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The evaporative drying of sludge by immersion in hot oil: Effects of oil type and temperature

Tae-In Ohm [a,*], Jong-Seong Chae [a], Kwang-Soo Lim [a], Seung-Hyun Moon [b]

[a] Department of Environmental Engineering, Hanbat National University, San 16-1 Duckmyung-dong, Yusung-gu, Daejeon 305-719, Republic of Korea
[b] Waste Energy Research Center, Korea Institute of Energy Research, Jang-dong Yusung-gu, Daejeon 305-343, Republic of Korea

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ABSTRACT

We investigated the evaporative drying by immersion in hot oil (EDIHO) method for drying sludge. This involved heating oil to a temperature higher than that needed for moisture to be evaporated from the sludge by turbulent heat and mass transfer. We fry-dried sewage and leather plant sludge for 10 min in each of four different oils (waste engine, waste cooking, refined waste, and B-C heavy) and three different temperatures (140 °C, 150 °C, and 160 °C). Drying efficiency was found to be greater for higher temperatures. However, giving consideration to energy efficiency we suggest that the optimal temperature for fry-drying sludge is 150 °C. At 150 °C, the water content of sewage sludge reduced from 78.9% to between 1.5% (with waste cooking oil) and 3.8% (with waste engine oil). The reduction in water content for leather plant sludge fry-dried at 150 °C was from 81.6% to between 1% (with waste cooking oil) and 6.5% (with refined waste oil). The duration of the constant rate-drying period was also influenced by the type of oil used: refined waste oil > waste engine oil > B-C heavy oil > waste cooking oil. The duration at 150 °C with waste cooking oil was 3 min for sewage sludge and 2 min for leather plant sludge. It is likely that the drying characteristics of oil are influenced by its thermal properties, including its specific heat, and molecular weight.

1. Introduction

Sludge is discharged as waste during the final stage of water treatment in sewage, water, and wastewater treatment plants. It consists of solid organic and inorganic substances, and microorganisms. There is an increasing amount of sludge being produced, in addition to other organic/inorganic chemical waste, via a variety of water treatment and chemical processes. In general, sludge that is discharged from treatment plants in the form of dehydrated cakes has a water content of 75–85%. Discharged organic sludge is comprised of 40% or more organic material [1]. In 2007, the total amount of sewage sludge discharged daily by the 347 public sewage treatment plants in South Korea was about 7631 tonnes [2]. While most (68.5%) of this sludge was dumped into the ocean, 18.5% was recycled, 10.9% was incinerated, and 2.1% was deposited in landfills. The London Dumping Convention completely prohibits the dumping of sludge from 2012 [2]. Indeed, rather than dumping, there are various methods used to treat sludge in Europe, including incineration, melting, and incineration of a sludge mixture containing other combustible waste [3]. In Korea there was an intention to develop new organic sludge treatment technologies, but with current high oil prices and energy security concerns the focus is now on using low-energy processes to dry sludge with a high water content for use as an energy source. However, the presence of cohesive agents used to solidify sludge during wastewater treatment processes makes drying difficult. Sludge that is to be dried typically has a water content of 80% or more, and the energy involved in producing the heat needed to vaporise this is considerable. Consequently, sludge is a very inefficient source of energy [2]. The typical methods currently widely used to dry sludge include convection heat transfer of direct hot gas blasting and conduction heat transfer of steam inside screw and sludge [4]. Approaches to the latter method involve heat conduction transfer within either an agitated vessel or a rotary vessel [5]. However, all of these technologies have disadvantages in requiring large quantities of energy and generating malodorous gases. Furthermore, the presence of combustible gases means that there is a potential danger of explosion.

Observing the drying characteristics of sludge involves recording its weight and surface temperature [6,7]. With hot blasting at a predetermined temperature the drying process can be divided into three periods: preheating, constant rate drying, and falling rate drying. The preheating period is very short, and during which the water content only begins to be reduced. In the constant rate-drying period that follows, the surface evaporation rate and internal diffusion rate of the sludge are equal. Water content is reduced linearly throughout this period. During the falling rate-drying period the

* Corresponding author. Tel.: +82 42 821 1262; fax: +82 42 822 7442.
E-mail address: tiohm1@hanbat.ac.kr (T.-I. Ohm).

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surface evaporation rate of the sludge is increased but the internal diffusion rate of heat is reduced. This results in a slowing of the overall rate at which water content is reduced, to a point at which there is no more reduction.

The typical methods of drying sludge have a problem in requiring very long durations for both the constant rate and falling rate-drying periods. The overall time needed to dry the sludge can thus be substantial. This problem can be addressed within wastewater treatment processes by replacing the polymer-based adhesive agent used to promote sludge solidification with an inorganic adhesive agent [8]. However, the high financial price of this option can be prohibitive.

In line with current environmental concerns there is considerable interest in using combustible waste as an energy source. Converting organic sludge to a solid fuel requires reductions in water content to below 10% after drying and it increases the lower heating value to 3000 kcal/kg or more. It is also important to minimise the energy costs of completing the drying process within a short period of time (ideally between 10 and 20 min).

But the convection and conduction heat transfer methods for converting sewage and wastewater sludge to a usable form of fuel are inefficient in terms of both energy and time.

In this study, the fry-drying technology using hot oil can be suggested for drying of sludge as an alternative to typical methods [9–11]. The fry-drying method is similar to the deep frying cooking technique also is efficient for high water content material such as meat, vegetables and organic sludge in view of energy consumption and time [12,13].

2. Experiment

In fry-drying technology of sludge, the oil used has a boiling point of between 240 °C and 340 °C, and a specific heat of between 0.5 kcal/kg °C and 0.7 kcal/kg °C, and been used repeatedly. Despite the high water content and adhesive characteristics of sludge, fry-drying elevates the temperature of surface water contacted by hot oil to a temperature between 120 °C and 170 °C, which is considerably efficient for energy. This leads to the formation of bubbles and the transfer of heat by a strong turbulent flow (boiling). Moisture of sludge is displaced by oil internally diffusing the sludge, resulting in rapid drying. There is also an increase in pressure that forces bound and interstitial water from the sludge and which is heated and vaporised upon diffusion into the hot oil [9,10]. This process forms a vacuum within capillary tubes of the sludge that promotes the rapid absorption of oil [7]. Furthermore, the glue zone generated by typical drying methods is not produced by fry-drying when the water content is between 40% and 60% [1,3]. It is thought that a glue zone does not form with fry-drying because most of the moisture is dried during the constant rate-drying period by the heat and mass transfer on the surface of the sludge and the rapid diffusion within the sludge.

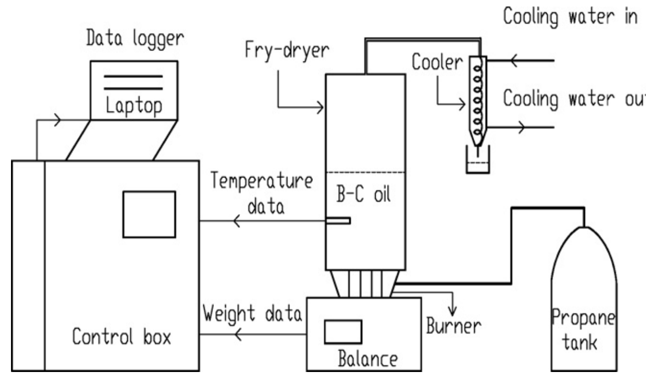

Fig. 1. Schematic of the batch sludge EDIHO system.

Various types of oil can be used for fry-drying, including fuel oil refined from crude oil, refined industrial waste oil, waste vegetable oil, and dissolved animal oil. Here, we investigated different types of oil with the aim to develop a large-scale process for drying organic sludge that would be both economical and highly energy efficient. For this, we obtained drying curves for four different oils: waste engine oil, waste cooking oil, refined waste oil, and heavy oil.

2.1. Experimental apparatus

Fig. 1 shows the batch sludge EDIHO system used in the present study. A stainless steel cylindrical batch vessel (height: 23 cm; diameter: 20 cm) contained 1.5 l of oil, and into which 50 g of sludge (in a square mesh net measuring 10 cm × 10 cm × 2.5 cm) was immersed to be dried for 10 min at one of three temperatures: 140 °C, 150 °C, and 160 °C. The weight of the vessel and contents was measured with an electronic scale, and an automated program controlled the oil temperature. Temperature and weight data were recorded in real-time on a laptop computer. Drying curves (sludge weight by time) for all three drying temperatures were constructed for each of the four oils used (waste engine, waste cooking, refined waste, and heavy).

2.2. Experiment of fry-drying sludge

Fig. 2 shows wastewater sludge before and after fry-drying. Sludge was immersed in oil heated to a temperature much lower than its boiling point (approximately 340 °C), and from which heat was directly transferred to the sludge. With its surface exposed to the hot oil, heat was rapidly transferred into the sludge, facilitating the discharge and evaporation of bound and interstitial water. High temperature and activity of hot oil with smaller spe-

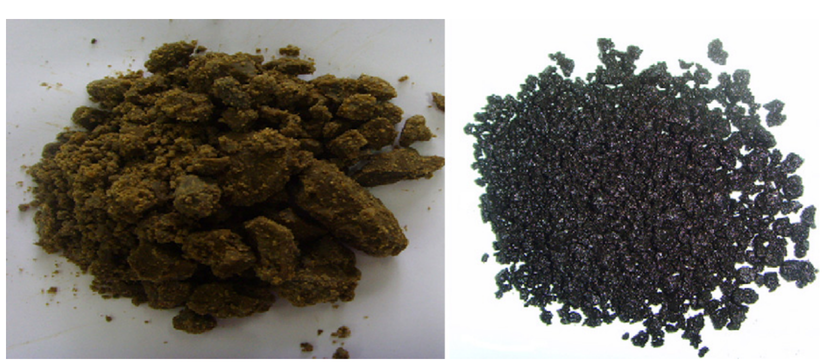

Fig. 2. Sludge before and after EDIHO.

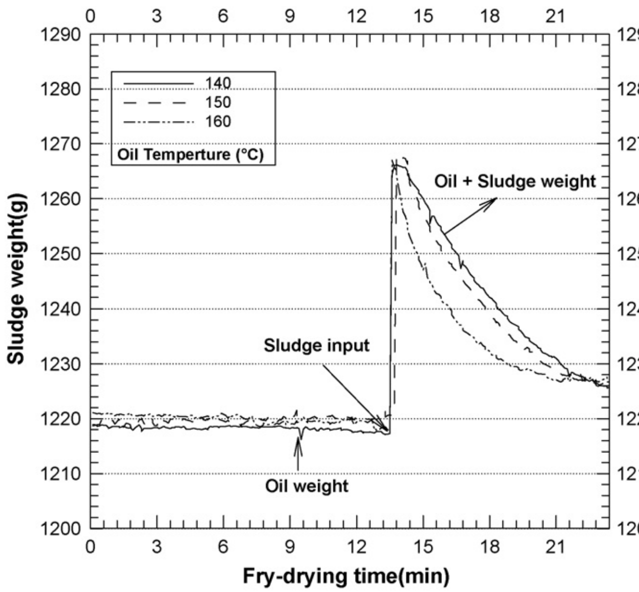

Fig. 3. Drying curves for sewage sludge immersed in waste engine oil heated to one of three temperatures.

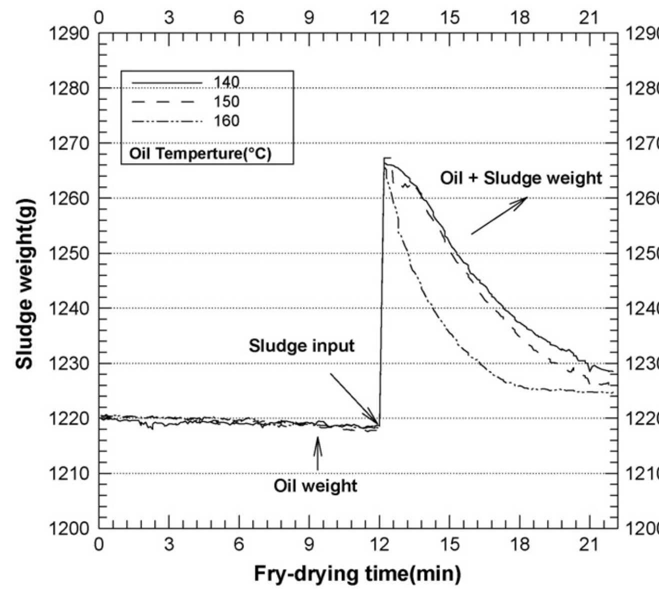

Fig. 4. Drying curves for leather plant sludge immersed in waste engine oil heated to one of three temperatures.

cific heat compared to water increase the temperature of moisture in sludge, resulting in the increase of internal pressure caused by a steam evaporation phenomenon, and such increase maximizes the structure of internal pores, which plays a role to deliver materials between internal moisture. Accordingly, the increased moisture pressure and expansion of emission path issue the steam outside, and the negative pressure inside of the sludge which is formed temporarily makes smooth the influx of waste oil, maximizing the dry efficiency.

We found that fry-drying reduced the water content of sludge from around 80% to 1%. In addition, analysis of dried sludge suggested that partial replacement of the evaporated moisture with oil increased the heating value of the sludge.

The proximate and ultimate analysis equipment are TGA-701 Proximate Analyzer, Truspechn Elemental Analyzer (LECO), SC-432DR Sulfur Analyzer (DIONEX), Analyzer (LECO) and IC-2000 Analyzer (LECO).

3. Results and observations

3.1. Drying characteristics of waste engine oil

We determined the drying characteristics of four different oils that could be used for large-scale sludge drying with the EDIHO method: waste engine, waste cooking, refined waste, and heavy oil. Fry-drying with waste engine oil for 10 min reduced the water content of sewage sludge from 78.9% to 3.9%, 3.8%, and 1.0%, for oil temperatures of 140 °C, 150 °C, and 160 °C, respectively. As shown in the drying curve, the result of reducing the water content within a relatively short time period is as follows: evaporation of moisture on the surface of the sludge gives rise to strong turbulent flow and consequent heat and mass transfer.

Fig. 3 shows sewage sludge drying curves for waste engine oil. From the slopes of these curves, it can be seen that there was an effect of oil temperature on evaporation velocity during the constant rate-drying period, and the increase in oil temperature was associated with an increase in evaporation velocity.

Furthermore, for oil temperatures of either 140 °C or 150 °C there was a transition from the constant rate-drying period to the falling rate-drying period around 6–7 min after the sludge was immersed. However, this transition occurred 2 min earlier with oil heated to 160 °C.

Fig. 4 shows drying curves for leather plant sludge that had an initial water content of 81.6%. With waste engine oil the water content of this sludge was reduced to 11.94% at 140 °C, 2.7% at 150 °C, and 1.0% at 160 °C. For oil temperatures of 140 °C and 150 °C, drying occurred at a constant rate for most of the 10-min period. The evaporation velocity was faster with oil heated to 160 °C, for which there was a transition from constant rate to falling rate drying 5 min after immersion of the sludge. However, as evident from Figs. 3 and 4, most of the moisture content of sludge vaporised during the constant rate-drying period.

3.2. Drying characteristics of waste cooking oil

Fig. 5 shows drying curves for sewage sludge fry-dried in waste cooking oil. With 10 min of drying the water content of this sludge

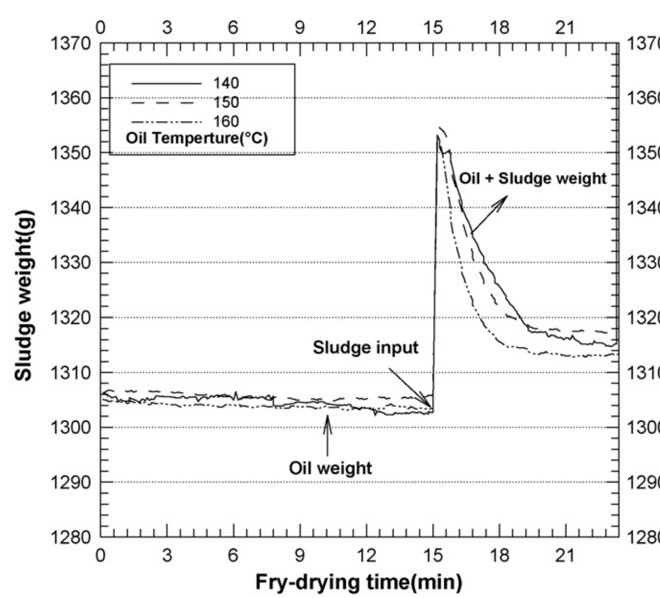

Fig. 5. Drying curves for sewage sludge immersed in waste cooking oil heated to one of three temperatures.

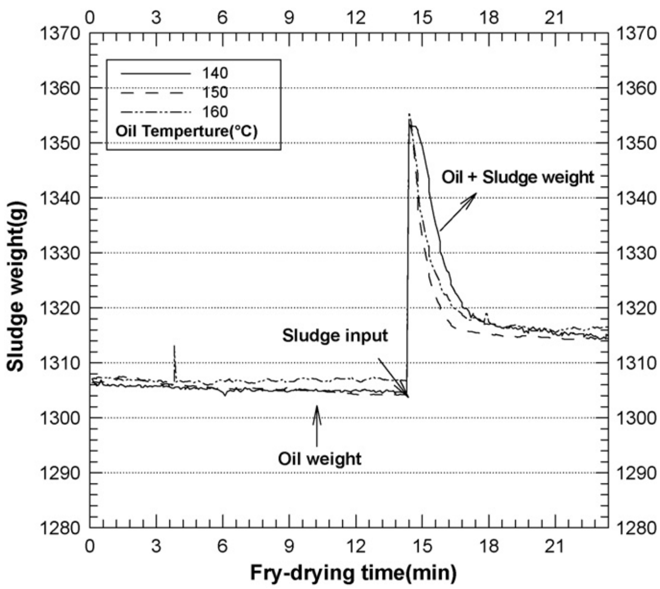

Fig. 6. Drying curves for leather plant sludge immersed in waste cooking oil heated to one of three temperatures.

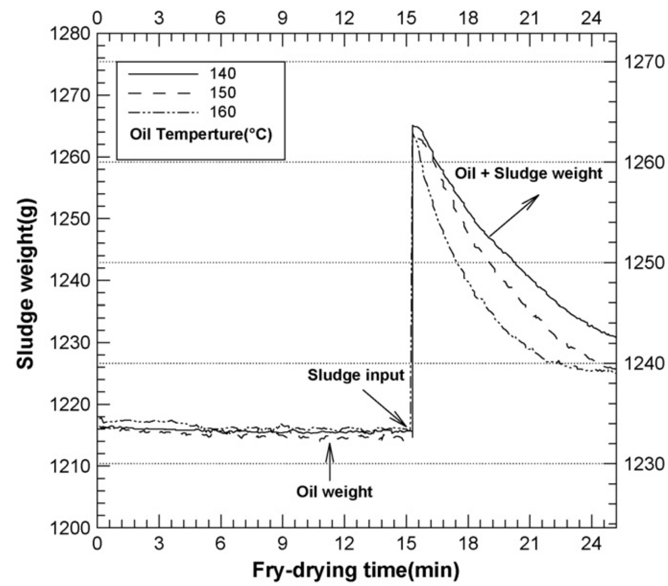

Fig. 7. Drying curves for sewage sludge immersed in refined waste oil heated to one of three temperatures.

was reduced from 78.9% to 1.9% at 140 °C, 1.5% at 150 °C, and 1.3% at 160 °C. As a vegetable oil, waste cooking oil has a lighter molecular weight than waste engine oil, and thus has a faster drying velocity. Indeed, with waste cooking oil most of the moisture content of sewage sludge was evaporated in a period of constant rate drying lasting only 2–5 min.

Fig. 6 shows drying curves for leather plant sludge fry-dried in waste cooking oil. The water content of this sludge was reduced from 81.6% to less than 1.4% after drying for 10 min at 140 °C. It was thus possible to produce almost total drying of leather plant sludge with waste cooking oil. The constant rate-drying period was less than 3 min in duration, and the falling rate-drying period of shorter duration than with sewage sludge.

3.3. *Drying characteristics of refined waste oil*

Figs. 7 and 8 show drying curves for sewage sludge and leather plant sludge, respectively, fry-dried for 10 min in refined waste oil. The water content of sewage sludge was reduced from 78.9% to 8.1% at 140 °C, 1.7% at 150 °C, and 1.4% at 160 °C. For leather plant sludge there was a reduction in water content from 81.6% to 15.5% at 140 °C, 6.5% at 150 °C, and 1.0% at 160 °C. In Fig. 7 it can be seen that the water content of sewage sludge was greater than 155 °C after drying at 140 °C, and that the constant rate-drying period lasted for 9 min at 150 °C, and for 6 min at 160 °C. In Fig. 8 it is apparent that constant rate drying occurred throughout most of the 10-min period for temperatures of 140 °C and 150 °C, but that there was a transition from constant rate to falling rate drying after about 7 min at 160 °C.

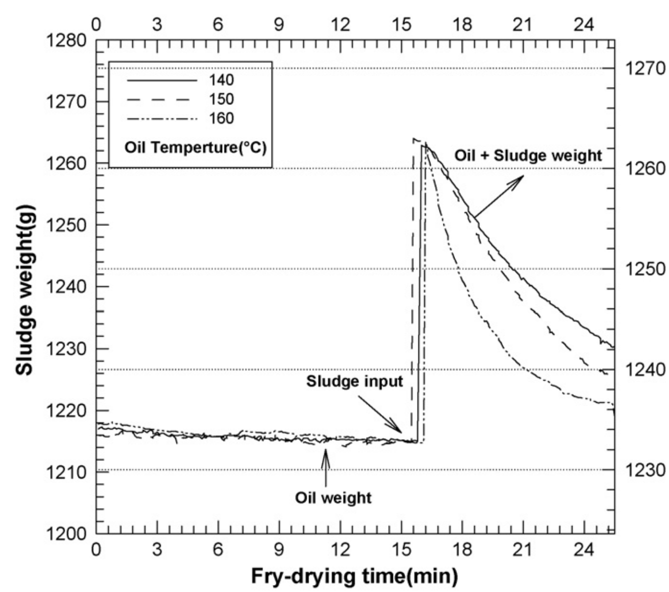

Fig. 8. Drying curves for leather plant sludge immersed in refined waste oil heated to one of three temperatures.

3.4. *Drying characteristics of heavy oil*

Fig. 9 shows drying curves for sewage sludge fry-dried in B-C heavy oil. The water content of sewage sludge was reduced from 78.9% to less than 1.7% with all three oil temperatures. The constant rate-drying period lasted for about 6 min for oil temperatures of 140 °C and 150 °C, and about 4 min for 160 °C.

Table 1
Result of proximate analysis of industrial sludge (oil temperature: 150 °C).

ComponentFrying oils	Moisture (wt.%)	Ash (wt.%)	Fixed carbon (wt.%)	Volatile matter (wt.%)	Low calorific value (kcal/kg)
Raw sludge	78.9	8.5	3.4	9.2	626
Waste engine oil	6.0	24.2	5.0	64.8	5501
Refined waste oil	5.5	24.0	5.1	65.4	5795
Heavy oil (B-C)	5.1	23.6	5.4	65.9	5875
Waste edible oil	4.8	24.1	4.9	66.2	5459

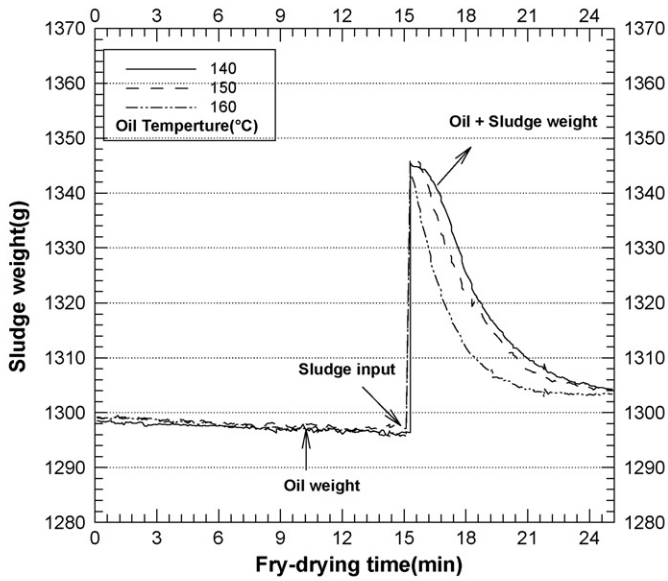

Fig. 9. Drying curves for sewage sludge immersed in B-C heavy oil heated to one of three temperatures.

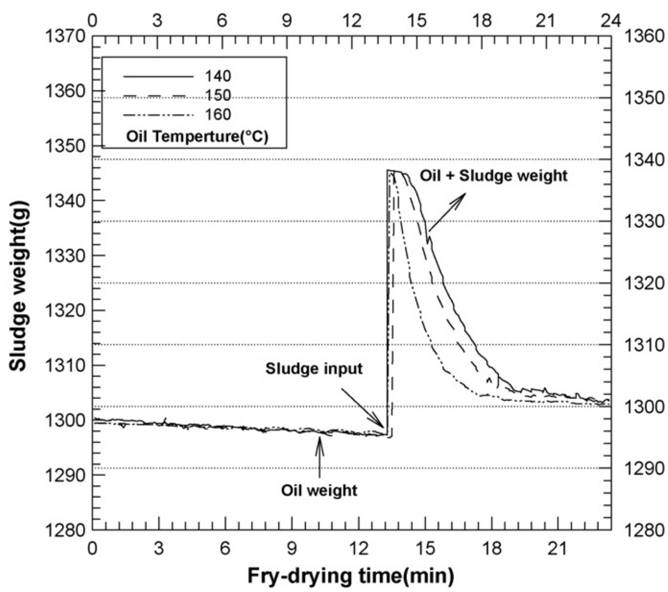

Fig. 10. Drying curves for leather plant sludge immersed in B-C heavy oil heated to one of three temperatures.

Fig. 10 shows drying curves for leather plant sludge fry-dried for 10 min in B-C heavy oil. The water content of this sludge was reduced from 81.6% to less than 1.7% at all three oil temperatures, and the constant rate-drying period lasted no more than 4 min.

3.5. Analysis of sludges

The proximate analysis of the sewage sludge used in this study is demonstrated in Table 1. Moisture of sludge from chemical plant changed from 78.9% before drying to 4.8–6.0% after drying, and the portion of ash, fixed carbon and volatile matter changed from 8.5% to 23.6–24.2%, and 3.4% to 4.9–5.1%, and 9.2% to 64.8–66.2%, for four kinds of frying oils, respectively. An increase of ash content of dried sludges is due to significant decrease of water content in dried sludge. As sludge is precipitated in the frying oil heated at 140–170 °C, which are far lower than the boiling point (approximately 240–340 °C) of the oil, in the sludge drying using heated oil, sludge and the heated oil contact directly and transfer the heat and the dried sludge surface exists in the oil. Hence, the heat is transferred rapidly inside of the sludge while easily evaporating bound and internal water. As a result, the moisture of the sewage sludge goes under 10%. In this experiment, an optimum temperature of oil is 150 °C considering water content of dried sludge, drying time and energy consumption for oil heating.

Table 2
Result of ultimate analysis of industrial sludge (oil temperature: 150 °C).

Element	Combustibles (wt.%)					
Frying oils	C	H	O	N	S	Cl
Raw sludge	6.5	0.9	3.9	1	0.3	0.008
Waste engine oil	45.4	8.5	14.4	1.5	0.2	0.009
Refined waste oil	47.2	8.8	13.0	1.2	0.3	0.01
Heavy oil (B-C)	48.0	8.9	13.0	1.2	0.2	0.01
Waste edible oil	46.5	7.9	14.9	1.5	0.3	0.02

The ultimate analysis of the sewage sludge used in this research is shown in Table 2. The table demonstrates the result of ultimate analysis on sewage sludge and dried sludges in oil at 150 °C. It is only a result of combustible components before and after the drying of sludge. The reason of increase of combustible elements is addition of oil in sludge during fry-drying. These after-drying carbon and volatile matter levels of sludge are significant because they allow the dry sludge to be used in coal combustor as a solid fuel. And the fry-drying oil can be used repeatedly.

4. Conclusion

We used the EDIHO method to dry both sewage sludge and leather plant sludge for 10 min, testing four different oils (waste engine, waste cooking, refined waste, and B-C heavy) and three oil temperatures (140 °C, 150 °C, and 160 °C). From our results we were able to conclude the following:

1. Drying efficiency was greater at higher temperatures for both sewage and leather plant sludge. However, giving consideration to energy efficiency we suggest that the optimal temperature for fry-drying sludge is 150 °C. The constant rate-drying period was short with this temperature, and the drying efficiency sufficiently high.
2. The water content of sewage sludge fry-dried for 10 min at 150 °C was reduced from 78.9% to 3.8% with waste engine oil, 1.5% with waste cooking oil, 1.7% with refined waste oil, and 1.6% with B-C heavy oil. For leather plant sludge dried under similar conditions the reduction in water content was from 81.6% to 2.7% with waste engine oil, 1.0% with waste cooking oil, 6.5% with refined waste oil, and 1.6% with B-C heavy oil.
3. From a total 10 min of drying time, the constant rate-drying period for sewage sludge at 140 °C was 7 min with waste engine oil, 5 min with waste cooking oil, 10 min with refined waste oil, and 6 min with B-C heavy oil. For an oil temperature of 150 °C, the duration of the constant rate-drying period was 6 min with waste engine oil, 3 min with waste cooking oil, 7 min with refined waste oil, and 6 min with B-C heavy oil. For 160 °C the duration was 5 min with waste engine oil, 2 min with waste cooking oil, 6 min with refined waste oil, and 4 min with B-C heavy oil.
4. For leather plant sludge the constant rate-drying period at 140 °C with waste engine oil lasted 9 min; with waste cooking oil, 3 min; with refined waste oil, 10 min; and with B-C heavy oil, 4 min. For 150 °C the duration with waste engine oil was 7 min; with waste cooking oil, 2 min; with refined waste oil, 10 min; and with B-C heavy oil, 3 min; for 160 °C, the duration with waste engine oil

was 5 min; with waste cooking oil, 1 min; with refined waste oil, 7 min; and with B-C heavy oil, 2 min.

5. We found the length of the constant rate-drying period during EDIHO to be dependent upon the type of oil used: refined waste oil > waste engine oil > B-C heavy oil > waste cooking oil. These differences are likely to stem from differences in the physical properties of the oils, such as the molecular weight, specific heat, and boiling point.

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