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Time requirement for rapid-mixing in coagulation

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Abstract

Mechanisms of coagulation have been widely investigated by many researchers. Little is understood about the critical role of rapid-mixing in water treatment. In this study, a photometric dispersion analyzer (PDA) was employed to monitor clay coagulation by alum and polymeric aluminum chloride (PACl). The effect of rapid-mixing time on particle removal was studied. A standard jar test was performed to determine the degree of destabilization of particles. Maximum ratio outputs of PDA measurements were inversely related to residual turbidities. Adequate rapid-mixing times evaluated from both PDA and mixing tests were close to each other. Studies of coagulation mechanisms at various rapid-mixing times indicated that mixing time had significant impact on charge neutralization and sweep coagulation. The difference in residual turbidity can be attributed to the characteristics of microflocs. The rise in residual turbidity in sweep coagulation suggested the breakage of microflocs. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Coagulation; Rapid-mixing; Photometric dispersion analyzer (PDA); Water treatment; Turbidity

1. Introduction

Coagulation can be broken down into several sequential steps. Chemical reactions occur immediately after the addition of coagulants, forming active coagulant species. The active species promotes the destabilization and the contact of suspended colloids through 'rapid-mixing'. The engineering practice of rapid-mixing has relied heavily on accumulated experiences. Since 1969 [1], a series of researches on rapid-mixing has been started. A study of rapid-mixing involves theories in coagulant chemistry, mixing, and mass transfer. Due to of such complexity, no simple and concrete guideline on the operation can be offered for the engineering design of rapid-mixing. Studies on rapid-mixing can be approached microscopically or macroscopically, depending on whether the focus is on the physical or chemical parameters.

From the microscopic point of view, the nature of coagulants and their coagulation mechanisms are the keys to the success of rapid-mixing. Studies have shown that the variation in hydrolysis species of coagulants dominates the coagulation mechanism. Edzwald et al. [2] employed a turbulent pipe-flow reactor to examine the influence of the hydrolysis time on particle destabilization of

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alum coagulation. They found that the Al hydroxo-complex species of maximum destabilization capacity formed within 0.1 s after chemical addition. The efficiency of coagulation decreased continuously in the first 6 s and then remained the same. In studying the rapid-mixing of alum coagulation, Amirtharajah and Mills [3] discovered that rapid-mixing is significant if adsorption and charge neutralization are the principal mechanisms of the coagulation. In a study on coagulation by polymers, Amirtharajah and Jones [4] found that rapid-mixing is critical in colloid bridging.

The microscopic view of study on rapid-mixing has drawbacks such as insufficient mixing when the operation is scaled up, as well as the failure to consider the break-up of aggregates during rapid-mixing. These phenomena were also noticed by Clark et al. [5–8] who performed a series of studies to explore the role of rapid-mixing on coagulation. In a continuous study on various sizes of mixing tanks, they found that small mixing tanks were more sensitive to experimental conditions. As a result, a feedback approach was introduced to include all of the operational parameters in rapid-mixing. Therefore, some researchers have shifted their focus towards the subsequent processes such as sedimentation and filtration to view rapid-mixing from a macroscopic point of view [1,9]. The idea is to monitor the turbidity of the effluent from sedimentation and filtration to reflect the efficiency of rapid-mixing. The optimal rapid-mixing condition is the one corresponding to the lowest residual turbidity. A macro-approach is more applicable in the operation of water treatment plants. However, no model can include all operational parameters due to the great variation in treatment units.

Other researchers focused their studies on the impact of rapid-mixing on flocculation (or slow-mixing) which is the immediate subsequent process. Vrale and Jordan [10] described the effect of rapid-mixing intensity on particle aggregation in flocculation. In the study, they introduced an apparent aggregation rate (K_{app}) to evaluate the operation of rapid-mixing. Letterman et al. [12] and Mhaisalkar et al. [11] have suggested that K_{app} is an effective index for rapid-mixing. The major disadvantage of this approach is that it is time-consuming to apply the K_{app} in water treatment works. Studies from the macro-point of view ignore important parameters such as the coagulant type and coagulation mechanisms. As a result, no general guideline for rapid-mixing can be established due to the great variation in experimental conditions.

To integrate both chemical and physical parameters of rapid-mixing, we applied an optical instrument, a photometric dispersion analyzer (PDA), to quickly determine the most important parameter for rapid-mixing, the duration required for coagulation. PDA was first introduced by Gregory to monitor the state of aggregation of flocculation [15]. Our laboratory has proven that the ratio output of PDA can accurately reflect the state of aggregation, which offers a useful aggregation index for determining the optimal coagulant dosage [19,20]. The signals, which reflect the scattering condition of the aggregates flowing through the detector, are recorded by a detector and their root-mean-square (rms) is calculated (V_{rms}). From the V_{rms} and the mean transmitted light intensity (dc), the state of aggregation in the suspension can be quantified using the ratio of V_{rms} to dc, as shown in Eq. (1):

$$\text{ratio} = \frac{V_{rms}}{dc} = \left(\frac{NL}{A}\right)^{1/2} C \quad (1)$$

where N is the number concentration, L is the length of the optical path, A is the effective cross-sectional area of the light beam, and C is the cross section of the scattered light. In this study, the PDA monitoring technique was explored to quickly determine the duration required for rapid-mixing in coagulation. The residual turbidity of the supernatant from the subsequent sedimentation was measured to examine the effect of rapid-mixing time on coagulation.

2. Materials and methods

2.1. Synthetic water sample

A synthetic stock suspension of clay was prepared by dispersing reagent-grade clay particles

(UK Ball Clay) in R.O. water to simulate the raw water sample. Three test suspensions were prepared by diluting the stock clay suspension into 250, 50 and 10 mg l^{-1}, with the corresponding turbidities of 180, 38 and 8 NTU, respectively. The particle size distribution of the synthetic water sample was analyzed by a particle size analyzer (PS-230, Coulter). The mean particle size of the synthetic water sample was 4.5 μm. The specific conductivity of the water sample was adjusted to 300 μs cm^{-1} by $NaClO_4$ solution (Merck, reagent-grade) and the alkalinity was adjusted to 100 mg l^{-1} as $CaCO_3$ by adding $NaHCO_3$ (Merck, reagent-grade). The pH remained within a range of ± 0.3 U in all experiments because of the high pH buffering capacity attributed to the abundant alkalinity.

2.2. Preparation of coagulant solution

The stock solution of alum was prepared by dissolving $Al_2(SO_4)_3 \cdot 18H_2O$ (Merck, reagent-grade) in D.I. water to 10 000 mg l^{-1} as Al. The fresh alum coagulant solution of 1000 mg l^{-1} as Al was prepared from the stock solution before each test. The stock Polymeric aluminum chloride (PACl) solution of 1000 mg l^{-1} as Al was freshly prepared for each trial by dissolving reagent-grade PACl (Showa Chemicals Inc, Japan) in the D.I. water. The basic characteristics of the PACl is given by the company as basicity (OH/Al) 2, 10% wt. as Al_2O_3 and 3.5% wt. as H_2SO_4. All coagulant dosages reported in this study were presented in the unit of mg l^{-1} as Al.

2.3. Jar test

In the study, jar tests and mixing tests were conducted with the same mixing device and agitator. Jar tests were performed on the synthetic water to evaluate the optimum coagulant dosing and the predominant coagulation mechanism. The mixing device was a square acrylic vessel ($L \times W \times H$, $11.5 \times 11.5 \times 21$ cm), which is often referred to as a gator jar. The mixing was provided by a 76×25 mm flat rectangular blade centrally located in the vessel. The blade was driven by a thin spindle via a motor of adjustable speed from 10 to 300 rpm (PB-700 Jar tester, Phipps & Bird Inc). The coagulant was injected directly above the liquid surface. This mode of injection is similar to the operation practiced in the Taiwan Water Works. The velocity gradient was determined following the work by Cornwell and Bishop [14]. The mixing was provided with a 1-min rapid-mixing and a 20-min slow-mixing at rotational speeds of 200 rpm ($G = 350$ s^{-1}) and 30 rpm ($G = 25$ s^{-1}), respectively. The zeta potential (ZP) of the particle was measured with a zeta-meter after rapid-mixing (Zeta-Meter System 3.0, ZETA METER Inc). After settling for 10 min, the residual turbidity of the supernatant was measured with a turbiditimeter (Hach Ratio/XR).

2.4. Mixing test

Rapid-mixing times were evaluated by the mixing tests. The experimental condition was the same as that of the jar tests mentioned above with the exception of the duration of the rapid-mixing. After settling for 10 min, the residual turbidities of the supernatant were measured. In this study, we also applied an optical technique to quickly determine the time required for rapid-mixing. The technique and the experimental procedure are discussed in the next section.

2.5. Particle aggregation monitored by PDA

The PDA monitoring system included a mixing device, coil tube, peristaltic pump and the PDA 2000. The mixing device was the same as that mentioned in Section 2.3. A Tygon tube of inner diameter (I.D.) 3-mm was coiled around a cylinder to convey the suspension from the mixing tank to the flow-through detector of the PDA. The flow of the suspension was provided by a pump located downstream of the PDA and the effluent was wasted.

To start the system, the raw water sample was first run through the PDA, the dc output was adjusted to 10 V, and the rms output was set at 0.5. The coagulant was injected and the motor was adjusted to 200 rpm to provide mix-

ing. After rapid-mixing, the coagulated suspension was siphoned out of the vessel at a flow rate of 22 ml min^{-1}. Ratio values of the PDA were recorded at 10-s intervals continuously for 370 s starting from the time the coagulant was added.

The destabilized particles after coagulant injection aggregated in the coiled tube due to the shear force in the tube. The extent of flocculation occurring in the tube flow depended on the dimensionless number *Gt*, in which *t* was the mean residence time of the tube. In this study, the length of the tube from the beginning of the coil tube to the flow-through detector of the PDA was 6 m. A *Gt* value of 10^4 was provided for the tube flocculation in this study [18].

3. Results and discussion

3.1. Determination of predominant mechanism of coagulation

Water samples containing 38 NTU turbidity were used in this section. The ZP and the residual turbidity for each coagulant dosage were measured to investigate the predominant coagulation mechanism.

3.1.1. Alum coagulation

Several alum dosages, ranging from 1 to 10 mg l^{-1} as Al, were selected to coagulate water samples. The ZP of the particles in the suspension and the residual turbidity after mixing and settling are

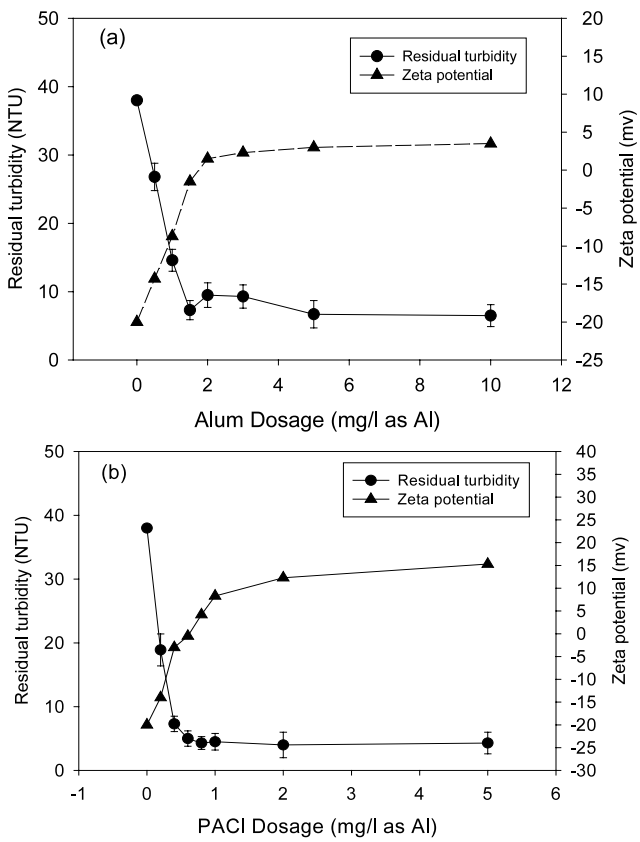

Fig. 1. Effects of (a) Alum; and (b) PACl dosages on residual turbidity and zeta potential of the suspension. Initial turbidity 38 NTU; final pH 7.5.

shown in Fig. 1(a). Each point of the residual turbidity represents the average from five jar tests. The ZP of the particles in the synthetic raw sample was −20 mV. The ZP increased with the addition of alum. A zero ZP was found at 1.5 mg l^{-1}, at which the first dip in the residual turbidity, 6.2 NTU, was observed. The zero ZP at this dosage indicates that the predominant mechanism of alum coagulation is charge neutralization.

The ZP continued to increase with the increasing coagulant concentration till 2 mg l^{-1} was added. After that, the ZP remained around 3.0 mV. The turbidities corresponding to both 2 and 3 mg l^{-1} as Al were around 9.5 NTU. According to the conclusion by Amirtharajah [3], the predominant coagulation mechanism at 1.5 mg l^{-1} of dosage was a combination of the adsorption and the charge neutralization. This mechanism was abbreviated ACN mechanism in this paper. The slight increase in the residual turbidity at 2 and 3 mg l^{-1} was due to the charge reversal by the $Al(OH)_{3(s)}$ precipitate. At dosages higher than 3 mg l^{-1}, the turbidity was reduced with increasing alum dosage. The lowest turbidity, 4.8 NTU, was observed at 10 mg l^{-1}, when sweep coagulation was the predominant mechanism. The large quantity of $Al(OH)_{3(s)}$ precipitate was capable of sweeping the fine colloidal particles from the water.

In our study, no obvious restabilization was detected between the ranges of ACN coagulation and sweep coagulation as observed by other researchers [16]. This could be due to the high alkalinity and the large amount of SO_4^{2-} in the test samples. High alkalinity maintained the pH of the solution at around 7.5, when the alum was largely in the form of $Al(OH)_{3(s)}$. The $Al(OH)_{3(s)}$ adsorbed on the surface of the particle and reduced the negative charge with its slightly positive charge. Although the adsorption of excessive $Al(OH)_{3(s)}$ resulted in charge reversal, the existence of SO_4^{2-} neutralized the positive charge and prevented the particles from restabilization. When a large amount of alum, at dosages of more than 5 mg l^{-1} as Al, was added, sweep coagulation became the predominant mechanism, and a lower residual turbidity was observed.

3.1.2. PACl coagulation

Jar tests with seven PACl dosages, ranging from 0.2 to 5 mg l^{-1} as Al, were performed. As shown in Fig. 1(b), the turbidity was reduced with increasing PACl dosage, and then stabilized at 0.6 mg l^{-1}, a dosage considered the optimal dosage. The ZP increased with the increasing coagulant concentration. A near zero ZP at the optimal dosage indicates that the coagulation mechanism with PACl is charge neutralization. The PACl are mostly polynuclear species of high charge valence.

In the over-dosing region from 1 to 5 mg l^{-1}, no increase in the residual turbidity was observed despite the fact that charge reversal was detected. This can be explained by the theory presented by Yao [17] that there are sites on the colloidal surfaces available for the adsorption of polynuclear Al, therefore, these particles can be further destabilized by the mechanisms of adsorption and bridging. The ZP of around 13 mV in this over-dosing region was maintained by the adsorption of SO_4^{2-} ions present in the original PACl stock solution.

In conclusion, the optimal coagulant dosages in regard to residual turbidities were 1.5 and 5 mg l^{-1} for alum and 0.6 mg l^{-1} for PACl. We used these three dosages to evaluate the time required for the coagulation of water samples.

3.2. Comparison of aggregation index and residual turbidity under various mixing times

Turbidity removal is highly related to the state of particle aggregation. The effect of the duration of rapid-mixing on turbidity removal and particle aggregation on a water sample of 38 NTU was investigated. The aggregation index, represented by the PDA ratio output, and the residual turbidity obtained from the mixing tests were compared. The optimal coagulant dosage and the predominant coagulation mechanism were investigated by previous jar tests as mentioned in Section 3.1.

To compare the results from the aggregation index and the residual turbidity, the rapid-mixing time corresponding to the PDA ratio output must be adjusted. Based on the flow rate and the tube diameter, a delay of 95 s was calculated to account for the time the suspension flows from the

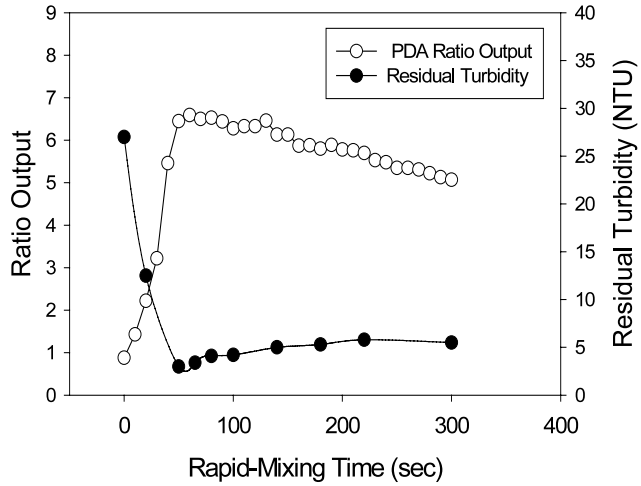

Fig. 2. Variations in PDA ratio output and residual turbidity with the change of rapid-mixing time. Initial turbidity 38 NTU; final pH 7.5; alum dosage 1.5 mg l^{-1} as Al.

vessel to the detector. However, the abrupt increase in the ratio output was observed after 70 s in each batch. This discrepancy can be explained by the theory proposed by Gregory [18]. He has suggested a Poiseuille flow for the particle flow. The effective concentration front advances in a parabolic profile in the PDA detector. The time for the destabilized particle to flow through the coil tube is 0.75 times the theoretical retention time. Ninety-five seconds times 0.75 times is approximately 70 s. In other words, the ratio output recorded at the 70th-s, rather than the 95th-s, should be used to represent the state of aggregation during the flocculation in the coil tube without any pre-mixing. Therefore, 70 s was subtracted from the PDA recording time to reflect the actual mixing time.

The results for 1.5 mg l^{-1} alum is shown in Fig. 2. In Fig. 2, the ratio output increased sharply with the rapid-mixing time. It reached a maximum value of 6.59 after 50 s of rapid-mixing, and then declined linearly to 5 after 300 s of rapid-mixing. As claimed by many researchers [19,20], the maximum ratio output indicates the formation of optimal aggregates, occurring after 50 s of rapid-mixing.

Residual turbidities from various rapid-mixing times were also shown in Fig. 2. Each data point represents the average result of three mixing tests. The residual turbidity was 27 NTU without any rapid-mixing. With increasing duration of rapid-mixing, the residual turbidity decreased sharply. The lowest residual turbidity, 2.7 NTU, was achieved at mixing time of 50 s. Beyond that, a slight increase in the residual turbidity was detected with the increasing mixing time. After 140 s, the residual turbidity was 5.0 NTU. The turbidity was maintained between 5.0 and 6.0 NTU till 300 s.

A similar result was observed for the test with 5 mg l^{-1} alum, as shown in Fig. 3. The minimum residual turbidity was detected at 20 s, at which the maximum ratio output was also observed. The ratio output continuously declined with the increasing time, and reached 2.5 at 300 s. Results with 0.6 mg l^{-1} PACl are given in Fig. 4. The ratio output reached a maximum value of 5.1 at 180 s, and then remained at around 5 after 300 s of rapid-mixing time. The residual turbidity of the sample without rapid-mixing was 12.8 NTU. The residual turbidity decreased continuously with increasing rapid-mixing time. The residual turbidity corresponding to 180 s of rapid-mixing was 3.3 NTU. It gradually declined to around 3.0 NTU between 180 and 300 s. Similar to the alum coagulation, a significant inverse correlation was discovered between the residual turbidity and the ratio output.

3.3. Time requirements for rapid-mixing

Water samples from low turbidity (8 NTU) to high turbidity (180 NTU) were investigated for their optimum coagulant dosages and predominant coagulation mechanisms by jar tests. As determined before, the optimum dosage was 1.5 or 5 mg l^{-1} for alum and 0.6 mg l^{-1} for PACl for water samples with 38 NTU. For samples with 180 NTU, the optimum dosage was 2.5 or 5 mg l^{-1} for alum and 1.5 mg l^{-1} for PACl. The optimum dosage for low turbidity water, 8 NTU, was 3 mg l^{-1} for alum because sweep coagulation was the only coagulation mechanism at low turbidity condition.

Matsui et al. [13] utilized a particle sizer to measure the state and the dynamics of the aggregation in a coagulated suspension. In their experiment, several important characteristic times were defined. The time required to complete the formation of active coagulant species and particle destabilization is T_1, the time required to reduce the

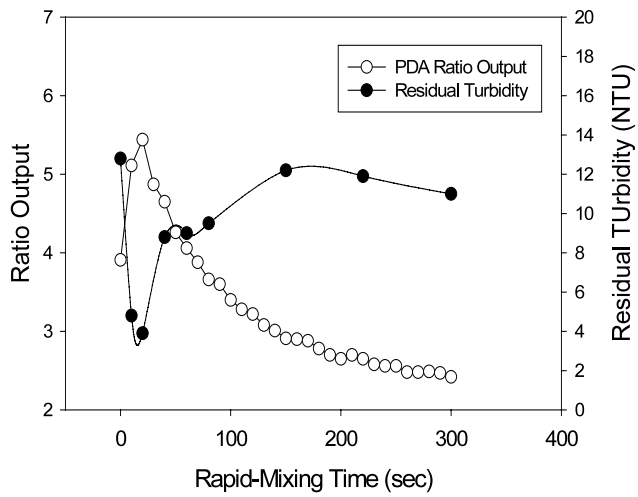

Fig. 3. Variations in PDA ratio output and residual turbidity with the change of rapid-mixing time. Initial turbidity 38 NTU; final pH 7.5; alum dosage 5 mg l^{-1} as Al.

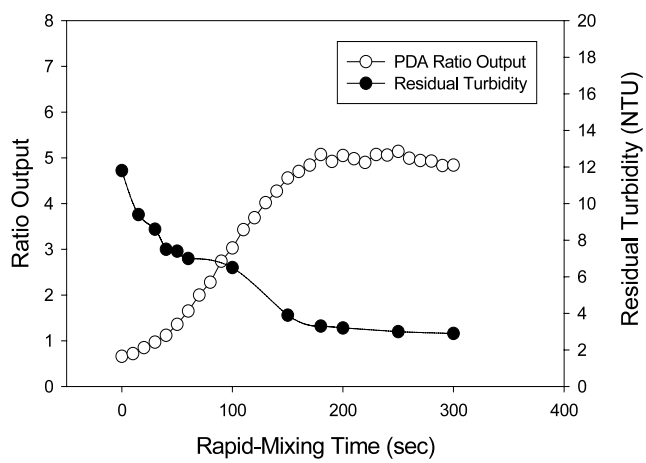

Fig. 4. Variations in PDA ratio output and residual turbidity with the change of rapid-mixing time. Initial turbidity 38 NTU; final pH 7.5; PACl dosage 0.6 mg l^{-1} as Al.

Table 1
Rapid-mixing times determined by three methods and suggested coagulation mechanisms for various turbid samples

Test number	Turbidity (NTU)	Coagulant type	Coagulant dosage	Coagulation mechanism	Rapid-mixing time (s)		
					Jar test method	PDA method	Empirical method
1	180	PACl	1.5	ACN	20	20	10–20
2	180	Alum	2.5	ACN	40	40	30–40
3	180	Alum	5.0	SWEEP	10	20	20–25
4	38	PACl	0.6	ACN	180	180	40–60
5	38	PACl	1.5	ACN	30	20	20–30
6	38	Alum	1.5	ACN	50	60	55–70
7	38	Alum	5.0	SWEEP	20	20	25–30
8	8	Alum	3.0	SWEEP	50	50	38–50

initial number of destabilized particles by half is T_2 and the time required for destabilized particles to aggregate into larger floc particles is T_3. They concluded that for optimal coagulation, the rapid-mixing time should be kept between T_1 and T_2 and should not exceed T_3. An empirical equation [13] was formulated from statistical and non-dimensional analysis of experimental data to determine the mixing time. Parameters used in the formula were the mixing intensity (G-value), particle concentration (mg l^{-1}), coagulant dosage (mg l^{-1}), and characteristic times (T_1, T_2 and T_3). Adequate times for rapid-mixing determined from the mixing test and the PDA method were compared with that from the empirical equation, as shown in Table 1.

The result shows that the times determined by from the mixing test and the PDA method are very close. The times predicted by the empirical equation were especially similar to those determined from the previous two methods. The only one exception occurred at 0.6 mg l^{-1} PACl dosing on the water sample of 38 NTU, in which the predominant coagulation mechanism was the ACN. Although the insufficient mixing resulted in high residual turbidity in both ACN and sweep coagulations, there was a distinctive difference between the two coagulation mechanisms when the time requirement for rapid-mixing was exceeded. When the mixing operation exceeded the adequate time, the same or lower residual turbidity was observed for the ACN coagulation. A rebound of the residual turbidity was, on the other hand, observed for sweep coagulation.

As mentioned before, the model based on a microscopic view failed to consider the break-up of aggregates during the rapid-mixing stage. This has been supported by Bache et al. [21] and Rossini et al. [22]. Some researchers [6,23] have suggested that the aggregation caused by hydrolyzing metal salts is irreversible. This means that flocs generated from the process of growth-breakup-regrowth will not have the same structure as the original flocs. Their studies showed that smaller but denser flocs formed after aggregates restructured. The floc formed during rapid-mixing was defined as the microfloc which determined the characteristics of the macroflocs and the aggregates formed in the slow-mixing [24]. Our study also suggests that the difference in residual turbidity is attributed to the size distribution and the structure of the microflocs. This theory will be discussed in our future study.

4. Conclusion

The time for rapid-mixing affects the destabilization of the colloid and the downstream aggregation of particles. By employing a PDA to directly monitor the aggregation, a simple method for determining the adequate time for rapid-mixing in the vessel is developed. Maximum PDA ratio output and minimum residual turbidity indi-

cate the adequate rapid-mixing time. Reaggregation of flocs formed from ACN coagulation results in the same or lower residual turbidity, while that formed from sweep coagulation results in higher residual turbidity. Time to form microflocs for good aggregation can be signaled by a maximum PDA ratio output. Small flocs produce a small ratio output, suggesting the break-up of microflocs in sweep coagulation.

Acknowledgements

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References

[1] ASCE, AWWA and CSSE, Water Treatment Plant Design, American Water Works Association Press, New York, 1969.
[2] J.K. Edzwald, J.Y. Bottero, R. Klute, in: J.B. McEwen (Ed.), Treatment Process Selection for Particle Removal, AWWARF Press, Denver, CO, 1998 Chapter 4.
[3] A. Amirtharajah, K.M. Mills, J. AWWA 74 (1982) 210.
[4] A. Amirtharajah, S.C. Jones, in: H.H. Hermann, E. Hoffmann, H. Odegaard (Eds.), Chemical Water and Wastewater Treatment IV, Proceedings of 7th Gothenburg Symposium, 23–25 September 1996, Springer, Edinburgh, Scotland, 1996, p. 23.
[5] A. Amirtharajah, N. Tambo, in: A. Amirtharajah, M.M. Clark (Eds.), Mixing in Coagulation and Flocculation, AWWARF Press, Denver, CO, 1991 Chapter 1.
[6] M.M. Clark, R.V. Joseph, J. Coll. Interf. Sci. 147 (1991) 407.
[7] M.M. Clark, R.M. Srivastava, Environ. Sci. Technol. 27 (1993) 2181.
[8] M.M. Clark, R.M. Srivastava, Selection and Design of Mixing Processes for Coagulation, AWWARF Press, Denver, CO, 1994.
[9] T.R. Camp, J. AWWA 60 (1968) 656.
[10] L. Vrale, R.M. Jorden, J. AWWA 63 (1971) 52.
[11] V.A. Mhaisalkar, R. Paramasivam, A.G. Bhole, Water Res. 25 (1991) 43.
[12] R.D. Lettermann, J.K. Quon, R.S. Gemmel, J. AWWA 65 (1973) 725.
[13] Y. Matsui, A. Yuasa, Y. Furuya, T. Kamei, J. AWWA 90 (1998) 106.
[14] D.A. Cornwell, M.M. Bishop, J. AWWA 75 (1983) 475.
[15] J. Gregory, Chem. Eng. Sci. 36 (1981) 1789.
[16] R.D. Letterman, A. Amirtharajah, C.R. O'Melia, in: R.D. Letterman (Ed.), Water Quality and Treatment, McGraw-Hill, New York, 1999 Chapter 6.
[17] C.H. Yao, The Preparation of Polymeric Aluminum Chloride (PACl) and its Application in Water Treatment, Johns Hopkins University Press, Baltimore, MD, 1987.
[18] J. Gregory, J. Coll. Interf. Sci. 118 (1987) 397.
[19] C.P. Huang, G.S. Chen, Water Res. 30 (1996) 2723.
[20] C.C. Kan, C.P. Huang, Water Sci. Technol. 38 (1998) 237.
[21] D.H. Bache, C. Johnson, E. Paravasilopoulos, E. Rasool, F.J. McGilligan, J. Water SRT-AQUA 48 (1999) 201.
[22] M. Rossini, J.G. Garrrido, M. Galluzzo, Water Res. 33 (1999) 1817.
[23] R.J. Francois, Water Res. 21 (1987) 1023.
[24] K. Higashitani, T. Shibata, J. Chem. Eng. Jpn. 20 (1987) 152.