Effect of tapering on the break-up and reformation of flocs formed using hydrolyzing coagulants

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Abstract The effect of tapered-shear (diminishing velocity gradient) flocculation on the formation, breakage and reformation of flocs using aluminium sulphate and an anionic polymer were evaluated. An on-line continuous optical monitoring technique was used for this purpose. Two different mean shear rates, \( G = 60 \, \text{s}^{-1} \) and \( G = 100 \, \text{s}^{-1} \), were tried in the slow stirring stage of the experiments. For the mean \( G = 60 \, \text{sec}^{-1} \), sample was stirred at 400 rpm \( (G = 518 \, \text{sec}^{-1}) \) for 10 seconds then the stirring speed was reduced to 100 rpm \( (G = 60 \, \text{s}^{-1}) \) and held at this value for the required time (9 minutes). In the other trial, slow stirring speeds of 130 rpm, 100 rpm and 70 rpm and 150 rpm, 100 rpm and 50 rpm for 3 minutes each were used. After slow stirring, the speed increased to 400 rpm \( (G = 518 \, \text{s}^{-1}) \) for 10 seconds and then reduced back to appropriate slow stirring speed as stated above. A similar approach was applied for mean \( G = 100 \, \text{s}^{-1} \). For continuous tests, a laboratory scale set-up was constructed as a tapered flocculation system that consists of three chambers. Flocs formation in the first and third chambers were monitored and compared. Larger flocs that have higher reformation rate were produced with tapered flocculation.

Keywords Floc breakage; floc strength; floc structure; hydrolysing coagulants; tapered flocculation

Introduction Removal of suspended particles is essential in solid–liquid separation practice. Generally it is necessary to add a suitable coagulant or flocculant under conditions of intense mixing, followed by a period of slower agitation in order to promote the growth of aggregates (flocs). Mixing conditions can have a very significant effect on the performance of coagulants and flocculants (Yukselen and Gregory, 2004a). The first requirement is for the additive to be distributed uniformly among the suspension and this should be achieved by some form of rapid mixing. The particles then need to collide in order to form aggregates, and this process can be greatly assisted by some form of agitation, either in stirred tanks or some form of flow-through device.

After coagulant dosing and mixing, flocs grow initially at a rate that is determined mainly by the applied shear, the particle concentration and the collision efficiency and hence on the degree of particle destabilization caused by the added coagulant (Yukselen and Gregory, 2002a). As flocs become larger, further growth is restricted by the applied shear for essentially two reasons. Existing flocs may be broken as a result of disruptive forces (Blaser, 2000) and the collision efficiency of particles in a shear field becomes lower as particle size increases (Brakalov, 1987). A dynamic balance between floc growth and breakage can lead to a steady-state floc size distribution, where the limiting size is dependent on the applied shear rate (Mühle, 1993). Applying diminishing velocity
gradients is thought to provide suitable flocs for the subsequent processes such as filtration (Ives and Hoyer, 1998).

When flocs are subjected to an increased shear rate, breakage can occur. This may be by rupture of flocs into roughly equal sized fragments or erosion of small particles from the surface of flocs. In turbulent flow the mode of breakage depends on the floc size relative to the turbulence microscale (Serra et al., 1997). After floc breakage, regrowth may occur on restoring the previous low shear conditions. However, in some cases floc breakage may be irreversible to some extent, in which case only limited regrowth occurs (Francois and Van Haute, 1984; Clark and Flora, 1991; Spicer et al., 1998, Yukselen and Gregory, 2004b). There have been only limited studies on this aspect and the influence of mixing conditions on the reformation of flocs has not been fully evaluated.

The aim of this study is to investigate the effect of tapered shear conditions (diminishing velocity gradient) on floc formation, breakage and reformation in clay suspensions, using aluminium sulfate and an anionic polyelectrolyte as coagulants.

Materials and methods

Batch and continuous tests were performed using online optical monitoring techniques for evaluating the effect of tapering on the floc formation and breakage.

Suspension

In the study, kaolin clay was used as a model suspension. About 200 g of kaolin was dispersed in 500 mL of deionized water in a high-speed blender. To obtain full dispersion it was necessary to raise the pH of the suspension to about 7.5. After blending at 4000 rpm for 10 minutes, the clay suspension was diluted to 1 L with deionized water and allowed to stand overnight in a measuring cylinder. The top 800 mL was decanted and its solids content was found to be 135 g/L. This was diluted to give a final solids content of 50 g/L. The particles were mostly below about 5 μm in size, with a mean size of about 2 μm.

For the flocculation tests, the stock suspension was diluted in tap water to give a clay concentration of 50 mg/L. The calcium content of tap water may cause destabilization of the kaolin particles, which slowly coagulate. This would give problems in interpreting the results with hydrolyzing coagulants. To avoid this difficulty, a small amount of commercial humic acid (Aldrich) was added to the stock kaolin suspension. Humic acid adsorbs on the clay particles and gives enhanced stability against divalent metal ions such as Ca²⁺. Humic acid solution was included in the stock 50 g/L kaolin to give a concentration of 0.5 g/L. The diluted samples for all of the batch coagulation experiments had a turbidity of about 10 NTU. Parts of the continuous tests were conducted using 100 NTU turbidity.

Coagulants

Aluminium sulfate hydrate (Al₂(SO₄)₃ · 16 H₂O; Merck, >96%) ‘alum’, was used. Stock M/10 alum solutions were prepared, kept in a refrigerator at 5 °C and renewed every two weeks. Magnafloc LT25 (Ciba), a high molecular weight anionic polyacrylamide, was diluted to give a stock solution of 0.1% or 1 mg/L and used mainly as a flocculation aid.

Apparatus

In the batch tests a continuous optical flocculation monitor (PDA 2000, Rank Brothers Ltd., Cambridge, UK) was used in a modified jar test procedure. The test sample was contained in 1 L beakers with stirrer units from a Floculator 2000, semi-automatic jar test device. This enables the rapid mixing and slow stirring speeds and times to be preset. For dynamic monitoring, the sample from one beaker was circulated through transparent
plastic tubing (3 mm i.d.) by means of a peristaltic pump. The pump was located after the PDA instrument to avoid effects of possible floc breakage in the pinch portion of the pump. The tubing was clamped in the PDA instrument so that the flowing sample was illuminated by a narrow light beam (850 nm wavelength). The PDA 2000 measures the average transmitted light intensity (dc value) and the rms value of the fluctuating component. The ratio (rms/dc) provides a sensitive measure of particle aggregation (Gregory and Nelson, 1986). In this work, the ratio value is called the Flocculation Index (FI). More details of the experimental method have been given by Yukselen and Gregory (2002b).

Continuous tests were performed in a flocculation tank that consisted of three basins with identical dimensions (240 × 240 × 200 mm). Two continuous optical flocculation monitors were attached to the first and third basins, respectively, and samples from each basin were circulated in the same manner as in the batch tests.

**Procedure**

Using standard jar tests with 800 mL of test suspension (50 mg/L kaolin and 0.5 mg/L humic acid in tap water) the optimum amounts of coagulant was determined. For dynamic batch tests, the sample was pumped from a stirred beaker at about 25 mL/min through the tubing and the average (dc) and fluctuating (rms) components of the transmitted light intensity were monitored by the PDA instrument. Readings were taken every two seconds and the results were stored in a computer for subsequent spreadsheet analysis. The standard test procedure was modified as follows. For the mean $G = 60 \text{ s}^{-1}$, after allowing 1 minute for steady-state readings to be established, the coagulant was dosed and the sample was stirred at 400 rpm ($G = 518 \text{ s}^{-1}$) for 10 seconds. Then, the stirring speed was reduced to 100 rpm ($G = 60 \text{ s}^{-1}$) and held at this value for the required time (9 minutes). In order to investigate the effect of tapering two more trials were conducted using slow stirring speeds of 130, 100 and 70 rpm for 3 minutes each and 150, 100 and 50 rpm for 3 minutes each. Furthermore, to investigate the floc breakage and reformation, the stirring speed was increased to 400 rpm ($G = 518 \text{ s}^{-1}$) for 10 seconds and then reduced back to appropriate slow stirring speed as stated above. The whole procedure was repeated for $G = 100 \text{ s}^{-1}$. All experiments were carried out 2–3 times and very little variation was observed. The $G$ values were calculated following Mejia and Cisneros (2000) who used a similar jar test device.

For the continuous tests, three different slow stirring rates (150 rpm, 100 rpm and 50 rpm) were applied to each of the flocculation chambers. Floc formation in the first and third chambers were monitored using the PDA instruments. Furthermore, water at the outlet of the flocculation tank was filtered using standard filter paper with medium retention and flow rate and the turbidity values were measured.

**Results and discussion**

**Batch tests**

Effects of tapering, progressive reduction of the applied shear rate on the floc formation, breakage and reformation were investigated using alum and an anionic polymer. For this purpose, two different mean $G$ values (60 and 100 $\text{ s}^{-1}$) were applied. Effect of polymer addition was also investigated under the same conditions.

Figure 1a shows the changes in FI during three sets of tapered flocculation experiments having the same mean $G = 60 \text{ s}^{-1}$. To clarify the effect of tapering, slow stirring for one set was kept constant (100 rpm). In the other two sets 130–100–70 rpm and 150–100–50 rpm were applied, respectively. Slow stirring was followed by rapid stirring at 400 rpm for 10 seconds and again at the slow stirring rate specified above for a total of 9 minutes for
As seen, the floc size increased rapidly in all three cases reaching a plateau (region of constant FI) that is generally thought to reflect a balance between floc growth and breakage. Initial parts of the curves showed that the greater the slow stirring rate, the quicker the FI is to reach the zone of constant FI. It is seen that tapering has a positive effect on the floc size at this mean shear rate $G = 60 \, \text{s}^{-1}$. It is observed that the floc breakage is rather rapid, with the 130–100–70 rpm case giving the smallest floc size after breakage. It is noteworthy that the same set of stirring conditions gave the largest FI prior to the breakage. The rise in FI for the non-tapered case is more rapid than for the tapered sets but the degree of recovery was almost the same at the end of the 9 minutes of slow stirring.

The effect of polymer addition (LT25) is shown in Figure 1b. At doses of 125 $\mu\text{g/L}$ larger flocs (higher FI values) were observed in all cases of slow stirring. The breakage
was rapid and gave 2–3 times reduction in FI. Regrowth of flocs at slow stirring was observed but the final FI values were less than these before breakage. A comparison of floc size has shown that increased shear caused an abrupt breakage of flocs to smaller sizes. On returning to the previous, low shear rate flocculation, regrowth occurred to only a limited extent for alum and alum plus polymer but both formation and reformation occurred to a greater extent for the polymer case.

Figure 2 shows that the results of experiments carried out in exactly the same way as $G = 60\, s^{-1}$ but using mean $G = 100\, s^{-1}$. The FI versus time curves are similar in both $G$ values tried but the effect of tapering is not so significant when alum is used as the only coagulant. It is clear that in both cases irreversible floc breakage is available since the FI value covers to only a fraction of its value before breakage.

![Figure 2](https://iwaponline.com/ws/article-pdf/6/2/139/418014/139.pdf)

**Figure 2** (a) Formation, breakage and reformation of flocs by aluminium sulphate at dose of 3.4 mg/L as Al. Coagulant is dosed at 60 s and rapid stirring is applied for 10 s, followed by slow stirring at three different sequence of speeds: (1) 130 rpm for 540 s; (2) 200 rpm for 180 s, 130 rpm for 180 s and 60 rpm for 180 s; (3) 160 rpm for 180 s, 130 rpm for 180 s and 100 rpm for 180 s. At 660 s, the stirring speed is increased to 400 rpm for 10 s. The stirring speed is then returned to the slow stirring speeds indicated above. (b) Same as Figure 2a but with 125 µg/L of anionic polymer added at the end of rapid stirring.
Continuous test
Continuous flocculation tests were conducted to investigate the effect of tapering on floc formation on a larger scale (Figure 3). For this purpose, the same kaolin clay suspension as used for the batch tests was prepared. For the first 3600 seconds of the test, a turbidity of about 10 NTU was used and then the turbidity was increased to about 100 NTU. The effect of tapering was not so significant with low turbidity but for the higher turbidity the effect of tapering became more apparent. The fluctuations in the FI correspond to the points of lower turbidity in the influent. Nevertheless, FI values of chamber 3 had higher values, indicating larger flocs. It should be noted that a retention time equivalent to the time required for the flocs to reach steady-state size (plateau value of FI) is used in the design of the flocculator. Turbidities obtained after filtration were all less than 1 NTU.

Conclusions
The concept of tapered shear flocculation is used to minimize fragmentation and improve flocculation performance but its effect on the floc reformation has not been investigated thoroughly. A comparison of tapered versus non-tapered flocculation under same average shear gradient indicates that tapered shear flocculation produces larger flocs and regrowth of these flocs after breakage are faster but irreversible. Although there have been previous reports of the irreversible nature of floc breakage in the case of hydrolyzing coagulants, the underlying mechanism remains unclear. It should be noted that floc size and degree of recovery after floc breakage is much more significant when an anionic polymer is used as a flocculation aid.

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