Treating High-Turbidity Water Using Full-Scale Floc Blanket Clarifiers

W. W. Lin[1]; S. S. Sung[2]; L. C. Chen[3]; H. Y. Chung[4]; C. C. Wang[5]; R. M. Wu[6]; D. J. Lee[7]; Chihpin Huang[8]; R. S. Juang[9]; X. F. Peng[10]; and Hsi-Lih Chang[11]

Abstract: Dynamic responses of the blanket in full-scale flat-bottom type floc blanket clarifiers at the PingTsan Water Works, Taiwan Water Supply Corporation, were monitored given a step-change in coagulant (polyaluminum chloride, PACl) dosage. The blankets in the clarifiers were easily washed out using the conventional coagulation-clarification process (the "single-stage process"), seriously threatening drinking water quality. Consequently, the PingTsan Water Works included a pretreatment stage before the single-stage process to enhance treatment efficiency. The performance of this full-scale "two-stage process" for treating high-turbidity storm water was monitored on November 9 to 10, 2000. The two-stage process achieved a stable blanket and good quality clarified water that was insensitive to variation in raw water turbidity or PACl dose. Pilot tests were also conducted on October 6 to 7, 2001 to reveal performance differences between the single-stage and two-stage processes in dealing with high-turbidity water. The single-stage process yielded a blanket that was sensitive to PACl change. Not only was the produced blanket easily washed out when the PACl dose was step-decreased, it was also slow to recover when the chemical dosage was returned to its original value. The blanket yielded by the two-stage process was more robust to low coagulant dose, and recovered more easily when coagulant supply was increased. Applying the two-stage process to achieve the same effluent quality from single-stage process could significantly reduce total PACl dosage.

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Introduction

Flocculation clarifiers have been widely used in clean water production since first being introduced in the 1930s. Owing to their more efficient flocculation and better chance of making solid contacts, flocculation clarifiers can deal with a surface loading two to three times higher than conventional coagulation-sedimentation basins (Kawamura 1991; Masschelein 1992; Stevenson 1997; Edzwald et al. 1999). The Taiwan Water Supply Corporation (TWSC) installed flocculation clarifiers for drinking water production in the early 1990s, and flocculation clarifiers now supply over 50% of Taiwan's drinking water. The floc blanket acts as both a particle coagulator and a filter, and thus is essential for clarifiers to produce quality drinking water. The settling velocity of the coagulated flocs and the assigned upflow velocity control blanket stability (Gregory et al. 1996; Head et al. 1997). Stringent operational control is required to prevent sludge washout from the clarifiers (AWWA/ASCE 1990).

The Ping-Tsan Water Works (the Works) takes raw water from the Shih-Min Reservoir and Da-Han River at a rate of 300,000–400,000 m^3/day, with polyaluminum chloride (PACl) as the coagulant. The turbidity of raw water displays a "two-state" characteristic. Under normal weather conditions raw water turbidity is typically below 10 NTU. Such conditions are referred to as the "low-turbidity period." However, in summer Taiwan becomes prone to tropical storms which produce heavy showers and serious flooding. The turbidity of raw water can increase to several hundreds or even thousands of NTU in a day, and can continue to exceed 100 NTU over the succeeding 2 to 3 weeks. These summer weather conditions are referred to as the "high-turbidity period." Presedimentation followed by conventional coagulation and flocculation with filter aid has been proposed for treating high-turbidity water (Janssens and Buekens 1993; Cotton et al. 1994; Zhu et al. 1996). This approach generally requires a large stormwater storage tank to homogenize water quality before treatment. Heinzmann (1994) proposed an alternative arrangement using coagulation and flocculation in a pipe designed for floc formation, followed by solids–liquid separation. Li and Gregory (1991) demonstrated the key role of coagulant dose and mixing

[1]Chemical Engineering Dept., National Taiwan Univ., Taipei 106, Taiwan.
[2]Chemical Engineering Dept., National Taiwan Univ., Taipei 106, Taiwan.
[3]Chemical Engineering Dept., National Taiwan Univ., Taipei 106, Taiwan.
[4]Chemical Engineering Dept., National Taiwan Univ., Taipei 106, Taiwan.
[5]Chemical Engineering Dept., National Taiwan Univ., Taipei 106, Taiwan.
[6]Chemical Engineering Dept., National Taiwan Univ., Taipei 106, Taiwan.
[7]Chemical Engineering Dept., National Taiwan Univ., Taipei 106, Taiwan.
[8]Institute of Environmental Engineering, National Chiao Tung Univ., Hsinchu, Taiwan.
[9]Chemical Engineering Dept., Yuan Ze Univ., Taoyuan, Taiwan.
[10]Thermal Engineering Dept., Tsinghua Univ., Beijing, 100084, China.
[11]Water Quality Section, Taiwan Water Supply Corporation, Taichung, Taiwan.

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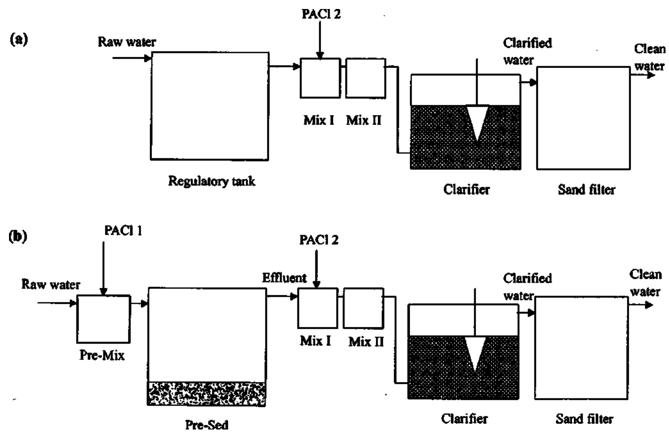

Fig. 1. Schematic of the treatment process: (a) Single-stage process and (b) two-stage process. Pre-Mix: premixing tank; Pre-Sed: regulatory tank.

condition on the ease of floc formation or floc breakage from high-turbidity water and noted a correlation between floc size and sedimentation performance. Head et al. (1997) discussed the use of their blanket model, in which the blanket was regarded as a continuous stirred tank reactor (CSTR) to correlate the observed effluent turbidity and operational parameters like temperature, rise rate, and surface loading.

The Works originally adopted the classical coagulation-clarification process (referred to as the "single-stage process") for treating raw water. In this process, the floc blanket is noted to be rather unstable and easily washed out (Chen et al. 2001). Furthermore, when treating high-turbidity raw water, coagulated solids rapidly accumulate in the clarifiers, and the flocs display very poor settleability. Consequently, the Works generally have to reduce water throughput, for instance, by 30% from its designed value at raw water turbidity of 200 NTU, and by 50% at 1,500 NTU. The turbidity of the clarified water is generally too high to produce quality clean water following sand filtering.

Since August 23, 2000, the Works has included a pretreatment stage before conventional coagulation-clarification. Specifically, the raw water is dosed with PACl and settled once. Then the effluent is dosed again with PACl and clarified in the clarifiers. This "two-stage process" produced a stable blanket and satisfactorily clarified water when running at full capacity and treating high-turbidity storm water from tropical storms Bilis (August 23 to 24, 2000) and Xangsnae (October 30 to 31, 2000). The pretreatment stage removes some turbidity, thus simplifying subsequent clarification. Chen et al. (2001) sampled the blanket from the clarifier bottom and also clarified water for the eight flat-bottomed floc blanket clarifiers at the Works, and reported their solid concentrations, zeta potentials, floc size, and capillary suction time, during May 25–September 8, 2000. These writers noted that, during both low- and high-turbidity periods, the two-stage treatment achieved a more stable operation than the single-stage treatment without blanket washout. However, Chen et al. (2001) provided no detailed information on blanket stability, especially its response to the PACl dose change. Consequently, this study examined the changes in clarified water quality and solids fraction/floc size *distributions* in the full-scale clarifiers using a two-stage process to treat high-turbidity raw water. Moreover, pilot tests were conducted to highlight the difference in clarification performance between the two-stage and single-stage processes.

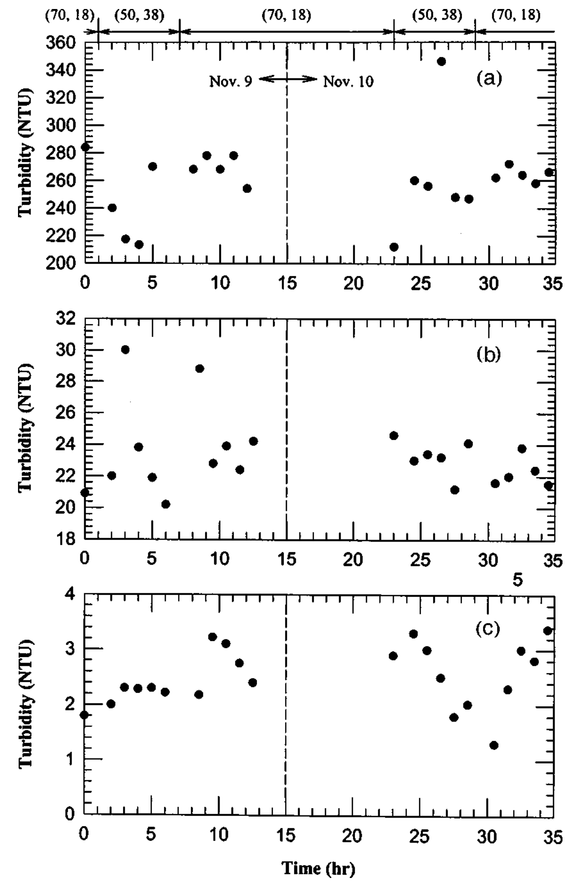

Fig. 2. Turbidities of water samples collected on November 9 to 10, 2000. (PACl 1, PACl 2) are in ppm. (a) Raw water; (b) dosed water in Mix I; and (c) clarified water.

Full-Scale Test

Treatment Process

The treatment process adopted by the Works is displayed in Fig. 1. The PACl coagulant adopted by the Works comprises 10% available Al_2O_3: In the single-stage process [Fig. 1(a)], the raw water was dosed with PACl (PACl 2) in Mixing Tanks 1 (Mix 1) and 2 (Mix 2). The dosed water was then fed into one of the eight flat bottom type floc blanket clarifiers, each sized 32.2 m×15.8 m×4.8 m. Coagulation and clarification occur in these blanket clarifiers, in which 16 sludge cones remove excess sludge. The clarified water overflows into a sand filter. After chorine disinfection, the filtered water is ready for distribution.

In the two-stage process [Fig. 1(b)], the raw water was dosed with a prescribed amount of PACl (PACl 1) in the premixing water tunnel (Pre-Mix), then the coagulated water was settled in the sedimentation tank (Pre-Sed), with a capacity of 70,000 m^3. The Pre-Mix and Pre-Sed stages comprise the "pretreatment stage." After a finite fraction of turbidity and other contaminants in the water were removed during this pretreatment stage, the effluent was dosed with PACl using Mixes 1 and 2 (termed PACl 2) and then clarified using the floc blanket clarifiers.

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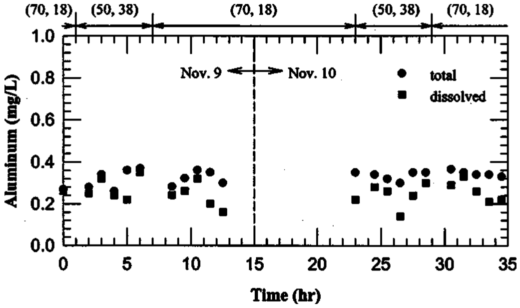

Fig. 3. Residual aluminum concentrations in waters collected on November 9 to 10, 2000. (PACl 1, PACl 2) are in ppm.

Sampling and Tests

This study step-changed the PACl dose to clarify the dynamic responses of the blankets in the clarifiers of the Works on November 9 and 10, 2000, respectively (approximately 8 days after Typhoon Xangsane struck Taiwan). Raw water turbidity increased as high as 750 NTU when Xangsane hit, and during the testing period it ranged from 200 to 300 NTU. Previous field experience applying the single-stage process suggested that the applied PACl would range from 90 to 110 ppm (4.76 to 5.82 ppm as Al), while water production would decrease to approximately 210,000 m^3/day (70% of the design value). However, using the two-stage process, the Works could produce drinking water at over its design capacity of 400,000 m^3/day (33% excess).

This work monitored the response of clarifier blankets to step-changes in PACl dose on November 9 and 10, 2000, respectively. On November 8, PACl 1 was set at 70 ppm, and PACl 2 was set at 18 ppm to produce a stable blanket. On the morning of November 9, the PACl 2 was step-increased to 35 ppm for 6 h, then step-decreased back to 18 ppm for another 6 h. Finally, on November 10, 2000, PACl 1+PACl 2 was maintained at 88 ppm, slightly below the recommended dosage (90–110 ppm). At the start of the test (PACl 1, PACl 2) was step-changed from (70 ppm, 18 ppm) to (50 ppm, 38 ppm) for 6 h. Subsequently, the dosages were returned to (70 ppm, 18 ppm).

Water samples were taken from the raw water intake port, Mixes 1 and 2, the eight clarifiers at various depths (1.0–4.5 m), and the clean water tank. A turbidimeter (HACH Model 2100 AN) measured water sample turbidity, while weighing and drying determined their solid concentrations. The size distribution of the flocs was determined from over 250 magnified images recorded by a digital camera (CV 950) and an image analyzer (Matrox Inspector 2.2). Finally, an ICP mass spectrometer (ELAN 6000, Perkin Elmer) measured the total aluminum concentrations, dissolved and precipitated (after digestion), in the water samples.

Water Qualities

The turbidities of the water samples gathered on November 9 and 10, 2000, are illustrated in Fig. 2. The turbidity of raw water fluctuated between 210 and 350 NTU during testing. Notably, the designed retention time of the presedimentation tank is approximately 4 h. However, field tests measuring blanket response to changing PACl1 revealed that actual retention time was approximately 1.5 h.

Raw water turbidity correlated with that of the preclarified water. For instance, at Hour 1–4 on November 9 raw water turbidity reduced from 284 to 215 NTU, while at Hour 3–6 preclarified and clarified water turbidity decreased from 30 to 20 NTU. Moreover, at Hour 4–6 raw water turbidity increased to 270 NTU, while at Hour 6–8 clarified water turbidity increased to 30 NTU. The clarified water displayed turbidity of 2–3.5 NTU, slightly different from that of the preclarified water.

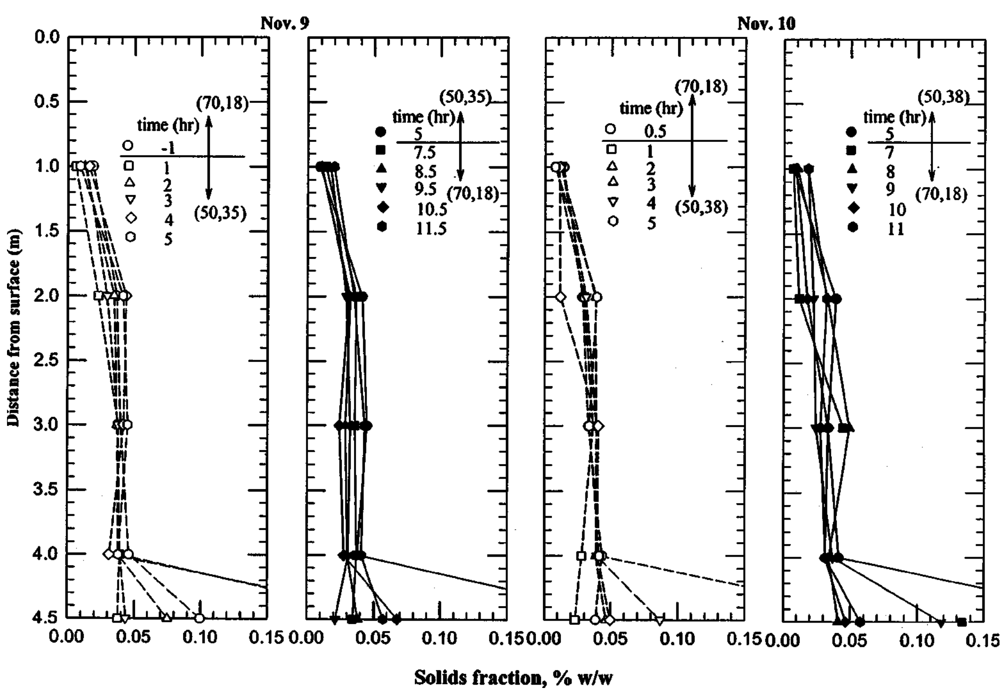

Fig. 4. Distributions of solids concentrations in floc blanket subjected to PACl change. Full-scale test.

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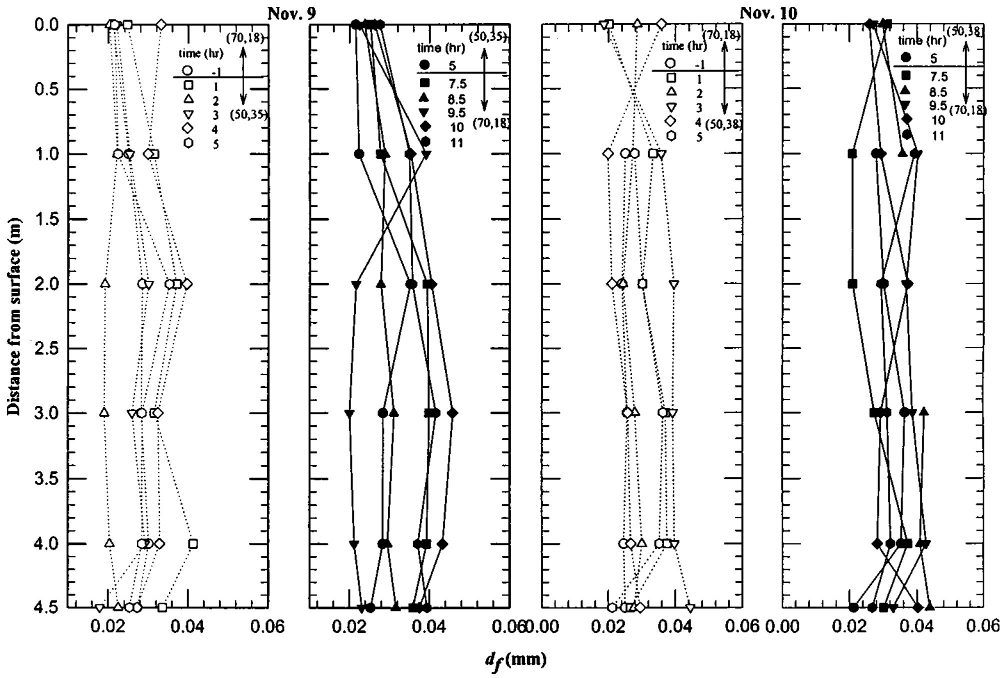

Fig. 5. Distributions of floc size in floc blanket subjected to PACl change. Full-scale test.

The aluminum concentrations (total and dissolved) in the clean water samples are illustrated in Fig. 3. The residual aluminum concentrations in the clean water ranged from 0.2 to 0.4 ppm, and over 60% was in dissolved form. Consequently, the two-stage process efficiently removed aluminum salt from water, although it is associated with a rather high PACl dose (>88 ppm, =4.6 ppm as Al).

Blanket Characteristics

The solids fraction distributions in the clarifiers gathered on November 9 and 10 are displayed in Fig. 4. The clarifier always contained a blanket of ~0.02–0.05% w/w, with the blanket–supernatant interface being located approximately a meter from the surface. (Note: The concentration of solids at the tank bottom is rather high, indicating that the coarse particles had settled on the tank bottom and do not comprise a blanket.) Visual observation also revealed a stable blanket in the clarifier, although small aggregates continuously drained out with the effluent. The concentration distribution of solids was significantly affected when PACl 2 step-changed from 35 to 18 ppm, and when both PACl 1 and PACl 2 were changed at a total dosage of PACl 1+PACl 2=88 ppm.

The corresponding floc size distributions in Clarifier 2A, collected on November 9 and 10, 2000, are demonstrated in Fig. 5. The floc sizes measured by image analysis were all approximately 20–40 μm. Close examination reveals that floc size distribution

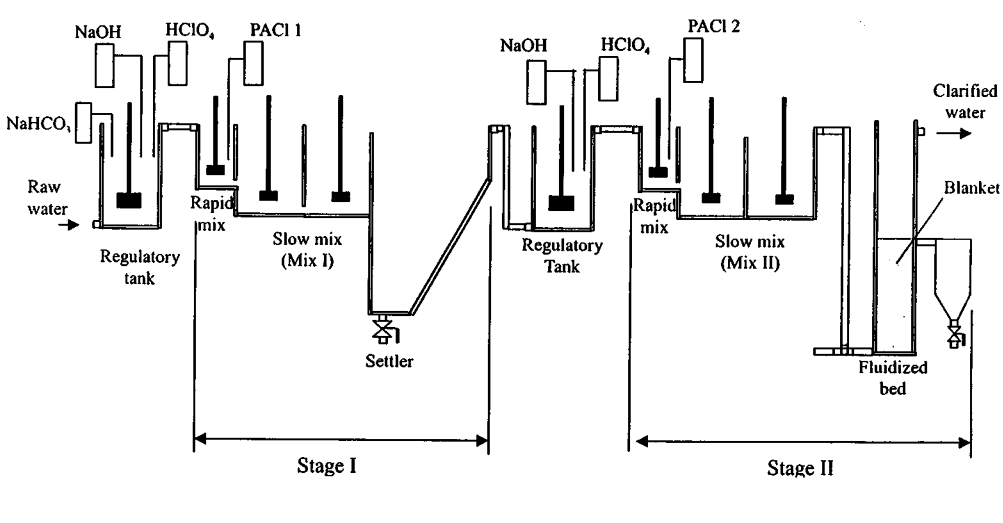

Fig. 6. Schematic of the pilot plant. Mix I: Mixing Tank 1; and Mix II: Mixing Tank 2.

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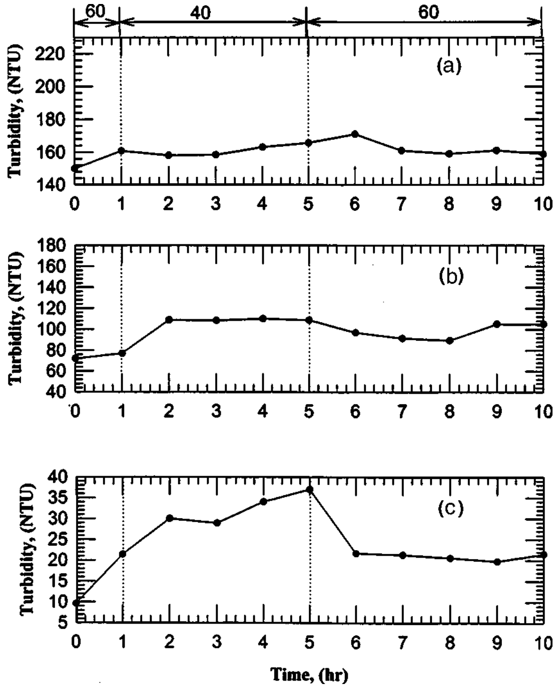

Fig. 7. Turbidities of water samples collected at single-stage test. (PACl 1, PACl 2) are in ppm. (a) Raw water; (b) dosed water in Mix II; and (c) clarified water.

changed over time. Although blanket deterioration subject to PACl dose drop persisted, its scale was too small to influence overall blanket stability.

The Works successfully produced drinking water from high-turbidity storm water while running full capacity by using a two-sage process that was not influenced by PACl dose. The clarified water thus produced not only has low turbidity (<3 NTU), but also contains low levels of residual aluminum. The spatial distributions of solids fraction and of floc size are relatively stable given step-changing PACl dosage. This study compares the performances of these two processes for treating high-turbidity water in a pilot plant, as reported in the following section.

Pilot Test

Apparatus and Tests

A pilot plant with the same retention times and the mixing intensity (G and t values) as the full-scale process was installed in the Works, as illustrated in Fig. 6. For the single-stage test, the raw water was dosed with PAC l (PACl 2) using a metering pump at the Mixing Tank II (Mix II) at $(G,t)=(315\ s^{-1}, 90\ s)$ for rapid mixing and $(G,t)=(27.6\ s^{-1}, 1{,}200\ s)$ for slow mixing. A cylindrical fluidized bed with diameter 10 cm and height 100 cm then received the dosed water used to develop the blanket. The upflow velocity in the fludized bed was equivalent to that employed in the full-scale operation. Meanwhile, for the two-stage test, the raw water was dosed with Mix I (rapid+slow mixing) at the same (G,t) as for Tank II, and then settled for 85 min. The supernatant then overflew into Tank II at another PACl dosing (PACl 2), after which the dosed water was fed into the fluidized clarifier.

The plot tests were conducted during October 6 to 7, 2001,

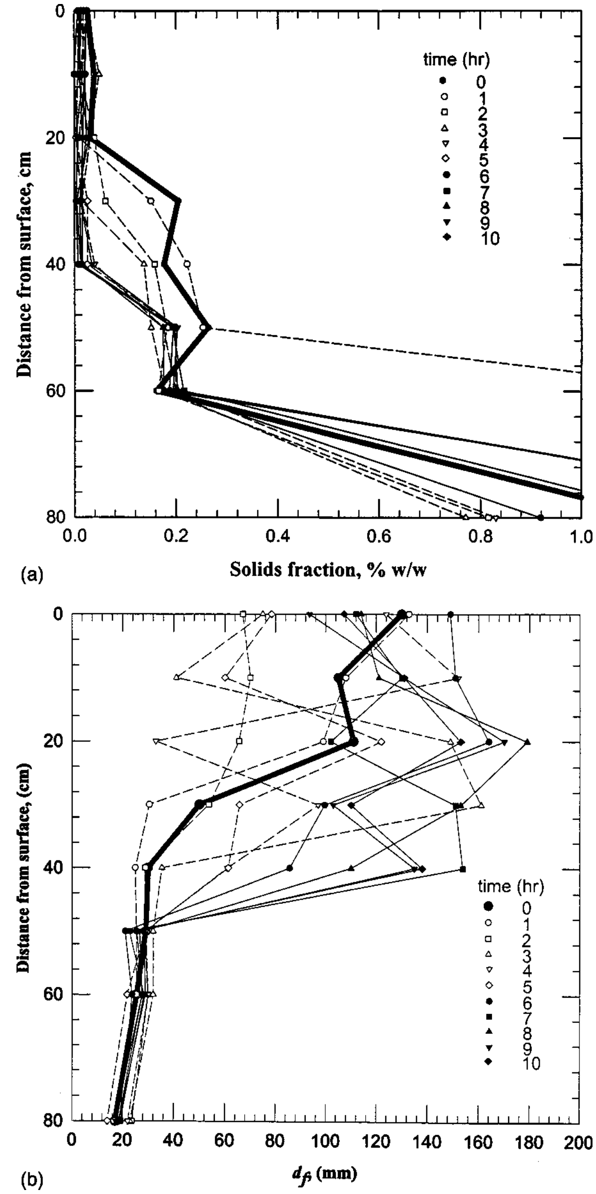

Fig. 8. Distributions of solids concentrations in floc blanket subjected to PACl change. Single-stage test. (a) Single-stage test and (b) two-stage test. Bold curve: initial sludge at Hour 0.

using high-turbidity storm water from typhoon Lekima, which hit Taiwan during September 26–28, 2001. The raw water turbidity during the sample period ranged from 150 to 200 NTU. Previous experience from the single-stage process suggests a PACl dosage of 60–80 ppm would be appropriate for treating such high-turbidity raw water. This study monitored the dynamic responses of the clarifier blanket to step-changes in PACl dose. On October 6, a single-stage test was conducted, with raw water flowing through Mix I and the settling tank without being treated. The PACl 2 was maintained at 60 ppm in Mix II on October 4 to 5 to produce a blanket with a thickness of approximately 70 cm in the fluidized clarifier. Meanwhile, on the morning of October 6, the PACl2 was suddenly reduced from 60 to 40 ppm. Then, after 4 h, the PACl 2 was returned to 60 ppm. Finally, on October 7, the two-stage test was performed with (PACl 1, PACl 2) step-changed from (30 ppm, 30 ppm) to (20 ppm, 20 ppm) for 4 h. Subse-

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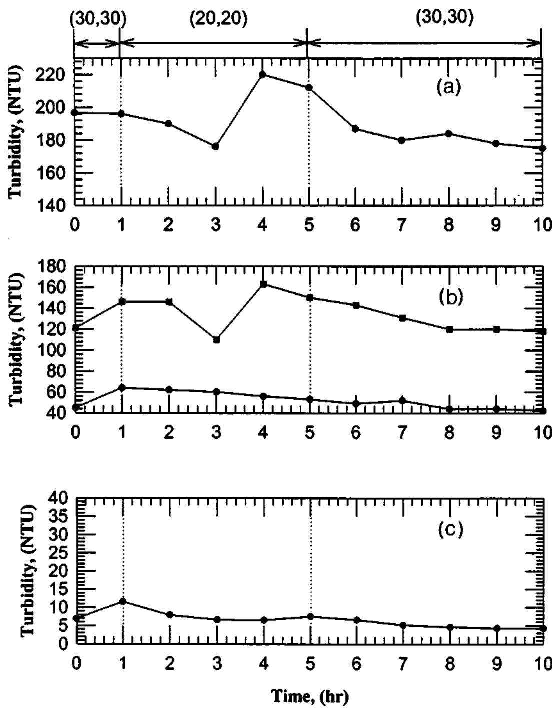

Fig. 9. Turbidities of water samples collected at two-stage test. (PACl 1, PACl 2) are in ppm. (a) Raw water; (b) dosed water in Mix I (squares) and Mix II (circles); and (c) clarified water.

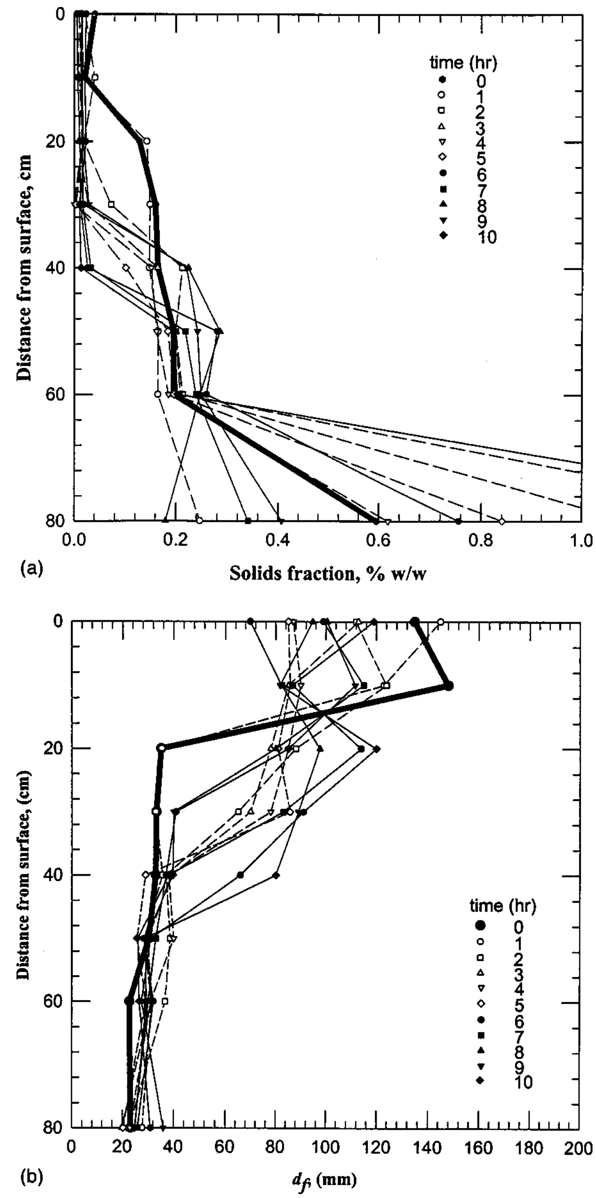

Fig. 10. Distributions of solids concentration in floc blanket subjected to PACl change. Two-stage test. Bold curve: initial sludge at Hour 0.

quently, (PACl 1, PACl 2) were returned to (30 ppm, 30 ppm). The total PACl dose was varied between 60 and 40 ppm, approximating that used in the single-stage test.

Results

The turbidities of raw water, dosed water (Mix II), and clarified water from the fluidized clarifier using the single-stage test are illustrated in Fig. 7. The turbidities of the dosed water and clarified supernatant increased significantly with time when PACl 2 was reduced from 60 to 40 ppm. For instance, the turbidity of the clarified water increased to over 35 NTU at Hour 5 after the start of the coagulant dosage drop. Therefore, if the single-stage process was adopted, the blanket would become excessively sensitive to PACl change. Consequently, high residual turbidity in the clarified water would flow into the sand filter and cause serious clogging/frequent backwashing there. When the PACl resumed its original dose, the turbidity of the clarified water declined to approximately 20 NTU, around twice that at Hour 0 (10 NTU).

The solid fraction and floc size distributions in the fluidized clarifier gathered during the single-stage test (October 6, 2001) are shown in Figs. 8(a and b). Initially the clarifier contained a blanket of solid fraction ca. 0.02–1.0% w/w, with the blanket–supernatant interface located at a depth of around 70 cm [Fig. 8(a)]. Notably, small aggregates continuously flowed out with the effluent. When PACl 2 was step-changed from 60 to 40 ppm, the blanket was rapidly washed out. At Hour 4 the solid fraction at 40 cm below the water surface decreased from 0.2% to around 0.02%. Simultaneously, the height of the corresponding blanket–supernatant declined from 70 to 50 cm. This phenomenon correlates with increased clarified water turbidity as displayed in Fig. 7.

The floc sizes in the blanket ranged from 15 to 30 μm, while the flocs gathered from the supernatant above the blanket had various sizes, from 40 to 180 μm, and were significantly greater than those found in the blanket [Fig. 8(a)]. Restated, the blanket, where existent, is stabilized not by gravitational settling of large flocs but by "networking" among constituent flocs. Meanwhile, blanket deterioration produces large fragments, which do not settle but rather are carried over by the effluent.

The turbidities of raw water, dosed water (Mixes I and II), and clarified water from the fluidized clarifier for the two-stage test are displayed in Fig. 9. Prior to testing the clarifier contained a blanket with a depth of around 80 cm. When PACl 1 and PACl 2 were reduced from 30 to 20 ppm, the turbidity of the dosed water in Mix I [squares in Fig. 9(b)] increased significantly. Meanwhile, the turbidities of dosed water in Mix II [circles in Fig. 9(b)] and clarified water do not change much. The turbidities of the clarified waters were all around 8–11 NTU regardless of raw water turbidity (175–220 NTU) and PACl dose for a range of dosages.

The distributions of solids fraction and floc size, respectively, in the fluidized clarifier collected in the two-stage test (October 7, 2001) are shown in Figs. 10(a and b), respectively. Like in Fig. 8(a), the blanket could be still washed out when PACl was reduced, but the rate of washing out decreased. In fact, the blanket structure remained almost intact at a depth up to 30 cm until Hour 5. The washout fragments in the effluent exhibit a narrower floc size distribution than those in Fig. 8(b). Finally, when the initial dose of PACl was resumed, the blanket recovered quicker than in the single-stage test.

The blanket produced by the two-stage process is more "resilient" to PACl change and raw water turbidity fluctuation. Meanwhile, the blanket produced by single-stage testing is excessively sensitive to change in PACl. Consequently, the two-stage process requires less coagulant than the single-stage process to obtain the same water quality from high-turbidity water.

Conclusions

This study monitored the dynamic responses of the sludge blanket in the full-scale flat-bottom type floc blanket clarifiers located at the Ping-Tsan Water Works (the Works), run by the Taiwan Water Supply Corporation (TWSC). Field experience using polyaluminum cloride (PACl) as coagulant revealed that the conventional coagulation-clarification process adopted by the Works suffered frequent blanket washout. However, when the raw water was dosed and settled prior to entering the coagulation-flocculation process, the clarifiers could produce quality clarified water while working at full capacity. To demonstrate the dynamic characteristics of the full-scale two-stage process on high-turbidity storm water treatment, this study step-changed the coagulant dosage during November 10 and 11, 2000, after tropical Typhoon Xangsane had struck Taiwan. Turbidity and residual aluminum in the clarified water were recorded, as were the spatiotemporal distributions of solid concentration and floc blanket floc sizes. The blanket produced by the two-stage process was resistant to the change in coagulant dosage.

Pilot tests were conducted in the Works to compare the performances of the single- and two-stage processes in treating high-turbidity waters. The single-stage process produced an unstable blanket subjected to PACl change. Not only was the blanket easily washed out when the PACl dose was reduced, it also recovered very slowly when the dose resumed its original value. Moreover, various sized floc fragments were eroded from the destabilized blanket and flowed out with effluent, causing high supernatant turbidity. On the other hand, the blanket of the two-stage process was stable to PACl dose change. Notably, local blanket deterioration owing to insufficient PACl dose quickly recovered when the dosage resumed its original value. Importantly, the two-stage process requires less coagulant for high-turbidity water treatment than does the single-stage process.

Acknowledgment

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