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A study on the dewatering of industrial waste sludge by fry-drying technology

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ABSTRACT

In sludge treatment, drying sludge using typical technology with high water content to a water content of approximately 10% is always difficult because of adhesive characteristics of sludge. Many methods have been applied, including direct and indirect heat drying, but these approaches of reducing water content to below 40% after drying is very inefficient in energy utilization of drying sludge. In this study, fry-drying technology with a high heat transfer coefficient of approximately 500 W/m^2 °C was used to dry industrial wastewater sludge. Also waste oil was used in the fry-drying process, and because the oil's boiling point is between 240 and 340 °C and the specific heat is approximately 60% of that of water. In the fry-drying system, the sludge is input by molding it into a designated form after heating the waste oil at temperatures between 120 and 170 °C. At these temperatures, the heated oil rapidly evaporates the water contained in the sludge, leaving the oil itself. After approximately 10 min, the water content of the sludge was less than 10%, and its heating value surpassed 5300 kcal/kg. Indeed, this makes the organic sludge appropriate for use as a solid fuel. The wastewater sludge used in this study was the designated waste discharged from chemical, leather and plating plants. These samples varied in characteristics, especially with regard to heavy metal concentration. After drying the three kinds of wastewater sludge at oil temperatures 160 °C for 10 min, it was found that the water content in the sludge from the chemical, leather, and plating plants reduced from 80.0 to 5.5%, 81.6 to 1.0%, and 65.4 to 0.8%, respectively. Furthermore, the heat values of the sludge from the chemical, leather, and plating plants prior to fry-drying were 217, 264, and 428 kcal/kg, respectively. After drying, these values of sludge increased to 5317, 5983 and 6031 kcal/kg, respectively. The heavy metals detected in the sludge after drying were aluminum, lead, zinc, mercury, and cadmium. Most importantly, if the dried sludge is used as a solid fuel, these heavy metals can be collected from the dust collector after combustion.

1. Introduction

While the full-scale construction of sewage and wastewater treatment facilities is generally undertaken to prevent water pollution caused by high concentrations of people in urban areas and intensive industrial development, it is becoming apparent that the sludge generated in these facilities is yet another pollutant that must be managed. The annual amount of organic sewage sludge in South Korea in 2007 was approximately 1.44 million tons [1]. About 63% of the sludge was dumped into the ocean, 4% was recycled, 6% was incinerated, and 10% was deposited in landfills. As such, approximately 0.9 million tons of sewage sludge is abandoned near the Korean peninsula each year, causing severe ocean pollution. Thanks to the London Dumping Convention and intergovernmental treaties, such dumping will be prohibited from 2012. In addition, the organic wastewater sludge accounted for approximately 3.6 million tons generated nationwide. In terms of organic wastewater sludge, 1.4 million tons (39%) were dumped into the ocean, 1.1 million tons (30%) were recycled, 0.36 million tons (10%) were incinerated, and 0.27 million tons (8%) were deposited in landfills. Because heavy metals contained in the sludge contaminate ground water and soil, a treatment process of sludge capable of eliminating heavy metals must be developed. The water content of sludge generated from wastewater treatment facilities is 70–90%, but this value must be reduced to below 20% after drying process. Indeed, current methods require large amounts of energy to achieve this goal.

Water contained in the sludge is categorized as follows: free water, surface water, interstitial water, and bound water. Free water and surface water are easily evaporated at 100 ± 5 °C, but the process of evaporating interstitial water and bound water requires temperatures upwards of 400 °C [2,3]. Current drying technologies that are widely used include the convection heat transfer method, wherein gas is heated between 400 and 600 °C to dry the sludge, and the heat conduction transfer method, which is an indirect heat transfer method that circulates high-temperature steam or gas

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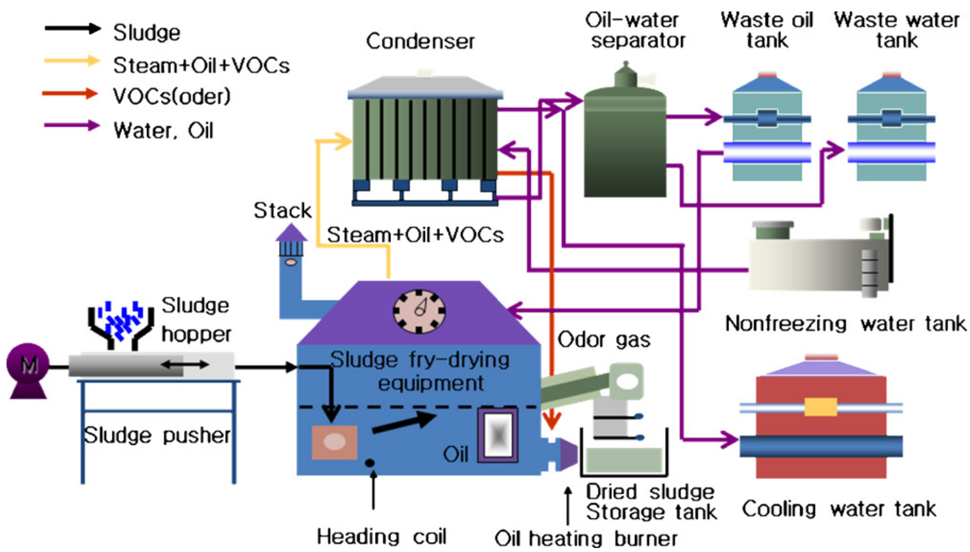

Fig. 1. Schematic diagram of the fry-drying system for sludge.

inside heat transfer equipment while the wet sludge moves outside. Indeed, this process is also time-consuming, because as the outer surface of the sludge dries, more time is required (from 40 to 60 min) to decrease the water content to about 40%. Furthermore, as the surface of the sludge becomes hard, the speed of the process becomes remarkably slow [4,5]. It can be seen that the sludge drying equipment currently used is inefficient with regard to energy and time, and in the end only partially dries the sludge.

The typical drying technologies of sludge have other serious obstacles such as a reduction in surface area, surface carbonation and solidification, fugitive dust, and the offensive odor of the heated gas. Compared to general material drying, sludge drying is a complicated process because the combination of bound water and interstitial water that exists inside the sludge shortens the constant rate drying period and lengthens the falling rate drying period.

In particular, hot gas drying transfers small amounts of heat to the sludge, causing convection heat transfer [6–9]. Although carbonation, solidification, incineration, and thermal degradation are currently being studied as alternative methods, many improvements still need to be made in terms of recycling and energy use. Particularly, the use of cover materials with the organic sludge in landfills causes ground water and soil contamination and produces methane (CH_4), which contributes to global warming.

In order to overcome the limitations on typical sludge drying methods, this study applied a fry-drying technology that uses a boiling heat transfer process [10,11]. While the coefficient of convection heat transfer methods is usually between 75 and 140 W/m^2 °C, the maximum heat transfer coefficient in the boiling heat transfer process is upward of 2500 W/m^2 °C [4,5]. Furthermore, the waste oil used for fry-drying has a lighter molecular weight than water, resulting in ease substitution and increased drying speeds. In addition, the dried sludge by fry-drying process can be used as an alternative solid fuel as the amount of heat that can be generated from the sludge increases remarkably. Finally, the cost of incineration of waste oil can be reduced significantly owing to reusing waste oil as the fry-drying oil.

The fry-drying technology has so far been applied in food manufacturing to rapidly remove moisture and has been determined to actually increase the amount of nutrients in the food because of the use of edible oil. Because the waste oil used in our process, is a heat carrier, the heated oil quickly permeates the sludge and replaces the moisture. Hence, the sludge is efficiently dried, even at relatively low temperatures [12–16]. The vacuum fry-dewatering process recently used in Japan to make a feed for animals began in the early 1990s as a mean of reusing agricultural, marine, and livestock wastes in an efficient manner. In Korea, studies of vacuum fry-drying began in 1995 at Donga University, Hallym University, and Daekyeong Machinery Co., Ltd., but it has been reported that researchers are having difficulties with regard to applying the technology on site [17,3].

The appropriate treatment and recycling of wastewater sludge emitted from various types of wastewater treatment facilities can be accomplished through fry-drying because this process allows for the disposal of both waste oil and wastewater sludge simultaneously. Waste oil is heated to between 120 and 170 °C under atmospheric pressure and sludge is then continuously inserted and submerged in the oil [17]. As a result, the heat of the oil is transferred to the sludge, and the moisture contained in the sludge evaporates rapidly. Conversely, vacuum drying technology extracts the moisture inside the sludge in vacuum and maintains the vacuum's status to prevent the oil from replacing the moisture.

This study investigated the chemical characteristics of wastewater sludges and the heavy metals present in the sludge before and after the fry-drying process. Furthermore, we analyzed the changes in the water content of the sludge, the temperature of the waste oil, the amount of sludge input per unit of waste oil, and the heating value of the dried sludge.

2. Test equipment and test methodology

Fig. 1 shows the fry-drying system for wastewater sludge used in this research. This system is divided into three parts: the first part consists of sludge feeding equipment, which inputs sludge to the evaporative drying tank. The sludge injector, which is operated by a variable-speed motor, pushes the sludge through five holes with 10 mm diameter. The second part is the sludge fry-drying tank where the supplied sludge is dried. The tank is 1.8 m in length, 1.2 m in height, and 1.0 m width, with a round screw drum (0.3 m in diameter and 2.0 m in length) attached. Inside the screw drum, a screw feeder controls the fry-drying time of sludge. In order to increase the temperature of the waste oil inside the drying equipment, 10 kW electric coils and a gas burner are attached and a temperature controller is used to adjust the temperature of waste oil. The third part is the condenser, wherein steam, oil, and volatile organic compounds (VOCs) generated from the drying equipment are separated into

Table 1
Result of proximate analysis of industrial sludge.

Sludge	Item	Moisture (wt.%)	Ash (wt.%)	Fixed carbon (wt.%)	Volatile matter (wt.%)
Chemical plant	Before drying	80.0	7.8	2.3	9.9
	After drying	5.5	22.5	38.0	34.0
Leather plant	Before drying	81.6	8.1	1.5	8.8
	After drying	1.0	21.0	51.3	26.7
Plating plant	Before drying	65.4	15.0	3.6	16.0
	After drying	0.8	20.5	51.7	27.0

condensed liquids and VOCs. And the condensed liquids are separated into water and oil at the oil–water separator. The separated oil is then transferred to the waste oil tank, and the condensed water is stored in the wastewater tank. The VOCs and odorous gases are burnt after being transported to the burner through a tube by using an I.D. fan. The entire process, from the input of the sludge to the output of the finished product, takes about 10 min, and the equipment can treat 50–100 kg of sludge in 1 h.

3. Results and observations

3.1. Results of the proximate and ultimate analysis of sludge

Table 1 illustrates the results of the proximate analysis of the three kinds of industrial wastewater sludge treated in this study. The water content of the sludge from the chemical plant was 80% before drying and 5.5% after drying. The percentages of ash, fixed carbon, and volatile matter before drying were 7.8, 2.3, and 9.9%, respectively, while the percentages after drying were 22.5, 38.0, and 34.0%, respectively. The water content of the sludge from the leather plant was 81.6% before drying and 1.0% after drying. The percentages of ash, fixed carbon, and volatile matter before drying were 8.1, 1.5, and 8.8%, respectively, while the percentages after drying were 21.0, 51.3, and 26.7%, respectively. The water content of the sludge from the plating plant was 65.4% before and 0.8% after drying. The percentages of ash, fixed carbon, and volatile matter before drying were 15.0, 3.6, and 16.0%, respectively, while the percentages after drying were 20.5, 51.7, and 27.0%, respectively. As sludge is precipitated in the waste oil heated at 120–170 °C, sludge and the heated waste oil contact directly and transfer the turbulent heat and mass between sludge surface and the waste oil. As a result, the water content of the wastewater sludge decreases to below 10%. Furthermore, the level of fixed carbon increases from between 1.5 and 3.6% before drying to between 38.0 and 51.7% after drying, while the level of volatile matter increases from between 8.8 and 16.0% before drying to between 27.0 and 34.0% after drying. The fixed carbon and volatile matter levels in dried sludge are significant because they allow the dried sludge to be used as a solid fuel.

The ultimate analysis of the three kinds of industrial wastewater sludge used in this research is shown in Table 2. It is only a result of combustible components of sludge before and after the drying, and an ultimate analysis of sludge measure C, H, O, N and S. The change in the levels of these elements before and after drying can be summarized as follows: C (2.3–44.3%), H (1.1–7.5%), N (0.3–1.1%), O (8.23–19.0%), and S (0.3–0.1%) for the sludge from the chemical plant; C (1.5–49.4%), H (1.2–8.2%), N (0.7–1.9%), O (6.6–18.5%), and S (0.2–0.1%) for the sludge from the leather plant; and C (3.6–49.2%), H (2.0–8.3%), N (0.9–1.5%), O (12.8–19.0%), and S (0.4–0.6%) for the sludge from the plating plant. After drying, the volumes of C and H increase (from 44.3 to 49.2% for C and from 7.5 to 8.3% for H) because the waste oil effectively replaces the moisture in the sludge.

Table 2
Result of ultimate analysis of industrial sludge.

Sludge	Element	Combustibles (wt.%)				
		C	H	Sludge	S	O
Chemical plant	Before drying	2.3	1.1	0.3	0.3	8.2
	After drying	44.3	7.5	1.1	0.1	19.0
Leather plant	Before drying	1.5	1.2	0.7	0.2	6.6
	After drying	49.4	8.2	1.9	0.1	18.5
Plating plant	Before drying	3.6	2.0	0.9	0.4	12.8
	After drying	49.2	8.3	1.5	0.6	19.0

Table 3
Heat value of after fry–drying industrial sludge.

	Chemical plant (kcal/kg)	Leather plant (kcal/kg)	Plating plant (kcal/kg)
Before drying	217	264	428
After drying	5317	5983	6031

Table 3 shows the higher heating values (HHVs) of the sludge before drying and the dried sludge in the fry-drying process, calculated using the Dulong formula. It can be seen that the HHV of the sludge increases dramatically from 217 to 428 kcal/kg before drying to 5317–6031 kcal/kg after drying. The HHVs of the three types of dried sludge are higher than 5000 kcal/kg owing to replacement of water in sludge with waste oil.

The results of the heavy metal analysis of the three types of sludge are shown in Table 4. For this analysis, we used the IRIS DUO, an ICP (Inductively Coupled Plasma Emission Spectroscopy). We analyzed Hg, As, Cd, Cr, Al, Cu, Pb, and Zn for each sample. The heavy metal content in the chemical plant sludge is as follows: Al, Cu, Pb, and Zn were detected in concentrations of 163,448, 255, 1058, and 1408 ppm, respectively. Hg and As were not detected, while Cr and Cd were detected in concentrations of 67 and 5 ppm, respectively. In the case of the leather plant sludge, heavy metal elements of Al, Cu, Pb, and Zn were found in concentrations of 64,022, 1160, 153, and 1100 ppm, respectively. Hg and As were not detected, while Cr and Cd were detected in concentrations of 341 and 0.4 ppm, respectively. The heavy metal element in the plating plant sludge is as follows: Al, Cu, Pb, and Zn were detected in concentrations of 8994, 1764, 591, and 12,177 ppm, respectively. Hg, As, and Cd were not detected, while Cr was detected in a concentration of 5384 ppm. The concentration of aluminum was extremely high in all three types of sludge because ($MgAl(SO_4)_2 \cdot 12H_2O$) was used as a cohesive agent during the wastewater treatment process. The

Table 4
Heavy metals content of after dry–frying industrial sludge.

Element	Chemical plant (ppm)	Leather plant (ppm)	Plating plant (ppm)	Waste oil (ppm)
Hg	ND	ND	ND	ND
As	ND	ND	ND	ND
Cd	5	0.4	ND	ND
Cr	67	341	5,384	1
Al	163,448	64,022	8,994	47
Cu	255	1,160	1,764	35
Pb	1,058	153	591	8
Zn	1,408	1,100	12,177	682

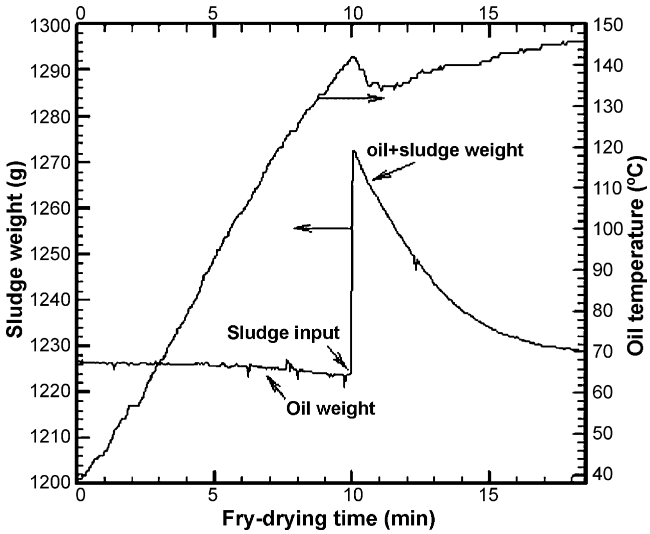

Fig. 2. Drying curve of sludge in fry-drying equipment.

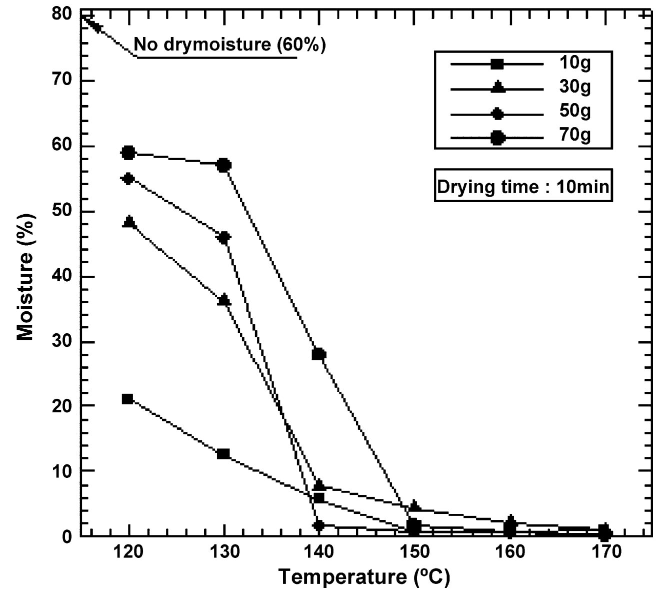

Fig. 4. Moisture contents of the sludge according to temperature of fry-drying(chemical plant).

concentrations of Cr and Zn were high in the plating plant sludge, and the concentrations of Al and Pb were high in the sludge from the chemical plant.

Fig. 2 shows the drying curve of sludge with a 78.0% water content that was evaporated in the fry-drying equipment with waste oil heated to 140 °C. In this figure, the constant rate drying period of the sludge lasted from 4 to 5 min. Generally the constant rate drying period is usually short, while the falling rate drying period is generally long when using other drying technologies such as direct and indirect heating system. But conversely the fry-drying process has the constant rate drying period is relatively long and the falling rate drying period is short due to high turbulent heat and mass transfer in the constant rate drying period. The final water content of the sludge dried for 8 min is 2.0%.

3.2. Results of the fry-drying process

Pictures taken before and after the fry-drying process for sludge are shown in Fig. 3. The sludge is input to the equipment, and the waste oil is heated to between 120 and 170 °C. When the sludge and the heated waste oil come into contact, the heat of the oil is transferred to the sludge, thereby evaporating the moisture. High temperatures and interaction between the waste oil and water in sludge increase the temperature of the moisture in the sludge, resulting in an increase in internal pressure due to steam evaporation. Accordingly, the increased pressure and expansion of the emission path cause a release of steam, and the negative pressure inside the sludge allows for the smooth influx of the waste oil, maximizing the drying process [14,15].

3.2.1. Results of drying the chemical plant sludge

In Figs. 4 and 5, the experimental results related to fry-drying of the chemical plant sludge are shown. Fig. 4 shows the results of the fry-drying test performed on the chemical plant sludge with a water content of 80%. For every liter of waste oil, we input 10, 30, 50, and 70 g of sludge at 120, 130, 140, 150, 160, and 170 °C, respectively. When the waste oil reached each set temperature, the sludge was supplied and then dried for 10 min to measure the drying efficiency of each drying time. The samples were not effectively dried at 120 and 130 °C, but it was possible to reduce the moisture content of the 10, 30, and 50 g samples to below 10% at 140 °C, and the water content of the 70 g sample was reduced to below 10% at over 150 °C.

Fig. 5 shows the time taken to effectively dry the 10, 30, 50, and 70 g sludge samples at 160 °C. It can be seen that 10 min of drying achieves the same result as 12, 14, or even 16 min of drying. Hence, drying times more than 10 min are not warranted.

The fry-drying experimental results of the leather plant sludge with a water content of 81.6% are shown in Figs. 6 and 7. This test conditions are the same temperature of waste oil and weight of sludge as the chemical plant and leather plant sludge. Fig. 6 shows the results of the fry-drying test performed on the leather plant

Fig. 3. Photography of before and after fry-drying chemical plant sludge.

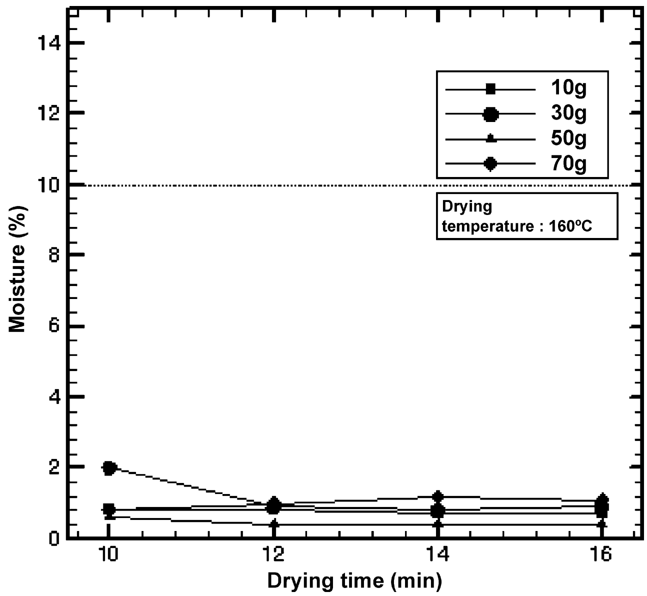

Fig. 5. Moisture contents of the sludge according to time of fry-drying(chemical plant).

sludge for 10 min. We input 10, 30, 50, and 70 g of sludge at 120, 130, 140, 150, 160C, and 170 °C, respectively. The samples were not effectively dried at 120 and 130 °C, but it was possible to reduce the moisture content of the 10, 30, and 50 g samples to below 10% at 140 °C, and the water content of the 70 g sample was reduced to 8.1% at over 150 °C. Fig. 7 shows the time taken to effectively dry the 10, 30, 50, and 70 g sludge samples at 160 °C. It can be seen that the 70 g sludge sample had a water content of 12.6% after 10 min and that this value reduced to 4.8% after 12 min.

In Figs. 8 and 9, the test results related to fry-drying the plating plant sludge with a water content of 65.4% are shown. For every liter of waste oil, 10, 30, 50, and 70 g of sludge were used. The temperature was adjusted to 120, 130, 140, 150, 160, and 170 °C, respectively to conduct the drying test. In Fig. 8, the samples were not effectively dried at 120 and 130 °C, but it was possible to reduce the moisture content of the 10, 30, and 50 g samples to below 10% at 140 °C, and the water content of the 70 g sample was reduced to 8.6% at over

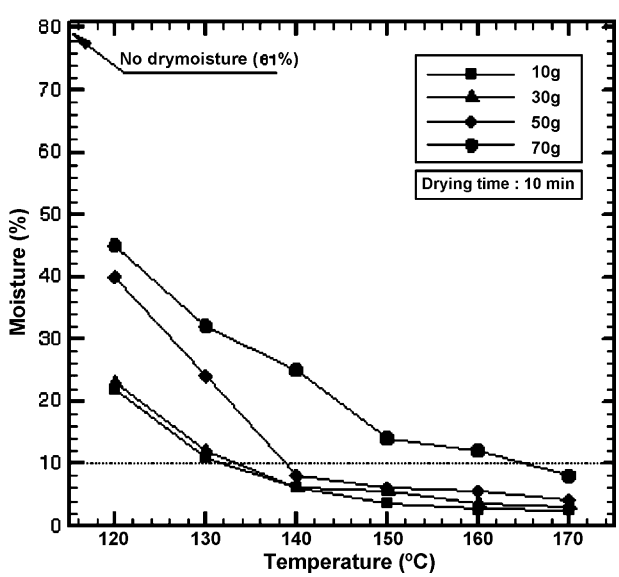

Fig. 6. Moisture contents of the sludge according to temperature of fry-drying(leather plant).

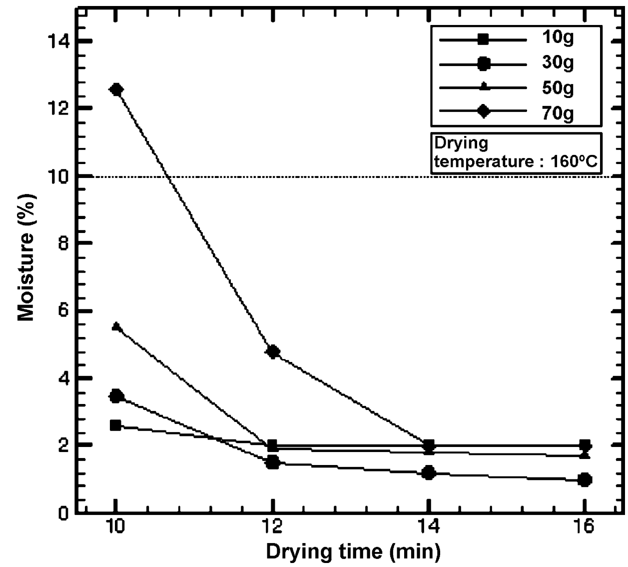

Fig. 7. Moisture contents of the sludge according to time of fry-drying(leather plant).

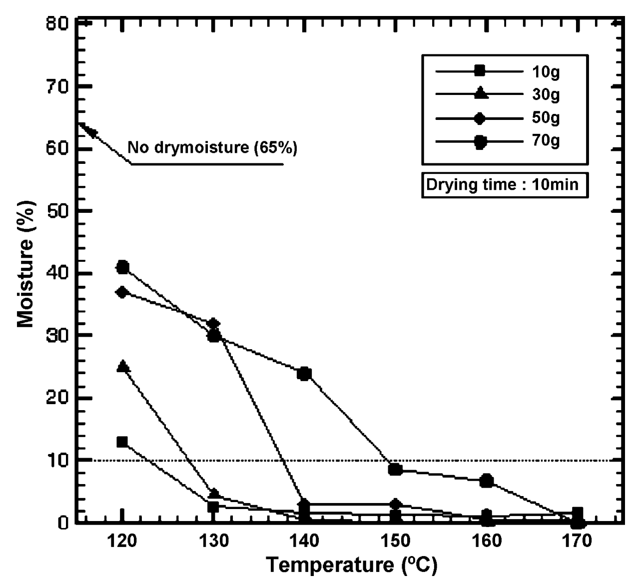

Fig. 8. Moisture contents of the sludge according to temperature of fry-drying(plating plant).

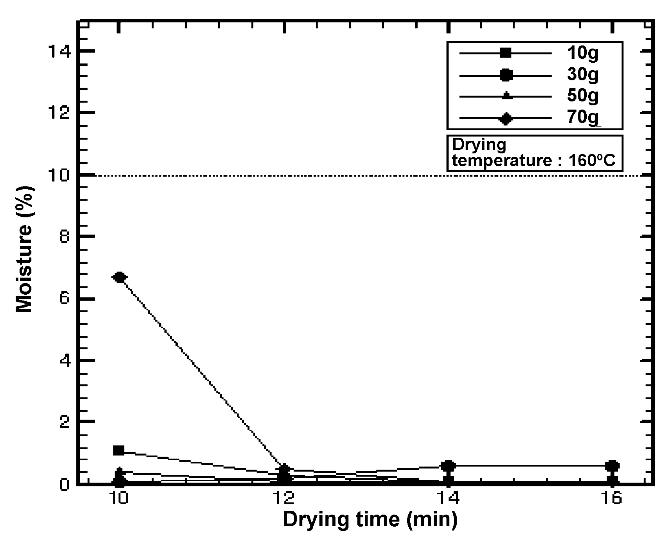

Fig. 9. Moisture contents of the sludge according to time of fry-drying(plating plant).

150 °C. Fig. 9 shows the time taken to effectively dry the 10, 30, 50, and 70 g sludge samples at 160 °C. It can be seen that the 70 g sludge sample had a water content of 6.7% after 10 min, and that this value reduced to below 1.0% after 12 min. With regard to the 10, 30, and 50 g samples, it was found that 10 min of drying achieves much the same result as 12, 14, or even 16 min of drying.

4. Conclusion

When the sludge collected from the chemical, leather, and plating plants was dried after heating the waste oil between 120 and 170 °C, the oil rapidly evaporated the water contained in the sludge, and the heating value of the dried sludge increased dramatically as the oil replaced the water in sludge. The following results were obtained from this study of the fry-drying process:

(1) The water content in the sludge from the chemical, leather and plating plants after fry-drying reduced from 80.0 to 5.5%, 81.6 to 1.0%, and 65.4 to 0.8%, respectively.
(2) The water content of the 50 g sludge sample for 3 kinds of chemical plant sludge after 10 min of fry-drying was less than 10% by using 1 liter of waste oil heated at140 °C. However, the 70 g sample had water content of over 10% when following the above specifications. With regard to the 10, 30, and 50 g samples, 10 min of drying achieves favorable results. Furthermore, 10 min of drying achieves the same result as 12, 14, or even 16 min of drying.
(3) A comparison of the elements of the sludges before and after drying can be summarized as follows: C (2.3–44.3%), H (1.1–7.5%), N (0.3–1.1%), O (8.2–19.0%), and S (0.3–0.1%) for the sludge from the chemical plant; C (1.5–49.4%), H (1.2–8.2%), N (0.7–1.9%), O (6.6–18.5%), and S (0.2–0.1%) for the sludge from the leather plant; and C (3.6–49.2%), H (2.0%–8.3%), N (0.9–1.5%), O (12.8–19.0%), and S (0.4–0.6%) for the sludge from the plating plant.
(4) The heat values of the sludge from the chemical, leather, and plating plants prior to fry-drying were 217, 264, and 428 kcal/kg, respectively. After drying, these values increased to 5317, 5983, and 6031 kcal/kg, respectively. Because of these HHVs, it is believed that the dried sludge can be used as a solid fuel.

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