Influence of chemically enhanced primary treatment on anaerobic digestion and dewaterability of waste sludge

G. Kooijman, M. K. De Kreuk and J. B. van Lier

ABSTRACT

To lower energy consumption at a sewage treatment plant (STP), primary settling could be enhanced to direct more chemical oxygen demand (COD) to anaerobic digestion (AD) for increased biogas production and decreased aeration. Primary settling can be chemically enhanced by applying flocculation aids (FAs). FAs are refractory compounds that may affect all sludge treatment facilities. In this study the consequences are investigated of the application of FAs for chemically enhanced primary treatment (CEPT) on AD and subsequent dewatering of digested sludge in a conventional STP. It was found that FAs maintain their effect throughout all sludge processing facilities. With CEPT, more readily degradable solids were removed, resulting in a higher bio methane potential of the primary sludge. In AD, FAs lowered the viscosity; meanwhile an increased hydrolysis rate was observed. But FAs also partially irreversibly bound substrate in such way that it is not available for biological degradation anymore. In subsequent dewatering of digested sludge, a higher dry solids concentration was observed with CEPT. A computer simulation showed that in a conventional STP, CEPT would not be economically feasible. However, several benefits were discussed that can make CEPT an interesting option for future low COD/N-tolerant STPs with, for example, Anammox processes for N removal.

Key words | anaerobic digestion, chemically enhanced pre-treatment (CEPT), dewatering, sludge, viscosity

NOMENCLATURE LIST

AD Anaerobic digestion
BMP Biomethane potential
CEPT Chemically enhanced primary treatment
COD Chemical oxygen demand
CST Capillary suction time
DS Dry solids
FA Flocculation aid
HRT Hydraulic retention time
PS Primary settler
SMA Specific methanogenic activity
SRF specific resistance to filtration
STP Sewage treatment plant
TN Total nitrogen
TP Total phosphorus
TS Total solids
TSS Total suspended solids
VS Volatile solids
VSS Volatile suspended solids

INTRODUCTION

In industrial wastewater treatment, there are many different applications for flocculation aids (FAs). For example, the solids of poultry or pig manure can be concentrated using cationic FAs to allow for smaller anaerobic digester volumes (Møller et al. 2007; Campos et al. 2008; Liu et al. 2016). In an upflow anaerobic sludge blanket, pre-treatment of the flocculent biomass with cationic FAs can improve the chemical oxygen demand (COD) removal performance at low hydraulic retention times (HRTs) (Garcia et al. 2008). Uncoupling HRT and solids retention time can be applied in a continuously stirred tank reactor by returning flocculated solids from the effluent using FAs (Cobbledick et al. 2016). In conventional sewage treatment plants (STPs) the application of FAs is often limited to sludge dewatering. Using FAs in the primary settler (PS), however, could lead to a more positive energy balance of STPs: more influent COD could be used for biogas production via...
anaerobic digestion (AD), instead of the current aerobic oxidation of COD in the aeration tanks.

Chemically enhanced primary treatment (CEPT) with FAs is not often applied in conventional STPs because of the critical COD/N ratio for denitrification. Since COD is required for denitrification, extensive COD removal by CEPT can compromise efficient nitrogen removal due to a lack of COD for denitrification (Van Nieuwenhuijzen et al. 2000). According to the electron balance, the minimum amount of COD required for nitrification and subsequent denitrification is 1.71 gCOD/gN. However, the organisms in sewage treatment require COD for growth as well. Therefore, in practice, a COD/N ratio of 6 to 10 gCOD/gN is required (Golterman 1985; Sobieszuk & Szewczyk 2006; Roy et al. 2010). Recently, novel, low COD/N-tolerant N removal technologies have been introduced such as N removal over nitrite or Anammox processes in the waterline of the STP (Kartal et al. 2010). With Anammox, for example, a COD/N ratio as low as <1 gCOD/gN is shown to be sufficient for N removal (Joss et al. 2009; Wett et al. 2010; Zeng et al. 2016). With the prospect of low COD/N-tolerant STPs, CEPT with FAs could be advantageous for the energy balance and space requirements of an STP in the future. However, there is not much known about the effects of FAs on AD and subsequent sludge treatment facilities. It is known that FAs are not readily biodegradable anaerobically (Chang et al. 2001; Chu et al. 2003). Therefore, FAs applied in CEPT may retain their flocculating capacity throughout all subsequent sludge processing facilities and affect the entire STP. For example, FAs present in the anaerobic digester are hypothesized to reduce the polymer consumption for subsequent sludge dewatering (Cobbledick et al. 2016). But also the solids content of dewatered sludge may be improved. Since sludge disposal is one of the largest cost factors of sewage treatment and can amount to up to 50% of the total operational costs (Spinosa & Vesilind 2001), small differences in dry solids (DS) percentage of dewatered sludge can have large effects on the operational costs of STPs.

This study presents a renewed perspective on the application of CEPT, using solely organic FAs to increase primary sludge production and enhance dewaterability of the digested waste sludge. Also the effects of the presence of FAs on the AD process are investigated. Finally, a computer simulation of a reference STP, using the experimental results, evaluates the economic effects of CEPT.

MATERIALS AND METHODS

Chemically enhanced primary treatment experiment (CEPT experiment)

The CEPT experiment tells us what the effects of FA in the PS are and it provides flocculated and settled sludges for the AD and dewatering experiments. The CEPT experiment was performed at STP Leiden Noord, The Netherlands (150,000 population equivalent (P.E.)), during dry weather flow conditions. Four grab samples of 80 L were collected after coarse screening. The samples are representative of the influent at this STP, since measured concentrations were in the range of the yearly averages for COD (557 ± 120 mg/L), TN (55 ± 10 mg/L) and TP (9.5 ± 1.8 mg/L). Three different settling situations using FAs were compared to the reference settling (reference situation (RS)) where there was settling without dosing FAs (Table 1). The used FAs were cationic flocculant (situation C), anionic flocculant (situation A) and a mix of coagulant and cationic flocculant (situation M). FAs were added during 3 minutes of vigorous stirring. Then 60 s of slow stirring was followed by a 30 min settling period. The supernatant water was syphoned off.

The FAs (Table 2) and concentrations (Table 1) were selected from a set of commercially available FAs based on turbidity removal performance in screened dry weather wastewater of STP Leiden Noord. Both cationic and anionic poly-electrolytes were used, as well as an organic coagulant.

Biomethane potential and specific methanogenic activity tests

Biomethane potential (BMP) tests assessed the rate and/or extent of methane production. The BMP tests performed are summarized in Table 1. In all BMP tests the substrate consisted of primary sludge, either from the CEPT experiment or directly taken from the STP Leiden Noord, and secondary sludge. The primary and secondary sludge was mixed in a 3:1 volatile solids (VS) ratio to resemble the composition fed to the anaerobic digester at STP Leiden Noord. As an inoculum, digested sludge of STP Leiden Noord was used with total suspended solids (TSS) of 35.6 ± 0.4 g/L and volatile suspended solids (VSS) of 25 ± 0.5 g/L. A VSS inoculum to VS substrate ratio (VSS/VS) of 2 was used. A control with only inoculum was included to correct for the biogas produced by the inoculum in the BMP_1 experiment. All BMP tests were done in triplicate in bottles of
400 mL and were incubated in a New Brunswick Scientific
Innova 44 at 35 °C and shaken at 150 rpm when appropriate
for the experiment. The produced biogas was scrubbed with
a 3 M NaOH solution to remove the CO2. The methane pro-
duction was measured over time with an automated
methane potential test system, Bioprocess Control (Lund,
Sweden). The BMPs were terminated when three consecu-
tive days of <1% biogas increase was measured, except for
the BMP_3_Unstirred experiment, where we were only
interested in the initial rate of digestion. The specific metha-
nogenic activity (SMA) test was performed with the same
equipment and settings. The VSS\textsubscript{inoculum}:COD\textsubscript{substrate} ratio
was 2 with sodium acetate in a buffer (10 mM phosphate,
pH 7) together with micro- and macro-nutrients according

### Analytical techniques

Particle counting was performed with a Met One particle
counter in the size range of 2–100 μm and equipped with an
LB1, 020 sensor (Beckman Coulter, Brea, United States). An
Anton-Paar USD200 rheometer with Z2 DIN and TEZ
180 bob (Graz, Austria) measured the viscosity of the
sludge mixtures. Merck kits (Germany) determined the
ammonium-N, COD (25–15,000 mg/L) and P concentrations
(0.015–5 mgP/L). Total solids (TS), VS, total TSS and VSS
were measured according to APHA (1999). The protein
measurements were done with protein reagent 0.01% (w/v)
Coomassie Brilliant Blue, 4.7% (w/v) ethanol and 8.5% (w/v)
phosphoric acid with a bovine serum albumin calibration
line and measured at 595 nm (Bradford 1976). Turbidity
was determined with the Hach 2100N turbidity measure-
ment device. Fluorescence spectra were recorded using a Perkin-
Elmer LS-50B luminescence spectrophotometer, which
uses a 450 W xenon lamp. All samples were diluted with
carbon-free electrolyte solution at pH about 7.5. The fluo-
rescence excitation–emission matrix (F-EEM) tests were
carried out at a concentration of 1 mg/L to minimize the
inner-filter effect. The acquisition interval and integration
time were maintained at 0.5 nm and 0.1 s, respectively.

### Table 1: Overview of settling, BMP and SMA experiments performed in this study

<table>
<thead>
<tr>
<th>Reference in paper</th>
<th>Type of experiment</th>
<th>FA dosage or substrate</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEPT Experiment</td>
<td>Primary sedimentation</td>
<td>Substrate: screened influent at STP Leiden Noord Situation RS: no FAs Situation C: 10 ppm ΦA Situation A: 10 ppm ΦFA Situation M: 10 ppm ΦFA and 2 ppm ΦA</td>
<td>Screened influent of STP Leiden Noord was settled, with and without CEPT</td>
</tr>
<tr>
<td>BMP_1</td>
<td>BMP test</td>
<td>Substrate: mixture of secondary sludge and sludge samples of CEPT experiment</td>
<td>Sludge samples of CEPT experiment were used in BMP test</td>
</tr>
<tr>
<td>BMP_2 C\textsubscript{FA}</td>
<td>BMP test</td>
<td>Substrate: secondary and primary sludge FA dosage: 0, 5, 7.5 and 10 g/kg ΦA</td>
<td>BMP test with primary and secondary sludge as substrate, with C\textsubscript{FA} in different concentrations added to the BMP test bottles at t = 0</td>
</tr>
<tr>
<td>BMP_3 Unstirred</td>
<td>BMP test</td>
<td>Substrate: secondary and primary sludge FA dosage: 0 and 5 g/kg ΦA</td>
<td>Unstirred BMP test with and without C\textsubscript{FA} addition at t = 0</td>
</tr>
<tr>
<td>SMA FA</td>
<td>SMA test</td>
<td>Substrate: acetate FA dosage: 5 g/kg ΦA</td>
<td>SMA test with flocculated and non-flocculated inoculum</td>
</tr>
</tbody>
</table>

### Table 2: Flocculants and coagulant used for the experiments on the flocculation of sludge

<table>
<thead>
<tr>
<th>Name</th>
<th>Reference in paper</th>
<th>Type</th>
<th>Active compounds</th>
<th>Molecular weight</th>
<th>Charge</th>
<th>COD [mg/g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Shell C\textsubscript{FA}</td>
<td>Cationic organic flocculant</td>
<td>Acrylamide-based polymer</td>
<td>Low</td>
<td>86 ± 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultimer A\textsubscript{FA}</td>
<td>Anionic organic flocculant</td>
<td>Acrylamide-based polymer</td>
<td>Medium</td>
<td>23 ± 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nalco M\textsubscript{FA}</td>
<td>Organic coagulant</td>
<td>Poly-ampholytic</td>
<td>High</td>
<td>42 ± 2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Right-angle geometry was used for liquid samples in a 10 mm fused-quartz cuvette. Three-dimensional spectra were obtained by repeatedly measuring the emission spectra within the range of 280–600 nm, with excitation wavelengths from 200 to 400 nm, spaced at 10 nm intervals in the excitation domain. Spectra were then concentrated into an EEM.

**Dewatering parameters**

Capillary suction time (CST) measurements were done with a Triton Electronics Type 304 m (Essex, UK). CST was used to indicate the optimal FA dosing values for the dewatering experiments. For the dewatering test, a mini filter press was used, which was custom made by Mareco (Kortehemmen, The Netherlands). The pressure was set at 3.5 bar with 200 s pressing time. The piston speed was set to ~1 cm/min. The specific resistance to filtration (SRF) tests were done with Grade 1 Whatman filters with 1 bar of pressure and a sludge volume of 100 mL. The values for SRF and blinding index β were calculated according to Novak et al. (1988).

**Biowin simulation**

To evaluate the impact of CEPT on the activated sludge process, the Biowin 3.1 simulator was used. The STP of Leiden Noord was simulated using a flow of 20,000 m³/d and the standard parameters of Biowin. To simulate flocculation in the PS, the removal percentages of the PS in the Biowin package were adapted to match the removal observed in the batch experiment and thus varied per FA used: 60% for the RS, 80% for M and 95% for C. Also the ortho-phosphate fraction was adjusted to obtain a similar phosphate removal as in the flocculation tests. The operational temperature was set to 15 °C.

**RESULTS AND DISCUSSION**

In order to determine the effect of FAs on AD and sludge dewatering, primary sludge was produced in the CEPT experiment. As expected, settling situation C and settling situation M showed a significant improvement in terms of COD, TSS and VSS removal, when compared to situation RS (Table 3). Dosage of 10 ppm cationic FA (CxFA) (settling situation C) showed a 66% increased COD removal, 120% increased TP removal and 45% increase in TSS removal. During settling situation M, these removal efficiencies increased by 47%, 88% and 28%, respectively. Application of 10 ppm AxFA (situation A) did not improve the removal at all, which can be explained by the fact that particles in domestic sewage are negatively charged (Elmitwalli et al. 1994) and thus are generally not bound by the negatively charged anionic FAs.

**Anaerobic digestion**

During a BMP test (BMP_1), the methane production per gram VS of primary sludges from the CEPT experiment was followed over time (Figure 1). The produced methane of the sludges during the first 2 days was comparable for all samples. The produced methane of sample A was similar to the methane produced by sample RS over the whole period. This was expected because situation A did not show any improved removal during settling and therefore is not likely to have affected the settled sludge composition. However, between 2 and 5 days, samples C and M displayed a significantly (p < 0.1) higher methane production rate. Also the BMPs of samples C and M were significantly higher than the BMP of sample RS.

Since FAs could be partially anaerobically digested (Chang et al. 2001), the added FAs may have contributed to the biogas production for samples C and M. However, the COD added by introducing FAs was too low (equivalent to <1 mLCH₄/gVS) to explain the differences in BMP

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Supernatant and influent characteristics of the CEPT experiment. Samples were taken at STP Leiden Noord (150,000 P.E.)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>COD [mg/L]</td>
</tr>
<tr>
<td>Supernatant situation RS</td>
<td>324 ± 11</td>
</tr>
<tr>
<td>Supernatant situation C</td>
<td>206 ± 14</td>
</tr>
<tr>
<td>Supernatant situation A</td>
<td>326 ± 17</td>
</tr>
<tr>
<td>Supernatant situation M</td>
<td>240 ± 11</td>
</tr>
<tr>
<td>Influent CEPT experiment</td>
<td>503 ± 7</td>
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</tbody>
</table>
and methane production rate. With CEPT additional small particles can be removed, which would not have settled without FA dosing. These particles may have had a different biodegradability and therefore may have caused the increased digestion rates and higher BMPs for C and M. To distinguish between the physiological effects on the sludge that FAs establish, such as change in viscosity, and the difference in flocculated material (substrate), a new experiment was performed: BMP_2_CFA. In BMP_2_CFA, CFA was added in different concentration at t = 0 to the incubation bottles of the BMP experiment with primary and secondary sludge as substrate. The methane production is shown in Figure 2.

In BMP_2_CFA, a significant decrease in BMP was found with an increased CFA addition (7.5 and 10 g/kg), when results were compared to the BMP without additions (0 g/kg). This indicates that increased BMP values in BMP_1 of samples C and M flocculated sludge are attributable to an increased fraction of readily biodegradable material in these sludges, which were removed from the sewage during the CEPT experiment.

Decreased biodegradability in BMP_2_CFA due to FA addition was observed before in other studies. Chu et al. (2005) hypothesized that substrate mass transfer resistance causes decreased biodegradability. However, mass transfer resistance may lower the rates of AD, but will not determine the BMP, since it is a measure of the ultimate biodegradability of the substrate. Chang et al. (2001) reported that parts of the FA are not available for AD. The structure of these refractory fractions might shield substrate from hydrolysis when irreversibly bound, which could be the reason for the observed reduced BMP values noted in the literature and in BMP_2_CFA.

The rates of AD in BMP_2_CFA were also affected by the addition of CFA. The initial digestion rates were enhanced significantly (p < 0.1) in all the flocculated samples compared to the non-flocculated sample (0 g/kg): the production rate in the first 4 days was 169 ± 6 N-mL/d for the non-flocculated batch and 214 ± 3, 212 ± 0 and 206 ± 0 N-mL/d for 5, 7.5 and 10 g/kg batches, respectively. On day 1, the volatile fatty acids (VFA) concentrations of the non-flocculated batches were below the detection limit, indicating a direct conversion of VFA intermediates to methane. Apparently, methanogenesis was not the rate limiting step during the BMP assays. However, on day 4, for the flocculated batches, 84, 125, and 169 mg/L of total VFA was found in the 5, 7.5 and 10 g/kg batches, respectively. An SMA test with flocculated and non-flocculated inoculum (SMA_FA) revealed
that the methanogenic activity was slightly lowered by the addition of CFA, yielding an SMA of 0.19 ± 0.00 gCOD/(gVSS·d) for the non-flocculated and 0.18 ± 0.00 gCOD/(gVSS·d) for the flocculated sludge. Based on these SMA results, the maximum expected rate of methane production in this setup was 206 N-mL/d for the non-flocculated and 195 N-mL/d for the flocculated batches. The observed VFA accumulation indicates that the initial methane production, and thus the hydrolysis rates, were enhanced by the addition of CFA and the methanogenic activity became rate limiting.

In the literature, a similar phenomenon was noted. Chu et al. (2005) reported that the addition of cationic FA to waste activated sludge digestion yields increased initial methane production rates as well; however, this was not statistically supported. In addition Li et al. (2013) reported enhanced digestion rates in the presence of cationic FA. It was postulated that increased digestion rates were the result of enhanced microbial interactions due to the reduced distance between acidogens, acetogens and methanogens, with the addition of cationic FA. However, no evidence was presented for this hypothesis.

We hypothesize that FA addition increases the hydrolysis rates by the increased interactions between inoculum bacteria and the substrate surface. Increased enzymatic hydrolysis effects can be provoked by higher particulate substrate concentration in the vicinity of the organisms excreting the exo-enzymes. FA in BMP_2 bound all solids, inoculum and substrate, together.

**Fluorescence excitation–emission matrix**

To investigate if FA addition enhances the interaction between substrate and exo-enzymes, the protein concentrations and the protein nature of the supernatant on day 7 of BMP_2_CFA were examined. If these interactions were indeed enhanced by binding exo-enzyme producing organisms and substrate together, lower exo-enzyme concentrations in the bulk would be expected. Tryptophan is a microbially synthesized amino acid and its concentration is an indication to what extent the proteins present in the supernatant are of microbial nature (Vivian & Callis 2001). With F-EEM measurement of the bulk liquid (Figure 3) it was observed that with increasing FA concentration, less microbially derived proteins, characterized by tryptophan, could be observed in the supernatant on day 7, whilst the total amount of proteins in the sample was similar in all bottles (RS: 59.5 ± 0.6 mg/L, C: 52.4 ± 0.6 mg/L, A: 52.2 ± 2.2 mg/L, M: 51.1 ± 1.0 mg/L). The lower fraction of microbial proteins in the supernatant of flocculated batches is an indication that substrate and protein – among which exo-enzymes – synthesizing organisms were bound together.

![Figure 2](https://iwaponline.com/wst/article-pdf/76/7/1629/450356/wst076071629.pdf)
leading to less exo-enzymes being free in the supernatant. This supports our hypothesis.

If exo-enzyme producing organisms and substrate interactions were enhanced by dosing FA, this enhancing effect on the digestion rate should become more profoundly visible when dosing FAs to a BMP test where no stirring is applied. This was tested, but no significant difference could be observed in digestion rates between the flocculated and non-flocculated samples in non-stirred conditions (BMP_3_U in Figure 4). The viscosity of the flocculated batch was, however, 19% lower than the non-flocculated batch.

To the authors’ knowledge, the effect of viscosity on the hydrolysis in AD has not been studied to date. The effect of viscosity on hydrolysis in human intestines, however, has been studied in detail. Increasing the viscosity in human intestines is shown to lower the hydrolysis rate of starch (Ellis et al. 1988; Dartois et al. 2010). The relation between hydrolysis rate and viscosity could be explained by the diffusion rates, which are enhanced by decreasing the viscosity (Einstein 1905). Low concentrations of hydrolysis products favour the enzymatic hydrolysis rates because of minimized product inhibition. Lower diffusion rates of hydrolysis products in high viscous solutions result in higher local product concentrations, subsequently leading to lower conversion rates. Therefore, the increased hydrolysis rates observed in this study may be explained by the lowered viscosity of the medium due to the presence of CFA or MFA. However, further research is needed in which a kinetic model can help to understand the factors involved in the increased hydrolysis rates (Zhen et al. 2015).

Figure 3 | F-EEM images of the supernatant of BMP_2_CFA on day 7 with 0 g/kg (sample nr 1), 5 g/kg (sample nr 2), 7.5 g/kg (sample nr 3) and 10 g/kg (sample nr 4). On 275 nm (Ex.) and 310 nm (Em.) is the area where fluorescence of tryptophan, characterizing microbial-derived proteins, is located. The higher the density in this area, the more microbially derived protein is present.
Sludge dewatering

As expected, due to their refractory characteristics, the FAs were capable of altering the sludge characteristics throughout the digestion process. CST results of the different digested sludges (of equal TS concentration) of BMP_1, shown in Table 4, indicate a positive effect of dosed FAs (CFA and MFA) after digestion. The lower CST values in the flocculated sludges (C and M) compared to non-flocculated sludges (RS) are probably due to the lower fraction of small particles in the flocculated sludges (Figure 5).

The application of CEPT (C and M) increased the percentage cake DS content when the sludge mixture was dewatered with the Mareco bench-scale filter press compared to RS (Table 4). The best dewatering results were obtained with CFA flocculated sludge but also the sludge treated with MFA showed improved cake DS content compared to the digested raw settled sludge.

Economic consequences

The evaluation of the possible economic consequences of CEPT application in combination with AD was based on a steady-state Biowin simulation (Figure 6) of the STP Leiden Noord during dry weather flow conditions. The addition of FAs resulted in a lower COD load fed to the water line, higher biogas production rates and an increased dewaterability and thus lower sludge disposal costs (Table 5). Since the COD/N ratio for STP Leiden Noord is already too low for complete biological denitrification, additional denitrification capacity is reached by sand filtration with acetic acid dosage. Therefore, flocculating/coagulating COD in the PS increases the acetic acid demand, impacting the operational costs.

### Table 4 | Dewatering characteristics: CST, SRF and blinding index (β, positive value indicates blinding)

<table>
<thead>
<tr>
<th>Sludge dewatering variables</th>
<th>Cake DS [%]</th>
<th>CST [s]</th>
<th>SRF [cm/g]</th>
<th>β [-]</th>
<th>Effluent filter press</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Proteins [mg/L]</td>
</tr>
<tr>
<td>RS</td>
<td>18.8 ± 0.4</td>
<td>159 ± 11</td>
<td>3.99 × 10^{10}</td>
<td>0.037</td>
<td>46.4 ± 0.0</td>
</tr>
<tr>
<td>C</td>
<td>20.0 ± 0.7</td>
<td>130 ± 13</td>
<td>3.80 × 10^{10}</td>
<td>0.089</td>
<td>39.3 ± 0.0</td>
</tr>
<tr>
<td>M</td>
<td>19.3 ± 0.1</td>
<td>128 ± 12</td>
<td>3.45 × 10^{10}</td>
<td>-0.221</td>
<td>38.2 ± 0.1</td>
</tr>
</tbody>
</table>

Figure 4 | BMP test with non-stirred conditions (BMP_3_Unstirred) with flocculated sludge (5 g/kg) and non-flocculated sludge (0 g/kg).
considerably. The simulation shows that a COD/N of 8.88 is sufficient for biological denitrification without acetate dosing.

**Economic consequences for dewatering**

Following the Biowin calculations, the final digested sludge disposal for C and M flocculated sludge is decreased, but it could not compensate for the increased costs of acetic acid and of the FAs themselves. In an STP with a higher COD/N ratio or with N removal over nitrite or autotrophic N removal, the outcome can be different. In these cases the dosage of a cationic FA in the PS can be considered, due to the avoided sludge disposal costs and increased biogas production.
Moreover, the footprint of the STP can be decreased, since the dosage of FA will allow the use of a belt filter instead of a PS plus a sludge thickener. This will also lead to a higher DS content that can be fed to the digester, and thus to a lower digester volume. The effect of this last aspect on the AD process itself should be further studied.

CONCLUSION

FAs added to the PS maintain their effect throughout all sludge processing facilities. In the PS, more readily degradable biomass is removed by flocculation, resulting in a higher BMP of the primary sludge. In the anaerobic digester, FAs lower the viscosity, which correlates to an increased hydrolysis rate. The latter is most likely caused by increased diffusion rates of the metabolic intermediates due to the lowered viscosity. However, FAs also contribute to binding substrate, such that it is no longer fully available for AD. The subsequent dewatering of digested sludge was also affected: an increased DS concentration was observed after CEPT. The filterability of the digested CEPT sludge improved and larger sludge flocs facilitated dewatering. A known drawback of CEPT is that the COD/N ratio can be lowered to such an extent that it may compromise the biological denitrification capacity. Therefore, even though increased biogas production and decreased sludge disposal costs can be achieved, the application of CEPT in a conventional STP targeting nutrient removal will not be economically feasible. However, with the prospect of a low COD/N-tolerant STP, such as Annamox, CEPT may become economically feasible. In such case, CEPT will increase the biogas production, decrease sludge production and reduce the footprint of the primary treatment, aeration tank and anaerobic digester.

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