Temperature effects on flocculation, using different coagulants

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Abstract Temperature is known to affect flocculation and filter performance. Jar tests have been conducted in the laboratory, using a photometric dispersion analyser (PDA) to assess the effects of temperature on floc formation, breakage and reformation. Alum, ferric sulphate and three polyaluminium chloride (PACl) coagulants have been investigated for temperatures ranging between 6 and 29°C for a suspension of kaolin clay in London tap water. Results confirm that floc formation is slower at lower temperatures for all coagulants. A commercial PACl product, PAX XL 19, produces the largest flocs for all temperatures; and alum the smallest. Increasing the shear rate results in floc breakage in all cases and the flocs never reform to their original size. This effect is most notable for temperatures around 15°C. Breakage, in terms of floc size reduction, is greater for higher temperatures, suggesting a weaker floc. Recovery after increased shear is greater at lower temperatures implying that floc break-up is more reversible for lower temperatures.

Keywords Coagulants; flocculation; floc breakage; floc strength; temperature effects

Introduction
Flocculation and filter performance are known to be affected by water temperature. Temperature affects the water viscosity and the chemistry and rate of the coagulation process.

Several researchers (e.g. Hanson and Cleasby, 1990) have reported that at lower temperatures flocculation is slower and flocs are smaller than at higher temperatures. Exall and Vanloon (2000) reported that low temperatures inhibited removal of organic matter by aluminium sulphate (alum) and that alum is a poor cold water coagulant with or without organic matter present. In direct filtration, the slower rate of flocculation could mean that there has been inadequate time for flocculation prior to filtration during the winter. Hanson and Cleasby (1990) also reported that alum flocs at low temperatures were very vulnerable to break up due to fluid shear, and that even the weakest ferric floc was stronger than the strongest alum floc. This has implications for both flocculation and filtration. Alum is generally seen to be less effective at low temperatures, which has been attributed to lower density flocs (Hanson and Cleasby, 1990) and aggregate size (Morris and Knocke, 1984).

Recent experiments to assess the effect of flow changes on filter performance displayed different effects for different water temperatures that could not be explained by viscosity changes alone (Thurston et al., 2002). In general the laboratory filter displayed less particle/floc shedding in response to a flow change at lower temperatures. Preliminary jar tests comparing alum and PAX XL1 at different temperatures showed alum flocs to be more resistant to break-up and to recover more easily at lower temperatures.

Conventional jar tests are useful for examining floc formation and settling rates but they do not quantify strength and re-attachment ability of the flocs. Yeung and Pelton (1996) developed techniques to pull apart individual flocs and in doing so, contradicted earlier theories that in fact there is no scaling relationship between floc strength and floc size. This
has important implications when considering water temperature variations, as larger flocs tend to form in warmer water, and they may not necessarily be stronger. The same research group later added to this by suggesting that floc strength depends on the shear rate in which flocs were formed and that conditions for optimum flocculation did not coincide with those for maximum shear strength of flocs (Yeung et al., 1997). Similarly, Dyer and Manning (1999) found that small flocs were, on average, of higher density than large ones and were stronger because there are more points of contact between the particles when densely packed.

The photometric dispersion analyser (PDA) was developed by Gregory and Nelson (1986) and can be used to give an indication of floc size, breakage and reformation. This was studied for alum flocs (Yukselen and Gregory, 2002) and it was found that breakage occurs rapidly after an increase in shear and that alum flocs do not reform to their original size when shear is subsequently reduced.

In this paper the effect of water temperature on floc size, strength and recovery after shear has been examined with the aid of the PDA.

**Experimental programme**

All experiments were conducted using a suspension of 50 mg/l of kaolin clay in London tap water. London tap water has a high total hardness (~280 mg/l as CaCO₃) and alkalinity (~240 mg/l as CaCO₃). The coagulants used in his study were aluminium sulphate, ferric sulphate and 3 polyaluminium chloride products, kindly supplied by Kemira Kemi AB, Helsingborg, Sweden. The PACl products are detailed in Table 1.

Jar tests were performed to find the optimum dose of aluminium sulphate (alum). From these jar tests it was decided to investigate alum doses giving 3.4 mg/l Al and 1.4 mg/l Al. Doses for the PAX coagulants were calculated to give the same concentrations of aluminium. Doses for ferric sulphate were chosen to give the same molar concentration of iron as for aluminium.

**Floc breakage and recovery experiments**

800 ml of the kaolin suspension were put in a jar test beaker and slow stirring (50 rpm, $G = 23 \text{ s}^{-1}$) was started. After 60 s the coagulant was added followed by 10 s of rapid mix at 400 rpm ($G = 520 \text{ s}^{-1}$). Slow stirring then continued for 600 s when the stirring rate was increased to 400 rpm for 10 s. The stir rate was then reduced to 50 rpm again. Throughout the formation, breakage and recovery of flocs the water was sampled at 19 ml/min. and passed through the photometric dispersion analyser (PDA) so that the flocculation index could be recorded. This procedure is described in a companion paper (Gregory, 2004). The flocculation index (FI) is from the ratio of amplified RMS/DC values that are the output from the PDA. It gives an indication of floc size.

Temperatures ranging from 6°C to 29°C were investigated. Cold water temperatures were achieved by storing water in a refrigerator before use. Intermediate temperatures were achieved by mixing refrigerated and tap water. The highest temperatures were achieved by using water that had reached summer room temperatures in the laboratory. The temperature was maintained during the lowest temperature experiments by placing the jar test beaker in

<table>
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<th>Table 1 Details of the PACl products used in this study</th>
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<tr>
<td><strong>Product</strong></td>
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<td>PAX-XL 19</td>
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<td>PAX-XL 1</td>
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<td>PAX 16</td>
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an insulated vessel filled with iced water. In this way temperatures were controlled to +/-1°C during an experiment.

Results and discussion

Figures 1 and 2 show the flocculation index for a range of temperatures for alum and PAX XL19, dosing the coagulants at 1.4 mg/l Al and 3.4 mg/l Al, respectively.

It can be seen that at all temperatures PAX XL19 produces bigger flocs than alum, as indicated by the flocculation index, which is related to floc size (see Gregory, 2004). The smallest PAX flocs are bigger than the biggest alum flocs. Floc breakage occurs at 600 s and in all cases the floc size reduced immediately. As the shear is reduced again, after 10 s, re-growth begins but none of the flocs reach their previous size (i.e. before breakage).

For higher doses of aluminium (3.4 mg/l Al, as in Figure 2) it can be seen that flocculation is much more rapid for all temperatures and that PAX XL19 shows less variation in floc size with temperature than for the lower Al dose.

![Figure 1](image1.png)

**Figure 1** Formation, breakage and recovery of flocs in a kaolin suspension flocculated with Alum and PAX XL19 (dosed at 1.4 mg/l Al) at different temperatures

![Figure 2](image2.png)

**Figure 2** Formation, breakage and recovery of flocs in a kaolin suspension flocculated with Alum and PAX XL19 (dosed at 3.4 mg/l Al) at different temperatures. (Data for additional temperatures has been omitted from the graph for clarity of presentation. The same trends were seen.)
The average flocculation index for the first plateau just before floc break-up, due to increased shear (FI1) was calculated for each temperature and five coagulants, dosed at the equivalent of 1.4 mg/l Al. These results are shown in Figure 3. All of the aluminium based coagulants show an increase in floc size with water temperature. PAX XL19 produces the largest flocs for all temperatures, followed by PAX XL1 and then PAX 16. Alum and ferric sulphate flocs are of a similar size, although the ferric sulphate flocs show less variation in size with temperature. Alum produces the smallest flocs at low (winter) temperatures which will have an impact on sedimentation. For similar sized flocs all year round then ferric sulphate would seem to be the best choice. These results are consistent with those of previous researchers.

The flocculation index data (e.g. displayed in Figure 1) can be used to obtain a floc strength factor and a floc recovery factor (adapted from Francois, 1987). These are calculated as follows:

\[
\text{Strength Factor (\%)} = \frac{\text{FI2}}{\text{FI1}} \times 100
\]

\[
\text{Recovery Factor (\%)} = \left( \frac{\text{FI3} - \text{FI2}}{\text{FI1} - \text{FI2}} \right) \times 100
\]

Figure 3 Variation of floc size, as indicated by flocculation index (FI), with temperature for different coagulants in a kaolin suspension

Figure 4 Strength and recovery factors for different coagulants, doses and temperatures
where FI1 is defined above, FI2 is the flocculation index after breakage and FI3 is the flocculation index after recovery to the new plateau value.

The strength and recovery factors are shown in Figure 4 for all the aluminium coagulants used. Three important general trends are apparent:
1. Floc breakage increases with increasing temperature
2. Floc recovery/re-formation decreases with increasing temperature
3. The smaller the flocs, the less they break and the better their recovery

There appears to be a drop in floc re-formation ability at around 15°C, which improves a little at temperatures above this. Further work is required to establish whether this is significant.

Water viscosity increases as temperature decreases and this cannot explain the observed effects. The influence of temperature on floc growth, breakage and recovery is most likely related to changes in coagulant chemistry. It is known that hydrolysis constants for aluminium species change appreciably over the temperature range studied (Hanson and Cleasby, 1990). Kinetic factors may also play a role.

**Conclusions**
Water temperature affects flocculation, by affecting floc size, strength and ability to reform after shear break-up. This will affect clarification and filtration processes, coupled with the effects of viscosity changes due to temperature.

Warmer temperatures generally produce bigger flocs that break more easily and re-form less well than at lower temperatures.

Aluminium based coagulants produce flocs that vary more with temperature, in size and strength, than ferric sulphate flocs.

The PDA is an extremely useful tool for examining the relative behaviour of flocs for changes in the flocculation conditions.

**References**