,b], Baozhong Wang[a,b], Yuhao Xing[a,b], Gang Wang[a,b], Xinchao Zhang[c] and Xiaoshu Lü[a,d]

[a]Beijing Municipality Key Lab of Heating, Gas Supply, Ventilation and Air Conditioning Engineering, Beijing University of Civil Engineering and Architecture, Beijing, People's Republic of China;

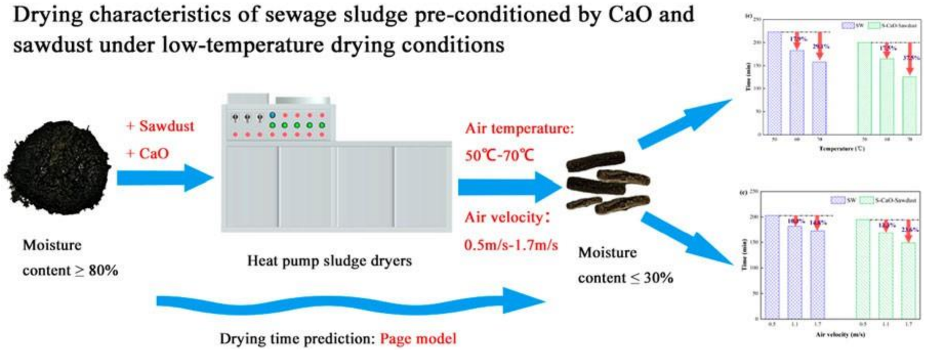
[b]Collaborative Innovation Center of Energy Conservation & Emission Reduction and Sustainable Urban-Rural Development in Beijing, Beijing University of Civil Engineering and Architecture, Beijing, People's Republic of China;

[c]College of civil engineering, Hunan University, Hunan, People's Republic of China;

[d]Department of Electrical Engineering and Energy Technology, University of Vaasa, Vaasa, Finland

ABSTRACT

Heat pump drying is a low-carbon method of sludge drying. The operating temperature of a heatpump is generally not more than 70°C. To improve the drying efficiency of heat pump dryers, the effects of air parameters and additives on sludge drying characteristics at low temperatures were studied. The sludge drying experiments were conducted at an air temperature 50-70°C and an air velocity of 0.5-1.7 m/s. The experimental results showed that the increase of air temperature, velocity and the addition ratio of additives can accelerate the sludge drying process. The average and maximum drying rates of sludge pre-conditioned by CaO and sawdust increased by 14.23% and 25.71%, respectively, compared with those of pure sludge. The two-way analysis of variance (ANOVA) revealed that the influence of air temperature on the sludge drying was higher than that of air velocity. Five reference models were fitted by the drying experiment data. The Page model has the highest R^2, so it is the most suitable model to predict the drying time of sludge at low temperatures.



KEYWORDS: Sludge; sawdust; CaO; low- temperature drying; regression analysis

Nomenclature

D	diameter of sludge samples [mm]
DR	drying rate [kg/kg/min]
L	length of sludge samples [mm]
m	wet basis moisture content [kg_w/kg_{wb}]

M	dry basis moisture content [kg_w/kg_{db}]
MR	dimensionless expression of sludge moist- ure content
SW	sewage sludge
S-CaO	mixture of sewage sludge and CaO
S-Sawdust	mixture of sewage sludge and sawdust
S-CaO-Sawdust	mixture of sewage sludge, CaO and sawdust
t	time [min]
T	air temperature [°C]
V	air velocity [m/s]
W	mass of the sample [kg]

Greek letters

Δ	a moment-independent sensitivity indicator

Subscripts

0	initial
db	dry basis
e	final
w	water
wb	wet basis

1.Introduction

With population growth and urbanisation expansion, a great quantity of sludge is produced [1]. In China, s11.75 million tons of dry matter were produced in 2019 [2]. The of sewage sludge produced in Europe is about 9 million tons of dry matter every year [2]. Sewage sludge with high moisture content takes up a lot of space, which increases transportation and storage costs [3]. Sludge is generally enriched in sewage pollution including heavy metals (Zn, Cu, Cr, Pb, etc.), which will cause damage to the soil [4]. Meanwhile, sewage sludge contains numerous pathogens causing health problems [5,6]. Drying is one of the main methods of sludge disposal and it plays an increasingly important role [7,8]. Thermal treatment has already accounted for the largest share of sludge disposal in Japan [9]. In Germany, about 70% of the sludge was disposed of by thermal treatment in 2017 [10]. However, sludge drying is typically energy-intensive. Using fossil fuels to dry sludge goes against the goal of carbon neutrality [11]. A heat pump is a low-carbon technology for supplying heat, which can use renewable energy and recover waste heat [12,13]. Therefore, drying sludge with a heat pump has gradually attracted attention [14]. Zhang et al. [15] constructed a heat pump sludge drying system and investigated its drying rate and energy consumption . Yu et al. [16] proposed a sludge drying device based on a heat pump and the operating cost was less than half of the dryer with electricity or natural gas as the heat source. The SMER of a closed-loop heat pump dryer can reach 3.5 kg/ kWh [17].

Sludge is characterised by stickiness and poor stiffness, resulting in a small heat exchange area between sludge and the drying medium [18]. Water in the sludge includes free water and bound water. Bound water refers to the water bound to the solid phase with binding energy and free water is the state of water unaffected by the solid phase [19]. Stickiness and bond water lead to a slow sludge drying rate and high-energy consumption. Adding physical additives to sludge can strengthen the structure of pasty sludge and increase the sludge porosity, which can improve the drying rate [18]. Zhao et al. [18] found that the drying rate was affected by mixing ratio, air temperature and sludge thickness. The addition of coal and biomass can accelerate the sludge drying process. Li et al. [20] proved that sawdust addition increased the total exchange surface, resulting in a higher drying rate. Cai et al. [21] found that adding less than 5% wb rice straw is helpful in improving the drying rate. Due to the low thermal conductivity of rice straw, the drying rate is reduced if the addition ratio is too high. A. Leonard et al. [22] showed that back-mixing can reinforce the texture of pasty sludge and improve the drying effect.

Some chemical additives can destroy the combined water in the sludge and make it easier to be absorbed by the drying medium [23]. CaO, Fenton's reagent, NaHCO3, etc. are common chemical additives [23–25]. Calcium oxide (CaO) is a common additive utilised for sludge stabilisation or landfilling [26]. CaO can destroy extracellular polymers and hydrolyse cell walls and tissues composed of proteins and carbohydrates [27]. CaO is also beneficial for desulfurisation and nitrogen fixation [23,27,28]. Deng et al. [29] studied the effect of CaO on the adhesion and cohesion characteristics of sludge under agitated and non-agitated drying con- ditions. She et al. [30] found that synergistic pretreat- ment of freezing and CaO can enhance dewaterability of waste-activated sludge and enhance volatile fatty acid recycling. Liu [23] showed that Fenton peroxidation combined with CaO can effectively enhance sludge heat transfer, reduce the amount of bound water and create a porous structure in sludge.

The heat and mass transfer process in sludge drying is complex. For heat pump sludge dryers, the process of drying is determined by many factors, such as air par- ameters, sludge type, sludge shape and sludge pretreat- ment [18,31,32]. Hence, the mathematical model of the drying process is very important for the design of dryers. Lyes Bennamoun et al. [33] built a heat and mass transfer model for modelling the convective drying of sewage sludge considering shrinkage. Jean- Pierre Ploteau et al. [34] developed a numerical model of a heat pump-assisted continuous dryer. In addition, many researchers have also studied the semi-theoretical and empirical models of the sludge drying process. Huang et al. [24] discussed thin-layer drying models based on two falling rate stages and found that the Modified Page model was the best model to fit the drying process. Zheng et al. [31] improved the prediction ability of the drying model by introducing humidity into the model coefficients.

To improve the drying efficiency of the heat pump dryers, the influence of additives, addition ratio, air temperature and velocity on sludge drying was studied in this paper. The research method of this paper is experimental research and data analysis. The experimental study includes the influence of additives and air parameters on the sludge drying effect.

Data analysis includes the influence of air temperature and air velocity on sludge drying (Two-way analysis of var- iance) and the prediction model of the sludge drying process (Nonlinear data fitting). The objectives of this study are (1) to study the drying characteristics of sewage sludge pre-conditioned by CaO and sawdust at low temperature; (2) to compare the effects of hot air temperature and velocity on sludge drying; (3) to find the most suitable drying model by fitting a variety of reference drying models and (4) to examine sludge drying characteristics for the design and optimisation of heat pump sludge dryers.

2.Materials and methods

2.1 Materials

The sewage sludge (SW), after mechanical dewatering, was collected from a wastewater treatment plant in Beijing, China. The initial moisture content of SW was about 82.96% (kg_w/kg_{wb}) (wet basis) using a constant temperature drying oven (DHG-9070A, China). The sludge was stored in a refrigerator at 4°C before exper- iments. Sawdust purchased from a local market in Beijing was dried in a constant temperature drying oven to a constant weight and then screened by a 40 mesh screen. The CaO chemicals used in experiments were of analytical grade with 98% purity.

2.2 Experimental set-up

To simulate the low-temperature drying conditions corresponding to a heat pump, we built laboratory-scale hot air drying equipment (Figure 1). The test stand included a heater with a fan, an air valve, a temperature controller, a precision balance, a computer, etc. The heater with a fan (Home of PTC; China) can heat the air at a constant temperature and blow the hot air into the drying hamber. The heater is composed of PTC ceramic heating plates, with a DC voltage of 24 V and a power of 200W. The temperature of the drying chamber was accurately controlled by a temperature test probe and a temperature controller (Home of PTC; XH-W3001, China). The hot air velocity was varied by the air valve and measured by the hot wire anemometer(Testo 425, Germany). The mass of the sample was recorded once every 20 min by a precision balance (ZHUOJING; BSM220.4, China) with an accuracy of 0.0001 g. The precisions of experimental devices are listed in Table 1.

In industrial production, sludge is often extruded into a cylindrical shape by granulator before drying. In this study, sludge samples were shaped into cylinders of diameter 10 mm (D = 10 mm) and length 50 mm (L =50 mm). Each sample weighed about 6 g. The drying experiments were conducted at three temperature settings at 50°C, 60°C, 70°C and three air velocity settings at 0.5, 1.1, 1.7 m/s. For sludge pre-conditioned with CaO (S-CaO), the CaO/sludge mixing ratios of 5%, 10% and 15% were set. Because the mixture was difficult to form when the addition of sawdust was large, the sawdust/sludge mixing ratios of 5% and 10% were set for sludge pre-conditioned with sawdust (S-sawdust). Sludge added 5% CaO and 5% sawdust was called SCaO-Sawdust.

Type B evaluation of measurement uncertainty includes instrument uncertainty and estimation error during measurement. The estimation error is generally far less than the uncertainty of the instrument and can be ignored [35,36]. The uncertainty can be calculated by Equation 1. The maximum uncertainty of the test parameters is listed in Table 2.

$$U = \frac{\triangle x}{C * X} \qquad (1)$$

where △x is the maximum allowable error of the instrument; X is the minimum value in the test data. If the source of maximum allowable error is normal distribution, C is √3.

2.3. Definitions of drying rate and moisture ratio

The wet basis moisture content is defined as the ratio of the mass of water contained in wet sludge to the total mass of wet sludge [31], which can be expressed as

$$m = \frac{W_t - W_0}{W_t} \qquad (2)$$

where m is the wet basis moisture content; Wt and W0 are the total mass of wet sludge at any time and the dried sludge mass in the wet sludge, respectively.

The dry basis moisture content is defined as the ratio of the mass of water contained in wet sludge to the dried sludge mass in the wet sludge [31], which can be expressed as

$$M = \frac{W_t - W_0}{W_0} \qquad (3)$$

where M is the wet basis moisture content.

The drying rate is determined by the mass of water evaporated from sludge per unit of time [31], as shown in Equation (4):

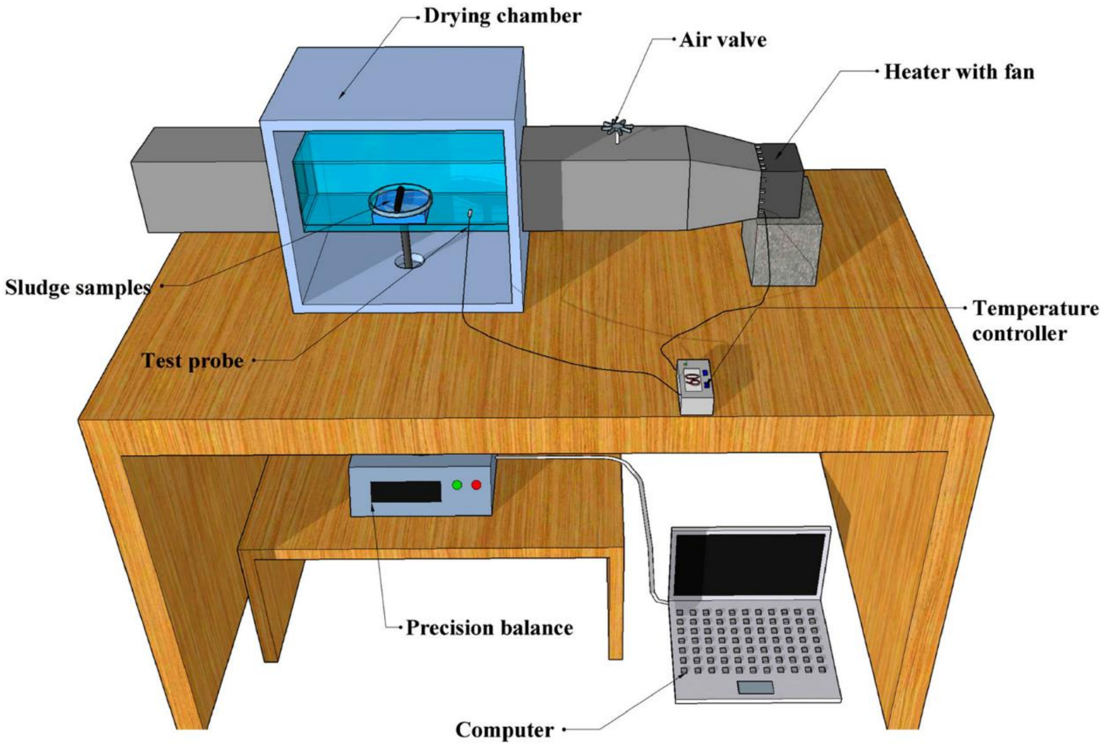
$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \qquad (4)$$

where Mt and Mt+Dt are the dry basis moisture contents at time t and Dt, respectively. The dimensionless expression of sludge moisture content is calculated using Equation (5) [31]:

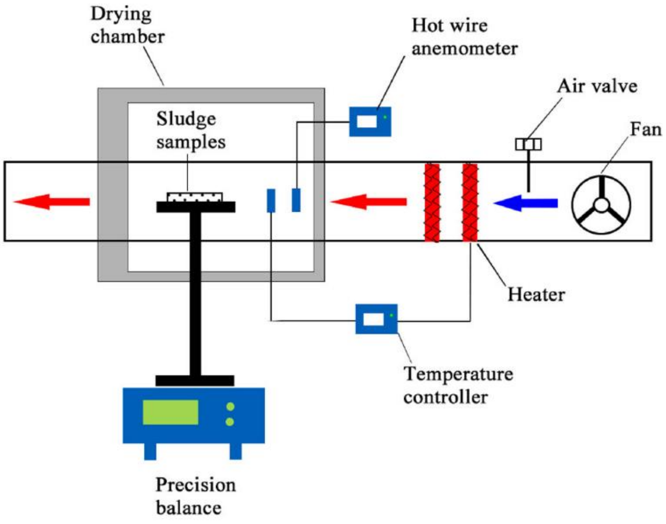
$$MR = \frac{M_t - M_e}{M_0 - M_e} \qquad (5)$$

where Meis the equilibrium moisture content and M0 is the initial dry basis moisture content. Since M0 and Mt
are much larger than Me [31], Equation (5) is often simplified to Equation (6)

$$MR = \frac{M_t}{M_0} \qquad (6)$$



(a) Pictorial view



(b) Schematic diagram

Figure 1. Drying experiment set-up. (a) pictorial view. (b) sSchematic diagram.

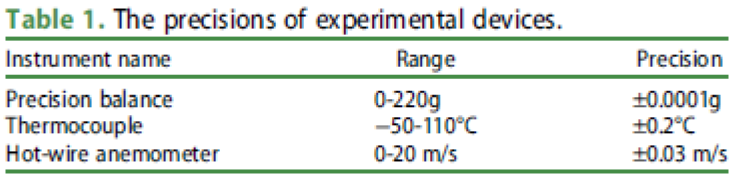


Table 1. The precisions of experimental devices.

Instrument name	Range	Precision
Precision balance	0-220g	±0.0001g
Thermocouple	−50-110°C	±0.2°C
Hot-wire anemometer	0-20 m/s	±0.03 m/s

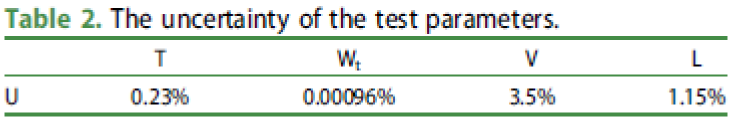


Table 2. The uncertainty of the test parameters.

	T	W_t	V	L
U	0.23%	0.00096%	3.5%	1.15%

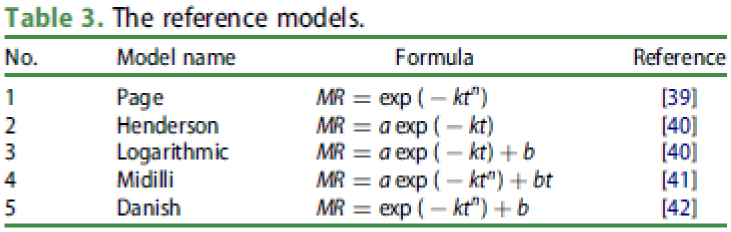


Table 3. The reference models.

No.	Model name	Formula	Reference
1	Page	$MR = \exp(-kt^n)$	[39]
2	Henderson	$MR = a\exp(-kt)$	[40]
3	Logarithmic	$MR = a\exp(-kt) + b$	[40]
4	Midilli	$MR = a\exp(-kt^n) + bt$	[41]
5	Danish	$MR = \exp(-kt^n) + b$	[42]

2.4 Two-way analysis of variance (Two-way ANOVA)

In this paper, the effects of air temperatures and air velocities on the sludge drying were analysed by applying two-way ANOVA [37,38]. We used SPSS19 for all data analysis.

2.5. Evaluation of the drying models

The heat and mass transfer process in sludge drying is complex. It is hard to construct an accurate model for modelling the sludge drying process. However, several semi-theoretical and semi-empirical models have been developed to describe sludge drying. These reference models are listed in Table 3. Five reference models were used to fit the experimental data in Origin Pro 2021 software.

3. Results and discussion

Drying time is an important design parameter for heat pump dryers. Therefore, the drying effect of sludge mainly refers to the time consumed for drying to the target moisture content. It is unnecessary to completely evaporate the water contained in the wet sludge because the drying process is energy-intensive and time-consuming. Han et al. [43] found that sewage sludge with a moisture content of more than 30% reduced the combustion efficiency and furnace temperature. The fluidised bed will not burn steadily when the value exceeds 40%. Therefore, 30% was considered as the target moisture content (wb) in drying.

3.1. Co-drying characteristics

Additives and addition ratios can affect the sludge drying process. The effects of different additives and different mixing ratios on the sludge drying process at the air temperature of 60°C and the velocity of 1.7 m/s are shown in Figure 2. At the same drying temperature and air velocity, S-CaO, S-Sawdust and S-CaO-Sawdust can reduce the drying time compared with SW (Figure2(a)). S-CaO-Sawdust had the best performance to shorten the sludge drying time. The drying time of SCaO-Sawdust was shortened by 23 min compared with

SW. One reason was that CaO destroyed extracellular polymers and hydrolysed cell walls and tissues composed of proteins and carbohydrates [27]. Bound water, including the physical and chemical bound ones, was released [19]. Another reason was that loose sawdust increased the sludge porosity, thus increasing the contact area with hot air [18]. It can be seen from Figure 2(d) that the average and maximum drying rates of S-CaO-Sawdust were 0.0297 and 0.0553 kg/kg/min, respectively, which were 14.23% and 25.71% higher than those of SW, respectively. Figure 2(b-c) shows that with the increase in mixing ratio, the drying time of S-CaO and S-Sawdust decreased from the initial moisture content to the target moisture content (wb) of 30%. For S-CaO, the drying time was shortened from 168 min to 148 min when the mixing ratio changed from 5% to 15%. Adding more Cao means more bound water in sludge is released.

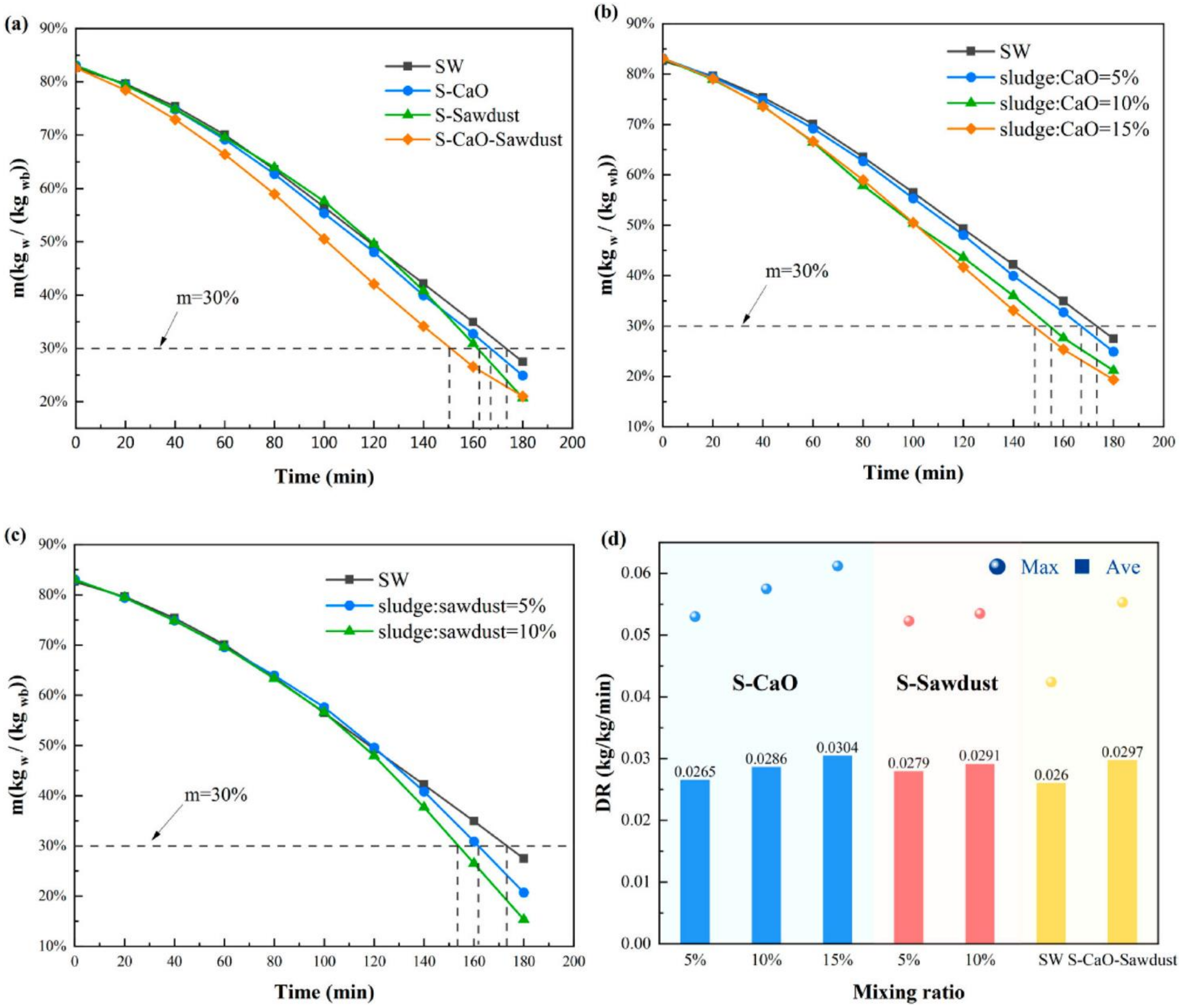


Figure 2. Effect of different additives on sludge drying (60°C,1.7 m/s) (a) wet basis moisture content vs. time for different additives, (b) wet basis moisture content vs. time of S-CaO at different mixing ratios, (c) wet basis moisture content vs. time of S-Sawdust at different mixing ratios, (d) drying rate vs. mixing ratio.

For SSawdust, the drying time was reduced by 8 min when the mixing ratio changed from 5% to 10%. The increase in sawdust particles leads to an increase in the porosity of S-Sawdust.

However, S-Sawdust was difficult to form when the mixing ratio exceeded 10%. The maximum amount of sawdust added was 10%. As the mixing ratio of S-CaO increased from 5% to 15%, the average and maximum drying rates increased by 1.92-16.92% and 25-44.34%, respectively. Similarly, as the mixing ratio of S-Sawdust increased from 5% to 10%, the average and maximum drying rates increased by 7.31-11.92% and 23.35-26.18%, respectively (Figure 2(d)). During the drying process, the shape change of SCaO-Sawdust was different from that of SW (Figure 3). Shrinkage was the main phenomenon for SW and a hard crust formation on the surface may reduce the drying rate. The shrinkage of S-CaO-Sawdust was less than that of SW. CaO can destroy extracellular polymers and hydrolyse cell walls and tissues and sawdust plays the part of a skeleton, which explains the higher drying rate of S-CaO-Sawdust. It can be seen that several large cracks were formed on the surface of SW, which can produce much fly ash and cause hidden danger in the drying process [44]. In contrast, a few cracks were formed on the surface of S-CaO-Sawdust. Therefore, the addition of CaO and Sawdust not only improves the drying rate but also reduces hidden danger in the drying process.

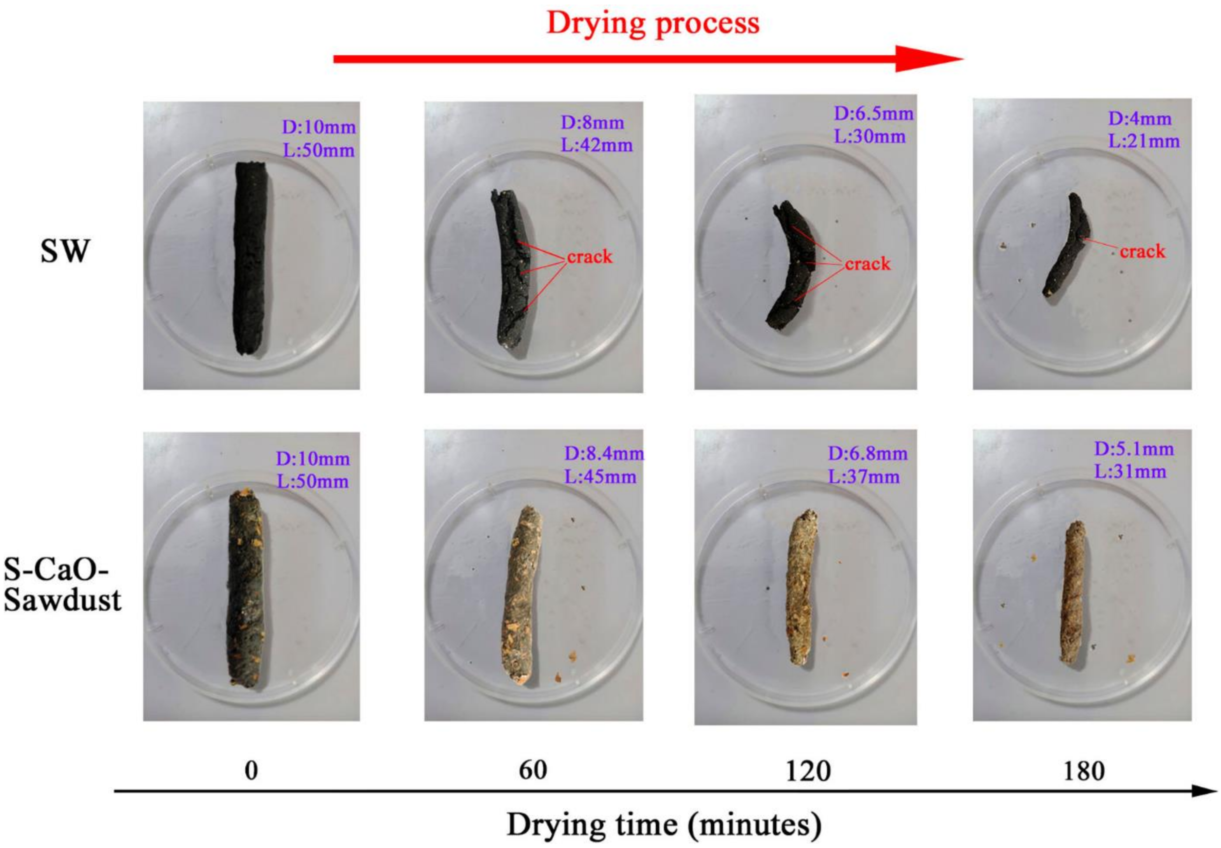


Figure 3. Shape changes of SW and S-CaO-sawdust at an air temperature of 70°C and a velocity of 1.7 m/s.

3.2. Effect of air temperature

Air temperature is an important factor affecting sludge drying time. Figure 4(a) illustrates the drying curves of SW and S-CaO-Sawdust for different air temperatures. It was seen that higher drying air temperature brought shorter sludge drying time. Under the same conditions, the drying curve of S-CaO-Sawdust was steeper than that of SW, which indicated that S-CaO-Sawdust can reduce drying time than SW. For SW, the drying time to 30% moisture content (wb) at the air temperatures of 60°C and 70°C decreased by 17.9% and 29.1%, respectively compared to that at the air temperature of 50°C. For S-CaO-Sawdust, the reduction is larger. The time required to dry to 30% moisture content (wb) at the air temperature of 60°C and 70°C decreased by 17.5% and 37.5%, respectively compared to that at the air temperature of 50°C. (Figure 4(c)).

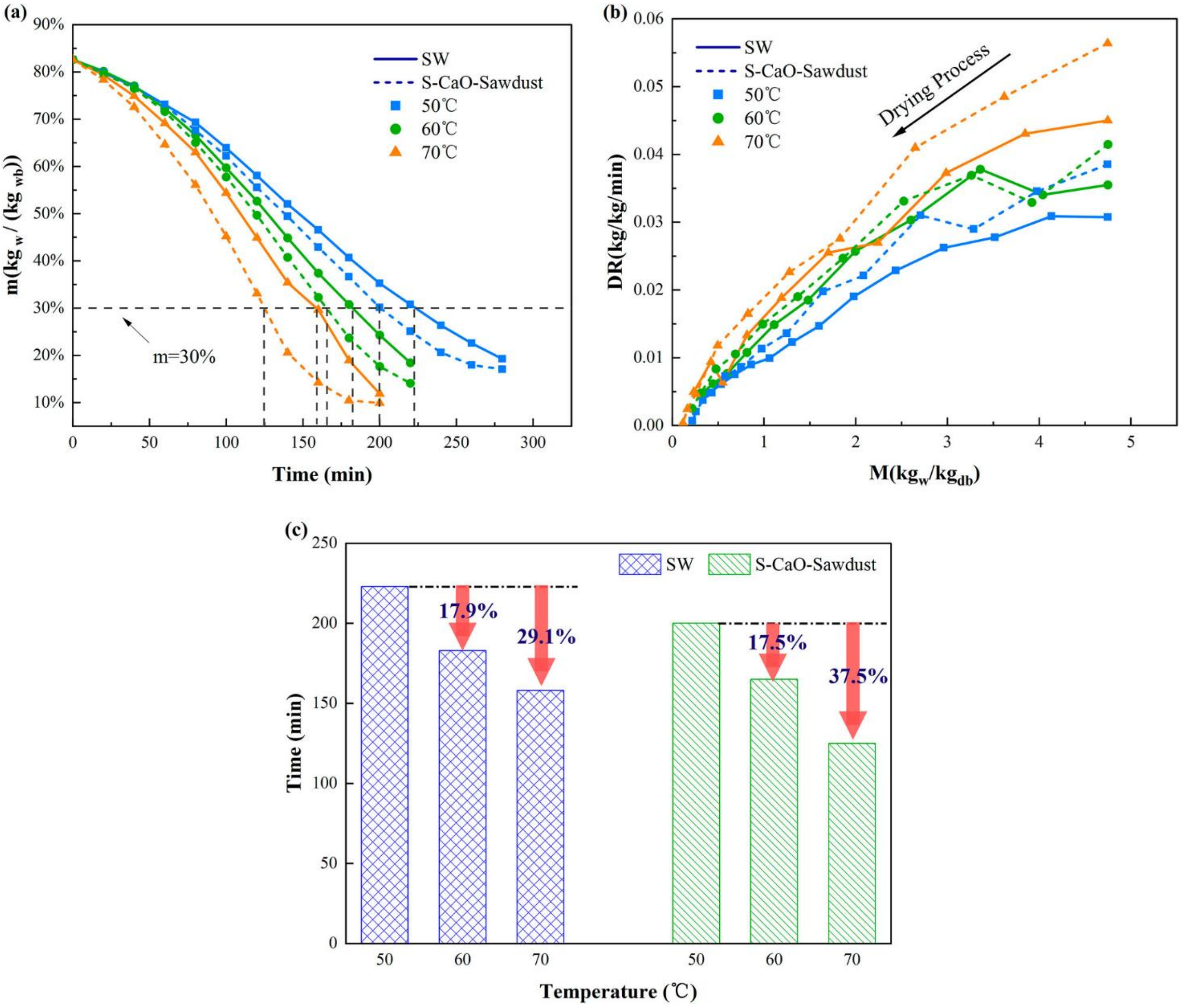


Figure 4. Drying process of SW and S-CaO-sawdust for different air temperatures at the air velocity of 1.1 m/s (a) wet basis moisture content vs. time, (b) drying rate vs. dry basis moisture content, (c) drying time to the target moisture content (wb) vs. temperature.

The reduction in drying time of S-CaO-sawdust at 60-70°C was greater than that at 50-60°C. The conclusion was the opposite for SW. The change process of drying rate at different air temperatures is illustrated in Figure 4(b). The increase in air temperature can significantly improve the average and the maximum drying rates, which is due to the enhancement of air's ability to receive moisture at higher temperatures [31]. In studies related to the sludge drying process, the drying rate curve was often divided into the warm-up period, the constant rate period, the first falling rate period and the second falling rate period [45]. Figure 4(b) shows that the constant rate period is insignificant because the sludge samples contain little free water after mechanical dewatering. Font et al. [46] reported a similar result. For heat pump dryers, drying sludge, containing CaO and sawdust at high temperatures, can significantly reduce drying time. The drying time for S-CaO-Sawdust at the air temperature of 70°C was almost half shorter than that for SW at 50°C.

3.3. Effect of air velocity

Air velocity is another important factor affecting sludge drying time. As shown in Figure 5(a), increasing air velocity can reduce sludge drying time. Under the same conditions, the drying curve of S-CaO-Sawdust was steeper than that of SW, which indicated that S-CaO-Sawdust was more sensitive to changes in air velocity. Figure 5(b) illustrates that the higher air velocity can improve the average and the maximum drying rates of sludge samples. At a higher air velocity, the moisture evaporated from sludge samples can be quickly taken away. A thinner sludge surface boundary layer at a higher velocity can improve the heat and mass transfer coefficients [35]. In addition, more cracks will be formed on the sludge surface with the increase in air velocity [47]. As the air velocity increases from 0.5 m/s to 1.7 m/s, the reduction of drying time becomes smaller. From 0.5 m/s to 1.1 m/s, the reduction rate for S-CaO-Sawdust and SW was 10.3% and 13.3%, respectively. From 1.1 m/s to 1.7 m/s, the reduction rate for S-CaO-Sawdust and SW was 4.5% and 10.3%, respectively (Figure 5(c)). This can be explained that the sludge drying process was mainly controlled by internal moisture diffusion. Hot air velocity belongs to outer drying conditions which have a slight influence on internal diffusion [18].

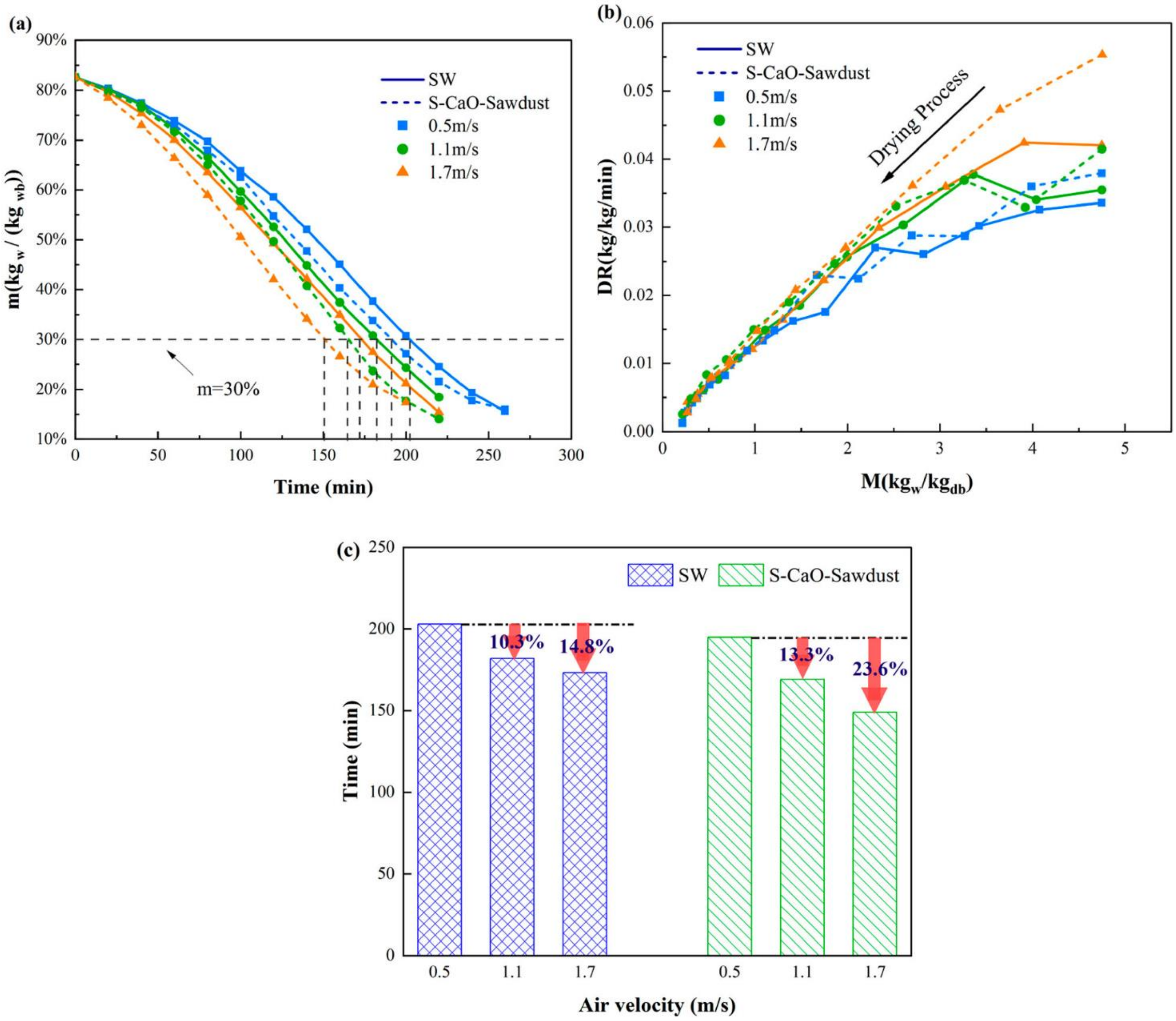


Figure 5. Drying process of SW and S-CaO-Sawdust for different air velocities at the air temperature of 60℃(a) wet basis moisture content vs. time, (b) drying rate vs. dry basis moisture content, (c) drying time to the target moisture content (wb) vs. air velocity.

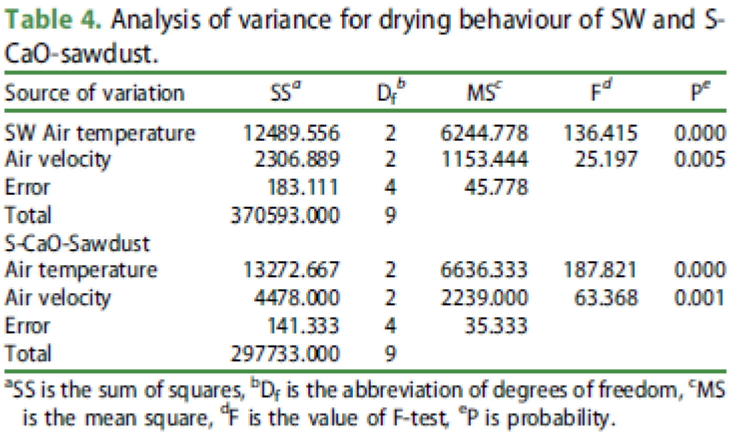


Table 4. Analysis of variance for drying behaviour of SW and S-CaO-sawdust.

Source of variation	SS[a]	D_f[b]	MS[c]	F[d]	P[e]
SW Air temperature	12489.556	2	6244.778	136.415	0.000
Air velocity	2306.889	2	1153.444	25.197	0.005
Error	183.111	4	45.778		
Total	370593.000	9			
S-CaO-Sawdust					
Air temperature	13272.667	2	6636.333	187.821	0.000
Air velocity	4478.000	2	2239.000	63.368	0.001
Error	141.333	4	35.333		
Total	297733.000	9			

[a]SS is the sum of squares, [b]D_f is the abbreviation of degrees of freedom, [c]MS is the mean square, [d]F is the value of F-test, [e]P is probability.

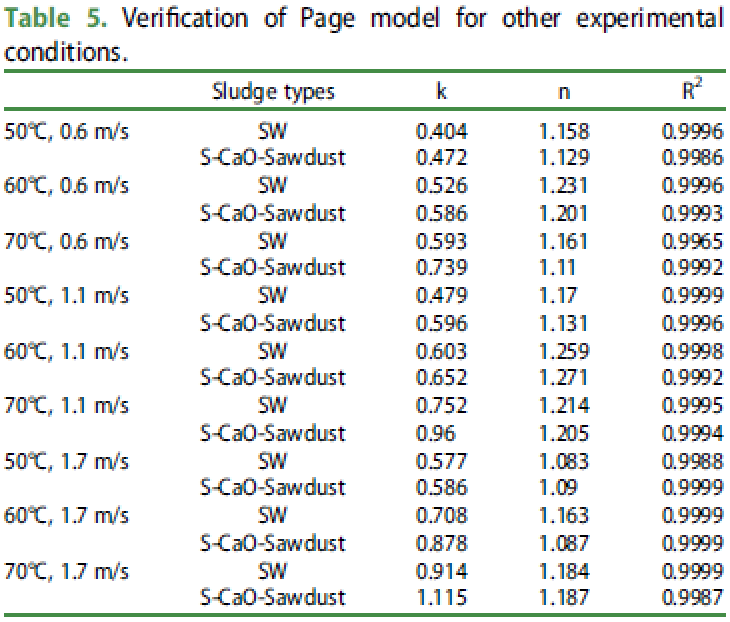


Table 5. Verification of Page model for other experimental conditions.

	Sludge types	k	n	R^2
50℃, 0.6 m/s	SW	0.404	1.158	0.9996
	S-CaO-Sawdust	0.472	1.129	0.9986
60℃, 0.6 m/s	SW	0.526	1.231	0.9996
	S-CaO-Sawdust	0.586	1.201	0.9993
70℃, 0.6 m/s	SW	0.593	1.161	0.9965
	S-CaO-Sawdust	0.739	1.11	0.9992
50℃, 1.1 m/s	SW	0.479	1.17	0.9999
	S-CaO-Sawdust	0.596	1.131	0.9996
60℃, 1.1 m/s	SW	0.603	1.259	0.9998
	S-CaO-Sawdust	0.652	1.271	0.9992
70℃, 1.1 m/s	SW	0.752	1.214	0.9995
	S-CaO-Sawdust	0.96	1.205	0.9994
50℃, 1.7 m/s	SW	0.577	1.083	0.9988
	S-CaO-Sawdust	0.586	1.09	0.9999
60℃, 1.7 m/s	SW	0.708	1.163	0.9999
	S-CaO-Sawdust	0.878	1.087	0.9999
70℃, 1.7 m/s	SW	0.914	1.184	0.9999
	S-CaO-Sawdust	1.115	1.187	0.9987

3.4. Results of two-way analysis of variance

It can be seen from Table 4 that the effects of air temperatures and air velocities on the sludge drying are much more significant ($P<<0.05$). For SW, the F value for the air temperature is larger than that for the air velocity (136.415 > 25.197), so the influence of the air temperature on the sludge drying is higher than that of the air velocity. A similar result can be obtained for S-CaOSawdust. The F value for the air temperature is larger than that for the air velocity (187.821 > 63.368), so the influence of the air temperature on the sludge drying is higher than that of the air velocity.

3.5. Evaluation of the drying models

The fitting information of different drying models of SW at the air temperature of 60°C and the velocity of 1.7 m/s is shown in Figure 6. The Danish model and Page model have the highest R2, and they fit better than other models. The predicted values of the Page model and the Danish model were very close to the test values. Considering the convenience of calculation, the Page model was selected for data prediction because it contained fewer coefficients. To verify the accuracy of the model, the Page model was used to fit the data in other experimental conditions. The verification results are shown in Table 5. It can be seen that the R2 of each fitting is around 0.999, which proves that the Page model can well predict the sludge drying process.

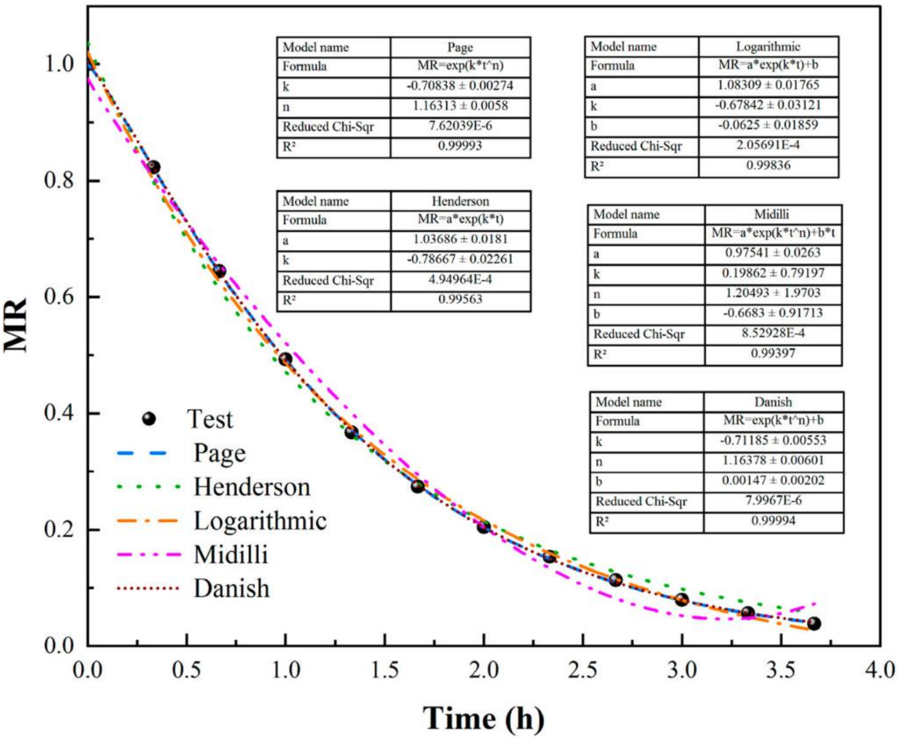


Figure 6. Fitting of different drying models of SW at the air temperature of 60°C and the velocity of 1.7 m/s.

4. Conclusions

In this paper, the drying characteristics of sewage sludge pre-conditioned by CaO and sawdust were studied for low-temperature drying conditions. The experimental parameters were set with corresponding operational conditions of the heat pump. In addition, the regression effect of the drying model was tested. The main conclusions are as follows.

(1) The addition of CaO and sawdust can accelerate the sludge drying process. With the increase in mixing ratio, the average and maximum drying rates of sludge samples increased. The average and maximum drying rates of S-CaO-Sawdust increased by 14.23% and 25.71%, respectively, compared with those of SW.

(2) The drying time to the target moisture content (wb) was greatly reduced with the increases in air temperature and air velocity. The time required to dry to 30% moisture content (wb) at the air temperature of 70°C can be reduced by 37.5% compared to that at the air temperature of 50°C. The time required to dry to 30% moisture content (wb) at the air velocity of 1.7 m/s can be reduced by 23.6% compared to that at the air velocity of 0.5 m/s.

(3) Two-way ANOVA shows that the effects of air temperatures and air velocities on the sludge drying are significant. For SW and S-CaO-Sawdust, the influence of the air temperature on the sludge drying is higher than that of the air velocity.

(4) Five reference models were fitted by the drying experiment data. The Page model was considered to be the most suitable model for modelling the low-temperature drying of sludge. R-squared measures for all the experimental fitting by the Page model were around 0.999, which proved that the Page model can well predict the sludge drying process.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This study was sponsored by the BUCEA Post Graduate Innovation Project and 'The Fundamental Research Funds for Beijing University of Civil Engineering and Architecture' (X20026, X20027).

Data availability statement

The data that support the findings of this study are available from the corresponding author, [Gang Wang], upon reasonable request.

References

[1] Kacprzak M, Neczaj E, Fijalkowski K, etal. Sewage sludge disposal strategies for sustainable development. Environ Res. 2017;156:39–46. doi:10.1016/j.envres.2017. 03.010

[2] Wu B, Dai X, Chai X. Critical review on dewatering of sewage sludge: influential mechanism, conditioning technologies and implications to sludge re-utilizations. Water Res. 2020;180:115912. doi:10.1016/j.watres.2020. 115912

[3] Salamat R, Scaar H, Weigler F, et al. Drying of biogas digestate: a review with a focus on available drying tech- niques, drying kinetics, and gaseous emission behavior. Dry Technol. 2020;40:5–29. doi:10.1080/07373937.2020. 1781879

[4] Rao B, Wang G, Xu P. Recent advances in sludge dewater- ing and drying technology. Dry Technol. 2022;40:3049– 3063. doi:10.1080/07373937.2022.2043355

[5] Mawioo PM, Rweyemamu A, Garcia HA, et al. Evaluation of a microwave based reactor for the treatment of black- water sludge. Sci Total Environ. 2016;548-549:72–81. doi:10.1016/j.scitotenv.2016.01.013

[6] Mawioo PM, Hooijmans CM, Garcia HA, et al. Microwave treatment of faecal sludge from intensively used toilets inthe slums of Nairobi, Kenya. J Environ Manage. 2016;184:575–584. doi:10.1016/j.jenvman.2016.10.019

[7] Chen G, Lock Yue P, Mujumdar AS. Sludge dewatering and drying. Dry Technol. 2006;20:883–916. doi:10.1081/ DRT-120003768

[8] Gao N, Kamran K, Quan C, et al. Thermochemical conver- sion of sewage sludge: a critical review. Prog Energ Combust. 2020;79:1–38. doi:10.1016/j.pecs.2020.100843

[9] Christodoulou A, Stamatelatou K. Overview of legislation on sewage sludge management in developed countries worldwide. Water Sci Technol. 2016;73:453–462. doi:10. 2166/wst.2015.521

[10] Schnell M, Horst T, Quicker P. Thermal treatment of sewage sludge in Germany: a review. J Environ Manage. 2020;263:110367. doi:10.1016/j.jenvman.2020.110367

[11] Heggelund GM. China's climate and energy policy: at a turning point? Int Environ Agreem. 2021;21:9–23. doi:10.1007/s10784-021-09528-5

[12] Shen C, Lei Z, Wang Y, et al. A review on the current research and application of wastewater source heat pumps in China. Therm Sci Eng Prog. 2018;6:140–156. doi:10.1016/j.tsep.2018.03.007

[13] Colak N, Hepbasli A. A review of heat pump drying: part 1 – systems, models and studies. Energ Convers Manage. 2009;50:2180–2186. doi:10.1016/j.enconman.2009.04.031

[14] Minea V. Drying heat pumps – part II: agro-food, biologi- cal and wood products. Int J Refrig. 2013;36:659–673. doi:10.1016/j.ijrefrig.2012.11.026

[15] Zhang T, Yan ZW, Wang LY, et al. Theoretical analysis and experimental study on a low-temperature heat pump sludge drying system. Energy. 2021;214:1–14. doi:10. 1016/j.energy.2020.118985

[16] Yu Wan YJ, Peisheng L, Yi H, et al. Sewage Sludge Drying Based on Heat Pump, International Conference on Power Engineering, p.2; 2007.

[17] Yuan G, Chu KH. Heat pump drying of industrial waste- water sludge. Water Pract Technol. 2020;15:404–415. doi:10.2166/wpt.2020.029

[18] Lijuan Z, Junhong Y, Shanshan W, et al. CO-drying charac- teristics of sticky sewage sludge pre-conditioned with biomass and coal. Dry Technol. 2019;38:2083–2093. doi:10.1080/07373937.2019.1692861

[19] Vesilind PA. The role of water in sludge dewatering. Water Environ Res. 1994;66:7. doi:10.2175/WER.66.1.2

[20] Li J, Wu C-W, Fraikin L, et al. Convective drying of sawdust-sludge mixtures: the effect of the sludge matrix. Dry Technol. 2019;37:920–927. doi:10.1080/07373937.2018.1480027

[21] Cai ZL, Ma XQ, Qing X, et al. Drying kinetics and character- istics of sewage sludge/rice straw mixture. Dry Technol. 2015;33:1500–1509. doi:10.1080/07373937.2015.1021928

[22] Leonard A, Meneses E, Le Trong E, et al. Influence of back mixing on the convective drying of residual sludges in a fixed bed. Water Res. 2008;42:2671–2677. doi:10.1016/j. watres.2008.01.020

[23] Liu H, Liu P, Hu H, et al. Combined effects of Fenton per- oxidation and CaO conditioning on sewage sludge thermal drying. Chemosphere. 2014;117:559–566. doi:10.1016/j.chemosphere.2014.09.038

[24] Huang YW, Chen MQ. Thin-layer isothermal drying kinetics of municipal sewage sludge based on two falling rate stages during hot-air-forced convection. J Therm Anal Calorim. 2017;129:567–575. doi:10.1007/s10973-017-6150-6

[25] Zhou J, Zhang R, Wang X, et al. NaHCO3-enhanced sewage sludge thin-layer drying: drying characteristics and kinetics. Dry Technol. 2016;35:1276–1287. doi:10. 1080/07373937.2016.1249878

[26] Akrivos J, Mamais D, Katsara K, et al. Agricultural utilis- ation of lime treated sewage sludge. Water Sci Technol. 2000;42:203–210. doi:10.2166/wst.2000.0207

[27] Wang R, Liu J, Yu Y, et al. Effects of calcium oxide on the surface properties of municipal wastewater sludge and its co-slurrying ability with coal. Sci Total Environ. 2013;456-457:9–16. doi:10.1016/j.scitotenv.2013.03.069

[28] Liu J, Zhao W, Zhou J, et al. An investigation on the rheo- logical and sulfur-retention characteristics of desulfuriz- ing coal water slurry with calcium-based additives. Fuel Process Technol. 2009;90:91–98. doi:10.1016/j.fuproc. 2008.08.006

[29] Deng WY, Yuan MH, Mei J, et al. Effect of calcium oxide (CaO) and sawdust on adhesion and cohesion character- istics of sewage sludge under agitated and non-agitated drying conditions. Water Res. 2017;110:150–160. doi:10. 1016/j.watres.2016.12.001

[30] She Y, Wei W, Ai X, et al. Synergistic pretreatment of CaO and freezing/thawing to enhance volatile fatty acids recy- cling and dewaterability of waste activated sludge via anaerobic fermentation. Chemosphere. 2021;280:130939. doi:10.1016/j.chemosphere.2021.130939

[31] Zheng Q, Hu Z, Li P, et al. Effects of air parameters on sewage sludge drying characteristics and regression ana- lyses of drying model coefficients. Appl Therm Eng. 2021;198. doi:10.1016/j.applthermaleng.2021.117501

[32] Leonard A, Vandevenne P, Salmon T, et al. Wastewater sludge convective drying: influence of sludge origin. Environ Technol. 2004;25:1051–1057.doi:10.1080/ 09593330.2004.9619398

[33] Bennamoun L, Fraikin L, Léonard A. Modeling and simulation of heat and mass

Transfer during convective drying of wastewater sludge with introduction of shrink- age phenomena. D Dry Technol. 2013;32:13–22. doi:10. 1080/07373937.2013.807281

[34] Ploteau J-P, Noel H, Fuentes A, et al. Sludge convection drying process: numerical modeling of a heat pump assisted continuous dryer. Dry Technol. 2019;38:1261– 1273. doi:10.1080/07373937.2019.1630425

[35] Huang YW, Chen MQ, Jia L. Assessment on thermal behavior of municipal sewage sludge thin-layer during hot air forced convective drying. Appl Therm Eng. 2016;96:209–216. doi:10.1016/j.applthermaleng.2015.11.090

[36] Luo X, Wang L, Zhao X, et al. Experimental investigation of heat transfer in a rotor–stator cavity with cooling air inlet at low radius. Int J Heat Mass Tran. 2014;76:65–80. doi:10.1016/j.ijheatmasstransfer.2014.04.013

[37] Kashaninejad M, Mortazavi A, Safekordi A, et al. Thin-layer drying characteristics and modeling of pistachio nuts. J Food Eng. 2007;78:98–108. doi:10.1016/j.jfoodeng.2005. 09.007

[38] Fu BA, Chen MQ. Thin-layer drying kinetics of lignite during hot air forced convection. Chem Eng Res Des. 2015;102:416–428. doi:10.1016/j.cherd.2015.07. 019

[39] Sun GY, Chen MQ, Huang YW. Evaluation on the air-borne ultrasound-assisted hot air convection thin-layer drying performance of municipal sewage sludge. Ultrason Sonochem. 2017;34:588–599. doi:10.1016/j.ultsonch. 2016.06.036

[40] Ameri B, Hanini S, Benhamou A, et al. Comparative approach to the performance of direct and indirect solar drying of sludge from sewage plants, experimental and theoretical evaluation. Sol Energy. 2018;159:722–732. doi:10.1016/j.solener.2017.11.032

[41] Adnan Midilli HK. Mathematical modeling of thin layer drying of pistachio by using solar energy. Energ Convers Manage. 2003;44:11. doi:10.1016/S0196-8904 (02)00048-1

[42] Danish M, Jing H, Pin Z, et al. A new drying kinetic model for sewage sludge drying in presence of CaO and NaClO. Appl Therm Eng. 2016;106:141–152. doi:10.1016/j. applthermaleng.2016.05.191

[43] Han X, Niu M, Jiang X, et al. Combustion characteristics of sewage sludge in a fluidized bed. Ind Eng Chem Res. 2012;51:10565–10570. doi:10.1021/ie3014988

[44] Xinchao Z. Experimental study on sludge drying system with heat recovery and double heat source heat pump. In: School of environmental and energy engineering. Beijing: Beijing University of Civil Engineering and Architecture; 2020. p. 59.

[45] Zhang XY, Chen MQ, Huang YW, et al. Isothermal hot air drying behavior of municipal sewage sludge briquettes coupled with lignite additive. Fuel. 2016;171:108–115. doi:10.1016/j.fuel.2015.12.052

[46] Font R, Gomez-Rico MF, Fullana A. Skin effect in the heat and mass transfer model for sewage sludge drying. Sep Purif Technol. 2011;77:146–161.

doi:10.1016/j.seppur. 2010.12.001

[47] Léonard A, Blacher S, Marchot P, et al. Measurement of shrinkage and cracks associated to convective drying of soft materials by X-ray microtomography. Dry Technol. 2004;22:1695–1708. doi:10.1081/DRT-200025629