Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2023.29560

301 (2023) 173–180
July

Hybrid conditioning methods for dewatering stabilised sewage sludge

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Received 22 February 2023; Accepted 7 April 2023

ABSTRACT

The search for methods and ways to intensify the fermentation process and, at the same time, the dehydration process, tends to move towards the use of various physical and chemical methods, as well as combinations of standalone methods. Based on research it was stated that combined methods (UD field + temperature) prior to the fermentation process contribute to a decrease the filtration capacity of the sludge (increase in capillary suction time and filtration resistance). In each case, the indicators in question were higher in relation to the values of sludge conditioned by standalone methods. The use of combined methods after the stabilisation process improved the filtration capacity. A reduction in CSK values, final hydration and resistance was observed with each day of the fermentation process. During the last days of stabilisation, the values of the sludge modified with combined methods were similar to those of the non-conditioned sludge. Hydration values were lowest on the last day of fermentation using an amplitude of 80% and a temperature of 80°C. This relationship was also observed by analysing the structure of the sludge.

Keywords: Sewage sludge; Conditioning; Fermentation; Dewatering

1. Introduction

The use of the ultrasonic field in sludge conditioning involves significant electricity consumption [1,2]. Extensive research in this area has been carried out for many years by Bień et al. [3–6]. According to the above research, the effect of conditioning agents is determined by the type of sludge and its hydration. Ultrasound has a more beneficial effect on sludge with higher hydration, as opposed to sludge characterised by low initial hydration. The application of the ultrasonic field first impacts the breakdown of the sludge structure (dispersion) and then coagulation, contributing to the formation of larger sludge flocs [7,8].

A series of studies and publications by Bien et al. [9] using the ultrasonic field aimed to apply it to the fermentation process. Intensification of the hydrolysis process affects the processes that are as important in sludge management as compaction and dewatering. Also, Zielewicz [10,11] in her studies showed that the ultrasonic field has a positive effect on the biological decomposition of organic parts and indirectly on the final stage of sludge dewatering.

The coagulative action of ultrasonic waves plays an important role in liquid systems, changing the values of specific resistance, final hydration, and accelerating the gravitational thickening process. The coagulation and dispersion effects depend on particle size, sound frequency, as well as on the properties of the studied systems such as viscosity of the fluid, presence of electrolytes, nature of the constituents, macrostructure of the medium and temperature [12–14].

Research by Na et al. [15] shows that the effectiveness of ultrasound depends on three factors: the input power delivered, the volume of the sample and the duration of operation. The efficiency of the sonification process is strongly affected by the frequency of vibration of the ultrasonic

Presented at the 15th Scientific Conference on Micropollutants in the Human Environment, 14–16 September 2022, Częstochowa, Poland

field, as well as the temperature rise induced by the ultrasounds [16–18].

An analysis of the results of Pilla et al. [19] showed that the ultrasonic field not only improves dewatering efficiency, but also has a significant effect on sludge biodegradation during anaerobic stabilisation. According to various sources, ultrasonic conditioning of sludge can have both positive and negative effects on dewatering [20–22]. The dispersion of the sludge floc formed under the impact of the UD field can adversely affect the parameters characterising dewatering efficiency [23,24]. Fragmented flocs can impair the filtration and sludge process, having a direct impact on dewatering [25–27].

Thermal conditioning methods result in changes to the properties and structure of the sludge caused by the provision or withdrawal of thermal energy [28]. Thermal conditioning involves heating the sludge for 30–90 min at a temperature of 60°C–150°C at a pressure of 0.5–2.0 MPa. Denaturation of proteins and a change in structure occurs in the sludge as a result of heating. The result of the changes is a significant reduction in specific resistance and improved sludge dewatering.

In order to improve the stabilisation and dewatering process, many studies of sludge pre-treatment have been carried out using thermal, mechanical and chemical methods. Carrère et al. [29,30] noted that the use of sonification in pre-treatment increased the rate of hydrolysis, but had no impact on dry matter reduction, in contrast to thermal conditioning, where improvements in hydrolysis and dry matter reduction were observed. A large amount of energy is consumed in thermal conditioning, some of which can be recovered from biogas production after the stabilisation process [31–33].

Studies to date have shown that a combination of the above methods (ultrasonic field and thermal conditioning) is more effective when it comes to the use of standalone conditioning methods [34,35]. Combining disintegration methods intensifies the dispersion of sludge flocs, which directly affects the stabilisation process as well as the filtration capacity of the sludge. Any mechanical method affecting the initial dispersion of the sludge floc intensifies the stabilisation process when a subsequent conditioning method is used. It has been observed that the use of combined methods in the conditioning of stabilised sludge results in increased biogas and methane production [36,37]. In the literature, it is also possible to see research results on thermal assisted stabilisation [38,39]. Support methods include combined (hybrid) methods, for example, by treating the test sludge with polyelectrolytes followed by ultrasound or combining UD field conditioning with thermal conditioning [40,41].

The aim of the conducted research was to determine the impact of hybrid conditioning methods on the efficiency of dewatering stabilized sewage sludge. The innovativeness of the research carried out consisted in a comprehensive and wide range (the use of various ranges of ultrasonic wave intensity and temperature, combining them with the stabilization process along with the study of the structure and determination of parameters characterizing the effectiveness of dewatering (capillary suction time, hydration, specific resistance, compaction efficiency). The entire research was carried out using the latest apparatus.

2. Substrate and methodology

Excessive sewage sludge from a mechanical and biological treatment plant with capacity of approximately 90.000 m^3/d was used in the study. It was characterised by the following parameters: dry mass 11.0 ± 2.8 g/dm^3, dry organic mass 7.3 ± 2.8 g/dm^3, capillary suction time 24 ± 5 s, initial hydration 98.6%, final hydration 84.6%, sludge specific resistance 2.96×10^{12} m/kg.

The surplus sludge was subjected to anaerobic fermentation after pre-conditioning (ultrasonic field, thermal or a combination of methods) and the addition of inoculation (10% fermented sludge).

The time and wavelength of the ultrasonic field used for conditioning prior to the stabilisation process were selected on the basis of preliminary research and available literature. The over-sounding process was carried out under static conditions for five test cycles for selected values of vibration amplitude (ultrasonic wave intensity): 7.88 μm (1.6 W/cm^2); 15.77 μm (2.2 W/cm^2); 23.65 μm (2.7 W/cm^2); 31.54 μm (3.2 W/cm^2) and 39.42 μm (3.8 W/cm^2). The sonification time was adopted from the range of 0 to 600 s. For further tests of the stabilised sludge, a UD wave intensity of 3.2 W/cm^2 and sonification times of 300 and 600 s were selected. The overblowing process parameters selected this way were used to condition the sludge prior to the stabilisation process. A Sonics VCX-1500 ultrasonic processor with a maximum output power of 1500 W was used for the sludge sonification process. The frequency of the ultrasonic field oscillation of the generator was 20 kHz and the maximum wavelength was 39.42 μm with an amplitude of 100%. The volume of over-sounded samples for sludge fermented in flasks, was 0.5 dm^3.

Thermal conditioning of the excess sludge was carried out using an ELPIN+ shaker water bath. Sludge samples of 0.5 dm^3 placed in laboratory flasks were tested and heated at 50°C, 60°C, 70°C, 80°C and 90°C. The thermal conditioning time of the sludge ranged from 10 to 180 min. Thermally pre-conditioned sludge subjected to fermentation, was subjected to temperatures of 60°C, 70°C and 80°C, heating the samples for 90 min.

Based on the results obtained for UD field disintegration of the sludge and thermal conditioning, the aforementioned methods were combined to carry out the disintegration process using a hybrid method in an appropriate configuration, that is, UD + thermal method, with optimum process conditions for standalone methods. UD field conditioning was conducted at a wavelength of 3.2 W/cm^2 and a supersonic time of 300 s. Thermal conditioning was carried out in a water bath for 90 min at temperatures of 60°C and 80°C.

Capillary suction time (CSK) was measured based on the method of Baskerville and Galle – measuring the transit time of the frontal boundary layer of the filtrate as a result of the suction forces of a tissue paper used – Whatman 17. To determine the sedimentation capacity of the sludge, gravity compaction was carried out at time intervals of 5, 10, 15, 20, 25, 30, 45, 60, 90, and 120 min.

Sludge dewatering was carried out on a vacuum filter. Using a vacuum filtration process, the final hydration and specific resistance of the sludge were determined.

In order to determine the effect of stabilisation on the efficiency of the thickening and dewatering process, fermentation of suitably pre-treated sludge samples was carried out. The process was carried out in glass flasks that served as models for the fermentation chambers. The prepared sludge samples were placed in 10 laboratory flasks with the volume of $V = 0.5$ dm^3. To maintain a fixed process temperature (mesophilic conditions), the flasks were placed in a laboratory incubator at 37°C for 10 d. To prevent air from entering, the flasks were plugged with a stopper fitted with a manometer tube to allow the produced biogas to escape. The contents of the flasks were stirred, using magnetic stirrers, thus removing the dross that formed and avoiding an overload of impurities. On each day of the process, indications were carried out after one of the flasks was removed from the incubator. Observations of the sludge structure were carried out using an Olympus BX 41 optical microscope. Images of the structure were taken with a camera attached to a microscope at 100 times magnification.

3. Results and discussion

3.1. Impact of conditioning methods on the degree of dry matter reduction after the fermentation process

The positive effect of sludge pre-conditioning prior to the fermentation process is evidenced by the results of the study shown in Table 1. The degree of dry matter reduction of fermented sludge pre-treated by different methods was higher in relation to non-fermented sludge. For thermally conditioned sludge, the dry matter reduction rate was 21% (temperature 60°C) and 32% (temperature 80°C). For sludge pre-exposed to an ultrasonic field, the dry matter content was reduced to 24%. The highest degree of reduction of the parameter in question was recorded for sludge conditioned by the combined method – UD + temperature 80°C, where the degree of dry matter reduction was 35%.

The noticeable, significant changes in the degree of dry matter reduction of the sludge tested confirm the existence of grounds for using sludge preconditioning prior to the anaerobic stabilisation process. There are some difficulties in defining the boundaries between disintegration methods and classical sludge conditioning methods. An example of this is ultrasonic wave conditioning, which, on the one hand, can be a method of conditioning sludge prior to thickening and dewatering, while on the other hand, it can be regarded as one method of disintegrating sludge leading to an accelerated hydrolysis process. Sewage sludge is a a place of storage of organic matter, which accounts for about 70% of dry matter. This content is not subject to biological decomposition, and is largely unavailable in stabilisation processes.

Based on literature data and exploratory (preliminary) studies, a positive effect of the initial modification on the fermentation process was noted. The changes in the degree of sludge fermentation thus affect sludge dewatering processes.

3.2. Susceptibility to dewatering of pre-conditioned fermented sludge by hybrid methods

In order to determine the effect of hybrid conditioning and the fermentation process on the filtration capacity of sludge, the values of capillary suction time, thickening, final hydration and specific resistance were determined.

Thermal disintegration of sewage sludge, disintegration with an ultrasonic field, as well as a combination of the above methods, that is, hybrid conditioning, extends the capillary suction time. Conditioning with a temperature of 60°C resulted in a twofold increase in the indicator in question with respect to non-conditioned sludge (the value for non-conditioned sludge was 52 s, while for conditioned sludge it was 118 s) (Fig. 1). As a result of the use of disintegration with the UD field, the CSK value increased to 1,331 s. Also when combined methods were used (UD field + temperature), the capillary suction time value was high and amounted to 1,133 s.

The stabilisation of sewage sludge improved its filtration capacity – a decrease in the capillary suction time was observed in the subsequent days of fermentation. For unconditioned and conditioned sludge at 60°C, similar CSK values were observed in 5 consecutive days of the process. A significant improvement in filtration capacity was noted for sludge conditioned with the UD field and with the hybrid method, where the value of the capillary suction time was reduced in the subsequent days of the fermentation process. The value of the discussed indicator decreased over the subsequent days of the fermentation process. On the 6th and subsequent stabilisation days, the capillary suction time values were the same as for unconditioned sludge. A similar relationship was noted for the sludge conditioned at 60°C. A clear downward trend was noted for sludge conditioned by the hybrid method, for which the values of the capillary suction time in the following days of fermentation decreased, reaching the final value of 92 s on the 10th day of the process, comparable to that for unconditioned sludge.

Similar relationships were exhibited by sludge conditioned at 80°C. For the analysed sludge, the CSK values were similar to those of the non-conditioned sludge (Fig. 2). The capillary suction time of sludge conditioned with the UD field, as well as using the combined methods, was systematically reduced in the subsequent days of fermentation. The values on day 10 were 80 s (UD) and 142 s (combined method), respectively.

Table 1
Dry matter reduction rate of conditioned sludge subjected to fermentation

Degree of dry matter reduction, %					
Non-conditioned sludge	Thermal conditioning 60°C	Thermal conditioning 80°C	Ultrasonic conditioning	Hybrid conditioning (ultrasound field + 60°C)	Hybrid conditioning (ultrasound field + 80°C)
20	21	32	24	25	35

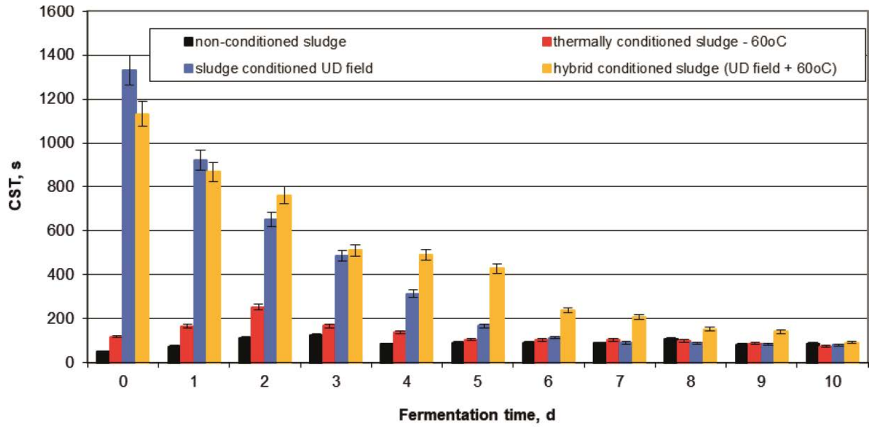

Fig. 1. The capillary suction time of sewage sludge pre-conditioned thermally with ultrasonic field and hybrid method (UD + 60°C).

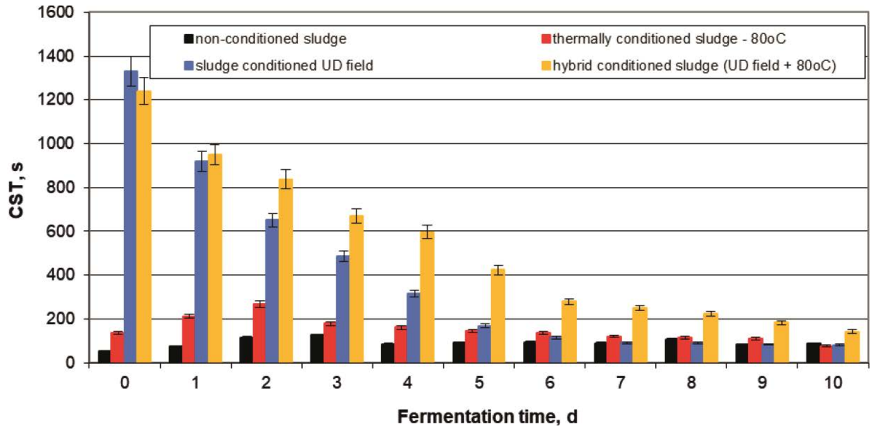

Fig. 2. The capillary suction time of sewage sludge pre-conditioned thermally with ultrasonic field and hybrid method (UD + 80°C).

The excess sludge subjected to tests was difficult to sediment. The application of one of the conditioning methods slightly improved its sedimentation capacity. Pre-conditioned sludge subjected to the stabilisation process has significantly increased the thickening capacity. Also, the unconditioned sludge subjected to stabilisation compacted better. The greatest thickening effects were observed for sludge conditioned by the combined methods (Figs. 3 and 4). After the third day of stabilisation, a clear improvement in thickening was noted, obtaining volume values of 31 mL on the last day of fermentation – a 69% degree of sludge volume reduction (field UD + 60°C and field UD + 80°C). Also, the application of ultrasonic field energy in sludge conditioning, increased the thickening effect. In this case, the sludge sedimented most intensively after the third day, maintaining a constant volume value until the last day of fermentation. Of the two temperatures tested (60°C and 80°C), the sludge compacted better when modified with higher temperatures. On the 10th day of the process, the volume of sludge conditioned at 60°C was 66 mL (34% volume reduction), while for 80°C its volume was 33 mL (67% volume reduction).

The use of combined methods in the initial preparation of sewage sludge resulted in an increase in the value of the final hydration of sewage sludge. The initial hydration value of the unconditioned sludge was 84.8%. As a result of conditioning by using a combination of UD field and temperature, it increased to 98.5% (UD 3.2 W/cm^2 + 60°C) and 98.4% (UD 3.2 W/cm^2 + 80°C) (Fig. 5a and b). Stabilisation of the hybrid-modified sludge resulted in lower hydration values. With each day of fermentation, a decrease in the value of the discussed parameter was observed in the case of two methods of preparation. The dehydration effect was more noticeable when pre-treated with an ultrasonic field and temperature of 80°C. On the 10th day of the process, the final hydration value for this conditioning method was 89.6% (Fig. 5b).

Modification of the sludge conditioning methods also had an impact on the specific resistance values of the sludge. As a result of the application of the ultrasonic field and a temperature of 60°C, the resistance value increased for the unconditioned sludge to 9.96 × 10^{12} m/kg (Fig. 6a). An increase in resistance values of 11.1 × 10^{12} m/kg was also recorded using the UD field and a temperature of 80°C (Fig. 6b). Subjecting pre-conditioned sludge to the fermentation process reduced the values of this parameter. With both ultrasound and temperatures of 60°C and 80°C applied, the sludge resistance values decreased with each day of the fermentation process. When applying the temperature of 60°C in the combined method on the 3rd day of stabilisation, sludge resistance values lower than those of unconditioned sludge

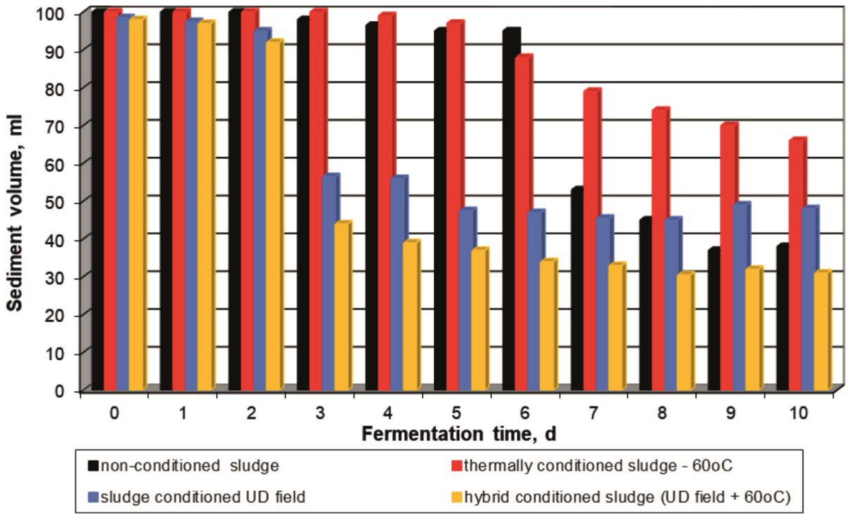

Fig. 3. Thickening of sewage sludge after 30 min of sedimentation, thermally pre-conditioned with ultrasonic field and hybrid method (UD field + 60°C).

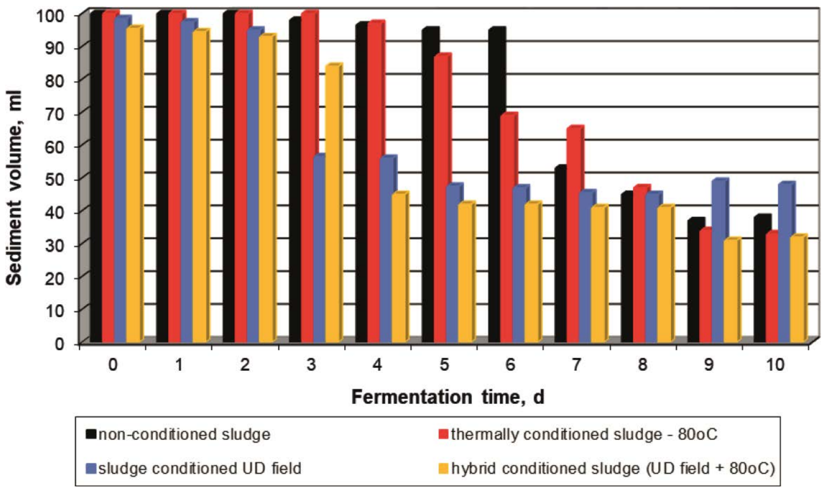

Fig. 4. Thickening of sewage sludge after 30 min of sedimentation, thermally pre-conditioned with ultrasonic field and hybrid method (UD field + 80°C).

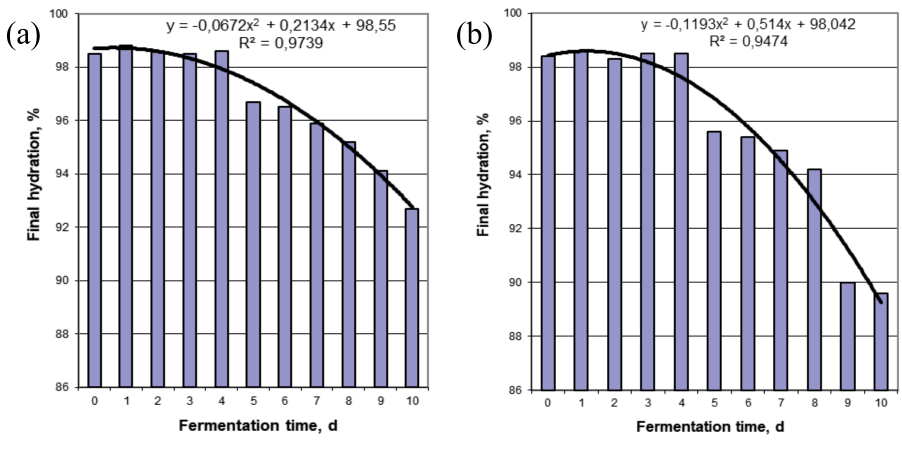

Fig. 5. Final hydration of sewage sludge pre-conditioned using the hybrid method and subjected to fermentation: (a) UD 3.2 W/cm² + 60°C and (b) UD 3.2 W/cm² + 80°C.

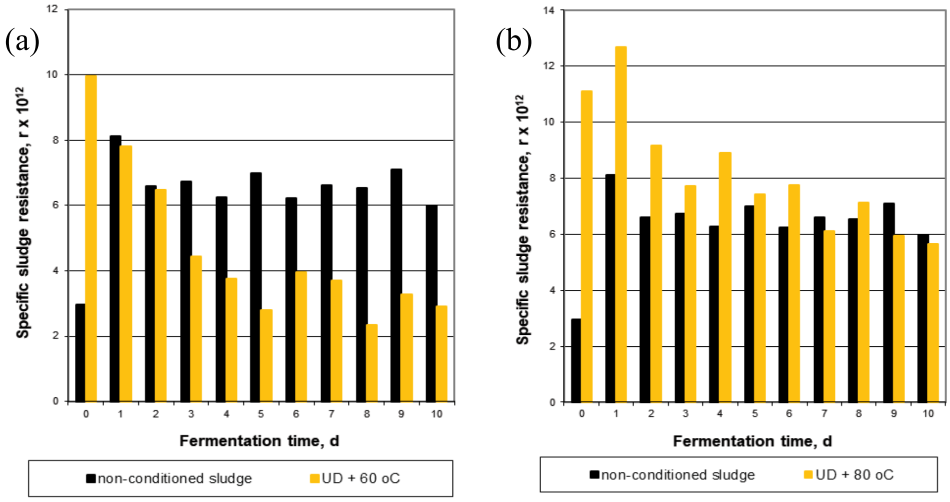

Fig. 6. Specific resistance of sewage sludge pre-conditioned with the hybrid method and subjected to fermentation: (a) UD 3.2 W/cm^2 + 60°C and (b) UD 3.2 W/cm^2 + 80°C.

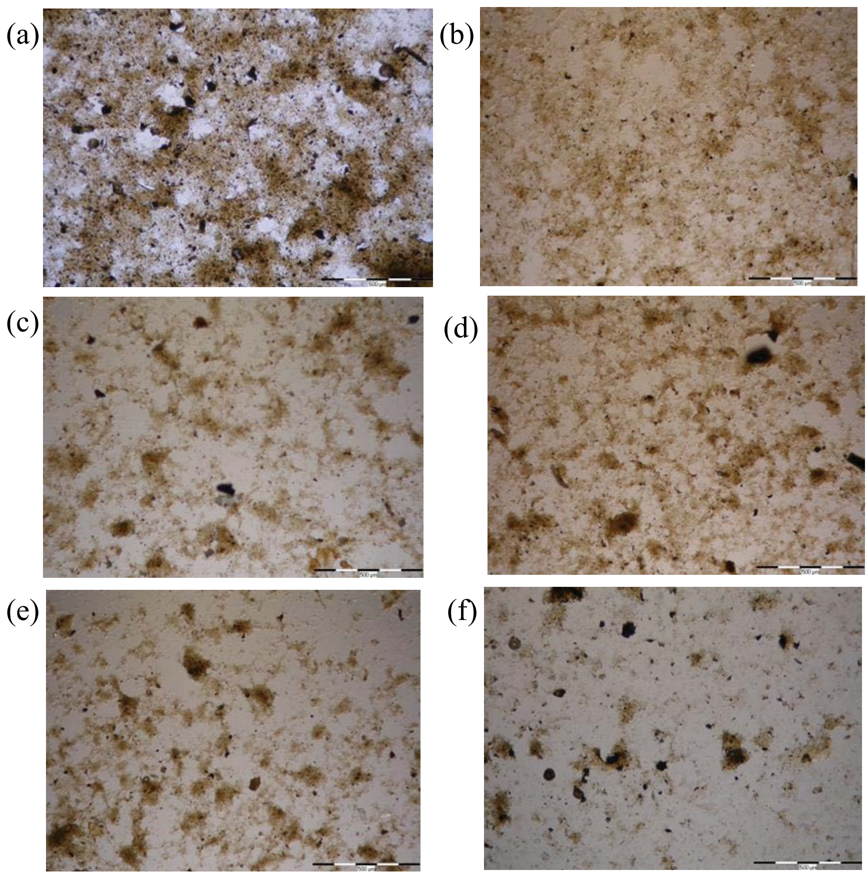

Fig. 7. Structure of sewage sludge pre-conditioned with UD field and temperature: (a) on day 0 of fermentation, (b) on day 2 of fermentation, (c) on day 4 of fermentation, (d) on day 6 of fermentation, (e) on day 8 of fermentation and (f) on day 10 of fermentation.

were recorded. On the 10th day, these were 5.99 × 10^{12} m/kg for non-conditioned sludge and 2.9 × 10^{12} m/kg for sludge preconditioned with the UD field and the temperature of 60°C. In the case of using a higher temperature, the resistance values of unconditioned and hybrid-conditioned sludge in the final days of fermentation were comparable.

The presented results correlated with the structure of the analysed sewage sludge. The clearest effect of the conditioning agent on the sludge structure was observed in the case of the hybrid method. In the field of view, large clusters of sludge flocs separated by free water were noted (Fig. 7a). The subsequent days of fermentation caused the breakdown of sludge flocs, the formation of increasingly larger stretched and single clusters of sludge with each day of the process, and the cloudiness of free water (Fig. 7b–f).

4. Summary and conclusions

The search for methods and ways to intensify the fermentation process, and at the same time dehydration, tends to apply various physical and chemical methods, as well as various combinations of standalone methods. Based on the obtained results, it was found that the combined methods (UD field + temperature) affect the reduction of filtration capacity by increasing the capillary suction time, as well as the specific resistance of sewage sludge. Similar relationships for the ultrasonic field were shown by Wang and Wolski [22,24] and Li et al. [38]. In each case, the indicators in question were higher in relation to the values of sludge conditioned by standalone methods. It is noteworthy that, similarly to the effect of fermentation on the values of sludge pre-treated with the UD field or thermally, also in the case of combined methods, a positive effect of stabilisation on the values of the discussed indicators was noted. In this respect, the research overlapped with that of Sahinkay et al. [36] and Dhar et al. [37]. It was observed that both the CSK and resistance values were lower with each day of the fermentation process, improving the filtering capacity of the sludge. In the last days of stabilisation, the values of the sludge modified with combined methods were similar to those of the non-conditioned sludge.

Along with the decrease in the value of the capillary suction time and the specific resistance of sludge with each day of the stabilisation process, the final hydration was also reduced. There was a correlation of the relationships of the indicators in question. Hydration values were lowest on the last day of fermentation using an amplitude of 80% and a temperature of 80°C. This relationship could also be observed by analysing the structure of the sewage sludge.

The analysis of the results also showed that the use of combined methods of sewage sludge conditioning improves their thickening capacity. In each case, hybrid pre-conditioning of fermented sludge improved the sedimentation capacity with reference to sludge conditioned by independent methods as well as for unconditioned sludge. The effectiveness of the fermentation process in combination with preconditioning is also confirmed by field studies by Kepp et al. [39] as well as by Bougrier et al. [42]. The mechanism and course of operation of the ultrasonic field process was described by Wang [43].

The findings of the study lead to the following conclusions:

- The use of combined methods in sludge preparation increases the capillary suction time with regard to the standalone methods used. Subjecting them to the stabilisation process reduces the CSK value.
- Combined methods significantly improve the thickening capacity of sludge. Their volume was lower in relation to the volume of untreated sludge, as well as those conditioned with the use of standalone methods.
- The application of combined methods in the initial preparation of sewage sludge resulted in an increase in the value of final hydration and filtration resistance of sewage sludge. Stabilisation of sludge modified with the hybrid method reduced the values of the above parameters.

Acknowledgements

The scientific research was funded by the statute subvention of Czestochowa University of Technology, Faculty of Infrastructure and Environment (BS/PB-400-301/23).

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