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Thermotechnical comparison of conventional heating and microwave radiation method for dewatering of sewage sludge

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ABSTRACT

In this study, variations on the dewatering of filter cake sludge following microwave irradiation and conventional drying processes were investigated. The rates of dewatering and operating costs were calculated. One hundred percent dewatering of the sludge was accomplished using 800 W microwave power for 15 min. Conversely, filter sludge was dewatered to only 45% by heating to 200°C for 60 min. To examine the cost analysis for the same conditions, a 45% dewatering rate was chosen. While energy consumption for conventional drying was 1.2 kWh/100 g sludge, energy consumption for the microwave radiation process was 0.126 kWh/100 g sludge. According to the Turkish legislation, sewage sludge must have a minimum 35% solid content to be stored in landfill areas. To ensure this, approximately 0.053 kWh/100 g sludge and 0.6 kWh/100 g sludge energy consumption was obtained for microwave radiation and conventional drying processes, respectively. According to the regulation, waste sludge can be used in soil with 90% solid matter content. In this context, energy consumptions of 0.173 kWh/100 g sludge and 1730 kWh/ton sludge, approximately, were calculated for microwave radiation process. Study results have shown that the microwave radiation process was 10 times faster, more effective, and 15 times more economical than conventional drying for sludge dewatering.

Keywords: Microwave irradiation; Sludge dewatering; Conventional drying; Cost analysis

1. Introduction

The disposal or storage of sewage sludge should not be undertaken haphazardly. Following treatment, it should be stored in sanitary landfill areas [1]. One of the most important issues in water treatment technology is carrying out sludge treatment in accordance with human and environmental health regulation. Sewage sludge must be dewatered prior to disposal. Water in the sludge is free (free water) or bound water (flock water, capillary water and chemically bound water). Chemically bound water cannot be removed from sludge with mechanical dewatering processes [2]. The solid content of final clarifier sludge is 2–3%. This ratio is 6% for digested sludge and 25% for mechanical (such as filter press unit) dewatered sludge [3]. Higher levels of dewatering efficiency could be achieved in less time with the microwave radiation process. Decreasing sludge volume using the microwave radiation process can reduce transportation costs. In addition, dried sludge is stored and marketed more easily.

Sewage sludge is usually dewatered following the sludge thickening process. Dewatering units should be selected from the high efficiency methods. Many methods are used for sludge dewatering, such as bioflocculation [4], electroosmosis [5], forward osmosis [6], ultrasound process [7], electro-dewatering [8–9], thermal drying [10–12], wetlands [13], microwave irradiation [14–17] and mechanical dewatering [17–19]. Following all these processes, sewage

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sludge is stored in sanitary landfills. To be stored in sanitary landfills in Turkey, sludge water content must be equal to or lower than 65% [20].

In this study, conventional drying and microwave irradiation, which are both widely used in current processes, were compared according to their success in sludge dewatering. The microwave irradiation process is expected to provide more efficient and economical results in a shorter period of time than the conventional drying processes.

Microwave irradiation application on sludge dewatering has not been studied in detail. This study will be one of the first to examine wastewater treatment sludge dewatering applications. Current applications in sludge dewatering include the conventional thermal dewatering processes. This conventional process requires more time and energy. From an environmental point of view, this is not a feasible treatment technique. The microwave drying process, on the other hand, saves both time end energy. With microwave drying, homogeneous drying is achieved over the entire sludge area in a short time. Microwave drying is feasible, practical, and requires a shorter period of time and less energy, thus allowing an alternative approach.

Microwave irradiation generates physical, chemical and biological changes in sludge, particularly through electrical waves (microwaves). In this method, the applied energy spreads through atoms, moving within the materials. Microwaves are generated by magnetrons. In addition to microwaves, 300 MHz–300 GHz, 2450 MHz frequency is also used in sludge dewatering [21–23]. The reason for using this frequency is that 2450 MHz is the resonance frequency of water molecules. In other words, water molecules mostly absorb the 2450 MHz microwave irradiation. The water molecules are heated via this resonance. As a result, substances with more water molecules will heat faster, causing microwave irradiation to heat them at a faster rate than conventional heating [24]. In this process, only irradiation-applied material will be heated, and not the environment. Microwave irradiation acts simultaneously and uniformly on each point of the material; however, there is no homogeneous temperature distribution in convective heating. In convective heating, the heating gradient acts from the surface towards the inner parts. Therefore, while the surface of the materials burns in convective heating, no heating will be observed in the inner zones. In this type of heating, not only the material, but the environment is heated as well, causing more energy to be consumed. This is the most important advantage of microwave radiation process compared to the conventional drying process.

In this study, filtered sludge was dewatered using microwave radiation, and the conventional drying processes and changes in dewatering ratios were investigated.

2. Materials and methods

In this study, a filter-press cake sludge provided by the ISKI Atakoy Biological Wastewater Treatment Plant was used for the laboratory tests. The solid matter content of the filter-press cake sludge was found to be between 23.5–25.8%. In this study, conventional drying and microwave irradiation processes on sludge dewatering were compared. These two types of drying methods were carried out with a household Kenwood 503 MW oven, which can apply both microwave irradiation and conventional heating. In the dewatering tests, the conventional drying method was carried out by applying 10 different temperatures to the sludge over 12 different drying times. The applied temperatures were 110, 120, 130, 140, 150, 160, 170, 180, 190 and 200°C, while the application times were 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55 and 60 min. The sludge sample weight and thickness were 100 g and 5 cm, respectively. After determining the optimum drying time and temperature values for the sludge drying process, and number of tests were performed as well to determine the optimal sludge thickness for the sludge drying process. Tests were performed at sludge thickness values of 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 cm.

The microwave irradiation process tests were conducted to determine its effects on sludge drying. Tests were performed at different microwave powers, which were 80, 240, 400, 640 and 800 W, and at different drying times, which were 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55 and 60 min. The weight and thickness of the sludge sample were 100 g and 5 cm, respectively.

Furthermore, sludge samples weighing 100, 250, 500, 750, 1000, 1500 and 2000 g were evaluated to observe the changes in the sludge drying time that resulted from an increase in the amount of sludge. The results of these tests are specifically described in the Results and discussion section.

Both the horizontal and vertical depths of the sludge drying rates were evaluated to determine how the temperature gradient takes shape in the sludge samples during the conventional and the microwave radiation drying processes. The final solid content of the sludge samples was determined using the Standard Method 2540 B. In the time comparison tests, cylindrical sludge samples of 5 cm diameter and 5 cm height were used. In the tests comparing horizontal and vertical drying, cylindrical sludge samples with 10 cm diameter and 10 cm height were used. The sludge samples are shown in Fig. 1.

3. Results and discussion

The initial solid matter content of the filter-press output sludge cake was calculated as 23.5–25.8%. The final solid content of sludge from conventional drying was determined, and the relevant results are shown in Fig. 2.

For the conventional drying process**,** the highest solid matter ratio, which was 45.9%, was obtained after a heating period of 1 h at 200°C. The ratio ranged from 39.8 to 45.9% for different temperatures from 110 to 200°C. As can be seen from the results, there was no significant increase in the solid content of municipal sludge based on temperature changes. According to Turkish regulations, sludge with this amount of solid content cannot be stored in landfill areas [25]. A number of tests were performed to understand how heat penetrates the sludge and affects the gradient of evaporation horizontally and vertically. Thus, the objective was to determine the drying paths and zones of the sludge. Sludge samples with a diameter of 5 cm and height of 5 cm were used for the conventional drying tests. A drying temperature of 200°C was selected. As in the previous tests, 12 different drying times were used, ranging

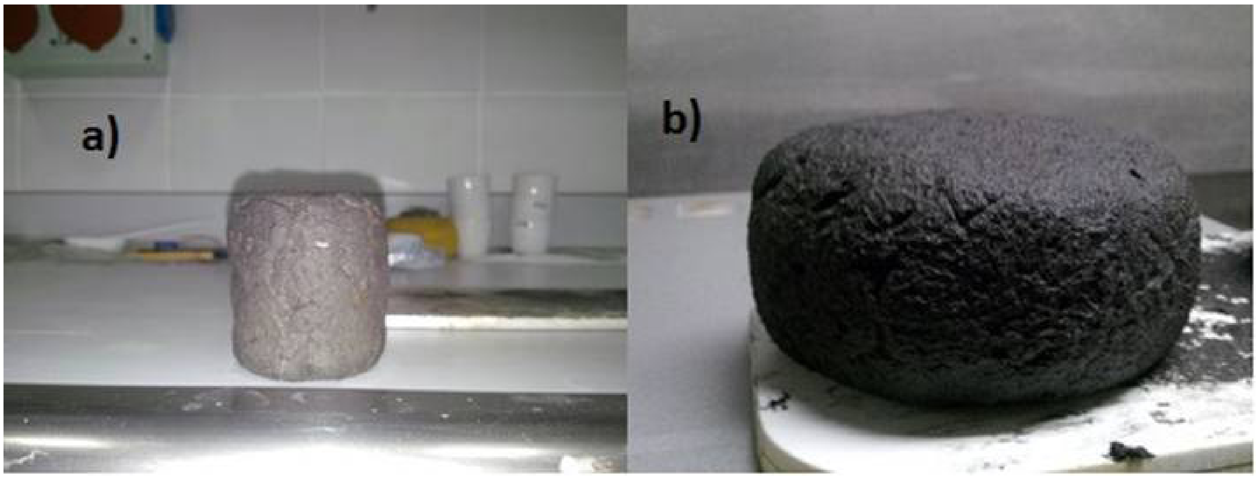

Fig. 1. a) Time comparison studies cylindrical sludge samples with 5 cm diameter and 5 cm height b) Comparison horizontal and vertical drying studies, cylindrical sludge samples with 10 cm diameter and 5 cm height.

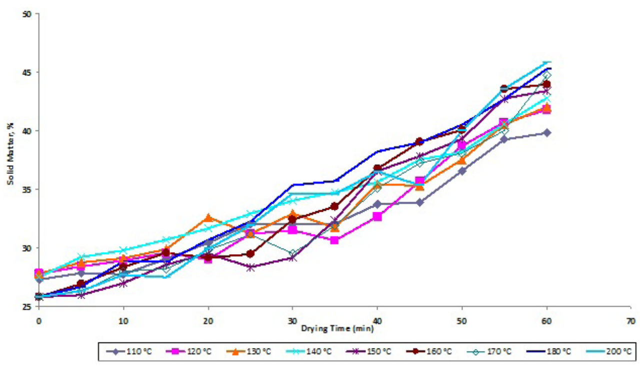

Fig. 2. Final solid contents of sludge after conventional drying.

from 5 min to 60 min. At the end of each test, sludge samples were taken from a depth of 1, 2, 3, 4 and 5 cm in the horizontal and vertical directions, and their solid contents were calculated. The results and sludge sampling sections in the vertical and horizontal directions are shown in Figs. 3–5.

The obtained results indicated that, during the conventional drying process, the drying process occurs starting from the sludge surface.

The conventional drying process was also applied to sludge samples of different thicknesses, at 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 cm, to determine the drying rates with different sludge thicknesses. In the present study, sludge samples with a 25% solid content were heated for 1 h at 200°C. The results are shown in Fig. 6.

Fig. 6 shows that the drying rates of the sludge decrease from 1 cm of sludge thickness to 5 cm. Inversely, the drying rate increases from 5 cm to 10 cm sludge thicknesses. These results are directly related to the sludge surface area, as the drying process occurs starting from the sludge surface during conventional drying, as described above. Therefore, as the surface area of the sludge decreases from 1 cm sludge thickness to 5 cm sludge thickness, the drying rate decreases as well. And as the surface area of the sludge increases from the 5 cm to 10 cm sludge thicknesses, the drying rate also

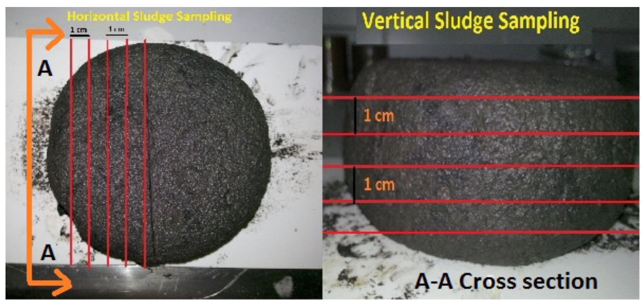

Fig. 3. Sludge sampling sections in a vertical and horizontal.

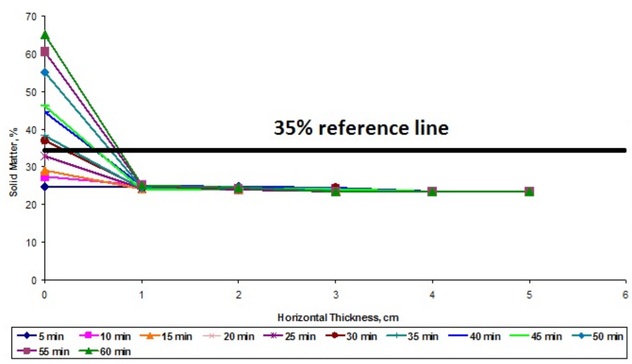

Fig. 4. Change of final solid contents on horizontal way after conventional drying process.

increases. These results reinforce the view that during the conventional drying process, drying by evaporation takes place mainly on the sludge surface.

Sludge dewatering tests were also carried out with the microwave irradiation process. Sludge samples weighing 100 g and with a depth of 5 cm were subjected to microwave irradiation at different power levels, which were 80, 240, 400, 640 and 800 W, for 12 different time periods, ranging from 5 to 60 min. The results are shown in Fig. 7.

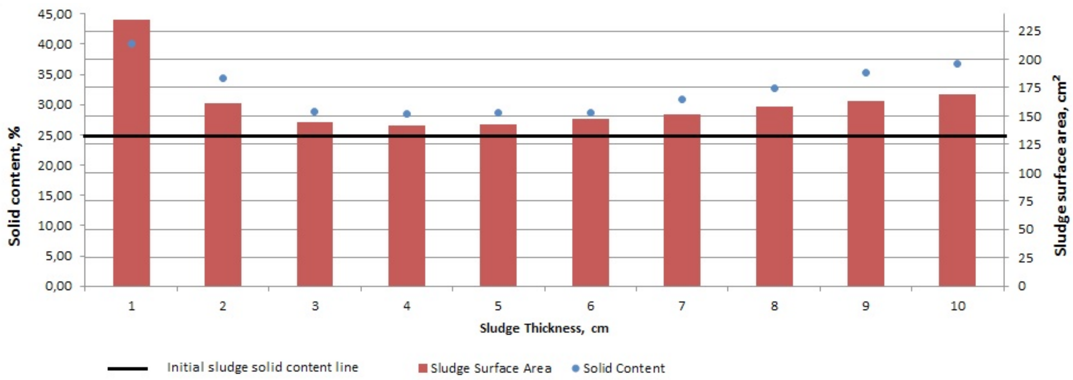

Fig. 5. Change of final solid contents on vertical way after conventional drying process.

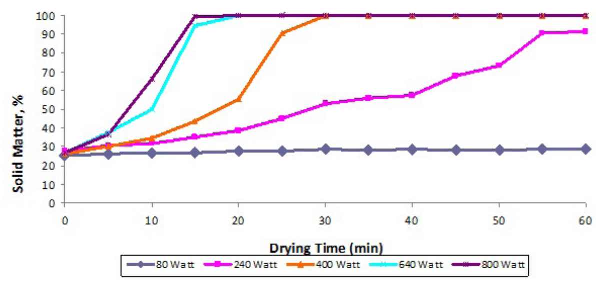

Fig. 6. Change of final solid contents of sludges with different thicknesses after conventional drying process (200°C; 60 min).

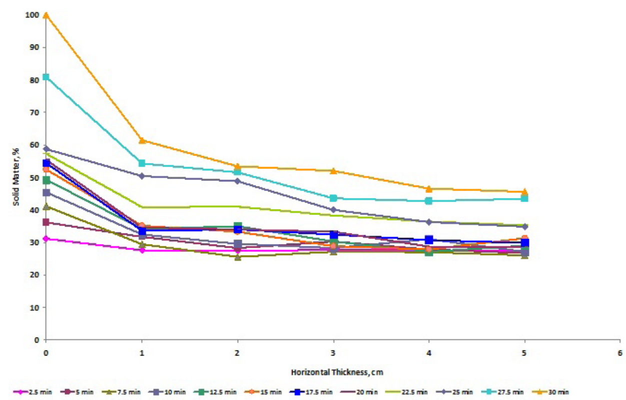

Fig. 7. Final solid contents of sludges after microwave drying process.

As shown in Fig. 7, 80 W microwave irradiation was applied to the sludge. However, there were no changes in the solid content of sludge. The dewatering process did not work in the low microwave irradiation power studies. When microwave irradiation power was increased to 240 W, the sludge solid content reached 91.8% at the end of the one-hour application time. When 400 W of microwave irradiation power was applied to the sludge, the sludge dried completely (100%) in 30 min. Similarly, 100% sludge drying efficiency was achieved when 640 and 800 W of microwave irradiation power was applied for 15 and 10 min, respectively.

According to these tests, the microwave irradiation process provided more effective results over a shorter period than the conventional drying process. As was the case with the conventional drying tests, drying rates in the horizontal and vertical directions were also examined during the microwave irradiation process to determine the gradient of drying. These tests were performed using 800 W microwave power for six different times, ranging from 5 to 30 min. Following each application, samples were taken from a horizontal or vertical depth of 1, 2, 3, 4 and 5 cm, and the solid content of the samples were calculated. The results are shown in Figs. 8 and 9.

When the results were analyzed, it was observed that microwave irradiation not only affected the surface of the sludge, but it also affected the interior of the sludge both horizontally and vertically. However, microwaves were more effective in drying the sludge in the vertical direction than in the horizontal direction. Using microwave irradiation, 500 g of sludge can completely be dewatered (100% solid content) in 43 min. According to Fig. 8, 50% dewatering efficiency in a horizontal direction was achieved in 30 min. Under the same conditions, sludge was dewatered 100% in the vertical direction. The rest of the sludge, which had not been dewatered, was dewatered in 13 min. These tests indicate that while microwaves effectively penetrated the sludge in both the

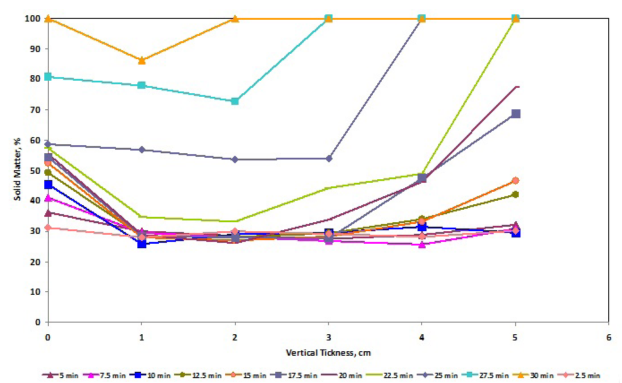

Fig. 8. Change of final solid contents on horizontal way after microwave drying process.

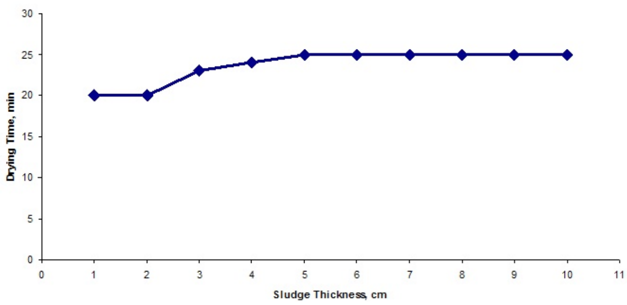

Fig. 9. Change of final solid contents on vertical way after microwave drying process.

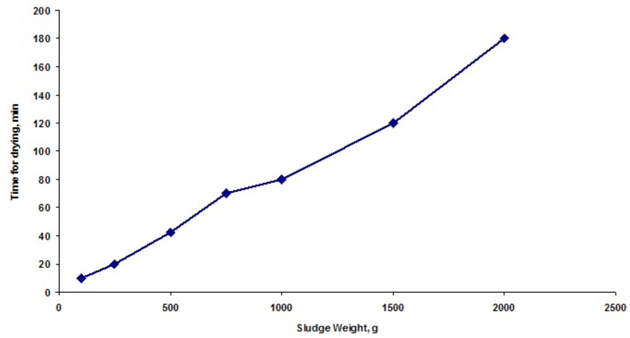

Fig. 10. Change of final solid contents of sludges (100% solid matter) with different thicknesses after microwave drying process.

vertical and horizontal directions, penetration was faster in the vertical direction.

Additional work was also performed to determine the effect of sludge thickness on dewatering using the microwave irradiation process. This study was carried out on 10 different sludge thicknesses, ranging from 1 to 10 cm. This study indicated that sludge thickness was not an effective limiting parameter for the microwave irradiation process. The results are shown in Fig. 10.

4. Cost analysis

Under Turkish regulations, sewage sludge must have a minimum 65% solid content to be stored in landfill areas [25]. And if sewage sludge is to be used as a soil improver, it must have a minimum solid content of 90% [26]. Taking these regulations into consideration, microwave irradiation tests were carried out to achieve these solid content ratios, and a cost analysis was then performed for both the conventional drying method and microwave irradiation. An initial test was performed by applying 800 W microwave irradiation on 100 g sludge to achieve a 65% solid content sludge, which took 9.5 min. A second test was performed with 100 g sludge to achieve a 90% solid content sludge with 800 W microwave irradiation, which took 13 min. Another study was carried out to determine the relationship between sludge quantity and drying time. The results are shared in Fig. 11.

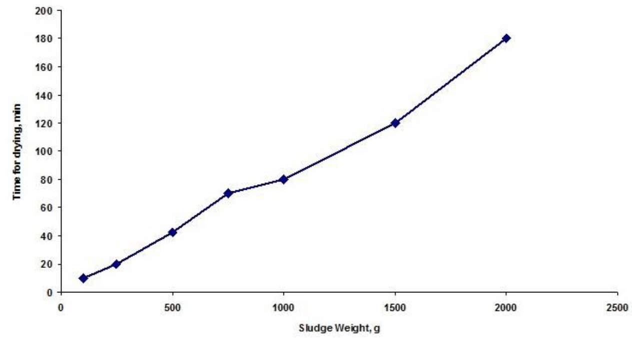

Fig. 11. Change of drying time of sludges (100% solid matter) according to sludge quantity.

From Fig. 11 it can be seen that there was a linear relationship between sludge quantity and drying time. In light of this information, a cost analysis of sludge drying was performed using conventional drying and microwave irradiation processes. As the highest solid content obtained during the conventional drying process was 45%, the comparison value between conventional and microwave dewatering process was considered to be 45%. For conventional drying and microwave irradiation, this ratio of solid content was obtained in 60 and 6 min, respectively, from a sludge with an initial solid content of 24%. For conventional drying and microwave irradiation, the energy required to obtain a 45% solid content rate was 1.2 kWh/100 g sludge and 0.08 kWh/100 g sludge, respectively. This study indicated that the microwave irradiation process is 15 times more economical and 10 times faster than the conventional drying process.

Further tests were performed to determine the costs associated with obtaining 35% and 90% solid contents using microwave irradiation. The cost analysis for 35% solid content was calculated as 0.053 kWh/100 g sludge, with energy consumption for 1 ton of sludge being approximately 530 kWh. A cost analysis for 90% was calculated to be approximately 1730 kWh/ton sludge.

5. Conclusion

In the dewatering test performed using the conventional drying method, 10 different temperatures were applied to the digested sewage sludge press cake for 12 different drying times. The applied temperatures were 110, 120, 130, 140, 150, 160, 170, 180, 190 and 200°C, while the drying times were 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55 and 60 min. Sludge sample weights and sludge thicknesses were selected as 100 g and 5 cm, respectively. For the conventional drying process, the highest solid matter ratio of 45.9% was obtained after a heating period of 1 hour at 200°C. For a 1 h heating period, the solid matter ratio ranged from 39.8% to 45.9% for different temperatures between 110–200°C.

Sludge dewatering tests were also performed using the microwave irradiation process. Sludge samples weighing 100 g and with a depth of 5 cm were subjected to microwave irradiation at power levels of 80, 240, 400, 640 and 800 W for 12 different times periods ranging from 5 to 60 min. An 80 W microwave irradiation was first applied to the sludge, but this did not change the solid content ratio of the sludge. The dewatering process did not work in the low microwave irradiation power studies. When the microwave irradiation power was increased to 240 W, sludge solid content reached 91.8% at the end of a 1 h application. When 400 W microwave irradiation power was applied to the sludge, it was completely dried in 30 min. Similarly, the sludge was 100% dry when 640 and 800 W microwave irradiation power was applied for 15 and 10 min, respectively. According to these tests, the microwave irradiation process provided more effective results in a shorter time than the conventional drying process. As with the conventional drying studies, drying rates in horizontal and vertical depths were examined to determine the gradient of drying during the microwave irradiation process. This study was performed using 800 W of microwave power for six different time periods, ranging from 5 to 30 min. Afterwards, a set of samples was taken from 1, 2, 3, 4 and 5 cm horizontal and vertical depth, and the solid content of these samples was calculated. When the results were analyzed, it was observed that microwave irradiation not only affected the surface of the sludge, but it also affected the interior of the sludge both horizontally and vertically. However, microwaves were more effective for drying the sludge in the vertical direction than in the horizontal direction. According to Fig. 11, 500 g of sludge can completely be dewatered in 43 min using microwave radiation, while in the horizontal direction, a dewatering efficiency of 50% is achieved in 30 min. Under the same conditions, sludge was dewatered 100% in a vertical direction. The rest of the sludge was dewatered in 13 min. This indicated that microwaves effectively penetrated the sludge in both the vertical and horizontal directions, although penetration was faster in the vertical direction.

An analysis of the study results revealed that microwave irradiation affected the sludge sample not only on the surface, but also on the inside, both horizontally and vertically. However, microwaves were more effective for drying the sludge vertically than horizontally. On the other hand, the drying process only occurred on the surface of the sludge during the conventional drying process.

Conventional drying and microwave irradiation processes were also applied to sludge samples with thicknesses of 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 cm, in order to determine the rates of drying for different sludge thickness. The obtained results reinforce the view that, during the conventional drying process, drying takes place mainly on the sludge surface by evaporation. On the other hand, results also showed that sludge thickness is not an effective parameter on the dewatering of the sludge with microwave irradiation.

This study indicated that the microwave irradiation process was 15 times more economical and 10 times faster than the conventional drying process.

Furthermore, these were carried out to determine the costs associated for obtaining 35% and 90% solid contents using microwave irradiation. The cost analysis for a 35% solid content was calculated to be 0.053 kWh/100 g sludge. When a cost analysis is required to calculate for 1 ton of sludge, the cost will be approximately 530 kWh/ton sludge. Similarly, the cost analysis for a 90% solid content was calculated to be approximately 0.173 kWh/100 g sludge, or 1730 kWh/ton sludge.

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