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Characteristics research on sewage sludge under thin-layered hot-press treatment

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ABSTRACT

Thin-layer thermal pressing is an innovative method that has the potential to further eliminate moisture content in liquid form from mechanical dewatering of sludge. Here, the dewatering performances of treated sludge are evaluated. The results demonstrate that the hot-press treatment is able to effectively reduce the moisture content of dewatered sludge with a thickness of less than 5 mm. A preliminary survey of the hot-press mechanisms for thin-layer sludge has also been conducted, by analysis of extracellular polymeric substance extracted from treated sludge. It can be deduced that hot pressing leads to cell damage in sludge by increased cell lysis.

Keywords: Hot-press; Dewatered sludge; EPS; Cell lysis

1. Introduction

Recently, there has been an exponential increase in excessive sludge, especially from domestic wastewater treatment plants (WWTPs) [1]. This increase has caught the attention of the global community and has driven research to reduce sludge output volume prior to disposal and reuse. There is, however, currently a shortage of usable technologies to reduce sludge output that follow current regulations and meet demands for subsequent disposal. Past work on sludge has yielded plentiful analyses at both the micro- and macro-levels, which have then been used toward structural or functional applications. Importantly, this information has also improved the general understanding of the physiological characteristics and technological parameters necessary to more efficiently handle sludge. Despite these advances, however, there is still a great need for more qualitative and quantitative parameters to improve sludge treatment efficiency.

Sludge exhibits complex organics [2,3], which are regarded as its major source of bioenergy. Activated sludge carries large amounts of moisture, ranging from 96 to 99%. Traditional dewatering methods, such as belt filtering and centrifugal dewatering, can only decrease the sludge moisture content to 78–85% [4,5]. Several methods have been applied to further reduce the moisture content of mechanically dewatered sludge [6]. For instance, solar drying [7,8] and biodrying technology may significantly decrease moisture content to 30–35%, but both take an average duration of 20–25 d. The foam mat drying process [9] has also been used and features both a lower drying temperature and shorter drying time.

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Although methods are now available, it is undeniable that mechanical dewatering of sludge with high moisture content is an energy-intensive process, due to the latent heat of water vaporization. In order to improve the solid–liquid separation efficiency and further reduce sludge water content, deep dewatering technology has been introduced to treat dewatered sewage sludge. This technology is different from other drying technologies in that sludge moisture can be removed in liquid form. Deep dewatering technologies include electro-dewatering, reagent dehydration [10,11], and the thermal press method [12,13]. Although electro-dewatering can improve dewatering efficiency, its major disadvantages include easy degradation and erosion of filter cloth and drum ring [14], as well as electrode. Liquefied dimethyl ether (DME) has been used in the reagent dehydration method as a water-extraction agent for sludge with high moisture content, but the technology is limited by the high amount of DME consumed [15]. Lime is also an ordinary reagent used in reagent dewatering, but the process limits the later disposal of the sludge [16]. By contrast, the hot-press method exerts heat and pressure on sludge to dewater it. It is not a simple combination of mechanical dewatering and drying as in the contrary system, which combines centrifugal dewatering with direct flash drying technology [17]. As an effective deep dewatering technology, the simultaneous exertion of heat and pressure can expel water from the sludge cake in liquid form during the hot-press process.

This study seeks to investigate the characteristics and component difference of sludge both before and after thermal pressing. The results offer a more comprehensive assessment of the coupled influence of heat and pressure on mechanically dewatered sludge.

2. Materials, equipment, and methods

2.1. Materials

The belt filter dewatered sludge was taken from a WWTP in the Dalian city and its wet-basis water content and organic matter content are 87.73 and 63.11%, respectively.

2.2. Hot-press equipment

Thin-layer hot pressing is a novel process to remove water in liquid state from mechanically dewatered sludge. A schematic diagram of this self-made device is shown in Fig. 1.

The process of hot pressing mechanically dewatered sludge is described below.

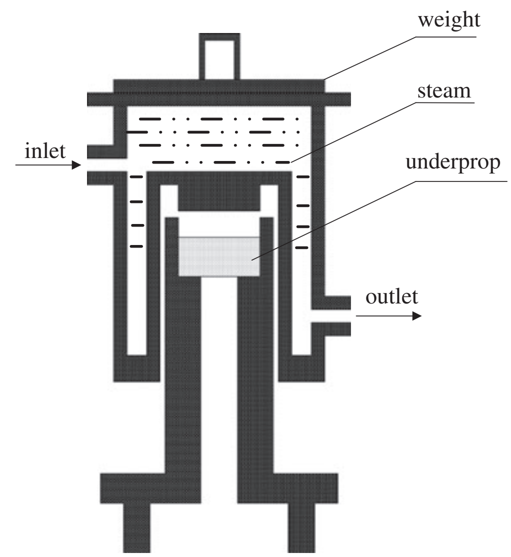

Fig. 1. Schematic representation of laboratory scale of the device.

First, dewatered sludge with a fixed thickness and uniform mass is put on a rigid, porous metal support, and a stainless steel sieve with 300 mesh is used as a filter. The press surface is adjusted by different weights and is also used as a heating surface. The temperature of the heating surface can be regulated by internal, saturated steam of different pressures. The diameter of the heated surface is 50 mm. The water content of the sludge at different hot-press times can then be obtained.

To some extent, the hot-press method has characteristics similar to those of the mechanical thermal expression (MTE) method. Firstly, a temperature higher than room temperature can reduce the viscosity and surface tension of moisture, as well as the water holding capacity of the pore structure. This transforms water into a porous gel in its mobilized state. Secondly, pressure can easily overcome the electrostatic forces between water and other particles, by destroying cellular structure [18].

Despite these commonalities, however, the hot-press method is significantly different from MTE, namely:

(a) In the hot-press method, the water in the sludge surface quickly evaporates as soon as it approaches the heat surface. This forms a steam front close to the heated surface.
(b) In the hot-press method, the sludge layer is thin enough for sufficient heat and mass transfer. This results in the destruction of the

cellular structure of the sludge and the release of its extracellular polymeric substance (EPS) and bound water.

(c) The initial water content of the sludge used in the hot-press method is 88%, which is lower than the initial water content of the sludge used in MTE methods. Therefore, only the compression, rather than the additional filtration, phase exists in the thin-film hot-press process.

2.3. Experimental devices used for the characterization of sludge

2.3.1. Magnetic resonance imaging analysis

The sludge NMR analysis was conducted using a Varian NMR imager (magnetic resonance imaging, (MRI)). The sludge sample was placed in a 2-ml Agilent clear glass vial, before the MRI analysis was begun.

2.3.2. Particle size analysis

Sludge particle size distribution was analyzed using a centrifugal particle size analyzer (SA-CP3, Shimadzu) by mixed sedimentation mode.

2.4. EPS extraction and composition analysis

Since protein, polysaccharide, and nucleic acid are the three main components of EPS. In this study, proteins and polysaccharides were analyzed using the Coomassie brilliant blue method [19] and the Anthrone colorimetry, respectively [20]. The nucleic acid content of the sludge was quantified using the UV absorption peak at 260 nm.

The water content of the mechanically dewatered sludge was 87.73%, while that of the hot-pressed sludge was 67.73%. Deionized water was added to both samples to obtain a suspension liquid with the same water content of 93%. The high-speed centrifugation method was then used to extract the EPS. Finally, the proteins, polysaccharides, and nucleic acids were analyzed. Organic matter accounted for 66.68% of dried sludge.

It should be noted that the EPS can be extracted using both physical methods and chemical methods. The physical extraction methods include high-speed centrifugation, ultrasonic, and heat extraction. And the chemical extraction methods include NaOH, EDTA, the cation exchange resin extraction method, and glutaraldehyde extraction. Since chemical reagents have the potential to interfere with EPS composition and content, physical methods for EPS extraction have been used [21]. Previous research has shown that of the three listed physical extraction methods, high-speed centrifugation is the most gentle, since it strips the polymer from the cell surface, resulting in less cellular damage [22]. The high-speed centrifugation method was therefore chosen for EPS extraction.

The EPS in the sludge can be further divided into loosely bound EPS (LB-EPS) and tightly bound EPS (TB-EPS). These two types are obtained by differential centrifugation speeds. The fraction of LB-EPS and TB-EPS can be centrifuged with rotational speeds of 7,400 and 15,000 rpm, respectively. The final precipitation layer was pellet. In this paper, a high-speed centrifuge (Avanti J-30I, Beckman Coulter, America) with a centrifugal rotational speed of 16,000 rpm and a centrifugal time of 40 min was chosen for EPS extraction. Thus, the final product may contain both the LB-EPS and TB-EPS.

The flowchart for EPS extraction and analysis is shown below in Fig. 2.

3. Results and discussion

3.1. Water content of thermally pressed sludge

Moisture content is the most meaningful parameter in evaluating the effectiveness of water removal during the hot-press process. These results are shown in Fig. 3.

As shown in Fig. 3, it is obvious that the dominant dewatering stage is in the first minute of the thin-layer hot process. In this stage, the maximum removal percentage occurs and the cake is compressed into a compact form (mass ratio decreases to 55% of the initial mass). The water content decreased slowly after this stage, despite further continuous pressure and heat. In the subsequent four minutes, the mass of the cake decreased from 55 to 40% of the initial mass. This small additional decrease was due to further, slow water removal, since the heat and mass transfer at this stage was similar to that in the drying process.

It should be pointed out that although the temperature of the saturated steam used as a heating medium was 135℃, the temperature of the heated surface

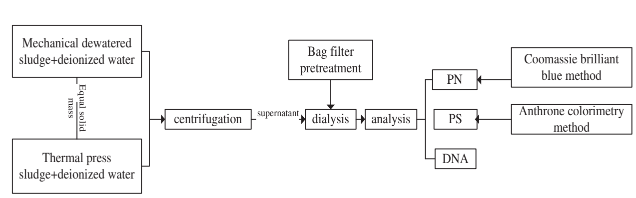

Fig. 2. Flowchart for EPS extraction and analysis.

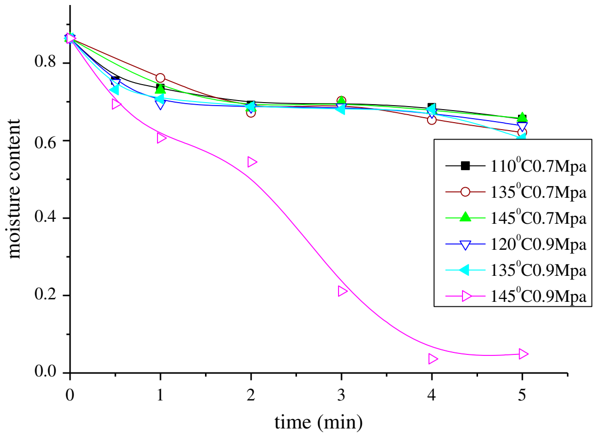

Fig. 3. Moisture content of dewatered sludge after thermal press.

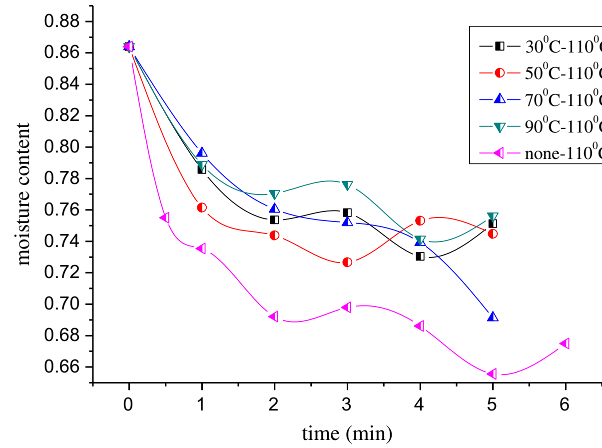

Fig. 4. Moisture content of pretreated sludge after thermal press treatment.

was only approximately 100℃, due to heat resistance and conductive heat loss.

Critical factors of the hot-press process include not only temperature and pressure, but also the thickness of the sludge. However, because sludge is a spongy, elastic gel, with a fixed thickness under constant pressure, experimental results indicated that dewatered sludge of different thicknesses was easily squeezed out under the pressure. Therefore, only a fixed amount of sludge in an effective area was treated. Since the parameter of thickness could not be considered in this paper, 2-mm-thick sludge layers were chosen as the sole initial thickness to study the influence of pressure and temperature on the hot-press of sludge.

As shown in Fig. 3, the curves for moisture content change over time indicated that the water content was different in just the first minute. The influence of residence time on the hot-press process then became weaker one minute later. It can also be found that the processing temperature had no obvious effect on sludge compression. Consequently, these results demonstrate that when a coupled heat and pressure process occurs within a short period of time, as with hot-press technology, the results really are different from those of drying.

The influence of thermal pretreatment on the hot-press process of sludge was also studied. Briefly, the pretreatment method involves placing the sealed sludge in water baths of different temperatures for 20 min. The conditions of 0.7 MPa and 110℃ were applied in the hot-press experiments for pretreated sludge. The moisture contents are shown in Fig. 4.

As shown in Fig. 4, thermal pretreatment has a negative influence on the hot-press treatment of sludge, in contrast to non-thermal pretreated sludge. This may be due to pores between the sludge granules disappearing and impeding the migration of moisture as mechanically dewatered sludge is being thermally pretreated. The other explanation is that thermal pretreatment may destroy the cellular structure of sludge.

During the hot-press process, water is expelled from the sludge structure via several mechanisms, including:

(a) Water expansion, due to a decrease in water density with increasing temperature.
(b) Partial evaporation of water; forcing water out of the sludge structure.
(c) Possible collapse of the sludge structure.

Since the operation temperature is not sufficiently high for much expansion of water in sludge, partial evaporation occurs during the treatment process. This not only affects water transfer, but also increases the temperature of the treated sludge. The primary effect of the combined heat and pressure is on the collapse of the sludge structure, which can be explained as follows.

Dewatered sludge has a cross-linked network of colloidal structures. With the bridging mechanism of cationic polyacrylamides (c-PAM), sludge becomes a polymer-induced flocculation with EPS structure [23].

Flemming [24] thought the two types of binding mechanisms between water molecules and the EPS-structure—electrostatic interactions and hydrogen bonds—should be considered. Within electrostatic interactions, the carboxylate and hydroxyl groups are expected to play the most important roles among the functional groups present in EPS. The hydrogen bonds are mainly active between the EPS hydroxyl groups (particularly frequent in polysaccharides) and water

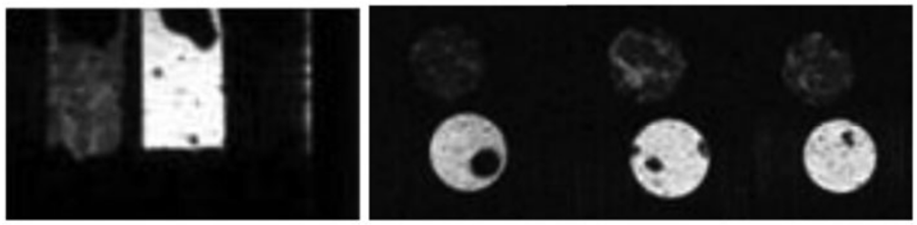

Fig. 5. Water distribution of sludge before and after thermal press.

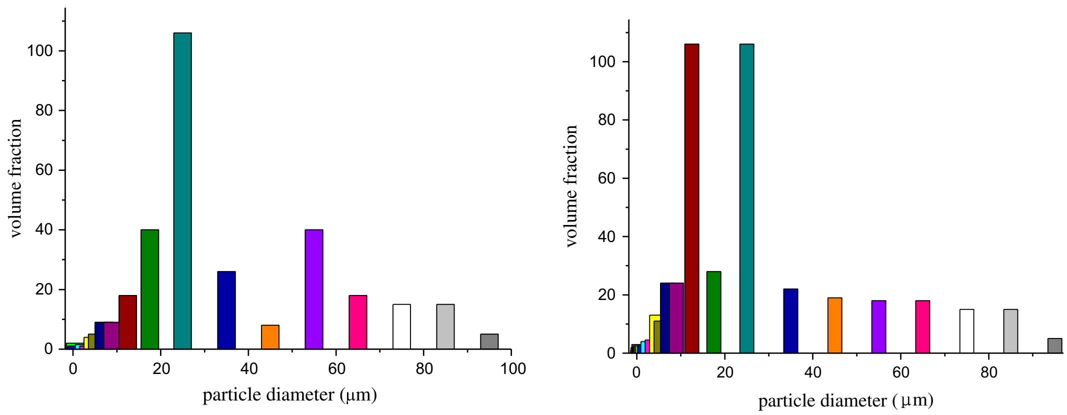

Fig. 6. Particle size distribution of dewatered sludge and thermal press sludge.

molecules. The individual binding force of any type of weak interaction is very small, compared to a covalent C–C bond. However, the large number of functional groups within a macromolecule may result in an overall binding energy that is well within the range of several covalent C–C bonds.

It is difficult to destroy the structure using only a conventional mechanical press due to the high overall binding energy of a large quantity of functional groups in the EPS. In the hot-press process for thin-layer sludge, the coupling of heat and pressure creates an effect that may decrease binding energy by destroying the electrostatic interactions of the EPS structure. This can lead to the destruction of the hydrogen bonds in the EPS structure and the release of water in the network structure. Thus, the thin-layer hot-press occurs over a short time and involves two processes. Initially, the rate of structural collapse due to pressure and heat transfer equals the flow rate of water. The three-dimensional structure is turned into sheets, as vertical contraction indicates that the EPS structure has been destroyed in this direction. Next, there are no further deformation yields, due to the high resistance of the solid–liquid network in sludge. The absence of further deformation indicates the end of the hot-press process.

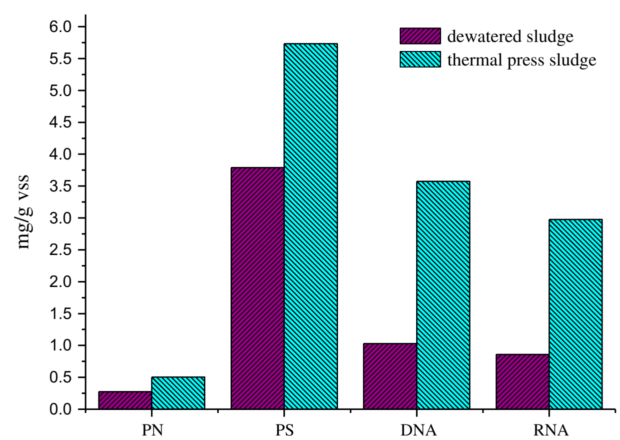

Fig. 7. Comparisons of typical compositions in sludge before and after thermal press.

3.2. Characteristics of thermal press sludge

3.2.1. Results of MRI analysis

The comparison of sludge before and after hot-press treatment is shown in Fig. 5.

As shown in Fig. 5, the image for mechanically dewatered sludge was very bright, indicating a large amount of water present in the sludge. The

Table 1
Typical composition and key indicators in sludge before and after hot pressing

Sludge type	PN (mg/gVSS)	PS (mg/gVSS)	DNA (mg/gVSS)	RNA (mg/gVSS)	(DNA + RNA)/PN	(DNA + RNA)/(PN + PS)
Mechanically dewatered sludge	0.27	3.79	1.03	0.86	6.91	0.47
Hot-pressed sludge	0.50	5.73	3.57	2.98	12.99	1.05

representative image of hot-pressed sludge was gray, indicating a lower free moisture content. This demonstrates that after hot pressing, a significant amount of moisture had been removed from the sludge. This resulted in a decrease in the water content, from 87.73 to 67.73%, as mentioned above.

3.2.2. Results of particle size distribution

The particle size distributions of the two sludge samples are shown in Fig. 6.

As shown is Fig. 6, after the sludge was treated by the hot-press, the average particle size decreased and the specific surface area increased. This is mainly due to the disintegration of microbial floc and the destruction of microbial cells. Particle size distribution before and after the hot-press of sludge therefore also indirectly indicates cell lysis during the treatment process.

3.3. Characteristics of EPS in sludge before and after thermal pressing

A typical activated sludge floc mainly contains filamentous bacteria as a cytoskeleton and suspended material, including micelles of bacteria and other micro-organisms [25]. EPSs are high-molecular weight compounds secreted by microorganisms [26]. In the sludge floc, EPS can adsorb organic compounds to form a porous polymer mesh structure by cross-linking with floc in microbial cells [27]. Results in this paper indicate that the main components in EPS were proteins and polysaccharides, which accounted for a combined 70–80% of the total mass of EPS. The other components were humic acid, uronic acid, and nucleic acids. Therefore, this article defined the total protein and polysaccharide content as the EPS value. Since nucleic acids were mainly present in microbial cells, the only source for nucleic acids in EPS was an autolytic release of intracellular substances. If the hot-press treatment was causing cellular damage in sludge, the content of nucleic acids would increase, via the release of intracellular substances. Two parameters: ratio of (nucleic acids)/protein and ratio of (nucleic acids)/(protein + polysaccharide) are adopted as indicators for cell lysis. Thus, these two indicators were used to assess the degree of cell damage. The experimental results are shown in Fig. 7.

Typical compositions and key indicators of the two ratios are shown in Table 1.

From Table 1, it can be seen that the concentration of nucleic acids in the EPS extracted from hot-pressed sludge was higher than that from mechanically dewatered sludge. The values of the two indicators also reached a twofold increase, which can be explained by the leakage of cellular inclusions [28]. Therefore, after the hot-press treatment of dewatered sludge, dissolution and cell rupture had occurred. As a result, the contents of nucleic acid increased significantly than that of proteins and polysaccharides. This strongly indicates that cell lysis was occurring during the hot-press treatment of sludge.

Cellular damage may release some bound water trapped within cells. Under pressure, the bound water could then be separated in liquid form from sludge. This could be seen as a mechanism of the thermal press deep dewatering treatment for dewatered sludge.

4. Conclusion

The thermal press treatment of dewatered sludge at different pressures and temperatures was studied and the following conclusions can be drawn.

(1) With the increase in temperature and pressure, the moisture content of treated sludge gradually decreased.
(2) After the thermal press treatment of sludge, particle size decreased and no water distribution could be seen in the resulting MRI image.
(3) Through cell lysis, thermal press treatment significantly increased nucleic acid concentration in the EPS extracted from sludge. The released intracellularly bound water was then able to be separated in liquid form. This process was identified as the mechanism of thermal press dewatering.

Acknowledgment

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