DRYING CHARACTERISTICS OF SLUDGE IN A ROTARY DRUM FOR FAST-DRYING APPLICATION

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High-temperature metallurgical slag (temperature, > 1450 °C) and high-moisture sludge (moisture content, > 80 wt%) are common wastes with huge outputs. Many problems, such as high cost, low level of harmlessness, and low efficiency, are encountered in current treatment methods. If these wastes can be recycled, they can be valuable secondary resources. Therefore, using the drum apparatuses to treat these two kinds of wastes is proposed. The process uses waste heat of slag to dry sludge with high moisture content and is a kind of alternative circulation treatment technology in which steel balls are used as ball milling media and intermediate heat carriers. Besides, this technology can break up slag or sludge in real time, thereby ensuring high heat or mass transfer rate. This study presents an experimental investigation of the dynamic drying process of wet sludge mixed with hot steel balls in a rotary drum. The relationship of operation parameters (including sludge moisture content, sludge treatment mass, steel ball diameter, and rotary speed of drum) and drying effect is obtained. There are three kinds of final drying results: completely dried to powder, few sludge agglomerations, and sludge-to-wall adhesion. If the operating parameters are set well, the sludge could be efficiently and completely dried and eventually in powder form.

Key words*: rotary drum; sludge; thermal drying; moisture content; direct heating*

1. Introduction

Blast furnace slag and steel slag are typical high-temperature materials produced at large outputs in metallurgical production, and discharging temperature can be as high as 1500 °C [1]. Presently no good method for utilizing the waste heat is available [2]. Meanwhile, with the rapid development of cities, sludge output is increasing [3, 4]. Sludge, a by-product generated in enormous quantity from various treatment processes, contains large amounts of moisture, colloids, and pollutants, which can cause serious pollution and thus must be treated and disposed [5]. In sludge treatment and disposal, the drying operation is usually required [6, 7] but is energy-consuming [8, 9]. Existing drying technologies, such as microwave drying technology [10, 11], thin layer drying technology [12, 13], solar drying technology [14], and paddle drying technology [15, 16], still have many shortcomings. Owing to the special properties of sludge [17, 18], such as fine particle size, easily agglomerating, and low heat and mass transfer rate, existing drying technologies cannot fulfill simultaneously the requirements of low cost, high efficiency, and large quantity reduction. Thus, a new drying technology for sludge combining slag treatment by drum apparatuses is proposed in the present study.

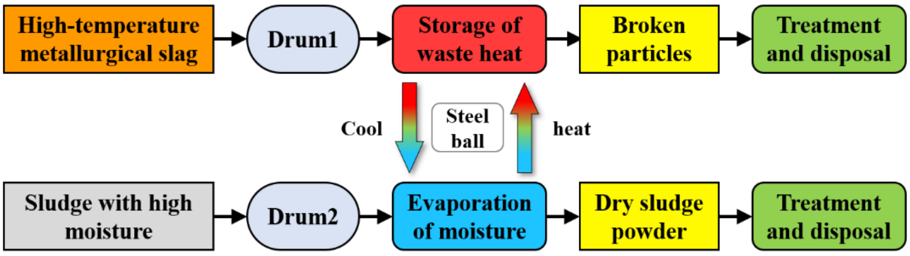


Fig. 1 Flowchart of alternative circulation treatment technology of metallurgical slag and sludge

This alternative circulation treatment technology uses steel balls as ball milling media and intermediate heat carriers to effectively utilize the waste heat of high-temperature slag to dry sludge, as shown in **Fig. 1**. In the slag treatment, drum 1 contains large amount of steel balls, which are mixed with high-temperature slag and heated by the rich waste heat. The slags are cooled and broken in drum 1. After the steel balls in drum 1 are heated, they are transferred to drum 2. In drum 2, the sludge which still has high moisture content after mechanical dewatering is broken, heated, and dried by hot steel balls.

This treatment technology not only enables the utilization of the waste heat of slag but also fulfilled simultaneously the requirements of drying technology. The large heat and mass transfer area of sludge can be maintained during drying by ensuring that the sludge is in motion and real-time crushing state. The influence of sludge agglomeration can be prevented, and the advantages of low cost, high drying rate, and large treatment capacity are obvious, and the potential value is great.

This study reports on the drying process of sludge in drum 2 of **Fig. 1**, but similar technologies are rare in literature, and few studies have been conducted on similar processes. Given that the dynamic sludge drying process in the drum is complex, involving phase transition, agglomeration, breakage, and quantity reduction, the process is difficult to be accurately described by mathematical methods. Thus, in this study, we explored this dynamic drying process in a drum by experiments. Considering that almost no chemical reaction exists in the sludge during drying, and a moisture content of sludge only corresponds to a single apparent state. Therefore, the relationship between the apparent state and moisture content of sludge in the research range was first investigated. Then, a drum drying test apparatus was designed and built for the exploration of the drying characteristics and reasonable scope of operation parameters. The variations in the temperature and moisture content of sludge with time was measured, and the different drying end states were summarized. Furthermore, the reasons of the drying phenomenon were given based on the relationship between apparent state and moisture content. The study results can provide qualitative and semi-quantitative guidance for subsequent work.

2. Experiment materials and methods

2.1. Sampling and pretreatment

The sludge used in this study is a kind of construction sludge in Beijing, China. This kind of sludge comes from the process of slurry wall-bored pile of pile foundation engineering that includes construction, subway, tunnel, and drilling. For example, 5 million tons of engineering waste sludge (wet basis moisture content, > 80 wt%) in Shanghai is produced annually. To date, this kind of sludge is only treated by mechanical dewatering, and the moisture content is still 22 wt% at least. The bulk density of the dried sludge (powder) is approximately 1045 kg/m^3.

Pretreatment of the studied sludge was carried out under laboratory conditions. The sludge was completely dried by the drying oven at 105 ℃ [19], and was ground and crushed. Then, it was passed through an 850 μm sieve to remove the coarse particles, and finally kept in a closed bag.

2.2. Analytical method

For convenience, the moisture content of sludge is uniformly expressed by the dry basis moisture content *MC*, g/g. Dry basis moisture content is defined as

$$MC = \frac{m_m}{m_{s,dry}} \tag{1}$$

where m_{m} is the mass of moisture content (water) in the wet sludge, g; and $m_{s,dry}$ is the mass of sludge when it is in absolute dry state, g.

2.3. Experimental setup and procedure

Based on the special physical and chemical properties of sludge, a laboratory-scale drum drying apparatus (**Fig. 2**) is especially designed. The drum has a diameter of 480 mm, a length of 320 mm in the axial direction, and a wall thickness of 4 mm. It is equipped with a 120 W motor at adjustable rotary speed by bolts. During the test, the outer wall of the drum will be wrapped with thermal insulation materials. The drum is not equipped with flights and the gas flow for drying is not set, and the steam generated in the sludge drying is discharged from the drum by natural convection. The following reasons are stated for not setting the flights and gas flow:

(1) Reducing fugitive dust. The dried sludge is in the form of powder, which easily generates dust due to the crushing effect of steel balls. However, flights and forced draft will greatly strengthen dust floating, which is disadvantageous in industrial applications.

(2) Reducing the sludge adhering to the wall. Dead zones of steel ball breaking at the joint of the flights and drum wall exist. Consequently, the sludge agglomerates, shrinks, and adheres to the dead zones during drying and seriously influence the effect of drying. The sludge in the dead zones would be difficult to remove.

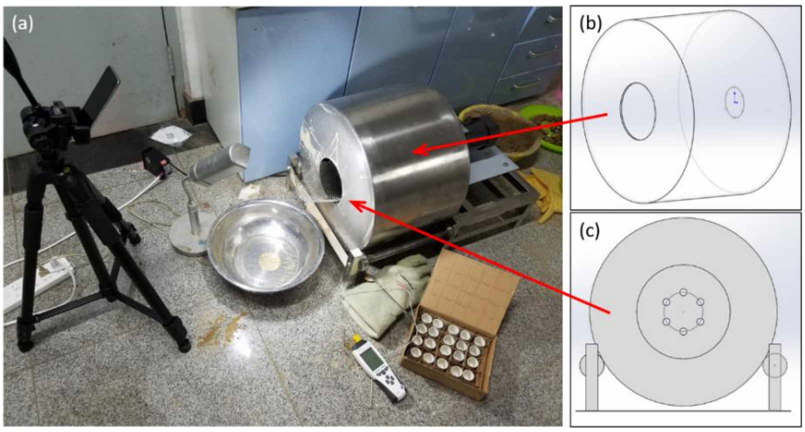


Fig. 2. Experimental equipment: (a) Physical photograph; (b) stereogram of drum; (c) front view of drum

This study reports on the drying law of sludge in the drum and the reasonable range of relevant operation parameters. The drum is placed horizontally (the inclination is 0°), and the drum is carried out under the open condition during experimental process. Other main instruments used are box furnace, drying oven, electronic balance, thermocouples, and timer.

The drying test in the drum: (a) Steel balls were heated to a specified temperature by a box furnace. (b) Configuring a certain mass of wet sludge with the required moisture content. (c) Starting the drum motor and setting the required rotary speed. Then the hot steel balls were added into the drum first. After the steel balls were in the stable motion state (waiting for about 15 s), the wet sludge at environmental temperature was added into the drum, and timing was started (the 0th second). (d) Sampling method was used to measure the variation of the temperature and moisture content of sludge during drying. The sampling position is the same each time. Every time a sludge sample was taken, its temperature and mass would be measured immediately. Each sample is approximately 0.5–2.0 g, and the total amount of samples accounted for 2.0–5.0 % of the total amount of sludge in the drum. As the steel balls had been in motion during drying, the sampling was affected, resulting in the inaccuracy of the sampling interval (range: 10–20 s). At the later stage of the experiment, the sampling interval would increase to 30 s as appropriate due to the near steady state. (e) The sludge samples would be dried after the experiment, and their moisture content would be calculated. (f) Given that the temperature and moisture content of sludge are not uniform in the initial stage of drying, to make some choices on the measured data and remove the extreme points so that the results can better reflect the regularity are necessary.

The orthogonal experiments were used to study the sludge drying under different operating parameters (experimental conditions). The operating parameters included the following: initial moisture content (dry basis) of sludge, initial treatment mass (wet) of sludge, steel ball diameter, and the rotary speed of drum. The experimental data are shown in **Table 1**. Every run experiment was replicated at least two times due to the data fluctuation problem in the abovementioned sampling method. In addition, the average of temperature and moisture content at each value was used for drawing the drying curves.

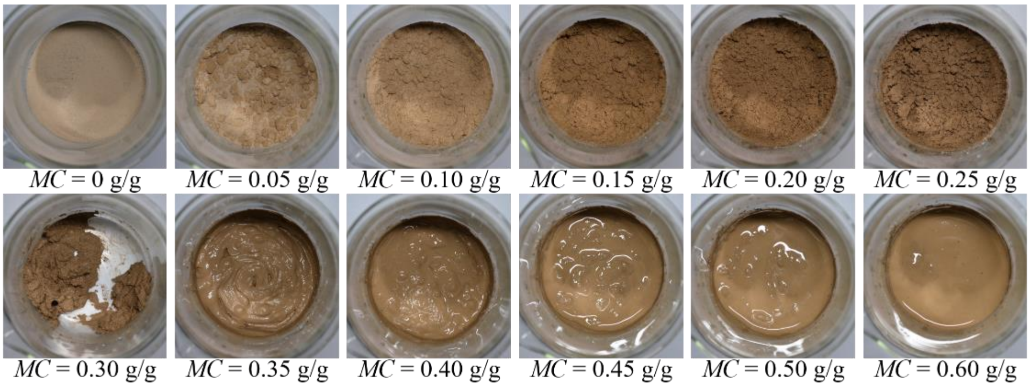
Table 1. Experimental data

Name	Operation parameters	Value
Sludge	Moisture content (dry basis)	MC = 0.30 g/g, 0.40 g/g, and 0.50 g/g
	Mass (wet)	m = 1.0 kg, 1.5 kg, and 2.0 kg
	Temperature	T_s = 16 °C
Steel ball	Diameter and number	d = 20 mm (N = 200) and d = 40 mm (N = 25)
	Temperature	T_b = 500 °C
Drum	Rotary speed	n = 3 rpm and 4 rpm

3. Results and discussion

3.1. Relationship between the apparent state and moisture content of sludge

Given that the drying temperature is not high, the physical and chemical properties of sludge would not change substantially before and after drying. In other words, as long as the moisture content is the same, the apparent state of sludge before and after drying is the same. The apparent state of sludge has obvious influence on its drying rate. Thus, to study the relationship between the apparent state and moisture content first is necessary. **Fig. 3** shows that sludge will present different apparent states under different moisture contents, which can provide reference for the state change of sludge during drying in the rotary drum.



MC = 0 g/g MC = 0.05 g/g MC = 0.10 g/g MC = 0.15 g/g MC = 0.20 g/g MC = 0.25 g/g

MC = 0.30 g/g MC = 0.35 g/g MC = 0.40 g/g MC = 0.45 g/g MC = 0.50 g/g MC = 0.60 g/g

Fig. 3 Relationship between the apparent state and dry basis moisture content of sludge

(1) Solid state (*MC* < 0.25 g/g): The absolutely dry sludge (*MC* = 0 g/g) is a light brown powder (dust), and the powder can be raised by breeze. The sludge (*MC* = 0.05 g/g and *MC* = 0.10 g/g) absorbing a small amount of water would bond with each other to form sludge agglomerations. When moisture content is in the range of 0.15–0.25 g/g, the sludge has large number of wet sludge agglomerations, and agglomerations are bonded to each other because of the moisture content. High moisture content means easiness for the sludge to form a whole agglomeration. Especially when moisture content is between 0.20 and0.25 g/g, the sludge has obvious adhesive wall phenomenon.

(2) Plastic state (0.30 g/g < *MC* < 0.35 g/g): The sludge (*MC* = 0.30 g/g) has the highest viscosity, enabling easy formation of a whole and soft agglomeration. Small amount of water appears on the surface. However, it can still maintain a certain shape, and the sludge-to-wall adhesion phenomenon is not obvious. The sludge (*MC* = 0.35 g/g) has been thick mud, and liquid water obviously appears on the mud surface. Mud is unable to maintain its shape, but liquid water cannot be poured out from the beaker easily. The sludge dynamic viscosity at this moisture content is about 16 Pa·s.

(3) Fluid state (*MC* > 0.40 g/g): When the moisture content reaches 0.40 g/g, the sludge cannot absorb the water completely. The surface obviously appears liquid water, which can be poured out from the beaker. The moisture content at this time is too high to accurately measure the sludge viscosity. When the moisture content reaches 0.60 g/g or above, the sludge shows obvious solid–liquid stratification. The upper layer was turbid liquid, and the lower layer was thick mud.

3.2. Characteristics of drying in the drum

The sludge drying would be categorized into pre-heating, fast-rate drying, and falling-rate drying stages [13]. In this work, a total of seven different working conditions were studied through experiments to obtain sludge drying characteristics in the drum. The pre-heating stage is usually very short, which cannot be observed in some experimental conditions.

3.2.1 Influence of initial sludge moisture content on the drying effect

Fig. 4 shows the variation of temperature and moisture content of sludge with different initial dry basis moisture contents (two cases: *MC* = 0.30 g/g and 0.40 g/g) during drying. In addition, another case (*MC* = 0.50 g/g) has also been conducted, but the sludge showed serious sludge-to-wall adhesion phenomenon during drying. In the experiments under this case (*MC* = 0.50 g/g), it is difficult to obtain effective temperature and moisture content variation curves by attaining representative sludge samples. But no obvious sludge-to-wall adhesion phenomena have been found in the experiments of the first two cases (*MC* = 0.30 g/g and 0.40 g/g). Consequently, the test results of this case are not shown in **Fig. 4**. The other operation parameters are the same in these three cases: *m* = 1.5 kg, *d* = 20 mm, *N* = 200, and *n* = 3 rpm.

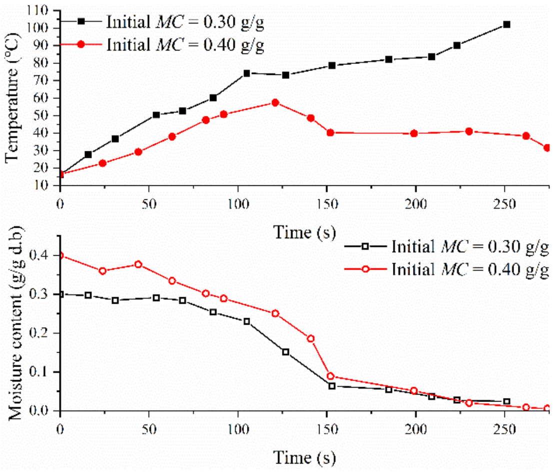


Fig. 4 Influence of the initial sludge moisture content on the variation of temperature and moisture content of sludge during drying (Case 1: *MC* = 0.30 g/g; Case 2: *MC* = 0.40 g/g)

Both sludge with different initial moisture contents were in the plastic state first, being fully in contact with the steel balls (heat source), and both could be rapidly heated up. However, due to the low moisture content of sludge in case 1, the heating rate in case 1 was faster than that in case 2. After a period of heating, the rise in temperature of case 2 (high moisture content) became gentle, then decreased. However, the sludge temperature of case 1 (low moisture content) had been rising all the time, because the heat carried by the steel balls is the same in two cases and the sludge of case 1 takes less amount of heat to evaporate the water.

The pre-heating stage of sludge in two cases are both obvious. After the preheating, both sludges entered the fast-rate drying and falling-rate drying stages, and both sludges were dried finally. The time required for complete drying (*MC* < 0.03 g/g) in case 1 (approximately 220 s) is similar to case 2 (approximately 220 s). The reasons for this phenomenon are as follows. (1) The heat carried by steel balls is completely sufficient. (2) Although both types of sludge were in plastic state firstly, sludge of case 1 would pass to solid state faster than case 2 after being heated. Thus, the sludge in case 2 had a more obvious phenomenon of agglomeration during drying. However, only the broken sludge (powder) was sampled in the experiment of case 2, and the agglomerations were not taken as much as possible, resulting in low moisture content value measured in the experiment (below average). On the whole, decreasing the initial sludge moisture content would bring high drying rate and good drying effect.

3.2.2 Influence of initial sludge treatment mass on the drying effect

Fig. 5 shows the variation of temperature and moisture content of sludge with different initial sludge masses (three cases: *m* = 1.0 kg, 1.5 kg, and 2.0 kg) during drying. The other operation parameters are the same in all cases: *MC* = 0.30 g/g, *d* = 20 mm, *N* = 200, and *n* = 3 rpm.

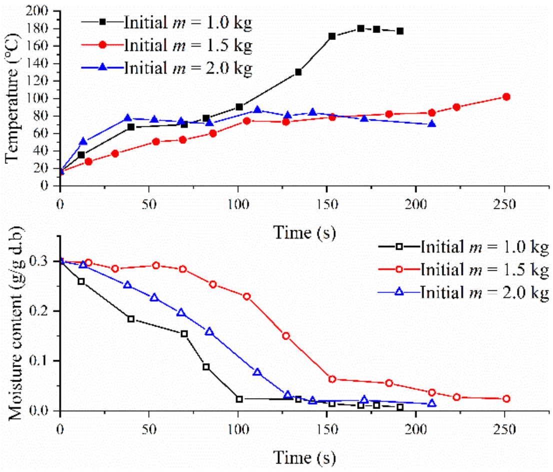


Fig. 5 Influence of the sludge treatment mass on the variation of temperature and moisture content of sludge during drying (Case 1: *m* = 1.0 kg; Case 2: *m* = 1.5 kg; Case 3: *m* = 2.0 kg)

Wet sludges with different initial masses have different temperature trends during different drying periods. In the initial period of drying, the sludge temperature from high to low is case 3, case 1, and case 2, correspondingly, because the sludge in the mass of 2.0 kg could wrap well the high-temperature steel balls and the contact area (heat and mass transfer area) is large. As a result, great amount of heat could be transferred to sludge, and less heat was lost to air. Therefore, the sludge temperature of case 3 is the highest. In the middle drying period, the sludge of case 3 tended to be gentle and maintained in a certain temperature range for a long time. The reason for this phenomenon is summarized as follows. (1) The heat carried by steel balls in different cases are the same, but the sludge mass of case 3 is the most, and the sludge was heated up quickly in initial drying period, leading to the lowest temperature of steel balls at this time. (2) A large amount of sludge in case 3 adhered to the drum wall without falling off, and this kind of sludge is not easily to be heated and dried. However, the sludge adhered to the wall would not be taken as samples in the experiment. The moving sludge, which is easy to be heated and dried, would be sampled. (3) Nearly no sludge-to-wall adhesion phenomenon was observed in the other 2 cases, and the sludge was finally completely dried to powder. The sludge of cases 1 and 2 was continuously heated in the middle period due to the low mass. In the later drying period, the sludge temperature from high to low is the mass of 1.0, 1.5, and 2.0 kg, correspondingly. The reason is that the less mass of sludge, the less heat is required for drying and the high final stable temperature.

The drying rate from fast to slow is the mass of 1.0 kg (case 1), 2.0 kg (case 3), and 1.5 kg (case 2). In general, small sludge mass means less heat is needed for drying and the rapid drop of the moisture content [20]. Therefore, the drying rate of case 1 is the fastest. However, the sludge drying rate of case 2 is the slowest. The reason for this phenomenon is summarized as follows. (1) Case 2 has the slowest heating rate. (2) Only the moving sludge was sampled in the experiment of case 3, resulting in low moisture content value measured (below average). In case 2, the pre-heating stage could be clearly observed (approximately 0–54 s) but not in the other two cases. In addition, the fast-rate drying stage and falling-rate drying stage have been experienced in all cases. The time required for complete drying (MC < 0.03 g/g) in cases 1 and 2 are approximately 100, 220, and 130 s. Reducing the initial sludge treatment mass could improve the drying rate and drying effect but would also limit the sludge processing capacity of the drum, which may have a balance point.

3.2.3 Influence of steel ball diameter on the drying effect

Fig. 6 shows the variation of temperature and moisture content of sludge with different steel ball diameters (two cases) during drying. To ensure that the total heat carried by the steel balls is the same, the total mass of steel balls in two cases were the same (case 1: d = 20 mm, N = 200, and case 2: d = 40 mm, N = 25). The other operation parameters are the same in the two cases: MC = 0.30 g/g, m = 1.5 kg, and n = 3 rpm.

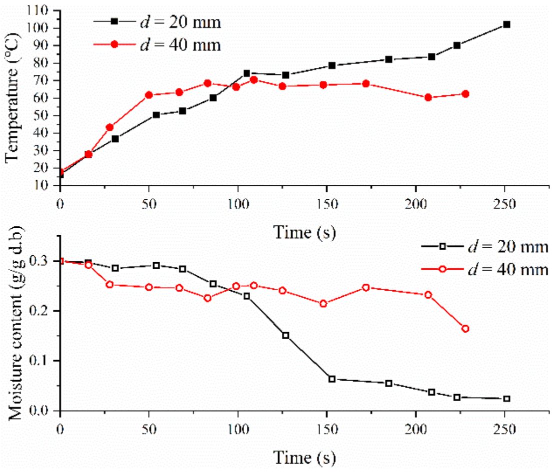


Fig. 6 Influence of the steel ball diameter on the variation of temperature and moisture content of sludge during drying (Case 1: *d* = 20 mm; Case 2: *d* = 40 mm)

The sludge temperature of case 2 (large-diameter steel balls) was higher in initial drying period, but lower in later drying period. In initial period, a single large-diameter steel ball carries great amount of heat, leading to fast heating (large temperature difference) of the sludge near the balls (local areas). Thus, the temperature field in case 1 would be uniform, and case 2 is prone to high-temperature local area. In addition, the sludge in initial period is in the plastic state and easy to form huge agglomerations, whereas the steel ball diameter of case 2 is large, which is easy to break up the agglomerated sludge and accelerate the heat and mass transfer rate. In middle period, the sludge temperature of case 2 maintained in a certain temperature range after a fast rising and started to drop in later period. However, the sludge temperature rose throughout drying in case 1. Three reasons are stated for this phenomenon. (1) Compared with case 1, the size of steel balls in case 2 is larger and the quantity is much less, but the mass of sludge is limited, resulting in small contact area (heat and mass transfer area) and less heat transferred to sludge. (2) The sludge in the later period is in solid state, the agglomerations are small, and it is not easy to form new large agglomerations, causing the crushing effect of the large-size steel balls (case 2) to not improve the heat and mass transfer. (3) Compared with the small-sized steel balls, the large-sized steel balls have a great pressing effect on the sludge, causing part of the sludge adhering to the wall of drum, resulting in less heat and mass transfer area and worse crushing effect.

At approximately 16–95 s, the sludge temperature of case 1 was lower than that of case 2, and the moisture content was higher than that of case 2. After approximately 95 s, the sludge temperature of case 1 was high, and the moisture content was low. Moreover, the drying of case 2 is different from case 1. Four main drying periods are observed in case 2. The first period was approximately 0–16 s, wherein the sludge was preheated during this period. The second period was approximately 16–28 s, during which the plastic sludge was dried rapidly by the large-diameter steel balls. The third period was approximately 28–172 s, during which large part of sludge adhered to the wall, and the drying rate was reduced seriously. After approximately 172 s was the fourth period, and the moisture content of sludge began to decline because large part of sludge was always adhered to the wall, and the collected sample is the sludge adhered to wall, which started to dry after a long enough time of low-temperature drying.

3.2.4 Influence of drum rotary speed on the drying effect

Fig. 7 shows the variation of temperature and moisture content of sludge with different rotary speeds of the drum (two cases: $n = 3$ rpm and 4 rpm) during drying. The other operation parameters are the same in the two cases: $MC = 0.30$ g/g, $m = 1.5$ kg, $d = 20$ mm, and $N = 200$.

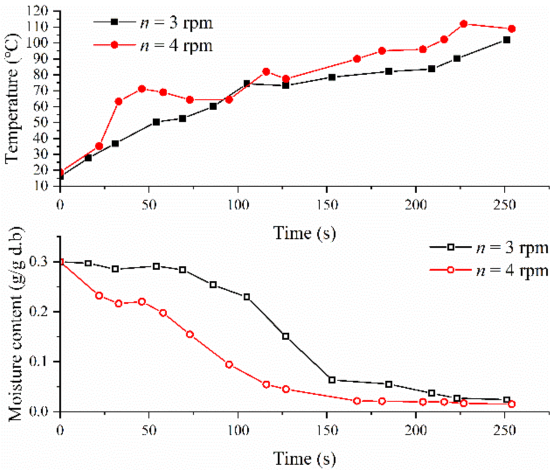


Fig. 7 Influence of the rotary speed of the drum on the variation of temperature and moisture content of sludge during drying (Case 1: *n* = 3 rpm; Case 2: *n* = 4 rpm)

The sludge temperature in the rotary speed at 4 rpm (case 2) is higher than that at 3 rpm (case 1), and the drying rate of case 2 was faster than that of case 1. The reason is that increasing the rotary speed of the drum could increase the sludge replacement rate (equivalent heat and mass transfer coefficient) on the surface of steel balls. However, because no flight is available to strengthen the mixing rate of steel balls and sludge, increasing the rotary speed could not clearly increase the temperature difference between the two cases. The pre-heating stage could be clearly seen (approximately 0–54 s) in the sludge drying of case 1 but could not be clearly observed in case 2. In addition, the fast-rate drying and falling-rate drying stages occurred in cases 1 and 2, and the time required for complete drying ($MC < 0.03$ g/g) are approximately 220 s and 190 s.

3.2.5 Summary of drying end states

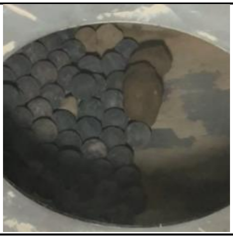
The experimental results showed three drying end states of sludge, as shown in **Table 2**.

(1) Complete drying: The dry sludge was in the form of a pale-yellow powder, and the agglomeration and sludge-to-wall adhesion were inconspicuous. A small amount of sludge adhering to the steel ball surface was also observed, but the sludge wrapping the entire steel ball was not observed. The drying end states can meet the engineering application requirements.

(2) Few agglomerations: The initial moisture content of sludge in these cases were slightly high, which easily caused sludge agglomeration during drying. The sludge agglomerations were not easy to be broken. Although the surface of the agglomeration would be dried in the end, the interior still had high moisture content.

(3) Adhering to wall: The hot steel balls could not quickly dry the sludge adhering to wall due to the high moisture content, large sludge treatment mass, or the poor heat transfer between the steel balls and sludge. This condition causes sludge-to-wall adhesion during drying. In addition, the press of steel balls would result in the sludge to firmly attach to the wall. The surface of the attaching sludge would form a hard crust during drying, which could affect the heat and mass transfer and hinder the evaporation of moisture. Eventually, the crust could be dried but not the interior of the attaching sludge.

Table 2. Summary of sludge drying end states

Drying end States	Photo	Drying effect	Proportion of absolute dry sludge	n (rpm)	d (mm)	MC (g/g)	m (kg)
Complete drying		★★★★	☆☆☆☆	3	20	0.30	1.5
		★★★★	☆☆☆☆	3	20	0.30	1.0
		★★★★	☆☆☆☆	4	20	0.30	1.5
Few agglomerations		★★★	☆☆☆	3	20	0.40	1.5
Adhering to wall		★★	☆☆	3	40	0.30	1.5
		★★	☆☆	3	20	0.30	2.0
		★★	☆	3	20	0.50	1.5

The number of symbols ★ represents the degree of the drying effect. ★ means poor, and ★★★★ means good; the number of symbols ☆ represents the proportion of absolute dry sludge (powder form) in all sludge. ☆ means very low, and ☆☆☆☆ means very high.

4. Conclusions

Based on the difficulty of metallurgical slag treatment, physical characteristics of sludge, and the shortcomings of existing technologies, a new drying technology of sludge by using a drum apparatus and hot steel balls is proposed, which utilizes the high-grade waste heat of slag to dry the high-moisture sludge. This study took construction sludge as an example to preliminarily investigate the sludge drying characteristics in a laboratory-scale drum apparatus. To ensure the drying rate and drying effect of sludge, the following are suggested: (1) appropriately reducing the initial sludge moisture content ($MC < 0.40$ g/g) and keeping sludge in solid state; (2) appropriately reducing the sludge treatment mass, such as using less than 1.5 kg of sludge per 200 steel balls ($d = 20$ mm); (3) appropriately reducing the diameter of steel ball ($d < 40$ mm); (4) appropriately speeding up the drum rotary speed ($n \geq 4$ rpm). Within the range of working conditions in this study, three types of drying ending states of the sludge are observed: completely dried to powder, few sludge agglomerations, and sludge-to-wall adhesion. This technology can be extended to treat other types of sludge. Under appropriate operating parameters, the sludge could be completely dried to powder, which could meet the requirements of engineering applications.

Moreover, these results are for a limited number of cases and further work is needed. Here are three examples: (1) Exploring the range of operating parameters that could ensure complete drying of the sludge. (2) Exploring the accurate proportion of sludge powder, sludge agglomerations, adhering wall sludge, etc. under different drying ending states. (3) Comparing the drying characteristics of different types of sludges in the drum. The above content is the scope of our future work.

Acknowledgment

This research was supported by the National Key R&D Program of China (No. 2018YFB0605900).

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