

Reducing turbidity and coagulant residue in treated water through optimization of rapid mix conditions

K. Ebie and Y. Azuma*

Department of Civil Engineering, Kitami Institute of Technology, 165 Koen-cho, Kitami, Hokkaido, 090-8507, Japan (*E-mail: dse99001@std.kitami-it.ac.jp)

Abstract This study reports basic research on the effectiveness of raising the rapid agitation strength (velocity gradient, or G_R value) in improving the treatment efficacy of coagulation and sedimentation. Coagulation and sedimentation treatment with a normal velocity gradient of 100–200 s^{-1} reduces turbidity to less than 1 mg/L but leaves a significant amount of coagulant residue and thus does not reduce the suction time index (STI) to a desirable level. By contrast, higher G_R values yield improvements in the turbidity of the treated water, as well as marked improvements in the STI. Good coagulation and sedimentation treatment is also related to reductions in filtration head loss.

Keywords Coagulant residue; G_R value; PAC; PSI-3; rapid agitation strength (velocity gradient); suction time index (STI)

Introduction

A great deal of attention with regard to existing coagulation and sedimentation treatment has been focused on finding ways to reduce suspended particles, such as turbidity, under conditions of relatively low rapid agitation strengths, or G_R values, and relatively large coagulant dosages. Nonetheless, as long as researchers continue to rely on these methods, the amount of generated sludge and coagulant residue in treated water will rise, the filtration head loss will increase rapidly, and aluminium will be discharged into filtered water.

The authors believe that to improve the treatment effectiveness of coagulation and sedimentation, it is important to increase the rapid agitation strength, or G_R value, in order to increase the dispersion of coagulants and to maintain a large adsorption surface area for a long period of time by controlling the agglomeration of coagulated floc. (Amirtharajah and Mills, 1982, Brown *et al.*, 1985, Camp, 1955, 1968, Letterman *et al.*, 1973).

To establish proof for this basic hypothesis, this study uses turbidity and the suction time index (STI) as indices to (1) analyze the factors that impact STI variance using a 3-way classification method, (2) perform conventional coagulation and sedimentation treatment with a normal, relatively low G value of 150 s^{-1} , and (3) to report the characteristics and results of coagulation and sedimentation treatment when, as the authors propose, the G value is increased significantly.

Testing conditions and methods

Test apparatus and G value calculation

Photo 1 and Figure 1 show the coagulation test apparatus used in this study. The apparatus consists of a square water tank (with 200 mm sides and a depth of 300 mm) and an agitator (capable of rotating 10–800 rpm). Its main feature is that it can generate the high agitation strength (maximum 3,000 s^{-1}). Agitation paddles (6, measuring 30 mm × 10 mm) are attached to three different levels at equal intervals on the rotation axis to ensure uniform agitation of the water tank contents. The following formula was used to calculate the agitation strength, or G value (s^{-1}):

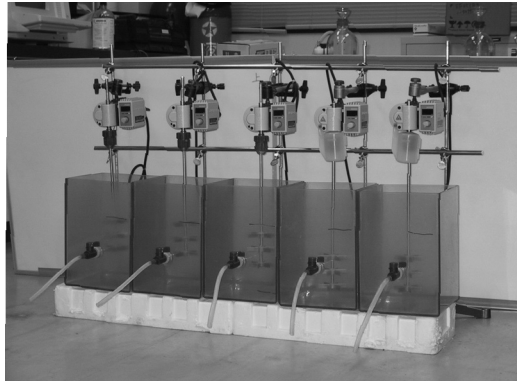


Photo 1 Apparatus for coagulation test

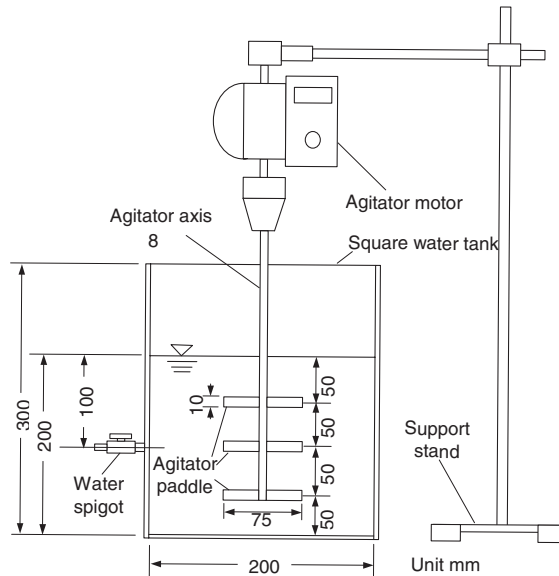


Figure 1 Apparatus for coagulation test

$$G = \{C \cdot A \cdot v^3 / (2\gamma \cdot V)\}^{0.5} \quad (1)$$

where C is the agitation coefficient (here, 1.5), A is the area of the agitation paddle (m^2), v is the angular velocity of the agitation blade (m/s), γ is the dynamic viscosity coefficient (m^2/s), and V is the agitation tank capacity (m^3).

Coagulation testing methods and conditions

The water used in the test was 8 litres of tap water from the Kitami Institute of Technology (deep well water, modified to $20 \pm 0.1^\circ\text{C}$) to which a prescribed amount of kaolin and coagulant (Poly-Aluminium Chloride, hereafter PAC, and Poly-Silicato Iron with molecular iron and silica ratio of 1:3, hereafter PSI-3) was added. (Ebie and Lee, 1998; Hasegawa *et al.*, 1989, van Benschoten and Edzwald, 1990b).

The modified water was then subjected to rapid agitation for 5 min, with a velocity gradient ranging from 60 to $1,000 \text{ s}^{-1}$, followed by 20 min of slow agitation at $G = 20 \text{ s}^{-1}$, and then 40 min of sedimentation (surface loading = 0.25 cm/min). (Gregory and Nelson, 1984;

Gregory, 1985; Hanson and Cleasby, 1990, Matsui *et al.*, 1994, 1998; Morrow and Rausch, 1974). At this point, the pH was modified to the optimal coagulation pH of a coagulant using 1N-HCl and 0.1N-NaOH (pH 6.8 ± 0.1 when using Al, and pH 6.0 ± 0.1 when using Fe). (Tambo, 1964–1965, van Benschoten and Edzwald, 1990a). After the test, a prescribed amount of treated water was collected from a spigot located 100 mm above the bottom of the agitation tank, and measurements were taken of the turbidity (integrating sphere photo-electrical method photometry), aluminium (using the oxine method) or iron (using the 1,10-phenanthroline method), and the STI, discussed below.

Measuring suction time and calculating the STI

The STI (nondimensional) was calculated by filtering both distilled water and the sedimentation-treated water collected after the coagulation test using a suction filtration device (membrane filter with a pore size of $0.45 \mu\text{m}$), and then inserting the filtration time (s) into the formula below:

$$\text{STI (nondimensional)} = \frac{\text{Suction time of 500 ml of test water (s)}}{\text{Suction time of 500 ml of distilled water (s)}} \quad (2)$$

The STI of the test water was measured based on a very precisely modified pH (the optimal coagulation value of each coagulant) and water temperature (all measurements are taken at 20°C).

Results and observations

Analysis of factors affecting the STI using the 3-way classification method

First, the following coagulation test was conducted in order to determine the factors influencing STI variance. A water sample containing approximately the same turbidity and coagulation residue contained in regular treated water was modified and subjected to rapid agitation for 10 min with a G_R value of 150 s^{-1} and $1,000 \text{ s}^{-1}$. Immediately after, 500 mL of the test water was collected and its STI was measured using the method described above.

Figure 2 shows the STI when using PAC. The STI remains nearly constant as the turbidity of the test water rises. Figure 3 shows the STI for an increased PAC dosage of 1 mg/L of kaolin. The STI decreases linearly with G_R , thought to be due to the formation of dense coagulation floc. When PSI-3 is used, the STI is remarkably high, but the trend resembles that for PAC.

Next, to quantitatively ascertain the impact of the factors that influence STI variance, a series of coagulation tests was conducted to test varying amounts of kaolin (3 levels 0, 1, and 2 mg/L), coagulant dosages (3 levels of Al or Fe, 0.2, 0.4 and 0.6 mg/L), and G_R values (3 levels of 150, 550 and 1000 s^{-1}). Table 1 shows the results for each factor that affects STI

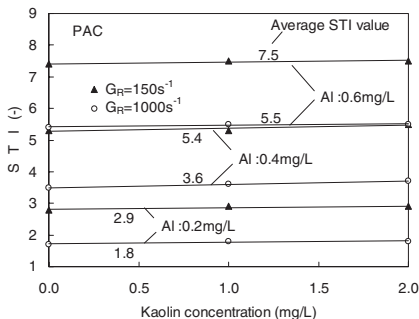


Figure 2 STI at various kaolin concentration

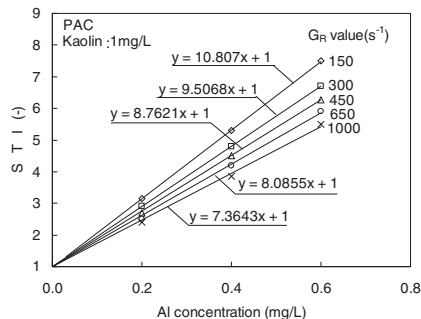


Figure 3 STI at various Al concentration

Table 1 STI variance analysis using a 3-way classification

Coagulant	Factor	DOF*	Variation	Variance	F test	Rate of impact
PAC	Al (A)	2	74.56	37.28	**	84.3
	G_R value (G)	2	12.89	6.44	**	14.6
	Turbidity (T)	2	0.07	0.03		0.1
	Error	20	0.94	0.05		1.0
	Total	26	88.46	43.80		100.0
PSI-3	Fe (F)	2	258.67	129.33	**	61.7
	G_R value (G)	2	122.92	61.46	**	29.3
	Turbidity (T)	2	2.29	1.14		0.5
	$G \times F$	4	31.88	7.97	**	7.5
	Error	16	3.48	0.22		1.0
	Total	26	419.24	200.12		100.0

* Degree of freedom

** F test with 1% significance

variance. As predicted from Figures 2 and 3, the amount of coagulant has the dominant impact; 84.3% for PAC and 61.7% for PSI-3. The next most significant factor was the G_R value. In comparison with these two, the impact of turbidity was negligible.

Coagulation and sedimentation treatment with increasing coagulant dosage

Figures 4 and 5 show the results of normal coagulation tests performed by gradually

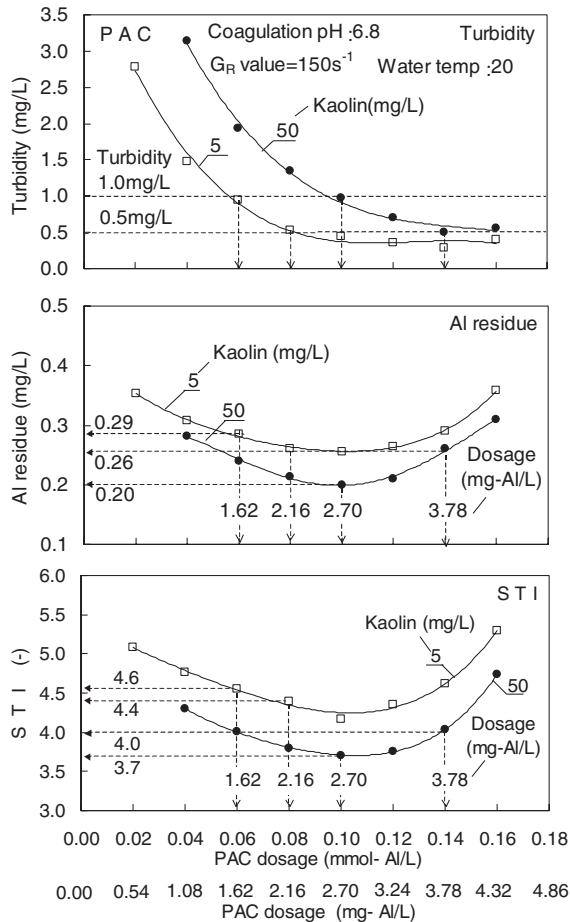


Figure 4 Turbidity, Al, and STI of treated water at various PAC dosage

increasing the coagulant dosage rates at a fixed G_R value of 150 s^{-1} . In Figure 4, the turbidity, Al, and STI improve as the coagulant injection rate rises, but turbidity is lowest when the PAC dosage is 3.78 mg-Al/L and Al residue and STI are both lowest when the dosage is 2.70 mg-Al/L . After these points, all values begin to rise again. By contrast, when PSI-3 is used, turbidity, Fe, and STI treatment effectiveness continue to improve even when the PSI-3 dosage reaches a high 8.94 mg-Fe/L , as shown in Figure 5.

Using these figures, the authors calculated the coagulant dosage needed to achieve a turbidity of 1.0 mg/L in the treated water. The treatment efficacy values at those points are shown in Table 2. This table shows that the magnitude of turbidity compared to the lowest turbidity (the figures in parentheses) under each set of conditions is quite large in every case. This means that there is still room for improving turbidity by raising the coagulant dosage. On the other hand, the same figures for Al and Fe residue show ratios of 1.1 and 1.0 when PAC is used and 2.2 and 1.3 when PSI-3 is used. The STI values are about the same. The magnitude is very low compared with that of turbidity. The target STI, the index of coagulant residue, for good coagulation and sedimentation treatment is 2.0. When PSI-3 is used, a certain level of improvement is possible if the coagulant dosage is raised significantly, but the post-treatment STI is still quite high. When PAC is used, there is very little room for improvement. These results indicate that the greatest problem is the inability to lower STI to desirable levels in normal coagulation and sedimentation treatment even if that treatment is pushed to its limits.

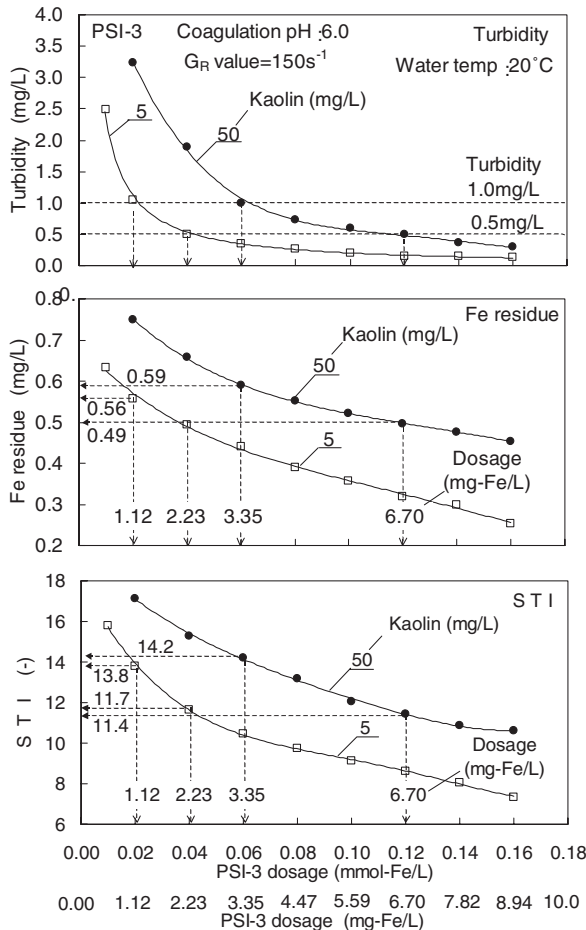


Figure 5 Variance in turbidity, Fe, and STI of treated water at various PSI-3 dosage

Table 2 Dosage required for turbidity of 1.0 mg/L in treated water, and treated water quality

Coagulant	Kaolin (mg/L)	Al or Fe dosage (mg/L)	Coagulation and sedimentation treated water quality		
			Turbidity (mg/L)	Al or Fe (mg/L)	STI (-)
PAC	5	1.62	0.94 (3.4)	0.29 (1.1)	4.6 (1.1)
		Lowest value	0.28	0.26	4.2
		Al (mg/L)	3.78		2.70
	50	2.70	0.97 (1.9)	0.20 (1.0)	3.7 (1.0)
		Lowest value	0.50	0.20	3.7
		Al (mg/L)	3.78		2.70
PSI-3	5	1.12	1.05 (8.3)	0.56 (2.2)	13.8 (1.9)
		Lowest value	0.13	0.25	7.4
		Fe (mg/L)	3.35	8.94	
	50	3.35	0.96 (4.4)	0.59 (1.3)	14.2 (1.3)
		Lowest value	0.22	0.45	10.5
		Fe (mg/L)		8.94	

* Figures in parenthesis are ratio of maximum to lowest value

Coagulation and sedimentation treatment with increasing G_R

Tables 3 and 4 show the results of a coagulation test conducted by raising the G_R value as high as $1,000 \text{ s}^{-1}$ while using PAC and PSI-3 dosages that reduce the turbidity to 1.0 mg/L at a G_R value of 150 s^{-1} .

The turbidity of the treated water for both coagulants fell with increasing G_R . With PAC, the turbidity reached a minimum of about 450 s^{-1} , and with PSI-3 the maximum was about 650 s^{-1} . In all cases, the turbidity fell to less than 0.5 mg/L, demonstrating that increasing G_R is highly effective in reducing turbidity. It should be noted that (1) the optimal G_R value at which the turbidity of the treated water was lowest differs depending on the coagulant used, and (2) as the G_R value exceeds the optimal value, the turbidity of the treated water gradually increases.

For both coagulants, the coagulant residue and STI fell with increasing G_R , and unlike the case with turbidity, reached their lowest point when the G_R value was $1,000 \text{ s}^{-1}$. The rates of improvement observed when the G_R value was raised from 150 to $1,000 \text{ s}^{-1}$ were quite remarkable; 71.7% (STI: 4.6 to 1.3) and 70.4% (STI: 3.7 to 1.1) when PAC was used, and 71.8% (STI: 13.8 to 3.9) and 83.8% (STI: 14.2 to 2.3) when PSI-3 was used. In this case, the STI could be reduced to an acceptable level.

Increasing the G_R value lowers turbidity, of course, but also greatly reduces the

Table 3 Treatment efficacy (upper level) and improvement rate (lower level) with increasing G_R

Kaolin (mg/L)	PAC (mmol-Al/L) <mg-Al/L>	G_R value (S^{-1})	Coagulation and sedimentation treated water quality		
			Turbidity (mg/L)	Al (mg/l)	STI (-)
5	0.06 <1.62>	60	1.26	0.41	5.9
		150	0.94 (0.0)	0.29 (0.0)	4.6 (0.0)
		300	0.42	0.21	2.7
		450	0.36 (61.7)	0.19 (33.3)	2.1 (53.8)
		650	0.46	0.16	1.6
		1000	0.68 (27.7)	0.15 (47.4)	1.3 (71.4)
50	0.10 <2.70>	60	2.36	0.28	4.9
		150	0.97 (0.0)	0.20 (0.0)	3.7 (0.0)
		300	0.66	0.12	2.4
		450	0.45 (53.6)	0.11 (45.0)	1.6 (56.9)
		650	0.60	0.11	1.4
		1000	0.82 (15.5)	0.10 (50.0)	1.1 (70.4)

Table 4 Treatment efficacy (upper level) and improvement rate (lower level) with increasing G_R

Kaolin (mg/L)	PSI-3 (mmol-Fe/L) <mg-Fe/L>	G_R value (S^{-1})	Coagulation and sedimentation treated water quality		
			Turbidity (mg/L)	Fe (mg/L)	STI (-)
5	<1.12>	60	1.50	0.67	15.0
		150	1.05 (0.0)	0.56 (0.0)	13.8 (0.0)
		300	0.58	0.44	8.4
		450	0.45	0.34	6.8
		650	0.38 (63.8)	0.25 (53.3)	5.1 (63.1)
		1000	0.50 (52.4)	0.18 (67.7)	3.9 (71.8)
50	<3.35>	60	2.12	0.68	15.1
		150	1.00 (0.0)	0.59 (0.0)	14.2 (0.0)
		300	0.49	0.35	7.5
		450	0.47	0.24	4.7
		650	0.46 (54.0)	0.16 (72.8)	3.5 (75.4)
		1000	0.80 (20.0)	0.13 (77.9)	2.3 (83.8)

Table 5 Relationship between final water qualities and filtration head loss

Coagulant	G_R value (s^{-1})	Turbidity (mg/L)	Al or Fe (mg/L)	STI (-)	Head loss (cm/h)
PAC	150	1.07	0.32	4.4	17.3
	450	0.45	0.22	2.5	11.6
	1000	0.80	0.17	1.7	9.2
PSI-3	150	0.59	0.52	11.1	48.8
	450	0.25	0.26	6.2	23.8
	1000	0.21	0.19	3.1	14.2

coagulant residue and STI, giving coagulation and sedimentation treatment a degree of effectiveness not possible under conventional conditions ($G_R = 150 s^{-1}$).

Table 5 shows the water quality of coagulation and sedimentation treated water for PAC and PSI-3, as well as the head loss when the water is filtered for 1 h at a filtration speed of 240 m/d using a 60 mm thick sand layer. For either coagulant, the coagulant residue and STI are significantly improved as the G_R value is increased. Furthermore, the more the STI falls, the more the head loss on the filtration drops. That is, when PAC is used and the G_R value is raised from 150 to 1,000 s^{-1} , the STI drops from 4.4 to 1.7, and the filtration head loss drops from 17.3 to 9.2 cm (61.4%). When PSI-3 is used, the STI likewise drops from 11.1 to 3.1, and the head loss drops remarkably from 48.8 to 14.2 cm (70.9%). Thus, when coagulation and sedimentation treatment is performed at high G_R , the STI falls. Furthermore, the more the STI falls, the more the head loss on the filtration drops, thus making it possible to achieve extended continuous filtration.

Conclusions

1. An analysis of the factors that impact STI variance revealed that the factor with the greatest impact is the coagulation residue, followed by the G_R value. The turbidity of treated water, by comparison, has negligible impact, and can be disregarded as a factor.
2. In normal coagulation and sedimentation treatment where a low G_R value is used, it is relatively easy to reduce turbidity. However, because of the high coagulant dosages needed to do so, there is an increased amount of sludge generated, leaving large quantities of coagulant residue in the treated water. This renders it impossible to reduce the STI to desirable levels.
3. If coagulation and sedimentation treatment is performed with higher G_R values, turbidity is reduced to its lowest levels when the G_R value is about 450 s^{-1} for PAC and about

- 650 s^{-1} for PSI-3 (less than half the turbidity recorded with a G_R value of 150 s^{-1}). The coagulant residue and STI can be further reduced by raising the G_R value as high as 1,000 s^{-1} , at which it is also possible to achieve acceptably low STI levels.
4. The more the STI falls, the more the head loss on the filtration drops, thus making it possible to achieve extended continuous filtration.

References

- Amirtharajah, A. and Mills, K.M. (1982). Rapid-Mix Design for Mechanism of Alum Coagulation, *Jour. AWWA*, **74**(4), 210–216.
- Brown, G.M., Gregory, J., Jackson, P.J., Nelson, D.W. and Tomlinson, E.J. (1985). An On-line Monitor for Flocculation Control, in *Instrumentation and Control of Water and Wastewater Treatment and Transport Systems*, R.A.R. Drake, Ed., Pergamon, pp. 239–245.
- Camp, T.R. (1955). Flocculation and Flocculation Basin, *Proc. ASCE*, **79**, No. 283, pp.1–18.
- Camp, T.R. (1968). Floc Volume Concentration. *Jour. AWWA*, pp. 656–673.
- Ebie, K. and Lee J.H. (1998). New Technology for Improving Settled Water Quality by Recycling Activated Sludge in Water Purification. *Proceeding of 11th IWSA-ASPAC Regional Conference*, pp.153–159.
- Gregory, J. and Nelson, D.W. (1984). A New Optical Method for Flocculation Monitoring, *Solid-Liquid Separation*, pp.172–182, Ellis Horwood, Chichester.
- Gregory, J. (1985). Turbidity Fluctuations in Flowing Suspensions, *J. Colloid Interface Sci.*, 105(2), pp. 357–371.
- Hanson, A.T. and Cleasby, J.L. (1990). The Effect of Temperature on Turbulent Flocculation, Fluid Dynamics and Chemistry, *Jour. AWWA*, **83**(11), pp. 56–73.
- Hasegawa, T., Onitsuka, T., Suzuki, M., Ehara, Y., Hashimoto, K., Goto, K. and Tambo, N. (1989). A New Inorganic Poly Coagulant. *International Conference on Water & Wastewater*, pp. 63–68.
- Letterman, R.D., Quon, J.E. and Gemmill, R.S. (1973). Influence of Rapid-Mix Parameters on flocculation, *Jour. AWWA*, **65**(11), pp.716–722.
- Matsui, Y., Ogawa, K. and Tanbo, N. (1994). Optimum-mixing condition of coagulation. *Jour. AWWA*, **715**, pp. 42–50.
- Matsui, Y., Yuasa, A., Furuya, Y. and Kamei, T. (1998). Dynamic Analysis of Coagulation with Alum and PACl, *Jour. AWWA*, **10**, pp. 96–106.
- Morrow, J.J. and Rausch, E.G. (1974). Colloid De-stabilization With Cationic Polyelectrolytes as Affected by Velocity Gradients. *Jour. AWWA*, pp. 646–656.
- Tambo, N. (1964–1965). A Fundamental Investigation of Coagulation (I–IV). *Jour. AWWA*, **361**, **363**, **365**, **367**.
- Van Benschoten, J.E. and Edzwald, J.K. (1990a). Chemical Aspects of Coagulation using Aluminium Salts, Hydrolytic Reactions of Alum and Poly-aluminium Chloride, *Water. Res.* **24**, pp. 1519–1526.
- Van Benschoten, J.E. and Edzwald, J.K. (1990b). Chemical Aspects of Coagulation using Aluminium Salts, Coagulation of Fulvic Acid using Alum and Poly-aluminium Chloride, *Water. Res.* **24**, 1527–1535.