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Impact of Sludge Floc Size and Water Composition on Dewaterability

In order to observe the impact of different water compositions on sludge dewaterability, assessments of floc sizes using a particle size analyzer and of sludge dewaterability based on the capillary suction time (CST) test were carried out. Synthetic raw water had small floc sizes, and synthetic domestic wastewater had both larger median floc sizes and a better correlation between sludge dewaterability and median floc sizes. The floc size distribution results showed that synthetic raw water is associated with a narrow particle size distribution. In comparison, synthetic domestic wastewater produced a wider distribution. However, the CST values were similar for both waters. Compared to synthetic wastewater, natural wastewater had the largest distribution with generally larger particle sizes.

Keywords: Biosolids, Coagulation, Natural water, Synthetic wastewater, Test apparatus design

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1 Introduction

1.1 Background

Generally, the water content of sludge, also called biosolids, is approximately 95 %. The excess water needs to be reduced prior to disposal in order to reduce the material volumes. Consequently, almost half of the treatment costs can be committed to dewatering and disposal [1]. Sludge dewatering has been considered as one of the most expensive but also one of the least well understood elements of the water and wastewater treatment processes [2, 3]. Since the early 1970s, the key test to measure sludge dewaterability is the capillary suction time (CST) test. The CST testing apparatus provides a simple, flexible, rapid, and inexpensive method to measure sludge dewaterability, which particularly supports the design of filter presses in the industry [1–3].

In the UK, large volumes ($> 11\ m^3 s^{-1}$) of raw water, usually reservoir water, and domestic wastewater are processed every day in water and wastewater treatment plants [4]. The treatment of raw water will produce tap water, while the treatment of domestic wastewater will separate contaminants from the water and subsequently enhance the quality of the resultant discharge. In water treatment, coagulation processes, which are followed by further treatment steps for liquid and solid separation, are the most commonly used processes to remove particles from water [5].

Coagulation increases the tendency of particles to attach to one another, thus forming larger-size agglomerates. Particle size is therefore an important factor in the coagulation process [6], where it has an important role in influencing the settling process following coagulation. The larger the agglomerate, or floc, particle size, the easier it can be removed from the water [7].

In relation to sludge dewaterability, sludge characteristics including particle size have an important role in sludge dewaterability assessment tests [8]. Sludge dewaterability is highly dependent on sludge floc characterization, in particular, the particle size distribution and the presence of small particles [9], which are determined by coagulation mechanisms.

Furthermore, the composition of sludge is highly dependent on the treatment process and the wastewater composition [10–13]. The quality of treated water and sludge is dependent on the quality of the source water [9, 14, 15]. The efficiency of the dewatering process is highly dependent on the nature of the sludge [9].

The quality of raw water, source of drinking water, will determine the selection of the treatment process in a water treatment plant. The quality of the drinking water sources is dependent on a range of factors such as natural geology, land use, and pollution [16]. The raw water content is often dominated by its inorganic matter such as clay particles [3]. In contrast, domestic wastewater is relatively high in organic content such as human feces [17, 18]. Furthermore, organic sludge contains fats, fibers, protein, and sugars [19].

1.2 Rationale, Research Aim, and Objectives

In order to obtain a sample with consistent water quality characteristics for laboratory tests, synthetic raw water and synthetic domestic water should be used (at least for benchmark-

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ing purposes) in all experiments. The use of synthetic waters minimizes differences in experimental conditions, which is particularly important for most laboratory-scale tests [19]. The properties of 'natural' or 'real' water samples can often be highly variable and very dynamic. These properties depend on the operational conditions of the treatment plant and may change over time during transport, handling, and storage [19]. Although the water and sludge compositions impact on the sludge characteristics, there has been no detailed investigation of the effects of different water compositions on the sludge floc size and on the dewaterability of the associated sludge. This paper seeks to assess these parameters.

Using ferric chloride as a coagulant, a range of experiments were conducted at the bench scale to assess the impact of different water compositions on floc size and sludge dewaterability, using a range of mixer shapes and applying different rapid mixing velocities to make the findings representative of various industrial scenarios. The main objectives of this research are to assess the impact of different:

(i) water compositions (synthetic raw water and synthetic domestic wastewater) on the relationship between floc sizes and sludge dewaterability;
(ii) mixer shapes (radial, axial, and magnetic stirrer) on the relationship between sludge floc sizes and sludge dewaterability; and
(iii) water compositions (synthetic raw water, synthetic domestic wastewater, and natural domestic wastewater) on floc size distributions.

The findings are of relevance for practitioners involved in sludge management and treatment associated particularly with water, wastewater, biotechnological and chemical industrial applications.

2 Materials and Methods

2.1 Dewaterability Tests

Coagulation experiments were undertaken to explore the influence of each variable on the CST. This section provides an overview of the dewaterability tests, the coagulants and mixers, how samples were prepared, and an outline of both the coagulation and floc size measurements.

The key measure of efficiency with respect to the sludge dewatering process is traditionally the CST test value [20, 21]. The capillary suction pressure generated by a filter paper is used to suck liquid from the sludge sample. The rate at which water permeates through the paper varies depending on the sludge characteristics and the filterability of the sludge cake formed on top of the filter paper. The CST is obtained from two electrodes placed at a specific interval from the funnel containing the sample. The time taken for the advancing liquid front to pass between these two electrodes is the CST value. A relatively low CST value indicates good sludge dewaterability [18].

The specific resistance to filtration (SRF) test, which is another common but more time-consuming and inflexible dewaterability test, was performed for some experiments to confirm the CST findings [17]. The test was performed by pouring a flocculated sample into a Buchner funnel operated at 80 kPa negative vacuum pressure, with a Whatman No. 1 filter paper (Whatman International Ltd., London, UK).

2.2 Coagulants and Mixers

The coagulant ferric chloride (Sigma Aldrich Company Ltd., Gillingham, UK) was investigated. Ferric chloride stock solutions were prepared by mixing ferric chloride concentrates with distilled water to produce a concentration of 1000 mg L^{-1}. Utilizing distilled water minimized quality variation and ensured consistent and repeatable process performance. These solutions were stored in the fridge and renewed every 3 weeks to obtain fresh solutions.

Three shapes of mixers and mixing methods were used (radial, axial, and magnetic) to disperse the coagulant into the water to be 'treated'. The influence of all mixers on the sludge dewaterability process was also assessed. The mixer types and shapes were chosen based on the information provided by the companies producing and/or selling standard mixers used by the water and wastewater industry, such as Chemineer Ltd. (Derby, UK) and Promix Mixing Equipment and Engineering Ltd. (Mississauga, Canada).

The radial and axial mixers were obtained from Monmouth Scientific Ltd. (Bridgwater, UK). The axial mixer represents the shape of a jar test paddle, whilst the radial mixer is a small version of a radial mixer used in the water industry. The radial mixer has two blades, which are 1.2 cm long and 0.8 cm wide and are located at a 45° angle from the mixer shaft. In comparison, the axial mixer has the same blade dimensions, but the blades are located at a 90° angle from the shaft. The magnetic stirrer IKA REO was purchased from Sartorius Instrumental Ltd. (Belmont, UK). The magnetic stirrer comprises an elongated rod, which operates at the base of the chamber, whereas the other mixers operate at a higher elevation (1.5 cm from the bottom) within the test beaker. The magnetic stirrer is 3 cm long and 0.5 cm wide. The edges of the stirrer are rounded. All mixers have diameters of 3 cm. Mixing took place in a 250-mL round glass beaker with internal dimensions of 6.5 cm in length and 9.0 cm in height.

2.3 Sample Preparation

Real raw water and raw wastewater and their corresponding biosolids have unstable properties, i.e. their water quality parameters are changing constantly. Therefore, synthetic raw water (representing reservoir water contaminated with inorganic solids) and synthetic domestic wastewater (simulating domestic wastewater containing both organic and inorganic matter) sludges were used for the CST tests in order to simulate consistent water properties, which is essential for research purposes. Tab. 1 shows the components of the synthetic domestic wastewater. For comparison only, natural domestic wastewater was also used. The wastewater was obtained from the United Utilities wastewater treatment plant at Davyhulme in Manchester. Samples were taken from the approach channel before the sedimentation unit.

Table 1. Composition of the synthetic domestic wastewater sample.

No.	Constituent	Concentration [$mg L^{-1}$]
1	Dextrin	150
2	Ammonium chloride	130
3	Yeast extract	120
4	Glucose	100
5	Soluble starch	100
6	Sodium carbonate	150
7	Detergent (commercial)	10
8	Sodium dihydrogen orthophosphate	100
9	Potassium sulfate	8.3
10	Kaolin	10 000

A kaolin solution was used in this study to simulate the sludge content of synthetic raw water [22]. Sample preparation was undertaken by adding 1 g kaolin (Sigma Aldrich Company Ltd., Gillingham, UK) to 100 mL distilled water. This solution was mixed at 1200 rpm using a magnetic stirrer for 5 min to produce a well-mixed solution. Samples were freshly prepared for each experimental run.

The synthetic domestic wastewater recipe followed recently published guidelines [23], using kaolin to simulate total suspended solids (TSS; Tab. 1). All chemicals were supplied by Sigma Aldrich Co. Ltd. (Gillingham, UK). The wastewater contained about 1 % of TSS. This solution was prepared freshly every day (or sometimes every 2 days) and was always stored in a fridge to avoid the uncontrolled growth of microorganisms that might influence the wastewater quality.

2.4 Coagulation Experiments

The experimental coagulation methods applied in this research study are based on previous methods [6]. The influence of the rapid mixing velocity on the coagulant performance using ferric chloride was assessed. A 100-mL water sample was poured into a glass beaker. The coagulant ferric chloride was subsequently added. After adjusting the pH value with sulfuric acid (H_2SO_4) or sodium hydroxide (NaOH) to reach a value of approximately 6.5, the sample was mixed rapidly by using a mixer at variable high rates (from 60 to 100 rpm at 5-rpm intervals) for 1 min at each step, and then at a moderate rate of 50 rpm for 15 min.

Sedimentation was permitted for 15 min and the sludge (dense flocs) was carefully separated from the supernatant by discarding the supernatant, so that only sludge remained in the glass beaker. After switching on of the CST apparatus (Triton Electronics Ltd., Great Dunmow, UK) and using Whatman 17 chromatographic paper, the sludge was poured into the funnel of the CST apparatus.

The particle characteristics of the sludge were determined using a particle size analyzer (Horiba Laser Scattering Particle Size Analyzer LA-950; Horiba Instruments Inc., Insine, CA, USA). The instrument calculates the correlation between the intensity and the angle of light scattered from a particle, and subsequently determines the particle size based on the Mie scattering theory (scattering of electromagnetic radiation by a sphere). Floc size shearing was minimized during the experiment by careful mixing during the measurement process. An overview of the detailed measurement procedure is outlined on the company website [24].

Three replicate measurements were undertaken for each experiment described above. All values mentioned or displayed in this paper are mean values unless otherwise specified.

3 Results and Discussion

3.1 Impact of Synthetic Raw Water Flocs on Dewaterability

The impact of different synthetic flocs on sludge dewaterability was evaluated (Figs. 1 and 2). Synthetic raw water together with ferric chloride as the coagulant was assessed in this section. The median floc size was determined after coagulation,

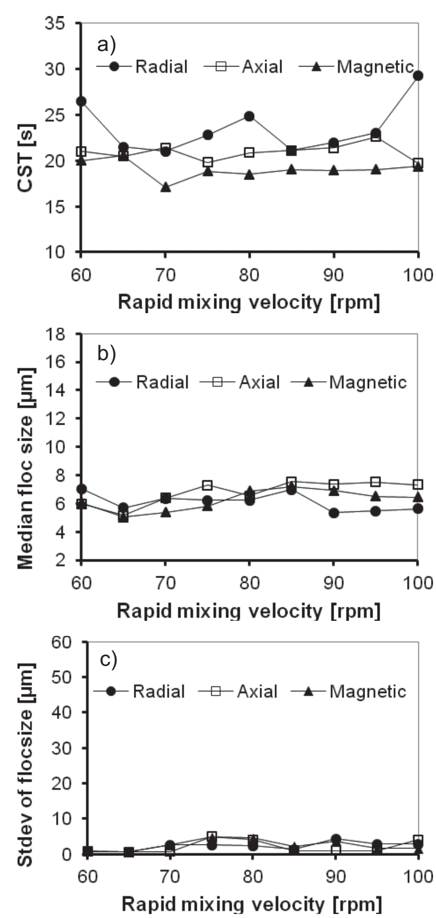

Figure 1. (a) CST, (b) median floc size, and (c) stdev of floc size as a function of the rapid mixing velocity and a specific stirrer type for synthetic raw water samples.

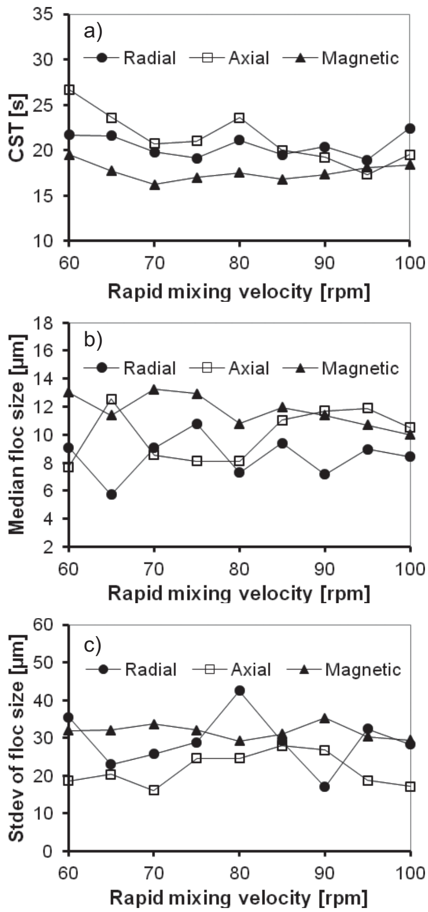

Figure 2. (a) CST, (b) median floc size, and (c) stdev of floc size as a function of the rapid mixing velocity and a specific stirrer type for domestic wastewater samples.

flocculation, and sedimentation. Figs. 1 a, 1 b, and 1 c indicate the CST values, floc median sizes, and floc size standard deviations (stdev), respectively. The scales were chosen to allow for an easy comparison between the components of Figs. 1 and 2. The findings indicate that different rapid mixing velocities correlate well with sludge dewaterability, but poorly with the floc median size and floc size stdev. The Pearson's product-moment correlation coefficients, which indicate the strength of the relationship between two variables, are shown in Tab. 2. The coefficient is a measure of the linear correlation (dependence) between two variables, giving a value between 1 and –1. It is widely used as a measure of the strength of the linear dependence between two variables; the higher the correlation value, the stronger is the relationship between the variables. The correlation values between different rapid mixing intensities and the sludge dewaterability values for three shapes of mixers were –0.73 for the radial, –0.87 for the axial and –0.89 for the magnetic stirrer, see also Fig. 1 a. The coefficients of correlation for different rapid mixing intensities and median floc sizes were –0.18, 0.75 and 0.44 for the radial, axial and magnetic stirrers, respectively (see also Fig. 1 b). The coefficients vary considerably if comparing Fig. 1 a with Fig. 1 b. This can be explained by the poor correlation between the CST value and the floc size for synthetic raw water, see also Sect. 3.4. In comparison, the coefficients for different rapid mixing velocities and floc size stdev were 0.64 for the radial, –0.63 for the axial and 0.40 for the magnetic stirrer, see also Fig. 1 c.

Table 2. Comparison of coefficients of correlation for different stirrers with respect to synthetic raw water.

Components of comparison	Coefficient of correlation		
	Radial	Axial	Magnetic
Rapid mixing versus CST	–0.73	–0.87	–0.89
Rapid mixing versus floc size	–0.18	0.75	0.44
Rapid mixing versus stdev of floc size	0.64	–0.63	0.40
CST versus floc size	–0.07	–0.46	–0.16

The CST value had a poor correlation with the floc median size and the floc size stdev, as illustrated in Fig. 1 b and 1 c, respectively, and by the coefficient-of-correlation data (Tab. 2). The coefficients of correlation for CST and median floc sizes were –0.07 for the radial, –0.46 for the axial and –0.16 for the magnetic stirrer.

With respect to the different mixer shapes, the application of the magnetic stirrer was associated with the lowest CST values (Fig. 1 a). The floc median size was relatively small, regardless of using a radial, axial or magnetic stirrer (Fig. 1 b).

This result can be explained by considering previous research [25, 26]. The floc strength plays an important role in sludge dewaterability testing. If the particle is large but has little strength, it disintegrates very easily. In comparison, small flocs are harder to break up [25].

Application of a magnetic stirrer produces low CST values but does not yield large floc sizes [27]. One of the factors that determine sludge dewaterability is the floc structure together with the associated physical characteristics such as size and density. Smaller flocs are created when there is a high concentration of relatively small solids with low bound water content. Sludges produced by using a magnetic stirrer tend to have denser flocs compared to sludges associated with other mixer shapes [27]. Therefore, the magnetic stirrer produces lower CST values even though it is associated with larger floc sizes.

Fig. 1 b shows that increasing the rapid mixing velocity has an impact on the floc size. The floc median and mean size figures indicated that lower rapid mixing velocities produce smaller floc sizes. However, as the rapid mixing velocity increased, the floc sizes became larger, and once the optimum rapid mixing was reached, the floc size decreased in response to the increase in rapid mixing velocity.

It is likely that the rapid mixing velocity has an important role in the formation of flocs and their corresponding floc sizes [28–30]. The floc size depends on hydrodynamic processes due to size changes if the mixing intensity is modified [29]. Lower rapid mixing velocities have less impact on the formation of flocs, which is due to the conditions produced by turbulence. Slow turbulence does not encourage an appropriate coagulant distribution within the water so that floc formation cannot occur perfectly and homogenously.

The requirement of rapid mixing to foster floc size creation is due to the formation of coagulant hydrolysis products in less than 7 s from the addition of the coagulant to the water [31]. Therefore, mixing should be very rapid to achieve the optimum mix between the coagulant and the particle. Moreover, in the destabilization process, high-intensity mixing will have additional benefits supporting floc formation [14]. After reaching optimum conditions indicated by the size of the flocs, enhancement of the rapid mixing intensity brings about a decrease in the floc size. This result is similar to findings of previous research [29, 32]. Rapid mixing velocities, using alum and ferric chloride as coagulants, were assessed in the past [32]. When using ferric chloride, primary iron particles are retained and the hydroxide flocs are eroded and split due to high-intensity mixing and the corresponding impact on floc size.

Furthermore, using synthetic raw water as the water sample in the coagulation process produces particle sizes with narrow-range stdev. Using kaolin as the only ingredient creates a more uniform floc size during the coagulation process. Moreover, the dewatering characteristics of kaolin are very much dependent on particle size and distribution, sphericity (measure of how round an object is) of the particles, bed porosity, water-retaining capacities, and variation in the dispersion properties [7]. The use of kaolin in the water sample results in rather uniform floc sizes (Fig. 3).

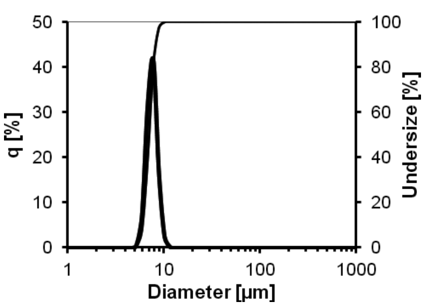

Figure 3. The percentage of similar particle size (*q*) and the accumulative of *q* value (undersize) as a function of the floc size diameter distribution for synthetic raw water.

The SRF test was performed to test the CST findings. The correlation coefficients between CST and SRF for the radial, axial and magnetic stirrer applications were 0.88, 0.99 and 0.99, respectively. These findings confirm that both tests provide similar findings.

3.2 Impact of Synthetic Domestic Wastewater Flocs on Dewaterability

Fig. 2 shows the CST, median floc size and stdev of the floc size as a function of the rapid mixing velocity and a specific stirrer type for domestic wastewater samples. The floc sizes in Fig. 2 b were similar to those in Fig. 1 b. In general, the application of a magnetic stirrer resulted in the lowest CST. This finding is supported by the particle size analyzer results, indicating that the magnetic stirrer produced the largest floc size. The stdev of the floc size using synthetic domestic wastewater is higher than that using synthetic raw water.

Tab. 3 presents the coefficient-of-correlation values of different parameters while using synthetic domestic wastewater. The coefficients between different rapid mixing intensities and sludge dewaterability are –0.85 for the radial, –0.83 for the axial and –0.87 for the magnetic stirrer. In comparison, the coefficients of correlation for different rapid mixing intensities and median floc sizes are 0.52, 0.72 and 0.62 for the radial, axial and magnetic stirrer, respectively. The coefficients for different rapid mixing velocities and floc size stdev are 0.52 for the radial, 0.66 for the axial and 0.83 for the magnetic stirrer. Finally, the corresponding values for CST and median floc sizes are –0.69 for the radial, –0.72 for the axial and –0.88 for the magnetic stirrer.

Table 3. Comparison of coefficients of correlation for different stirrers with respect to synthetic domestic water.

Components of comparison	Coefficient of correlation		
	Radial	Axial	Magnetic
Rapid mixing versus CST	–0.85	–0.83	–0.87
Rapid mixing versus floc size	0.52	0.72	0.62
Rapid mixing versus stdev of floc size	0.57	0.66	0.83
CST versus floc size	–0.69	–0.72	–0.88

Furthermore, the highest coefficient of correlation between the CST and the median floc sizes was noted when the magnetic stirrer was used. This can be explained by the median floc size influencing the sludge dewaterability. This data shows that large median floc sizes result in lower sludge dewaterability and vice versa.

The floc size assessments undertaken in this study support previous findings indicating that a decrease in CST value correlates with an increase in floc size [33]. A lower CST value means that it is easier for the sludge to release water. Normally, the larger the floc size, the easier it is for water to be released [27]. Smaller flocs with narrow capillaries do not easily release water [7]. A large floc size makes it easier for particles to settle [33], thereby reducing turbidity.

Synthetic clay floc studies indicated poor correlations between CST and floc size. This effect is probably due to the relatively high density of the small particles, which influences the dewaterability of sludge [27]. Concerning synthetic domestic wastewater, the larger the floc size, the easier it is to dewater the floc [34]. This usually results in a linear correlation between CST and floc size.

The correlation coefficients between CST and SRF for the radial, axial and magnetic stirrer applications were –0.93, 0.66 and 0.97, respectively. These findings indicate that both tests provide rather similar results.

3.3 Floc Size Distribution in Synthetic Raw Water

Synthetic raw water represents reservoir water where the main contaminants are of inorganic nature. The particle size data of this study allow for the assessment of the distribution of floc sizes. Each data point is based on three particle size analyzer readings. Particle size statistical distribution graphs illustrate the floc size distribution influenced by the coagulation process.

Kaolin was the only ingredient in the synthetic raw water recipe. Fig. 3 presents the corresponding general particle size analysis, indicating a short range of uniform floc distribution (concentrated around 7 µm) with kurtosis and skewness values of 3.51 and 0.47, respectively. The kurtosis value indicates that the particle size distribution of this sample is extremely leptokurtic, i.e., with a narrow and sharp peak. Moreover, there is very little skewness in the distribution.

3.4 Floc Size Distribution in Synthetic Domestic Wastewater

Synthetic domestic wastewater represents 'real' domestic wastewater where the main contaminants are of organic nature. In this investigation, the recipe for synthetic domestic wastewater encompassed three different ingredients [23]. Fig. 4 indicates the corresponding general particle size distribution for synthetic domestic wastewater, which has no clear peak when compared to the distribution of raw water (Fig. 3). Synthetic domestic wastewater has a wider range of particle sizes and a larger mean floc size compared to synthetic raw water. The distribution can be described as platykurtic, i.e., with a wide and flat profile, with an asymmetric particle size distribution and a tendency towards coarse characteristics. The synthetic domestic wastewater may also have a different impact on the floc formation process. A synthetic domestic wastewater floc is characterized more by its size (Tab. 3), while a synthetic raw water floc is influenced considerably by its density, as indicated by the poor correlation between the CST value and the floc size (Tab. 2).

Synthetic domestic wastewater generally produced a wider range of particle sizes and larger flocs. In comparison, synthetic raw water, which has only one instead of three ingredients, produces a narrow particle size range and relatively small flocs. This might be explained by the more likely presence of naturally developing microorganisms within synthetic domestic wastewater compared to the synthetic raw water. The presence of any microorganism is associated with a relatively large area and a higher viscosity [21], ultimately impacting on the floc size distribution and CST value.

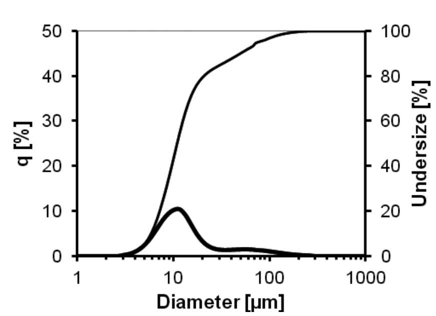

Figure 4. The percentage of similar particle size (q) and the accumulative of q value (undersize) as a function of the floc size diameter distribution for synthetic domestic wastewater.

3.5 Natural Water Floc Size Distribution

In order to obtain further information about the influence of floc sizes, a sample of natural domestic wastewater was also assessed in terms of floc size using the particle size analyzer. This comparison was made to better interpret the impact of the floc size distribution on sludge dewaterability.

The floc size distribution for natural sludge is shown in Fig. 5. The distribution is platykurtic and asymmetric. Natural sludge has a larger floc size and a more uniform particle size distribution compared to synthetic sludge. This is due to the ingredients in natural sludge being more diverse in terms of their sizes than synthetic sludge. The agglomeration process seems to be more efficient when using natural wastewater rather than synthetic water.

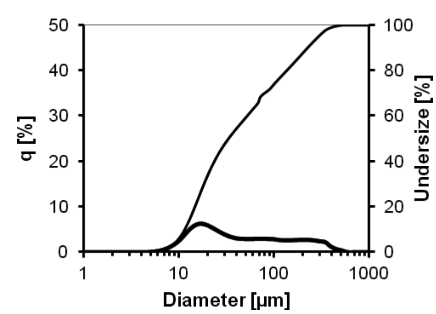

Figure 5. The percentage of similar particle size (q) and the accumulative of q value (undersize) as a function of the floc size diameter distribution for natural sludge.

Total suspended solids within natural sludge are usually relatively large and dense [35]. Natural sludge has also more hydrophobic (repelling water) content than synthetic sludge, so that it is more easily coagulated, producing bigger floc sizes than synthetic sludge [13]. Hydrophobic components can also support the formation of ferric hydroxide flocs [36, 37]. Moreover, the hydrophobic fraction has a higher molecular weight and lower repulsion against the flocculant, so that the natural sludge has a bigger floc size and a more uniform floc size distribution than the synthetic wastewater sludge [38].

4 Conclusions and Further Work

The CST findings were similar for both synthetic raw and synthetic domestic wastewater, and were confirmed by the SRF test. However, the application of a magnetic stirrer resulted in the lowest CST.

Synthetic raw water had relatively small floc sizes and a narrow-range stdev compared to synthetic domestic wastewater. Nevertheless, real wastewater has the widest and more uniform floc size distribution, indicating that synthetic waters, which are good for benchmarking purposes, might, however, not be very representative of real waters. Findings for synthetic raw water also indicate that the floc size does not correlate with sludge dewaterability, in contrast to synthetic domestic wastewater.

It seems that synthetic raw water is affected more by its floc density than by its floc size. In contrast, the synthetic domestic wastewater is affected by floc size. This may reflect the presence of microorganisms, which have a large diameter and thus influence the floc size and subsequently the sludge dewaterability process.

Further research using more complex, and therefore realistic, wastewater recipes representing discharges from different industrial sectors would be advantageous. As the main alternative dewaterability test, SRF should also be assessed for waters with different particle size distributions, and compared with CST findings for a wide range of mixers.

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The authors have declared no conflict of interest.

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