*Desalination and Water Treatment*
www.deswater.com

doi: 10.5004/dwt.2018.22496

117 (2018) 282–289
June

# Changes in filtration properties of digested sludge under the influence of magnetic field

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Received 22 January 2018; Accepted 14 May 2018

**ABSTRACT**

A key element in the management of sewage sludge is the process of sludge dewatering. The reduction of sludge hydration is the basis for its efficient and economical drying and also transport, natural utilization, or combustion. An important aspect is also the quality of supernatant from sludge dewatering. Supernatant is recirculated to the wastewater treatment process and increases the load of pollution in the influent wastewater. In order to efficiently dewater sewage sludge, conditioning agents, especially polyelectrolytes, are used. There are many known and tested conditioning methods such as chemical, physical, biological, as well as their combinations. In this study, the possibility of sludge conditioning prior to the dewatering process was investigated. Ferric coagulant, polyelectrolyte, and magnetic field generated by a solenoid were used as conditioning agents. It was suggested that dual conditioning of sludge with ferric coagulant and polyelectrolyte could be effectively supported by the use of a magnetic field. It was assumed that the magnetic field would enhance the forming of rigid and condensed dry matter structures in the sludge. Such changes in the structure and properties of sludge could allow for an easier extraction of the water contained in the flocs. Substantial importance was attributed to the presence of the paramagnetic material in the conditioning mixture. It was concluded that the superior method of conditioning was the dual method using the PIX-113 and polyelectrolyte. The use of the magnetic field caused heterogeneous changes in the characteristics of the conditioned sludge. The doses of the PIX coagulant and the direction of sludge flow by the solenoid were the main variables in this study.

*Keywords:* Digested sludge; Conditioning; Polyelectrolyte; Ferric coagulant; Magnetic field; Dewatering

## 1. Introduction

A priority issue in sewage sludge management is the process of its dewatering. Reduction of sludge hydration by dewatering is the basis for an efficient and economic transport, drying, and agricultural reuse or combustion of sewage sludge [1,2]. However the quality of the separated water during sludge dewatering is as important as the degree of sludge dehydration. The reject water is characterized by a high concentration of nutrients such as orthophosphates and ammonium [3,4]. In order to efficiently dehydrate sewage sludge as well as obtain the least contaminated reject water, suitably selected types and doses of conditioning agents such as organic flocculants, polyelectrolytes, are used. There are many well-known and studied methods of conditioning including chemical, physical, biological ones, and their combinations. Essential actions of these conditioning methods include coagulation and flocculation of solid particles or decomposition of extracellular polymeric substances followed by the release of bound water or compressibility reduction of sludge [1,5].

In many cases, the tested methods of conditioning are based on the use of iron ions, which neutralize the electric

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*Presented at the 13th Conference on Microcontaminants in Human Environment, 4–6 December 2017, Czestochowa, Poland.*

1944-3994/1944-3986 

charge of the particle surface and agglomeration of colloidal particles, and the resulting iron hydroxides act as skeleton builders [5,6]. Typically, the addition of iron salts is accompanied by addition of other compounds or agents to achieve a synergic effect. An alkaline ferrate solution containing Fe(VI) and KOH was tested by Liu et al. [7] as a means of improving sedimentation and dewatering. It is possible to enhance sludge dewaterability via a biological ferric flocculant produced by Acidithiobacillus ferrooxidans culture [8]. Sludge conditioning technology can also be a step-by-step sequence consisting of sulfuric acid, bioleaching using Acidithiobacillus ferrooxidans along with the addition of iron ions [9]. Shi et al. [10] investigated a method of sludge dewatering by using $Fe^{2+}$ ions and sodium persulfate combined with thermal-pretreated phosphogypsum. Another potential sludge conditioner is a combination of sulfuric acid, synthesized ferric nanomaterial, and polydiallyldimethylammonium chloride [11]. An often investigated technology of sludge conditioning is Fenton's reaction in combination with other substances or agents such as lime or electro-Fenton [12–14].

In this study, a hybrid method based on the sequential use of iron salts or ferric nanomaterial, polyelectrolyte, and magnetic field was investigated. In materials engineering, the use of magnetic fields is primarily focused on the separation of magnetic materials [15–17]. In chemical and biochemical engineering, the combined effect of the magnetic field, magnetic material, and other components or factors results in new products or process intensification. Filtration or sedimentation of magnetic materials in the magnetic field allows for the removal of other particles mixed and attached to the magnetic material. Lakshmanan and Kuttuva Rajarao [18] for intensification of sedimentation used a permanent magnet placed under the bottom of the sedimentation tank. The wastewater suspension before sedimentation was mixed with iron oxide nanoparticles [18]. Tanaka et al. [19] for filtration of colloidal particles and starch granules used a magnetic filter layer composed of $FeCl_3$ and $FeCl_2$. The filtration layer was placed in a column in a magnetic field which was created by horizontally arranged permanent magnets [19]. Qian et al. [20] for separation of the solid phase form activated sludge suspension used a multistep procedure. Initially, the activated sludge suspension was mixed with micromagnetic particles, then gravity separation in the magnetic field was used (permanent magnets placed vertically above and below the tank) and finally gravity drainage and electro-dewatering [20]. In the case of cake filtration, it was observed that magnetic forces reduce the velocity of cake building which result in structured cakes with higher permeability [21,22]. The agglomeration and sedimentation of particles in a water solution may be changed due to an interaction of the applied magnetic field and van der Waals forces as well as polarization forces [23]. The interaction of magnetic material and magnetic field can be used to reduce fouling in a magnetic membrane bioreactor [24]. Ifthikar et al. [25] prepared a magnetic sewage sludge biochar for elimination of lead ions in aqueous solutions. Many studies have focused on the application of the magnetic field and magnetic particles as means of intensification of the mass transfer process inside the immobilized enzyme bioreactor [26,27]. There is also the possibility of using the magnetic field for inhibiting bacterial growth, for example, in circulating cooling water. In experiments Liu et al. [28] flow conditions were used, and water was pumped through a solenoid at induction in the range of 21.41–46.57 mT. It is documented that it is possible to enhance the activity of activated sludge in wastewater treatment [29,30], formaldehyde biodegradation [31], and enhance nitrification [32]. Yavuz and Celebi [29] used a biological reactor located in the centre of the induction coil, operated at magnetic induction in the range 8.9–46.6 mT. Tomska and Wolny [30] used a pair of magnets located on the recirculation loop of activated sludge process. The maximum applied induction was 40.0 mT [30]. Łebkowska et al. [31] used two blocks of magnets placed around a biological reactor. This magnetic device produced a field in the range of 2–16 mT [31]. In the studies of Wang et al. [32], the magnetic field was provided by permanent magnets installed outside the reactor. The strength of the generated field was in the range of 5–25 mT [32].

This study verified the possibility of sludge conditioning before dewatering, with a combination of iron coagulant, polyelectrolyte, and the magnetic field generated by a solenoid. Substantial focus was put on to the presence of paramagnetism in the mixture of sludge and conditioning agents. It was suggested that the dual conditioning of the iron coagulant—polyelectrolyte—could be effectively supported by the use of a magnetic field. It was assumed that the use of the magnetic field would result in creating rigid and porous structured sludge flocs, which would allow for a more efficient water transfer from the flocs during drainage.

In the study, the possibility of sludge conditioning before dewatering was determined using iron coagulant, polyelectrolyte, and electromagnetic fields generated by solenoid. Substantial emphasis was put on the presence of paramagnetism in the conditioning mixture. It was suggested that the dual conditioning of the iron compound—polyelectrolyte—could be effectively supported by the use of a magnetic field. It was assumed that the magnetic field would form a rigid and condensed dry matter structure in the sediment, which would allow for easier release of water contained in the flocs.

## 2. Experimental setup

### *2.1. Materials*

The analyzed samples of digested sludge were collected from the wastewater treatment plant (WWTP) located in the Silesian province (Poland). The WWTP functioning in an University of Cape Town technological system operates at a sewage inflow of 45,000 $m^3$/d. At the WWTP, primary and excessive sludge is subjected to methane fermentation at a hydraulic retention time of 25 d (four fermentation tanks with an active volume of 2,200.0 $m^3$). The studied sludge after digestion was taken from the heat exchanger installation. The sludge collection for research was done three times. After sampling, the fermented sludge was stirred in the laboratory for 24 h for purpose of degassing. The basic physicochemical properties of the tested sludge are summarized in Table 1.

As the conditioning agent, an inorganic ferric coagulant, Kemira Kemipol PIX-113 was used, which is based on iron (III) sulfate with a total iron content of nearly 12%. Polyelectrolyte was also used in the study namely Superfloc C–494 (medium-cationic polymer) at a working concentration of 0.1%.

### 2.2. Experimental devices

The used solenoid generated a constant magnetic field with a maximum value of 0.04 T. The length of the solenoid was $L$ = 220 mm, the inner diameter of the bobbin $d_C$ = 33.0 mm, the wire diameter $d_W$ = 0.40 mm, the number of turns $z$ = 30,000, coil resistance $R$ = 964 Ω, current supply $I$ = 0.228 A, power $P$ = 50 W. The magnetic field distribution inside the solenoid was measured with a Teslameter Phywe sensor and calculated with the software Comsol Multiphysics 5.2a. Fig. 1 shows the distribution of the magnetic field induction in a solenoid.

In the middle of the bobbin, a polyvinyl chloride (PVC) pipe (internal diameter $d_P$ = 25.0 mm) was placed. This element did not disorder the magnetic field. PVC is a paramagnetic material, and due to its magnetic permeability, it is treated like air. Through the pipe, the sludge was pumped. The volume of the pipe (amount of sludge injected), measured on the length of the coil, was $V_{SLU}$ @ 110 mL. Peristaltic pump type Masterflex I/P was used. Sludge was pumped at two flow rates $Q_1$ = 1 L/min and $Q_2$ = 2 L/min. Based on the flow rate ($Q_1$ and $Q_2$) through the coil and volume $V_{SLU}$, the exposure time in the magnetic field was calculated as $t_1$ = 1.2 s and $t_2$ = 0.6 s, respectively. Two combinations of sludge flowing through the coil were used. In the first one, the direction of the sludge flow was consistent with the direction of the magnetic field lines (flow S–N) and in the second, combination was opposed (flow N–S). Fig. 2 shows the experimental apparatus.

Table 1
Physicochemical characteristics of fermented sludge after degassing

| Parameter | Minimum | Maximum | Mean | Standard deviation |
|---|---|---|---|---|
| Hydration (%) | 96.37 | 99.1 | 98.08 | 1.47 |
| Dry solids (g/L) | 24.88 | 35.31 | 28.5 | 8.96 |
| Volatile solids (% DS) | 38.26 | 56.96 | 43.76 | 11.03 |
| pH | 7.05 | 7.74 | – | – |
| Alkalinity (mg $CaCO_3$/L) | 2,054 | 3,329 | 2,518 | 604 |

### 2.3. Experimental design

The study was conducted in two stages (Stage I and Stage II). These were two separate conditioning operations with different doses of coagulant PIX-113. In Stage I, a steady dose of coagulant 2 mL/L was used (0.16 kg/kg $_{DS}$). In Stage II, it was 4 mL/L (0.30 kg/kg $_{DS}$). The experiments were performed in seven combinations for each stage (Table 2).

The optimal dose of the polyelectrolyte Superfloc C–494 was determined using the capillary suction time (CST) test, and it was 4.4 g/kg $_{DS}$. To further study, a dose 20% lower than the optimum was used—3.5 g/kg $_{DS}$. Reduction of the optimal dose of polyelectrolyte was due to the coagulant dosage and the magnetic field action. The aim was to demonstrate the impact of these agents on the possibility of replacing the doses of the polymer.

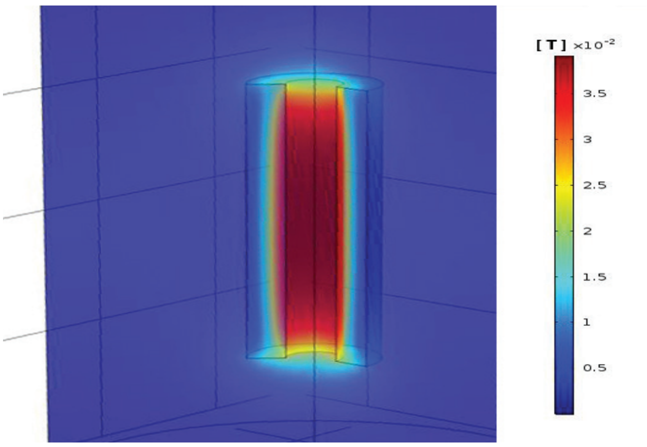


Fig. 1. Magnetic field induction distribution in a solenoid.

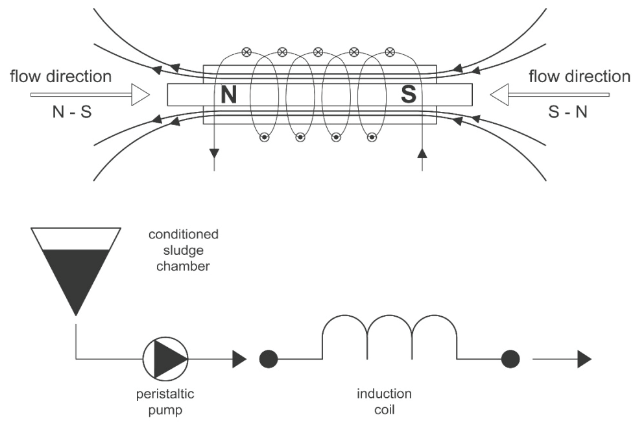


Fig. 2. Scheme of experimental apparatus.

Table 2
Combinations of sludge conditioning for stages I and II, respectively

| | | |
|---|---|---|
| Non-prepared sludge | Combination 0 | |
| Sludge conditioned only polyelectrolyte | Combination A | Optimal dose of polyelectrolyte C-494 |
| | Combination A1 | Polyelectrolyte dose reduced by 20% |
| Sludge conditioned dually | Combination B | PIX-113 + reduced dose of polyelectrolyte C-494 |
| Sludge conditioned dually and exposed to a magnetic field | Combination C1 | Flow S–N, $Q_1$ = 1.0 L/min, $t_1$ = 1.2 s |
| | Combination C2 | Flow S–N, $Q_1$ = 2.0 L/min, $t_2$ = 0.6 s |
| | Combination D1 | Flow N–S, $Q_1$ = 1.0 L/min, $t_1$ = 1.2 s |
| | Combination D2 | Flow N–S, $Q_1$ = 2.0 L/min, $t_2$ = 0.6 s |

Mixing of the tested sludge was carried using a 10.0-cm-diameter paddle stirrer in a glass shield vessel with a working volume of 1 L. In combination A and A1 (Stage I and Stage II), the sludge was stirred with the polymer for 20 s (400 rpm). In combination B, the samples were mixed, first for 60 s with coagulant PIX-113 at 200 rpm and next with polyelectrolyte (400 rpm, 20 s). In combination C and D, the conditioning procedure was the same as for combination B, immediately after which the sludge was pumped through the coil.

### 2.4. Analysis

The characteristics of the tested sludge were determined on the basis of dry solids (DS), volatile solids, pH, alkalinity, all measured according to standard methods for the examination of water and wastewater [33].

To characterize filtration properties of the conditioned sludge measurement of CST, specific resistance to filtration ($r$) and coefficient of compressibility ($s$) were performed in accordance to European and Polish standard procedures [34–36].

The specific resistance to filtration was determined on a vacuum filter. The 100 mL of sludge was filtered for 30 min at 70 kPa (filter paper—Whatman 1). In order to determine the coefficient of compressibility, the pressure filtration was applied in a maximum time of 30 min (applied pressure—300 kPa, 500 kPa, and 700 kPa). The coefficient of compressibility is related to the applied pressure by the following equation [36]:

$$r = r_0 \cdot p^S \tag{1}$$

where $r_0$ is the specific resistance to filtration at pressure 300 kPa, $r$ is the specific resistance to filtration at pressure $p$, and $p$ is the pressure drop across the cake and cloth [36].

In order to determine the influence of the conditioning methods on the quality of supernatant, a centrifuge (3 min at 3,500 rcf) was used. No effluent from vacuum filtration was used. It was considered that the centrifugation allows for a better comparison of the effects of these methods based on the quality of the supernatant than based on cake filtration on filter paper. In the supernatant, chemical oxygen demand (COD) and ammonium nitrogen ($NH_4$-N) was measured using cuvette tests and a spectrophotometer Hach DR 5000 (Hach Lange, Poland). Prior to COD measurement, 50 mL samples of supernatant were homogenized for 60 s using the IKA T10 basic homogenizer. Prior to $NH_4$-N measurements, supernatant samples were once again centrifuged (15 min at 12,100 rcf) and filtered through a membrane filter (0.45 µm, cellulose acetate).

Concentration of total organic carbon (TOC) in sludge supernatant was analyzed in accordance to the differential method performed using a TOC analyzer (Analytik Jena multi N/C 3100, Germany).

In order to investigate the relationship between the magnetic field and the dose of ferric coagulant (dose of ferromagnetic), the nonparametric Mann–Whitney $U$ test was used. The null hypothesis $H_0$ assumed that the coagulant dose (stages I and II) does not affect the differences in the effects of conditioning. The accepted significance level $\alpha = 0.05$ was used. A probability value ($p$) of less than alpha resulted in the rejection of the null hypothesis. This meant that increasing the coagulant dose with the application of a magnetic field resulted in a significant change in the value of the examinated parameters. When the value of the probability test ($p$) was smaller than alpha, there were no grounds to reject the null hypothesis [37,38].

## 3. Results

### 3.1. Dewaterability

The sludge conditioned using the hybrid method (combination B–D2) showed increased susceptibility to dewatering compared with the sludge exposed to the conventional polymeric method. On the basis of the CST test (Fig. 3), it can be concluded that a higher dose of coagulant (Stage II) plays a key role in dewaterability. The use of PIX-113 at a dose of 0.29 kg/kg $_{DS}$ coupled with a polyelectrolyte dose 20% lower than optimum, resulted in a more beneficial CST compared with the sludge conditioned using the polymeric method. The influence of the magnetic field on the sludge was dependent on the flow rate and flow direction S–N or N–S as well as the dose of the coagulant. The most advantageous CST results were achieved for combination C1 in Stage II, where the CST was 53 s.

Vacuum filtration has also shown that the sludge conditioned by the dual chemical methods have better susceptibility to dewatering than the sludge prepared using polyelectrolyte only. Final hydration of filter cake (Fig. 4) was dependent from

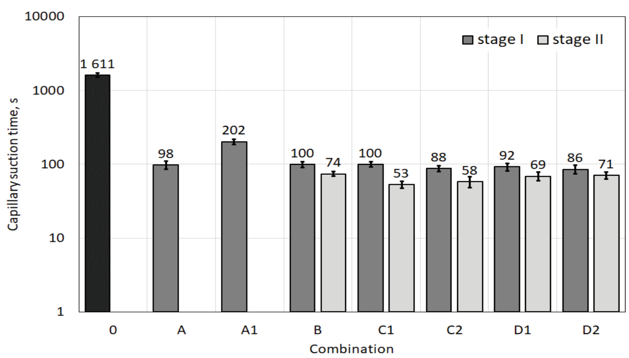


Fig 3. CST results for the analyzed sludge.

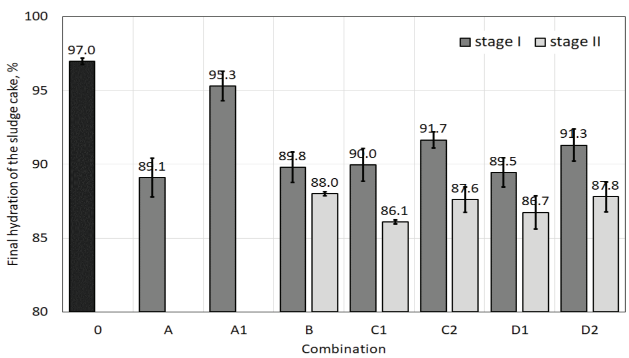


Fig 4. Hydration of the filter cake after vacuum filtration.

the conditioning method and dose of PIX-113. The higher dose of coagulant (Stage II) determined lower final hydration (combination B). A higher dose also resulted in a better effect of the magnetic field action (combination C and D). A noticeable reduction in the final hydration of the filter cake was achieved only at a dose of 0.29 kg/kg $_{DM}$ (Stage II). It could also be the result of the magnetic field impact on a sludge sample with a higher content of ferromagnetic material (iron in coagulant). The use of a coagulant dose of 0.15 kg/kg $_{DM}$ with exposure sludge in the magnetic field was considered a low-beneficial combination of conditioning (Stage I). The effect of the magnetic field action was also dependent on the flow rate of the sludge through the coil. The preferred flow rate was 1.0 L/min. The flow direction was of secondary importance. The lowest final hydration of the filter cake (86.1%) was achieved in Stage II for combination C1 (flow S–N). When changing the direction of the magnetic field lines (combination D1, flow N–S) hydration increased by less than 1% (86.7%).

Based on the values of specific resistance to filtration, it was also found that the dually conditioned sludge had the highest susceptibility to dewatering (Fig. 5). It was crucial to use a higher coagulant dose (Stage II). The influence of the magnetic field on the value of the specific resistance to filtration varies. It depended on the flow rate and the flow direction of the sludge through the installation. Sludge C1 in the second stage was characterized by the lowest specific resistance to filtration. Exposure to a magnetic field with a flow direction of S–N and flow rate of 1.0 L/min reduced the *r* value by more than 30% compared with an analogically conditioned sludge, but without magnetic field treatment. According to norm PN-EN 14701-1:2007 [34], the sludge can be considered as filterable on industrial scale, when its specific resistance to filtration is lower than $5\times0^{12}$ m/kg. The results show that only the dually conditioned sludge (combination B–D2) using the coagulant at a dose of 0.29 kg/kg $_{DM}$ (Stage II) is filterable on industrial scale.

### 3.2. Statistical analysis

The Mann–Whitney *U* test allowed to determine whether the susceptibility to dewatering of the sludge conditioned using the hybrid method (combination B–D2) was significantly dependent on the PIX dose. The results are shown in Table 3.

Based on the test, it can be concluded that a higher dose of the coagulant significantly affects most parameters of dually conditioned sludge ($p \leq 0.05$). Only in the case of final hydration of sludge B, the test probability value was greater than alpha ($p = 0.3731$). The values observed in the figures as well as the statistical test confirmed that the effectiveness of the magnetic field is closely related to the increasing dose of the coagulant (ferromagnetic material).

### 3.3. Compressibility

Compression ability was tested selectively and conditioning tests with magnetic field were limited to the most advantageous combination C1. Fig. 6 shows the changes in specific resistance to filtration of conditioned sludge depending on filtration pressure. In all tests, increasing the filtration pressure caused an increase in the *r* value.

The sludge conditioned in combination B and C1 was characterized by the lowest specific resistance to filtration. The greatest difference in *r* values were observed at a pressure

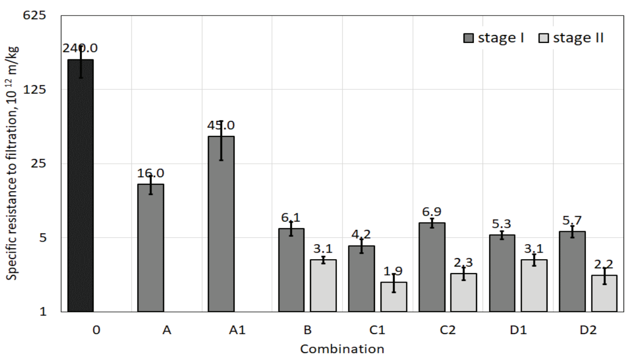


Fig. 5. The specific resistance to filtration for the analyzed combinations.

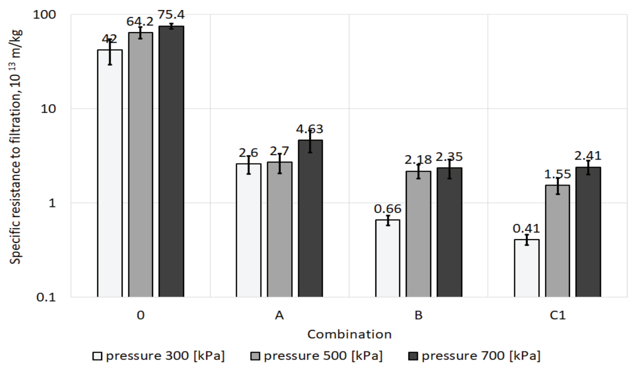


Fig. 6. Resistance to filtration of sludge conditioned in the selected combinations.

Table 3
The results of the Mann–Whitney *U* test

| Parameter | Combination | | | | |
|---|---|---|---|---|---|
| | B | C1 | C2 | D1 | D2 |
| | Stage I/Stage II | Stage I/Stage II | Stage I/Stage II | Stage I/Stage II | Stage I/Stage II |
| | Test probability (*p*) | | | | |
| Resistance to filtration | 0.0069 | 0.0021 | 0.0083 | 0.0182 | 0.0021 |
| Final hydration | 0.3731 | 0.0107 | 0.0145 | 0.0214 | 0.0198 |
| Capillary suction time | 0.0076 | 0.0031 | 0.0131 | 0.0097 | 0.0408 |

of 300 kPa. At this filtration pressure, the best conditioning results were obtained for combination C1 ($r = 4.11\ 10^{12}$ m/kg). Using a 500-kPa filtration pressure, the conditioning method with magnetic field application was also advantageous. The influence of the magnetic field on the specific resistance to filtration disappeared at a pressure of 700 kPa.

Based on the linear regression equations, the coefficient of compressibility was calculated. Its values were as follows: $s = 0.71$ for the non-pretreated sludge, $s = 1.24$ for the combination A, $s = 1.54$ for the combination B, and $s = 2.04$ for the combination C1. According to norm PN-EN 14701-3:2007 [36], values higher than $s = 1$ indicate an increase of the specific resistance to filtration more than proportional to the pressure, thus it is non convenient to operate at high pressures.

The change in the filtration pressure also influenced the hydration of the sludge cake (Fig. 7). Preferred combinations of preparation were B and C1, but at a filtration pressure of no more than 300 kPa. At a filtration pressure of 700 kPa, the use of a double chemical method and also with magnetic field was not justified.

### *3.4. Analysis of the supernatant quality*

Ammonium nitrogen, TOC, and inorganic carbon content in supernatants of the investigated sludge are summarized in Table 4.

The analysis of ammonium nitrogen showed that the conditioning method does not significantly affect the content of this biogen in the supernatant. It was expected that ammonium sulfate would precipitate after addition of PIX and that the ammonium nitrogen content would decrease. Sewage sludge is a complex medium. It contains a variety of contaminants, such as metal ions, which react with the sulfate ions contained in the coagulant. This makes it difficult to precipitate ammonium sulfate. On the basis of inorganic carbon (IC) and TOC analyses, it was found that the supernatants from the dual conditioned sludge (combination B) contained less carbon, compared with the sludge conditioned by the polymeric method (combination A). The exposure of the hybrid conditioned sludge to the magnetic field affected the reduction of ammonium nitrogen, IC, and TOC content by 20%, 11%, and 15%, respectively, compared with the sludge not subjected to magnetic field.

The smaller values of COD translate to lower loads of pollutants recycled to the technological wastewater treatment line, in result of the dual conditioning (combination B and C1). It was noted that the exposure of the hybrid conditioned sludge to the magnetic field significantly affected the reduction of COD value in the obtained supernatant (combination C1). The supernatants from this combination had a COD of 1,403 mg $O_2$/L. For the rest of the combinations, the values of this parameter equaled to 32% (combination B) and 50% (combination A) higher, compared with combination C1.

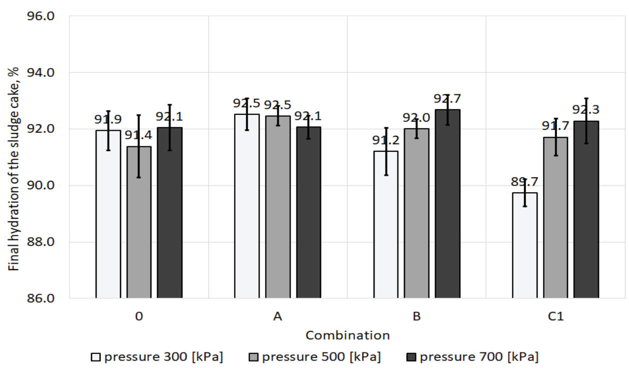


Fig. 7. The final hydration of the sludge cake obtained during compressibility tests.

Table 4
Carbon and ammonium nitrogen content in supernatant

| Parameter | Combination | | | |
|---|---|---|---|---|
| | 0 | A | B | C1 |
| Ammonium Nitrogen, mg/L | 405 | 393 | 375 | 304 |
| Total organic carbon, mg/L | 3,539 | 1,133 | 671 | 573 |
| Inorganic carbon, mg/L | 26 | 17.90 | 11.15 | 10.00 |
| Chemical oxygen demand, mg $O_2$/L | 3,527 | 2,816 | 2,073 | 1,403 |

## 4. Conclusions

On the basis of studies, it was found that the use of dual conditioning method improves filtration and dehydration of sludge. Comparing the combination of A (C-494) and B (PIX-113—0.29 kg/kg and C-494), the specific resistance to filtration decreased from $16\times10^{12}$ to $3.1\times10^{12}$ m/kg (vacuum filtration at 70 kPa). In the pressure filtration process, at the lowest applied pressure of 300 kPa, was also achieved improvement in filterability of the sludge. The dual method with the use of a higher dose of PIX coagulant (0.29 kg/kg $_{DM}$—Stage II) determined better susceptibility to dehydration.

During the sludge conditioning in the magnetic field (combination C and D), a higher dose of coagulant 0.29 kg/kg $_{DM}$ was also significant. Moreover, the effect of the magnetic field on the properties of sludge was dependent on parameters such as flow rate and direction of flow through the coil. The best dewaterability of sludge was achieved by magnetic field treatment with a flow rate of 1.0 L/min in the S–N direction (combination C1). The combination of C1 conditioning factors caused the largest reduction of the specific resistance to filtration to $1.9 \times 10^{12}$ m/kg and also final hydration of the sludge cake to 86.1%.

The compressibility test showed that regardless of the conditioning method, sludge was characterized by high compressibility, especially for combination B ($s = 1.54$) and C ($s = 2.04$). However, based on the partial $r$ values, which were the basis for calculating the value of compressibility, it was found that it is possible to improve the filterability of the sludge. The condition was the use of a double chemical method and a magnetic field (combination 1) for sludge conditioning and filtration at a pressure of not more than 300 kPa. Application of this condition caused that in the scope of compressibility tests, the lowest values of specific resistance and final hydration of filter cake were obtained, respectively, $0.41\times10^{13}$ m/kg and 89.7%.

The basic conclusion from the conducted research is confirmation of the possibility of using the dual method with or also without conditioning with a magnetic field in order to increase the sludge filterability, generally defined as the filtration rate. The obtained values of the final hydration of the sludge cake also indicated the possibility of increasing sludge dewaterability by using a magnetic field as the conditioner. Nevertheless, from the operational point of view, obtained hydration of the filter cake was not satisfactory. It is possible, that the water in the sludge structure is still strongly associated with solid particles despite the use of polymeric coagulation, conventional coagulation, and magnetic field.

The contamination of supernatant after sludge dewatering was also dependent on the combination of conditioning. Supernatant from sludge conditioned by a double chemical method with or without magnetic field contained less almost 50% less carbon compounds (TOC and COD) than those obtained from sludge prepared only polyelectrolyte. Conditioning with a magnetic field was also effective in reducing the concentration of ammonia nitrogen. Specifying conclusions regarding the operation of the magnetic field in such complex samples of conditioned sludge and their supernatants is difficult. The mechanism of operation of the magnetic field on aqueous solutions is not fully understood. The action of the magnetic field causes changes in the forces between the atoms and the energy of the atoms, which can influence the precipitation of crystals of inorganic salts and the formation of particle agglomerates [39].

The influence of the magnetic field on various types of environmental samples can be realized in two methods, by applying a permanent magnet or an induction coil. In the first method, positioning of magnets (change of distance) is required to achieve the appropriate induction values. In the second method, it is necessary to change the current supply conditions. It is difficult to prove the superiority of one of the solutions. In the case of conditioned sludge prior to dewatering, it would be more beneficial to use an induction coil due to the control of the induction value. In WWTPs, dosing of conditioning agents to the sludge takes place while mixing the stream of sludge in the pipeline with a stream of polyelectrolyte, for example. Therefore, the ideas of flow of conditioned sludge and the use of induction coils were used in the conducted research.

The induction of 0.04 T used in the study corresponds to the value used in the studies of other authors [28–32], where the primary aim was to intensify biochemical transformations. The application of magnetic field at the stage of sludge conditioning before dewatering is in no way related to the activity of microorganisms. Therefore, in further studies, it is planned to use a higher values of induction. The basic idea of increasing the magnetic induction concerns the increase of the physical effect on solid particles. An increase in the iron coagulant dose as a ferromagnetic material can also be considered. However, the authors observed that further increase in the PIX-113 dose resulted in more extensive foaming of sludge (no results are presented in this article). This resulted from the reaction of the coagulant (iron [III] sulfate) with the high alkalinity of the digested sludge and the release of carbon dioxide. Strong foaming would have adverse consequences in pumping sewage sludge and their mechanical dewatering. It is possible to increase the iron coagulant dose as a factor increasing the influence of the magnetic field on the prepared sludge. However, this requires the use of a degassing buffer tank, and then the conditioning in the magnetic field and finally mechanical dewatering.

## Acknowledgment

This work was supported by the Grant no. BS/PB-401-301/11 and BS/MN-401-303/17 (Faculty of Infrastructure and Environment, Czestochowa University of Technology).

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