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Innovative technology for reducing the finished water turbidity during sand filtration

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Abstract Sand filtration efficiency in treating low turbidity water greatly depends on the electrostatic interactions of both the surface of influent particles and that of sand grains or the deposited matter on the grains. This article describes two innovative filtration techniques to increase the particle separation efficiency: (1) coagulant-coated filter medium by enhancing the electrical potential of the surface of the filter medium; and (2) coagulant dosing in the influent by controlling the electrical potential of particles entering the filter layer. From the results of the various filtration experiments using a pilot plant, these two techniques were found to be very effective in reducing the effluent water turbidity during an initial stage of a filter run, and from the start to the end of a run, respectively. It should be also noted that the effectiveness of each method increased, as the amount of coagulant PACl used in the experiment increased. Moreover, in the filtration experiments using these two methods simultaneously, substantially higher removal efficiency of approximately 3 log (99.7%) was realized, resulting that the finished water turbidity was accordingly reduced to 0.004 mg/L.

Keywords Coagulant-coated filter medium; coagulant dosing in influent; filtration; kaolin; PACl

Introduction

The particle removal efficiency of current rapid sand filtration systems is about 2.5 log when influent turbidity is round 20–30 mg/L. In order to solve the various issues related to water quality, this efficiency needs to be increased to 4.0 log, which is 31.6 times higher than current levels. In order to increase the process efficiency by such a large degree, efforts need to be taken to investigate and improve the overall rapid sand filtration process, starting with the selection of coagulant and coagulation methods that are suitable for particular raw water conditions, through to the improvement of separation efficiency by focusing on filtration in the final stage of the particle removal process, as well as on coagulation and sedimentation.

In light of the present situation, the objective of this article is to examine the effectiveness of two new techniques in the filtration process: (1) coating the filter medium with coagulant PACl to increase separation efficiency in the early stages of filtration by increasing the electrical potential of the filter medium; and (2) coagulant dosing in the influent in order to increase the particle separation efficiency by increasing the electrical potential of incoming particles.

Materials and methods

Filtration experiments

Figure 1 is a schematic of the experimental apparatus. This apparatus is a direct sand filtration line consisting of the following components: (1) raw-water conditioning; (2) filtration/filter-washing; (3) head-loss measurement; (4) turbidity measurement and particle counts; and (5) coagulant coating. The filter column has a cross-sectional area of 52.0 cm^2, in which silica sand was packed to a depth of 60 cm. The silica medium has an effective size of 0.61 mm, a uniformity coefficient of 1.39, and a specific gravity of 2.60. The raw water

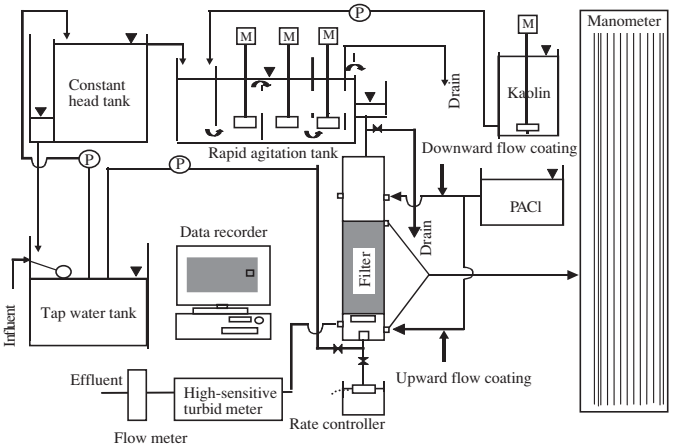

Figure 1 Schematic diagram of experimental apparatus

used in the experiments was tap water from the Kitami Institute of Technology (KIT), to which reagent-grade kaolin was added as suspended particles at a rate of 1 mg /L of influent. PACl (Poly Aluminium Chloride, $[Al_2(OH)_nCl_{6-n}]_m$, here, $1 \leqq n \leqq 5$, $m \leqq 10$, 10 to 12% Al_2O_3) was added as the coagulant at the specified concentration.

Turbidity measurements and particle counts were made using a turbidity meter with a particle count function. The average turbidity of the tap water without the addition of kaolin and PACl was 0.033 mg/L, and the number of particles in the size range of 0.5–1.0, 1.0–3.0, 3.0–7.0 and ≧7.0 μm was shown in Table 1 for the influent with PACl added at 0–3 mg/L. The zeta potentials of the particles were determined through the electrophoretic mobility method using a microscope and a Briggs' glass cell. The values measured for kaolin particles ranged from –25 to –30 mV at pH 7.0.

In the coagulant-coated experiments, the sand filter medium was coated with PACl by downward flow of a PACl solution of specified concentration prior to filtration. In the coagulant dosing experiments, a PACl solution was injected continuously at a given rate into the influent at the inlet of the rapid agitation tank. The duration of all filtration experiments was set at 20 h at a filtration velocity of 120 m/d. The turbidity measurements and particle counts were made 10 times every minute, and the mean value per minute was used for evaluation of the phenomena. As the maximum head loss after 20 h filtration was very low (as little as 11.8 cm), head loss will not be addressed in this article.

Table 1 Particle number of KIT tap water with PACl dosage

PACl (mg/L)	Turb.(mg/L)	Particle Size (μm)			
		0.5–1.0	1.0–3.0	3.0–7.0	≧7.0
0.0	0.033	47,642	1,525	137	11
		96.83	2.88	0.27	0.02
0.2	0.034	52,424	1,602	139	6
		97.00	2.74	0.25	0.01
1.0	0.036	57,818	1,392	133	3
		97.64	2.13	0.22	0.01
3.0	0.041	66,605	1,461	130	5
		97.82	1.98	0.19	0.01

Upper portion: particle number (counts/mL)
Lower portion: particle distribution (%)

Particle counts and zeta potential measurements for coagulant-dosed influent

Table 2 shows the results of turbidity measurements and particle counts for the influent containing 1 mg/L kaolin and 0–3 mg/L PACl, both of which were injected at the inlet of the rapid agitation tank as shown in Figure 1. Even with the addition of the maximum PACl concentration of 3 mg/L, there was no significant increase in the number of particles. This result implies that particle agglomeration did not occur in these cases because the rapid agitation conditions employed here (velocity gradient of 160 s^{-1} and agitation time of 4.4 min) did not reach agglomeration onset time τ_1 as proposed by Matsui *et al.* (1998).

Figure 2 shows the zeta potentials of particles measured through the electrophoretic mobility method. The zeta potentials increased with increasing PACl addition by approximately 6.5 mV with the addition of 1.0 mg/L PACl, 11.5 mV with 3 mg/L PACl, and 14.0 mg/L with 5 mg/L PACl, indicating the gradual approach to the coagulation range proposed by Tambo (1964a, 1964b, 1965a, 1965b). It was also noted that the increase in the potential per unit PACl dosage was higher at lower dosage. From these results, it was found that the addition of PACl to the influent did not change number of particles significantly, but the zeta potential of particles was significantly improved.

Distribution of Al and zeta potential inside the filter after PACl coating

In case of filter medium coating, PACl solutions of twice the filter porosity volume with specified concentration and pH of 5.0 were introduced into the filter column through a vinyl hose from a storage tank. The flow rate of the PACl solution was set at 80 m/d; coating was therefore completed within 10 min. After that, the water was drained from the filter, the acrylic filter cover was opened, and sand samples of 1 cm depth (about 78 g) were extracted from designated filter levels. The zeta potential measurements of the extracted sand

Table 2 Turbidity and particle counts by particle size for influent containing 1 mg/L kaolin and dosed with PACl

PACl (mg/L)	Turb. (mg/L)	Particle size (μm)\ 0.5–1.0	1.0–3.0	3.0–7.0	≧7.0
0.0	1.343	1,527,029	58,630	7,549	326
		95.83	3.68	0.47	0.02
0.2	1.399	1,597,964	59,565	7,656	393
		95.94	3.58	0.46	0.02
1.0	1.321	1,508,355	58,162	7,440	323
		95.81	3.70	0.47	0.02
3.0	1.303	1,499,096	58,625	7,547	290
		95.75	3.75	0.48	0.02

Upper portion: particle number (counts/mL)
Lower portion: particle distribution (%)

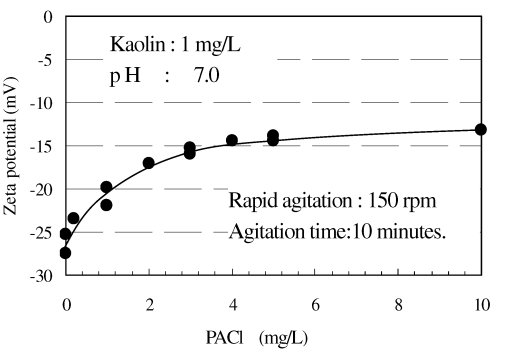

Figure 2 Zeta potential of kaolin partile after PACl dosing

samples were made using the streaming potential analyzer as shown in Figure 3. That is, the sand sample was packed into a cylindrical cell ($f14 \times 50$ mm), and then the streaming potentials (E_1, E_2) and pressures (P_1, P_2) across the cell were measured in ambient N_2 gas. These values were then substituted into the following Helmholtz–Smoluchowski formula to determine the zeta potential of the sand sample

$$\zeta = 1.15 \times 10^{10} \times \frac{\mu}{\varepsilon} \times \frac{\kappa}{M} \times \frac{E_1 - E_2}{P_1 - P_2} \quad (1)$$

in which ξ is the zeta potential (mV), μ is the viscosity coefficient of the fluid (g mass sec/cm), ε is the dielectric constant of water, κ is the cell constant of electric conductivity (cm^{-1}), and M is the resistance of water (Ω).

The distributions of Al coating and zeta potential inside the filter bed are shown in Figure 4. The amount of Al retained represents the maximum value at the top of the filter bed, and rapidly decreases with filter depth. As an example, in the case of using 80 mg/L PACl solution for filter coating, the amount of Al retained was approximately 3.0 mg in the first 1 cm to the filter bed, but was negligible at filter depths exceeding 30 cm.

On the other hand, the zeta potential at the top of the filter, where the sand is the finest with corresponding maximum surface area per unit volume, before coating was –6.1 mV. This value gradually increased to –3.4 mV in the deepest part of the filter, where the unit surface area is the smallest. After coating, the amount of Al retained in the upper layer had increased in proportion to the concentration of the PACl solution applied, with a corresponding positive shift in zeta potential in this section.

Using a PACl solution with a concentration of 80 mg/L, the zeta potential in the first 1

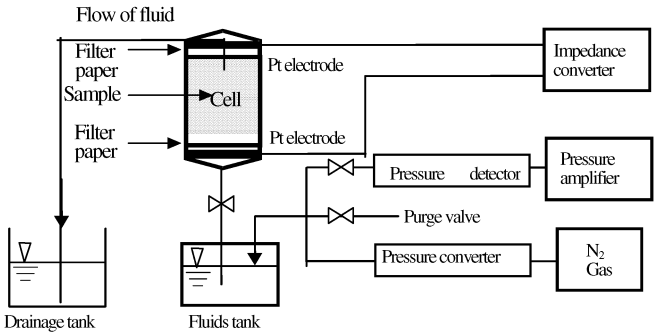

Figure 3 Streaming potential analyzer

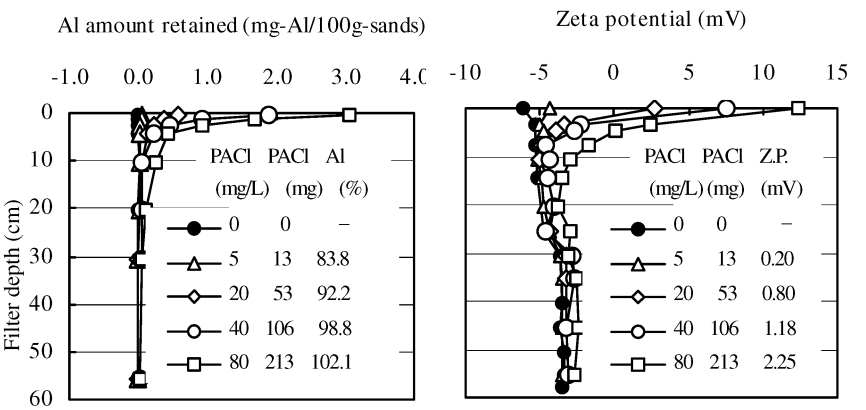

Figure 4 Distribution of retained Al and zeta potential inside filter media

cm of the filter was greatly increased by 18.6 mV from –6.1 to +12.5 mV, although the average zeta potential for the whole filter was increased by 2.25 mV.

Results and discussioin

Effects of coagulant-coated filter medium

Figure 5 shows the turbidity of finished water for the PACl-coated filter systems. In the non-coated filter, the initial removal rate is as low as 55% (turbidity 0.5–0.6 mg/L). However, the removal rate improves with filtration time to about 85% (0.2 mg/L) after 5 h, thereafter improving very gradually with time. As shown in Table 3, the average finished water turbidity and removal efficiency were 0.111 mg/L and 91.7% at the best levels in the 15–20 h period. The average removal rate over the entire 20 h filtration period was 86.2%. In this filtration experiment, the dominant particle removal mechanism at the start of this filtration process is mechanical support of kaolin particles at the upper filtration front in the filter media. As filtration progresses, however the effect of secondary capture in the concavo-convex field formed around particles trapped on the filter media is considered to become predominant. The retention of larger particles is thought to be primarily due to physical entrapment by constriction formed between the filter media.

The removal efficiency of the coagulant-coated filtration was significantly improved. There was a clear improvement when using the 5 mg/L PACl solution, and the performance was markedly improved at the 20 and 80 mg/L of PACl levels. As indicated in Table 3, the average removal rates over the 20 h filtration period were increased to 90.5, 95.3 and 96.7% for coating with the PACl solutions of 5, 20 and 80 mg/L, respectively.

The most remarkable feature of this coagulant-coated filtration is that the finished water turbidity at the start of filtration was extremely suppressed. In particular, in the case of coating with the 80 mg/L PACl solution, the removal efficiency in the first hour was as high as 99.0%, compared to 65.5% for non-coated filtration, representing an approximately 35 fold reduction in finished water turbidity. However, the turbidity of the finished water increases slightly with time as the quantity of trapped particles increases. Even so, the turbidity of the finished water in the 15–20 h period is more than 2.3 times lower than that for the non-coated filtration.

Comparing these findings with the results in Figures 4 and 5, the reduction in the initial and long-term turbidity of the finished water appears to be proportional to the increase in the amount of Al retained on the surface of the filter media, or the increase of the zeta potential. The extension of the high zeta potential zone deeper into the filter may also contribute to the increase in performance. Based on these results, we consider that the negatively

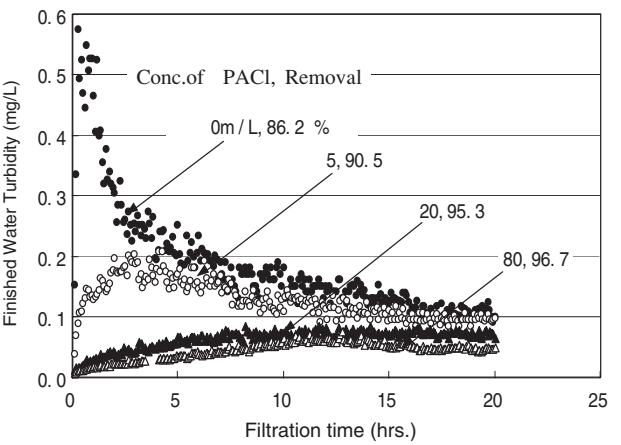

Figure 5 Finished water turbidity for PACl coated filtration

Table 3 Finished water turbidity (mg/L) and removal rates (%) for PACl coated filtration

Filtration time (h)	Conc. of PACl coating solution (mg/L)			
	0	5	20	80
0–1	0.463	0.111	0.021	0.013
	(65.5)*	(91.7)	(98.4)	(99.0)
0–5	0.310	0.158	0.040	0.022
	(76.9)	(88.2)	(97.0)	(98.4)
15–20	0.111	0.096	0.072	0.048
	(91.7)	(92.9)	(94.6)	(96.4)
0–20	0.185	0.127	0.063	0.044
	(86.2)	(90.5)	(95.3)	(96.7)

*The values in parenthesis indicate removal rates (%)

charged kaolin particles are trapped with high efficiency in the upper part of the filter where the zeta potential is positively high as a result of coagulant coating. The filter media then eventually becomes coated with kaolin particles.

Coagulant coating therefore dramatically increases the performance of the filtration system for low-turbidity influent, and the performance increase is maintained for long periods of filtration. Therefore, this technique of pre-coating the filter medium with PACl is expected to become very important for the highly efficient treatment of low-turbidity influent, for which the filter ripening period is typically very long.

Effects of coagulant dosing in influent

Figure 6 shows the finished water turbidity for the PACl-dosing filtration. There was an initial brief period of turbidity breakthrough in all these filtration experiments, similar to the untreated case. As pointed out by Ebie *et al.*, the degree of initial breakthrough is reduced with an increase of coagulant dosing, and the period of high finished water turbidity is also shortened. However, the initially higher turbidity levels cannot be suppressed completely. These results demonstrate that an untreated filter with negative zeta potential always requires the coating with coagulant before the start of filtration.

As filtration proceeds, the finished water turbidity with PACl dosing decreases sharply from the initial high values, thereafter decreasing slowly with filtration time. Although the effect of coagulant dosing during the initial period of filtration is smaller than that of coagulant coating, the notable feature of this method is the trend toward the complete removal of particles as filtration proceeds.

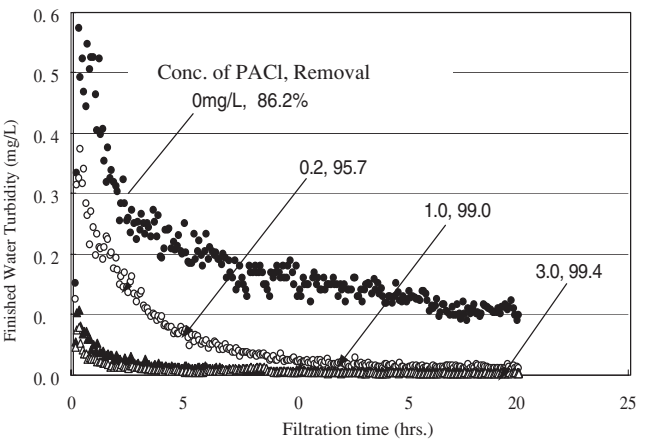

Figure 6 Finished water turbidity for PACl dosing filtration

Table 4 shows the finished water turbidity and the removal efficiencies for coagulant dosing. As shown in Figure 2, the zeta potential of the influent particles is increased according to the PACl dose. At 0.2 mg/L PACl dosing, the removal efficiency in the first 5 h was 88.1%, increasing to 99.0% in the 15–20 h period, which represents an almost 12 fold decrease in finished water turbidity, compared to 0.111 mg/L for non-dosed filtration. The turbidity is 8.5 times lower than for the non-dosed filtration in the same period, and 12.3 times lower than that in the first 5 h. The removal rate also was 91.7% in the 15–20 h period in the non-dosed filtration, increasing to 99.8% at 3.0 mg/L PACl dosing. The effectiveness of coagulant dosing has been shown to increase with filtration time, although the initial filtration efficiency for the coagulant-coated filter system is initially extremely high and gradually decreases with time.

Combined use of PACl-coated filter medium and PACl dosing in influent

Figure 7 and Table 5 show the finished water turbidity and removal efficiency for a filtration incorporating both coagulant-coated filter media and continuous coagulant dosing in the influent. The removal rates are significantly improved over the use of coagulant coating or coagulant dosing alone, with remarkably low turbidity values over all periods of filtration. The combined effects of the two techniques can be clearly recognized in the figure; the rise in finished water turbidity with filtration time seen for coagulant coating (Figure 5) is completely suppressed by the effect of coagulant dosing, and the initial breakthrough of turbid matter characteristic of coagulant dosing (Figure 6) is largely prevented by the initial high performance of coagulant coating.

Specifically, the removal efficiency in the first hour for coagulant dosing with 3 mg/L

Table 4 Finished water turbidity (mg/L) and removal rates (%) for PACl dosing filtration

Filtration time (hrs)	PACl dosage (mg/L)			
	0	0.2	1.0	3.0
0–1	0.463	0.272	0.068	0.042
	(65.5)*	(79.7)	(94.9)	(96.9)
0–5	0.310	0.160	0.031	0.018
	(76.9)	(88.1)	(97.7)	(98.7)
15–20	0.111	0.013	0.005	0.003
	(91.7)	(99.0)	(99.6)	(99.8)
0–20	0.185	0.058	0.013	0.008
	(86.2)	(95.7)	(99.0)	(99.4)

*The values in parenthesis indicate removal rates (%)

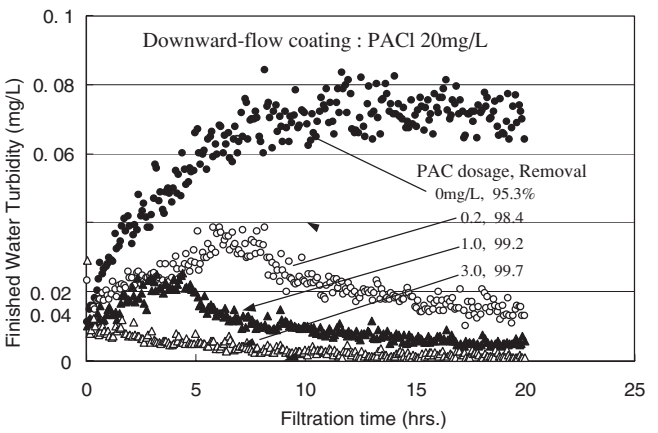

Figure 7 Finished water turbidity in filtrations using both PACl coating method and PACl dosing method

Table 5 Finished water turbidity (mg/L) and removal rates (%) for combined techniques

Filtration time (hrs)	PACl dosage (mg/L)			
	0.0	0.2	1.0	3.0
0–1	0.021	0.017	0.013	0.011
	(98.4)*	(98.7)	(99.0)	(99.2)
0–5	0.040	0.023	0.018	0.008
	(97.0)	(98.3)	(98.7)	(99.4)
15–20	0.072	0.015	0.006	0.002
	(94.6)	(98.9)	(99.6)	(99.9)
0–20	0.063	0.022	0.011	0.004
	(95.3)	(98.4)	(99.2)	(99.7)

*The values in parenthesis indicate removal rates (%)

PACl was 96.9%, and that for coagulant coating with a 20 mg/L PACl solution was 98.4%. The combined effect was 99.2% for this period as shown in Table 5. This 0.8% increase in efficiency corresponds to a 50% reduction in the turbidity of the finished water. In the 15–20 h period, the removal rate for coagulant coating with a 20 mg/L PACl solution was 94.6%, and that for coagulant dosing of 3 mg/L PACl was 99.8%.

By combining these two methods, we have achieved a maximum turbidity removal rate of 99.9%, or 3 log in the 15–20 h filtration period, corresponding to a turbidity of 0.002 mg/L.

Table 6 shows the particle counts and removal rates for filtration in the first hour, when coagulant coating is dominant, and Table 7 lists the results for the 15–20 h period when the effect of coagulant dosing is greater. Firstly, from these tables, a strong correlation can be seen between the particle counts and the turbidity in the finished water.

As an example, the effect of coagulant coating and coagulant dosing in the first hour of filtration can be seen in the particle count for sizes between 0.5 and 1.0 μm (run 7 in Table 6) (PACl coating: 20 mg/L, PACl dosing: 3 mg). The effect of coagulant coating can be seen by comparing run 7 with run 5; the particle count for the 0.5–1.0 μm particles is reduced by 26,560 (38,455–11,895) counts/mL, representing a reduction of 69.1%. The effect of coagulant dosing can be seen by comparing run 7 with run 2; the particle count is reduced by 9,283 (21,178–11,895), representing a 43.8% reduction.

Making the same comparison for the 15–20 h period, coagulant coating reduces the particle count by 1,182 counts/mL (32.3%), and the combined effect is a reduction of

Table 6 Particles counts (counts/mL) and removal rates (%) for 0–1 hour filtration period

No.	PACl coating (mg/L)	PACl dosing (mg/L)	Turb. (mg/L)	Particle Size (μm)			
				0.5–1.0	1.0–3.0	3.0–7.0	>7.0
1	–	–	0.463	66,388	27,315	3,869	82
			65.5	95.7	53.4	48.7	74.8
2	20	–	0.021	21,178	1,037	81	0
			98.4	98.6	98.2	98.9	100.0
3	80	–	0.013	12,672	649	33	0
			99.0	99.2	98.9	99.6	100.0
4	–	1.0	0.068	60,945	4,685	617	5
			94.9	96.0	92.0	91.8	98.5
5	–	3.0	0.042	38,455	2,690	326	4
			96.9	97.5	95.4	95.7	98.8
6	20	1.0	0.012	15,399	739	72	0
			99.1	99.0	98.7	99.0	100.0
7	20	3.0	0.011	11,895	647	19	0
			99.2	99.2	98.9	99.7	100.0

Table 7 Particles counts (counts/mL) and removal rates (%) for 15–20 h filtration period

No.	PACl coating (mg/L)	PACl dosing (mg/L)	Turb. (mg/L)	Particle size (μm) 0.5–1.0	1.0–3.0	3.0–7.0	>7.0
1	–	–	0.111	68,211	7,671	1,210	12
			91.7	95.5	86.9	84.0	96.3
2	20	–	0.072	38,809	4,121	576	3
			94.6	97.5	93.0	92.4	99.1
3	80	–	0.048	22,579	2,461	301	1
			96.7	98.5	95.8	96.0	99.7
4	–	1.0	0.005	6,949	362	17	0
			99.6	99.5	99.4	99.8	100.0
5	–	3.0	0.003	3,655	204	6	0
			99.8	99.8	99.7	99.9	100.0
6	20	1.0	0.006	5,579	299	13	0
			99.6	99.6	99.5	99.8	100.0
7	20	3.0	0.002	2,473	132	4	0
			99.9	99.8	99.8	99.9	100.0

36,336 counts/mL (93.6%). Therefore, the effectiveness of the combined use of coagulant coating and coagulant dosing is confirmed.

It has therefore been verified that the use of a coagulant-coated filter medium is more effective in the initial periods of filtration, and coagulant dosing in the influent becomes more effective as filtration progresses. It is expected that the turbidity reduction efficiency can be further improved by increasing the amount of coagulant used in each process. The implementation of this technology will depend on the minimum coagulant doses required to achieve a desired level of water quality with respect to the development of head loss and Al contamination of the finished water.

Conclusion

In order to enhance the particle removal efficiency of rapid sand filtration systems, two new filtration techniques were examined. As a result, the following findings were obtained from the filtration experiments using a pilot plant.

- The coagulant coating of the filter medium has been shown to suppress the initial breakthrough of particles in the period of filter ripening by increasing the zeta potential of the medium, allowing negatively charged influent particles to be trapped efficiently.
- Coagulant dosing in influent was also shown to increase the removal efficiency of the filter progressively with filtration time.
- The combination of these techniques results in a filtration system exhibiting extremely high removal efficiency over the entire filtration period.
- As an example, in the case of using 20 mg/L PACl solution for filter coating and 3 mg/L PACl dosing in the influent, the average removal rate over the entire 20 h filtration period was 99.7%, corresponding to a finished water turbidity of 0.004 mg/L.

Finally, we expect that rapid sand filtration systems incorporating new technologies such as those presented in this article will be widely utilized in many countries.

References

Amirtharajar, A. and Wetstein, D.P. (1980). Initial degradation of effluent quality during filtration. *J. AWWA*, **79**(9), 518–524.

Camp, T.R. (1964). Theory of water filtration, *J. Sani. Eng. Div. ASCE*, **90**(SA4), 1–30.

Dennett, K.E., Amirtharajah, A., Moran T.F. and Gould, J.P. (1996). Coagulation: its effect on organic matter. *J. AWWA*, **88**(4), 129–142.

Ebie, K. (1975). A fundamental study of removal mechanisms of suspended particles in deep filter (I). *J. JWWA*, **493**, 25–46.

Ebie, K. (1976). A fundamental study of removal mechanisms of suspended particles in deep filter (II). *J. JWWA*, **498**, 15–37.

Ebie, K. (1976). A fundamental study of removal mechanisms of suspended particles in deep filter (III). *J. JWWA*, **507**, 20–34.

Ebie, K. (1977). A fundamental study of removal mechanisms of suspended particles in deep filter (IV). *J. JWWA*, **508**, 18–37.

Ebie, K. (1977). A fundamental study of removal mechanisms of suspended particles in deep filter (V). *J. JWWA*, **518**, 2–27.

Ebie, K. and Shibuya, S. (1994). Improving filter effluent turbidity during the initial stage of direct sand filtration. *J. JWWA*, **63**(8), 10–20.

Ebie, K. and Doi, K. (1998). Experimental studies on the removal behavior of coagulated particles inside constant-rate sand filters. *J. JWWA*, **67**(10), 25–35.

Ebie, K., Lee, J.H. and Tamakawa, Y. (2000). Effect of influent water pH values on the removal of suspended particles in sand filters. *J. JWWA*, **791**, 46–56.

Ebie, K., Lee, J.H. and Jang, I.H. (2001). Effectiveness of PACl coated sand filters in reducing initial effluent turbidity. *J. JWWA*, **798**, 8–20.

Ebie, K. and Lee, J.H. (2001). Effect of short time change in influent water pH on the removal of suspended particles in sand filters. *J. JWWA*, **70**(9), 2–13.

Ebie, K. and Lee, J.H. (2001). Pilot studies on improving the finished water quality during sand filtration of low turbidity water. *J. JWWA*, **70**(12), 21–32.

Edzwald, J.K. (1993). Coagulation in drinking water treatment: particles, organics and coagulants. *Wat.. Sci. Tech.*, **27**(11), 21–35.

Ives, K.J., Gregory, J., Scutt, J. and Pugh, H. (1993). A microsphere in water: *Cryptosporidium parvum*. *Proc. Sixth World Filtration Congress*, 224–231.

Ives, K.J. (1969). Theory of filtration. *International Water Supply Congress & Exhibition*, Special Subject No.7, Munchen, Germany.

Iwasaki, T. (1937). Some notes on sand filtration. *J. AWWA*, **29**(10).

Kelly, O.C. and Amirtharajah, A. (1987). Improving the initial effluent quality of a dual-media filter by coagulants in backwash. *J. AWWA*, **79**(12), 50–63.

Leslie, H.W. (1970). High-rate filter efficiency. *J. AWWA*, **62**(8), 515–519.

Logsdon, G.S., Symons, J.M., Hoye Jr. R.L. and Arozarena, M.M. (1981). Alternative filtration methods for removal of giardia cysts and cysts model. *J. AWWA*, **73**(2), 111–118.

Magara, Y. (1997). The control and management of cryptosporidium. *The 5th Sanitary Engineering Symposium*, Hokkaido University, Japan.

Matsui, Y., Yuasa, A., Furuya, Y. and Kamei, T. (1998). Dynamic analysis of coagulation with alum and PACl. *J. AWWA*, **90**(10), 96–106.

Mintz, D.M. (1966). Modern theory of filtration. *International Water Supply Congress & Exhibition*, Special Subject No. 10, Barcelona, Spain.

Mosher, R.R. and Hendricks, D.W. (1986). Rapid-rate filtration of low turbidity water using field-scale pilot filters. *J. AWWA*, **78**(12), 42–51.

O'Melia, C.R. and Crapps, D.K. (1964). Some chemical aspects of rapid sand filtration. *J. AWWA,* **56**(10), 1326–1344.

Qureshi, N. and Malmberg, R.H. (1985). Reducing aluminum residuals in finished water. *J. AWWA*, **77**(10), 101–108.

Smith Jr. C.V. (1967). Determination of filter media zeta potential. *J. Sani. Eng. Div., ASCE*, **93**(SA5), 91–107.

Smith Jr. C.V. (1967). Electrokinetic phenomena in particulate removal by rapid sand filtration. *J. New England Water Works Association*, **81**, 170–214.

Stein, P.C. (1940). *A study of the theory of rapid filtration of water through sand*. Science Doctor Thesis, PhD thesis, M.I.T., USA.

Tambo, N. (1964a,b, 1965,a,b). A fundamental investigation of coagulation (I–IV). *J. JWWA*, **361**, **363**, **365**, **367**.

Tsunoda, S. and Aoyanagi, Y. (1975). Study on direct rapid filtration using reduced coagulants, *J. JWWA*, **486**, 2–10.

Van Benschoten, J.E. and Edzwald, J.K. (1990). Chemical aspects of coagulation using aluminum salts: hydrolytic reactions of alum and poly aluminum chloride. *Water Res.*, **24**, 1519–1526.