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Drying of Water Treatment Process Sludge in a Fluidized Bed Dryer

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Abstract−The drying characteristics of water treatment process (WTP) sludge were investigated with a fluidized bed. The equilibrium moisture ratio of WTP sludge increased with relative humidity and decreased with temperature of drying air. However, equilibrium moisture ratio of WTP sludge was more sensitively dependent on relative humidity than temperature of drying air. When the sludge was dried in a batch fluidized bed, the drying rate of sludge decreased as the moisture ratio of sludge in the bed decreased. The periods of constant drying rates were apparently not observed on the drying rate curves. In addition, the maximum drying rates were increased with bed temperature and superficial air velocity. As the fluidized bed was operated continuously, the degree of drying of WTP sludge increased with bed temperature but was weakly dependent on superficial air velocity. However, the drying efficiency was decreased with bed temperature and relatively insensitive to superficial air velocity and increased with feed rate of sludge.

Key words: Fluidized Bed Dryer, Waterworks Sludge, Equilibrium Moisture Ratio, Drying Rate, Drying Efficiency

INTRODUCTION

Large amounts of sludges are produced from water treatment processes (WTP). These kinds of sludges are called WTP sludges, and production rates depend on the quality of raw input water and chemicals added in the treatment processes. Proper techniques to reduce the volume of WTP sludge, which are available at this time, include composting, dewatering, drying, incineration and recycling of added chemicals. Dewatering is one of the most widely used techniques in the volume reduction of sludge from the wastewater treatment processes as well as water treatment processes. However, final moisture contents of dewatered sludge cakes are generally higher than 70% with mechanical dewatering machines such as the belt press filter. When the moisture content of the sludge needs to be lower than 70%, it should be dried further after the primary dewatering step. Drying of WTP sludge is one of the most effective candidates with respect to the degree of volume reduction, total cost, and environmental effects. Among the various types of dryers in industrial processes, the fluidized bed dryer is one of the most economical, having a high drying rate, high efficiency, large capacity and operating flexibility. Thus, many investigations have been performed on heat and mass transfer phenomena in various drying systems [Reay and Baker, 1985; Kunii and Levenspiel, 1991; Yoshida et al., 1997]. Recently, inert medium fluidized bed technology has been developed to dry sticky powder or slurry of fine powder [Nakagawa et al., 1992; Lee and Kim, 1992; Lee and Kim, 1994; Xu et al., 1998].

In this study, WTP sludge (moisture content was about 98%) was dried in a fluidized bed. Prior to the drying experiment, equilibrium relationships between the moisture contents of WTP sludge and the relative humidity of drying air were measured at several temperatures. When the fluidized bed dryer was operated in batch mode, the effects of superficial air velocity and the temperature of inlet air on the drying characteristics of WTP sludges were investigated. In a continuously operated fluidized bed dryer, drying efficiency and the degree of drying of WTP sludge were measured with respect to bed temperature and superficial air velocity.

EXPERIMENTAL

The fluidized bed drying system is shown in Fig. 1. The fluidized bed dryer was made of 0.1 m I.D. stainless steel pipe and had a height of 2 m. It was insulated by Kaowool with a 20 cm thickness. The perforated type plate, containing 25 evenly spaced holes with diameter of 2 mm, was used as a distributor.

The WTP sludge used in this study had moisture content of 98%. Prior to the drying experiment, a proper amount of sludge was naturally dried and crushed to be used for the bed material. Fig. 2 shows the size distribution of the bed material, and the mean diameter and true density of the bed material were 716 μm and 1.84 g/cm^3, respectively.

When the fluidized bed dryer was operated in batch mode, the dryer was heated only by input air. In order to measure the drying rate of WTP sludge, a small amount of WTP sludge (about 15 ml) was injected into the batch fluidized bed in pulse function. After the injection of sludge, the humidity and temperature of exit air were continuously measured by a humidity sensor and transmitter (VAISALA, HMP 135Y) and recorded by using an IBM PC. The experimental technique was the same as previous work [Shin et al., 1996a]. When the fluidized bed dryer was operated in continuous mode, the dryer was heated by the input air and a 3 kW Kanthal heating element, which was wrapped around outer wall of bed section. When fluidized bed dryer maintained steady state conditions, humidities and temperatures of inlet and exit air were measured by using a hygrometer (VAISALA,

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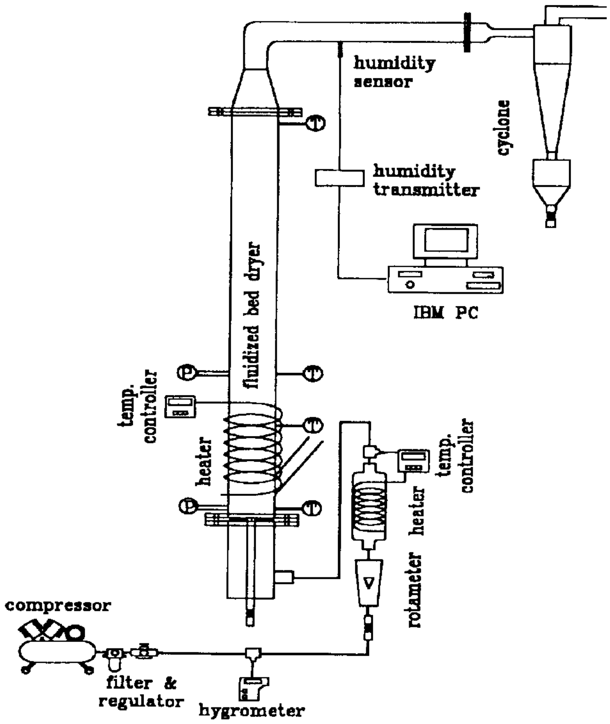


Fig. 1. Schematic flow diagram of experimental apparatus.

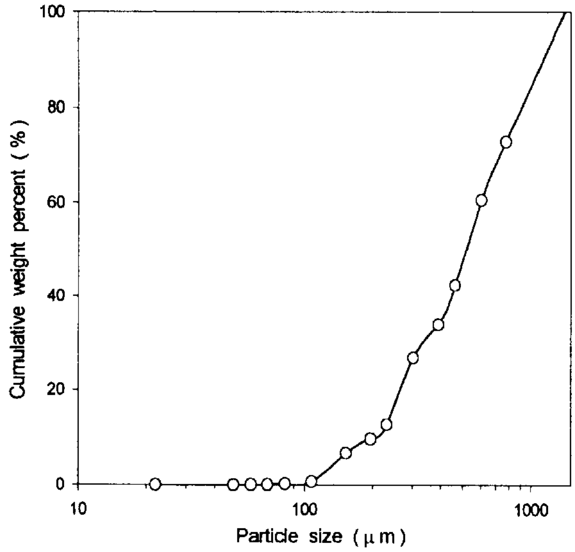


Fig. 2. Cumulative size distribution of bed material.

HMI31) and humidity transmitter (VAISALA, HMP135Y), respectively. After the fluidized bed dryer was steadily operated for 1 hour, elutriated and drained particles were collected and their amounts and moisture contents were measured. As the size distribution of bed material could be changed by the long period of operation, bed material was completely drained and the bed was refilled with fresh bed material after every continuous operation. The superficial air velocity was varied from $4U_{mf}$ to $7U_{mf}$ and the minimum fluidization velocity (U_{mf}) was decreased with the temperature of drying air. The measured values ranged from 6.5 cm/s to 4.7 cm/s. The inlet air and bed temperatures varied from 50 °C to 110 °C and the feeding rate of WTP sludge was 18 g/min.

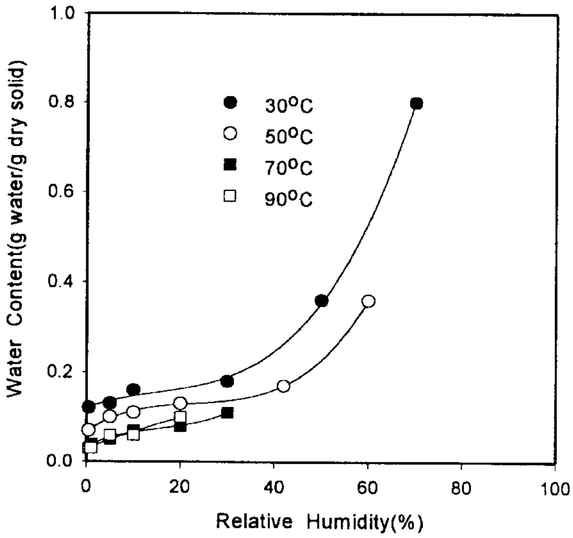


Fig. 3. Relationship between moisture content of WTP sludge and relative humidity of air.

RESULTS AND DISCUSSION

The equilibrium relationships between the moisture content of WTP sludge and relative humidity of drying air are shown in Fig. 3. These relationships were measured in a drying chamber, which was used in the authors' previous work [Shin et al., 1996b]. As shown in Fig. 3, equilibrium moisture ratio of WTP sludge increased with relative humidity and decreased with temperature of drying air. However, the equilibrium moisture ratio of WTP sludge was more sensitively dependent on relative humidity than temperature of drying air. Especially, as temperature of drying air approached to 90 °C, the equilibrium moisture ratio behaved independently of temperature of drying air. Furthermore, below 30% relative humidity of drying air, equilibrium moisture ratios showed almost constant values. These results indicated that if WTP sludge is dried at a lower temperature than the boiling temperature of water, it is more important to control relative humidity of drying air to below 30% rather than increase the temperature of drying air. However, the final equilibrium moisture content in the vicinity of 0% of relative humidity of drying air was dependent on temperature of drying air. As Tsang and Vesiland [1990] reported in their paper, it seemed that the final equilibrium moisture content of sludge was determined by the characteristics of moisture distribution and amount of bound water in the sludge.

When the fluidized bed was operated in batch mode, humidity variations of exit air were measured with drying time. Fig. 4 shows the typical relationships between drying rates and residual moisture content in the bed. These results were calculated from the mass balances between measured humidities of exit air and initial input amounts of sludges. The moisture ratio, X, in Fig. 4 was defined as the ratio of total amount of moisture to total amount of dry solid material in the bed, and X_o designated the initial moisture ratio. As shown in Fig. 4, there are maximum drying rates and falling rate periods in all cases. However, the constant drying rate periods are not clearly apparent. Reay and Baker [1985] suggested that the constant drying rate period in a fluidized bed might be too short to be observable, except under very mild drying conditions. Thus, it seemed that the measured maximum drying rates were equal to the drying rates of constant drying rate periods. Increasing the inlet air temperature, the bed temperature, heat and mass transfer rate were also increased. Therefore, when the inlet air temperature was increased, the maximum drying rate and drying rates in the falling rate period were increased.

Fig. 5 shows the relationship between maximum drying rate and inlet air temperature. As discussed above, the maximum drying rate was equal to drying rate in the constant drying rate period. In the constant drying rate period, the particle surface was saturated with water and in equilibrium state with the air layer adjacent to the particle surface. Hence, the drying rate was controlled by the vaporization rate of moisture at the particle surface. Since the particle surface temperature did not rise in this period and remained constant at a wet bulb temperature, the heat transfer rate across the boundary layer from air to particle surface could be used to determine the vaporization rate of moisture and finally the drying rate of sludge. Therefore, as the inlet air temperature was increased, air temperature in the bed and heat transfer coefficient across the boundary layer of particle surface were increased, and these effects resulted in the increase of drying rate of sludge.

Comparing these results with those of municipal sewage sludge dried in a fluidized bed [Shin et al., 1996a], behaviors of the maximum drying rates showed similar trends in both cases. However, values of the maximum drying rates of sewage sludge were about three times greater than those of WTP sludge. And this might result from the difference between moisture distribution characteristics of WTP sludge and those of sewage sludge.

Fig. 6 shows variations of the total amounts of elutriated particles and drained particles with superficial air velocity. F_o, F_1, and F_2 are feed, drain and elutriation rates, respectively. As shown in Fig. 6, the total amount of elutriated particles was increased with superficial air velocity. It could be expected that the elutriation of the fine particles might reduce degree of drying of sludge. Conversely, the total amount of drained particles was decreased with superficial air velocity.

Fig. 7 shows the effect of bed temperature on moisture contents of elutriated and drained particles. These results were measured from a continuously operated fluidized bed dryer. As shown in Fig. 7, moisture contents of elutriated and drained particles were decreased with bed temperature. As shown in Figs. 4 and 5,

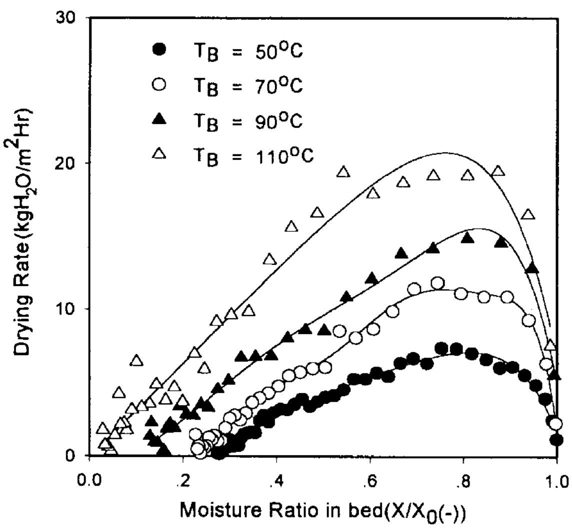


Fig. 4. Drying rate vs. moisture ratio in the bed (6U_{mf}).

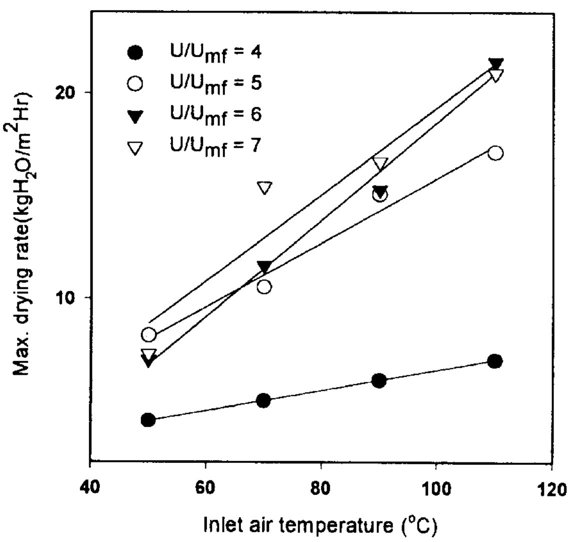


Fig. 5. Maximum drying rate vs. inlet air temperature.

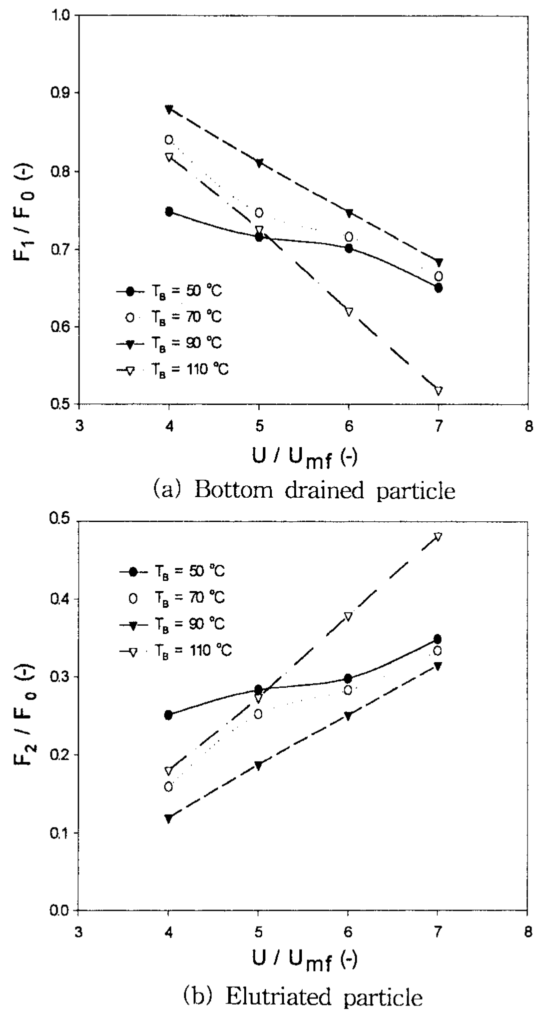
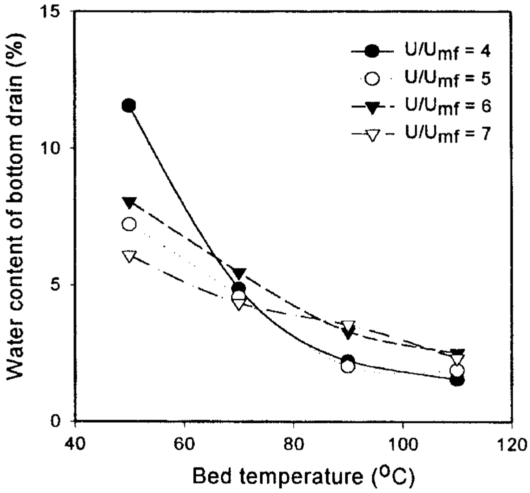
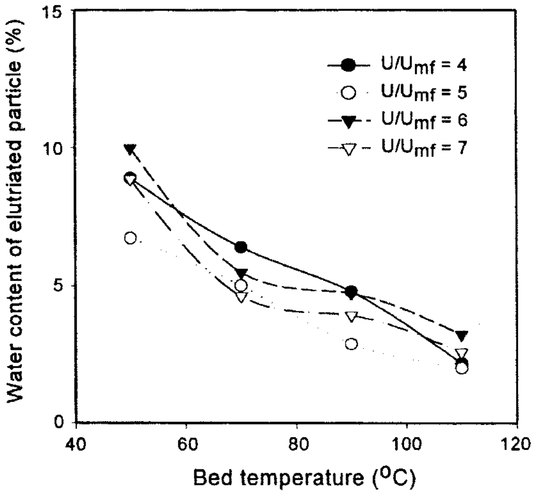


Fig. 6. Total amounts of drained and elutriated particles vs. U/U_{mf}.



(a) Bottom drained particle



(b) Elutriated particle

Fig. 7. Moisture contents of drained particles vs. bed temperature.

the drying rate of WTP sludge was more sensitively dependent on the drying temperature. Therefore, moisture contents of those particles were decreased with bed temperature and slightly dependent on superficial air velocity. One thing of interest in Fig. 7 is that moisture contents of elutriated particles were similar values to those of drained particles. Generally, it is considered that elutriation rates of fine particles from the fluidized bed increase with superficial air velocity and elutriated particles have short residence times in the bed. In fact, the elutriated amounts of particles in this study were increased with superficial air velocity and ranged from 10% to 50% of total solid input. Thus, it could be expected that moisture contents of elutriated particles were much greater than those of drained particles and increased with the superficial air velocity. However, measured results, as shown in Fig. 7, were inconsistent with the general expectation. Using the drying mechanism proposed by Lee and Kim [1992], this result could be explained. As wet fine particles were sticky, fine particles might have stuck on the surfaces of large particles during the drying process. After particles were dried enough to move freely, they then disintegrated and were elutriated by the drying air. According to this drying mechanism, it seems that moisture contents

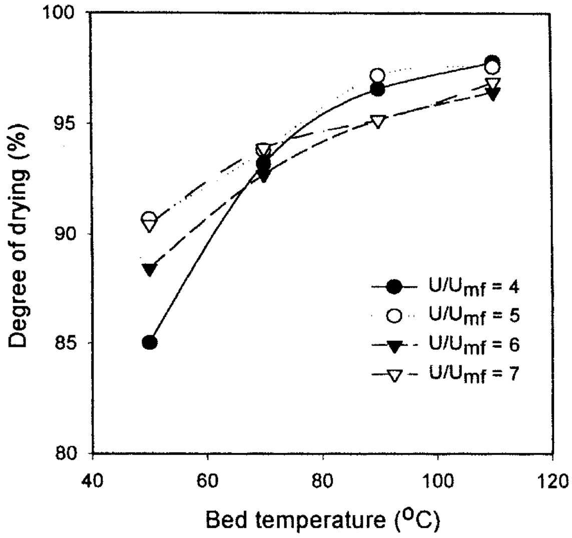


Fig. 8. Degree of drying vs. bed temperature.

of elutriated particles had about equal values to those of drained particles and were weakly dependent on the superficial air velocity.

Fig. 8 shows the effect of bed temperature on the degree of drying of WTP sludge. The degree of drying of WTP sludge is defined as follows:

$$\eta_d=\left(1-\frac{X_1F_1+X_2F_2}{X_oF_o}\right)\times 100\% \qquad (1)$$

Where, X_o, X_1, and X_2 are moisture fractions of feed, bottom drain, and elutriated particles, respectively. As the bed temperature increased, the degree of drying increased and asymptotically approached 100%. The degree of drying was determined by the final moisture content of dried sludge, and it could be controlled by both the drying rate and equilibrium relationship between the moisture content and drying temperature. When the drying temperature was increased too high, the drying rate of WTP sludge became so fast that the equilibrium relationship between moisture content of sludge and drying air would be used to determine final moisture content of dried sludge.

As shown in Fig. 3, the equilibrium moisture ratio of WTP sludge asymptotically approached 0% as drying temperature increased to the boiling point of water. Thus, the degree of drying should asymptotically approach 100% as bed temperature exceeds the boiling point of water.

Variations of drying efficiencies with bed temperature are shown in Fig. 9. In this study, drying efficiency was defined as follows:

$$\eta=\frac{F_o\times X_W\times\Delta\hat{H}_v\times\eta_d}{(\hat{H}_B-\hat{H}_i)\times F_{air}} \qquad (2)$$

Where $\hat{H}_i$ is specific enthalpy of inlet air and $\hat{H}_B$ is specific enthalpy of exhausted air at bed temperature and $\Delta\hat{H}_v$ is heat of vaporization and F_{air} is air feeding rate and X_W is water content of sludge. Drying efficiency could be determined by how net input energy supplied to the dryer was efficiently used to vaporize water in WTP sludge. As shown in Fig. 9, drying efficiency decreased with bed temperature. This could have resulted from the excessive increment of net heat input with bed temperature. However, changing superficial air velocity hardly affected the degree of dry-

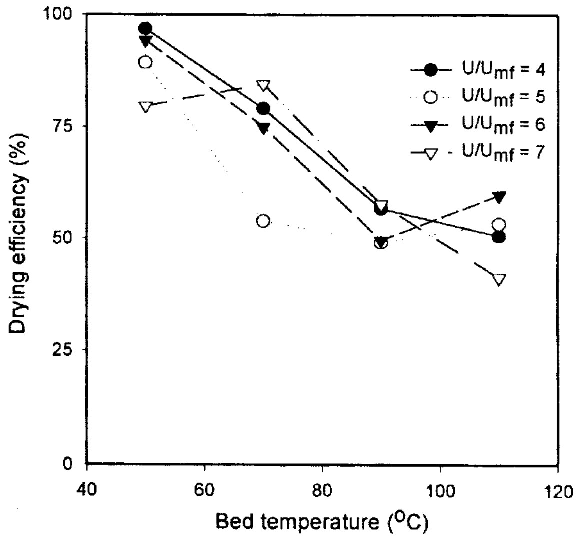


Fig. 9. Drying efficiency vs. bed temperature.

Table 1. Variation of drying efficiency with feed rate of sludge

(T_B=70 °C)

Feed rate (g/min) \ U/U_{mf}	4	5	6	7
18	68.6%	55.5%	78.9%	86.5%
45	99.6%	84.7%	88.5%	91.3%

ing and drying efficiency. As shown in Fig. 8, the degree of drying of WTP sludge showed an almost independent behavior on the superficial air velocity. If moisture contents of dried particles in Fig. 7 were compared with equilibrium moisture contents in Fig. 3, it could be noted that final moisture contents of dried particles almost approached the equilibrium moisture contents. Therefore, it could be supposed that final moisture content of dried sludge might be determined by the fact that equilibrium relationship and superficial air velocity showed little influence on the drying efficiency.

Depending on the researchers, many different drying efficiencies have been defined and used for their purpose [Ormos and Szentmarjay, 1987; Nakagawa et al., 1992]. And the drying efficiency used in this study did not include all energy terms as other definitions made by other researchers. Thus, it could be considered that if the other energy terms, such as power consumption of air blower, I.D. fan, etc., should be included in the definition of drying efficiency, the actual drying efficiencies could have somewhat lower values than those shown in Fig. 9.

Table 1 shows variation of drying efficiency with feed rate of sludge. The drying efficiency tends to rise with the increase of relative humidity of outlet air with the increase of feed rate.

CONCLUSION

In this study, WTP sludge was dried in a fluidized bed. Prior to the drying experiment, equilibrium relationships between moisture contents of WTP sludge and relative humidity of drying air were measured at several temperatures. And the effects of superficial air velocity and drying temperature on the drying characteristics of WTP sludge were investigated.

The equilibrium moisture ratio of WTP sludge increased with relative humidity and decreased with temperature of drying air. However, equilibrium moisture ratio of WTP sludge was more sensitively dependent on relative humidity than temperature of drying air. The periods of constant drying rates did not clearly appear on the drying rate curves, but maximum drying rates were detected in all cases. It seemed that maximum drying rates were equal to the drying rates in the constant drying rate periods. The maximum drying rates increased with increasing inlet air temperature and superficial air velocity by the improvement of heat transfer rate and air temperature in the bed. As the fluidized bed was operated continuously, the degree of drying of WTP sludge increased with bed temperature but was weakly dependent on superficial air velocity. However, the drying efficiency decreased with bed temperature and was relatively insensitive to superficial air velocity and increased with the feed rate of sludge.

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