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Turbidity reduction in Taiwan reservoir environment using bio-based polymer—Chitosan

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ABSTRACT

Water derived from storm events in Taiwan is a critical issue because of its high turbidity, which could be larger than 100,000 Nephelometric Turbidity Units (NTU), due to the fragile geology and steep topography of the island. The high turbidity water lowers the efficiency of a water treatment plant or can even shut down the facility resulting in a loss of water supply. Commonly used coagulants, such as aluminum salt, iron salt, and polymers, have dosage limitations and application restrictions due to health concerns. This study provides a new method for turbidity reduction, which can be applied both inside and outside of a water treatment plant. This method then provides a more stable, safe, and environment-friendly water supply by using Chitosan as bio-based polymer for extremely high turbidity water. Representative samples are used to evaluate the effectiveness of Chitosan: (1) the collected sample from Chengqing Lake Reservoir in southern Taiwan; (2) Kaolin soil (or Kaolinite clay), and (3) Ottawa standard sand. The results show that the residual turbidity is directed related to (1) bio-polymer dosage, (2) initial concentration, (3) particle size, (4) mixing method, and (5) settling time. Also, the bio-polymer dosage of 0.2 mg/L can reduce the turbidity from about 50,000 to 25 NTU, which is well below the drinking water standard of 30 NTU for high turbidity periods.

Keywords: Chitosan; Coagulant; High turbidity raw water; Turbidity reduction

1. Introduction

Because of mountainous area with steep slope and fragile geological condition, storm events can cause extremely high turbidity in river due to erosion, landslides, or debris flows. As a result of this high turbidity, water supplies become unstable. In Taiwan, the turbidity can reach levels greater than 100,000 Nephelometric Turbidity Units (NTU) and can stay at high turbidity level for more than a week after the storm event. To reduce the turbidity, coagulants such as Polyaluminum Chloride (PAC) and polymers are popularly used in water treatment plants. However, these coagulants may only be used in specific water treating processes with limited allowable dosage due to health concerns.

This study provides a new concept on handling turbidity reduction to stabilize water supplies during high turbidity storm events. This turbidity reduction process can be performed inside or outside of a water treatment plant. An environmental friendly material is

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required to meet the turbidity levels and provide safe water supplies. Chitosan, a natural and environmentally safe polymer, has been widely applied to a number of fields such as heavy metal adsorbents, antibacterial agents, functional foods, cosmetics, and artificial skin [1–5]. For the applications of water treatment [6], Chitosan has been applied to food processing wastewater [7–12], milk processing plant [13], brewery wastewater [14], wash water [15,16], effluents containing dyes [17,18], pulp and paper mill wastewater [19–23], oily wastewater [24–27], aquaculture wastewater [28], partially purified sewage [29], brackish water [30], and raw drinking water [31]. This study uses Chitosan as the bio-based polymer to reduce the extremely high turbidity in Taiwan reservoir environment. The effects of dosage, initial concentration, particle size, mixing method, and settling time on turbidity reduction then are evaluated.

2. Materials and methods

2.1. Biocompatible and biodegradable material

Chitosan is usually produced by deacetylation of chitin, the structural element in the exoskeleton of crustaceans such as crabs and shrimp. Chitin is the second most popular organic substance in the natural world ranked after the cellulose. The biocompatible and biodegradable characteristics make Chitosan a nice selection as an environmental friendly coagulant [32–34]. Table 1 shows the comparison between commonly used coagulants and Chitosan. Aluminum salt, iron salt, and polymers are three commonly used categories of coagulants. However, the downside of all these coagulants is the health concerns followed by dosage limitation. This limitation leads to difficulty of treating extremely high turbidity water. Chitosan, with very low toxicity to environment and creatures, has a more relaxed limitation on dosage. In fact, the application of Chitosan is so effective in turbidity reduction that there is no need for consideration of dosage limitation.

2.2. Case study

Chengqing Lake Reservoir supplies 30,000 CMD to the city of Kaohsiung. The main source of water for this reservoir is the Kaoping River, which is the largest river in southern Taiwan. During a storm event, the turbidity easily exceeds several thousand NTU. Fig. 1 depicts the Kaoping River raw water turbidity historical data during and after typhoon Mindulle [35], which shows that high turbidity occurred and continued for more than one week. Our case samples, as depicted in Fig. 2, were taken at the inflow location of the reservoir. The sampled material is classified as ML according to Unified Soil Classification System (USCS). This material is composed of low-cohesive silt and clay.

2.3. Experimental design

The collected soil samples underwent a series of steps outlined in Fig. 3. The soil is first collected and dried. After the particle size distribution is identified, the samples are artificially prepared for the selected suspended solid (SS) concentrations. The jar test method is then used to evaluate the influence of biopolymer dosage, original concentration, particle size, mixing methods, and settling time on the effectiveness of reducing the turbidity. The dosage used is between 0.2 and 2.0 mg/L. The original concentration is prepared from 4,000 to 110,000 ppm representing the extremely high turbidity conditions during storm events. To evaluate a real world situation, three types of high turbidity samples were prepared from the Chengqing Lake Reservoir, Kaolin soil, and Ottawa standard sand. The Kaolin soil and Ottawa standard sand represents the fine and coarse particles. These samples are used to understand how particle size influences the results and describe the range of potential values. Two mixing methods, rapid then slow mixing and slow mixing, are applied to evaluate the influence resulted from the way we mix the bio-polymer with high turbidity water. The influence time is also investigated because the settling velocity is directly related to the particle size.

The non-cohesive Ottawa standard sand and cohesive Kaolin soil were applied in the experiments for comparison with the Chengqing Lake Reservoir samples. The Kaolin soil has specific weight of 2.7 with major components of SiO_2 and Al_2O_3. The particle size distribution of soil obtained from Chengqing Lake Reservoir and Kaolin soil are shown in Figs. 4 and 5, respectively. Table 2 shows the comparison of particle size between two samples. The comparison shows that the medium particle size of Chengqing Lake is about six times larger than the medium particle size (D_{50}) of Kaolin soil. For fine particles, the values of D_{20} and D_{10} show that it is about 20 times larger.

The high turbidity water sample is prepared based on the SS concentration. The relationship between the SS concentration and the turbidity is required because most turbidity measurement devices have an upper limit of 1,000 NTU. This study develops these

Table 1
Comparison between commonly used coagulants and Chitosan

Item	Aluminum salt	Iron salt	Polymer	Chitosan
Type	(1) Polyaluminium Chloride (PAC) (2) Aluminum sulfate (alum)	(1) Ferric chloride	(1) Polyacrylamide (PAM) (2) Poly (Diallyldimethyl Ammonium Chloride) [Poly (DADMAC)] (3) Epi-DMA Polyamines (Epichlorohydrin Dimethylamine)	–
Advantage	(1) Low price (2) Stable effect (3) No residual color	(1) Low dosage (2) High floc density (3) Wide PH range (4–9)	(1) Not affected by PH (2) Less sludge volume	(1) Environmental friendly (2) Biocompatible and biodegradable (3) Efficiency (4) Less sludge volume
Disadvantage	(1) Maybe pathogenicity (2) Large sludge volume (3) Narrow PH range (6–9)	(1) High price (2) Corrosive (3) Residual chroma	(1) Maybe carcinogenic (2) Unstable effect (3) Application and dosage limitation by regulations	(1) Price

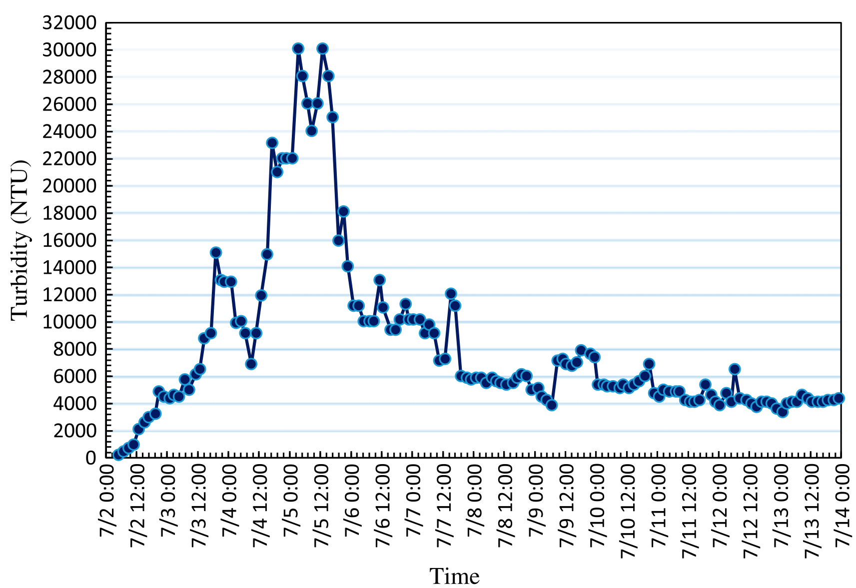

Fig. 1. Kaoping River raw water turbidity historical data during and after typhoon Mindulle (2 July 2004–4 July 2004).

relationships to extrapolate beyond the 1,000 NTU limit. Fig. 6 shows the relationship between SS concentration (C) and turbidity (T) for all three experiment soils. The figure illustrates a linear relationship where smaller particle size have higher turbidity under same SS concentration.

In the experiment, the terminologies need to be clarified. Two representations for water quality used in this study are SS concentration and turbidity. The SS concentration is calculated by the weight of SS and water. The unit is mg/L or parts per million (ppm). The turbidity is the measure of relative clarity of a

Fig. 2. Satellite map of the Chengqing lake reservoir with the sampling location indicated with a red pin cushion.

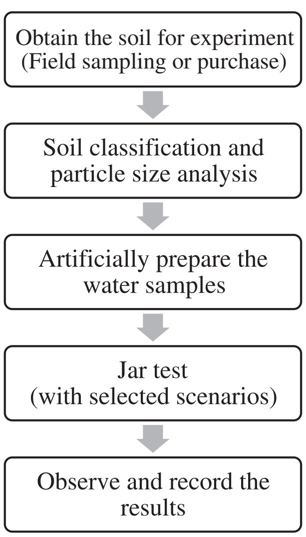

Fig. 3. The flowchart that illustrates the steps involved in evaluating the effectiveness of reducing the turbidity.

liquid and is an optical characteristic which can be detected by light and its scattering. The unit of turbidity is NTU. To represent the experiment results, the SS concentration is used for the initial concentration because the water sample is prepared using weight calculation. The turbidity is used for residual turbidity due to consideration of water quality standard for water supply. Note that the SS concentration and the turbidity can be transformed using the linear relationship shown in Fig. 6. The bio-polymer dosage refers to the bio-polymer applied to the water sample. The unit of the dosage is mg/L. The residual turbidity indicates the turbidity of water sample after treated by the specified bio-polymer dosage and mixing method. The mixing method is the way this experiment used to mix the bio-polymer with the water sample. Two mixing methods are used for the experiment. Details of mixing methods will be expressed later.

3. Results and discussion

3.1. The influence of original sediment concentration

Figs. 7 and 8 show how initial concentration affects the result. Two initial concentrations, 70,000 and 110,000 ppm, are tested. The bio-polymer dosage ranges from 0.2 to 2.0 mg/L. The dosage of 0.2 mg/L produces residual turbidity below than 24 NTU for both initial concentrations and water samples. This turbidity is well below the regulation limit of 30 NTU for raw water turbidity. This is quite a substantial reduction considering the original water samples had turbidity levels greater than 20,000 NTU. For all the samples, the larger the initial concentration the larger the final residual concentration. There is a gap, not large but exists between the residual turbidity of these two initial concentrations. In addition, a terminal turbidity, not zero, seems exists. The dosages of 0.8 and 1.6 mg/L are enough for the residual turbidity to

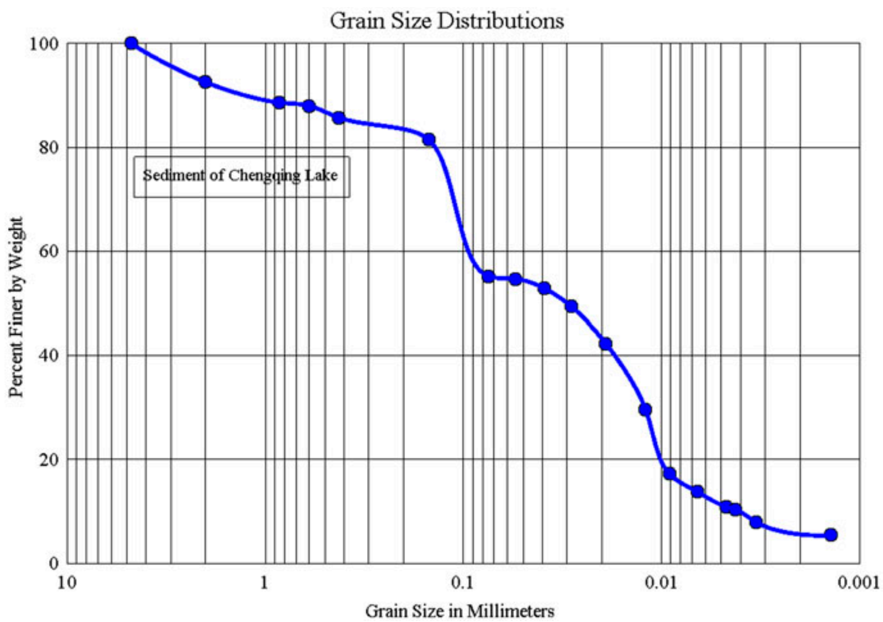

Fig. 4. The particle size distribution of soil obtained from Chengqing Lake Reservoir.

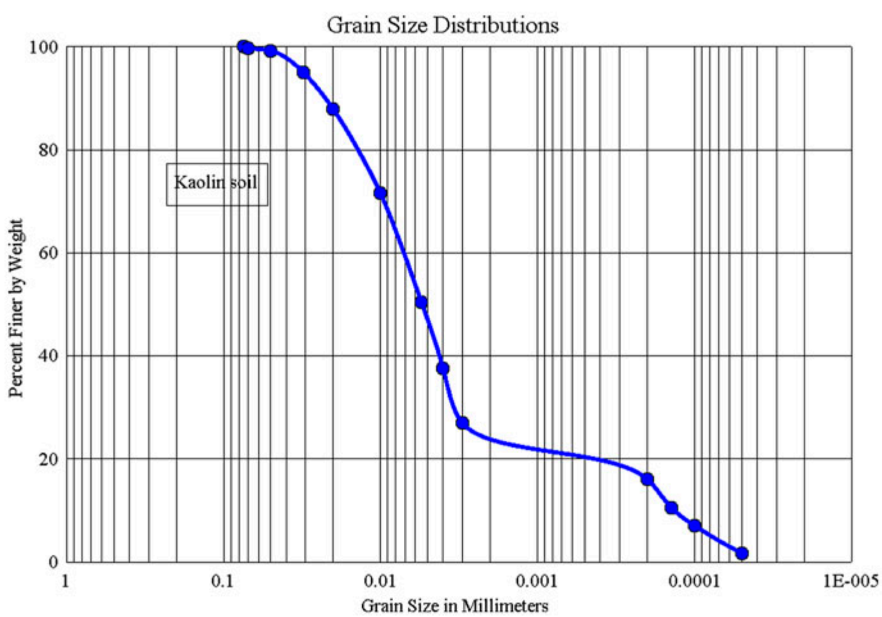

Fig. 5. The particle size distribution of Kaolin soil.

reach terminal turbidity for Chengqing Lake and Kaolin soil samples, respectively. In other words, the dosages more than 0.8 and 1.6 mg/L are overdosing for two water samples. A similar reduction trend is observed for different initial concentration samples. Although the initial concentration has large difference, one water sample has about 40% more on SS concentration, the dosage needed to reach the terminal turbidity is just slightly different, which is less than 20% difference in dosage.

Table 2
Particle size of Chengqing lake reservoir and kaolin soil

	D_{50}	D_{20}	D_{10}
Chengqing lake reservoir	0.03 mm	0.01 mm	0.004 mm
Kaolin soil	0.005 mm	0.0005 mm	0.002 mm

Notes: D_x is the value of the particle diameter at x% in the cumulative distribution. For example, if D_{50} = 0.03 mm, then 50% of the particles in the sample are larger than 0.03 mm.

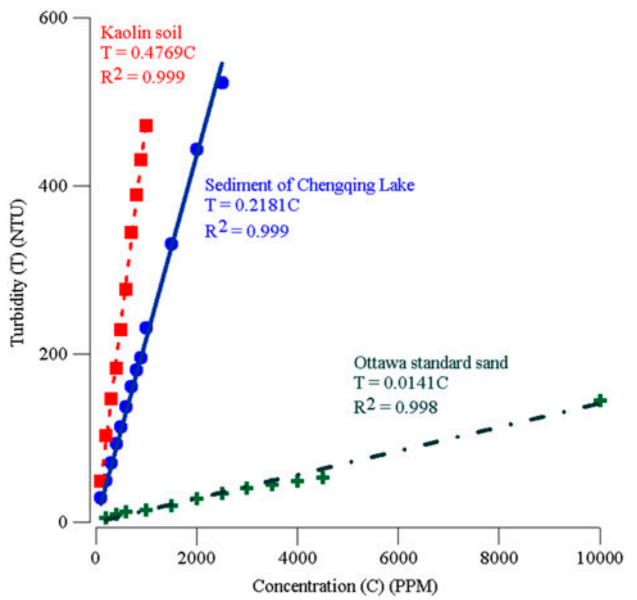

Fig. 6. The relationship between sediment concentration and turbidity.

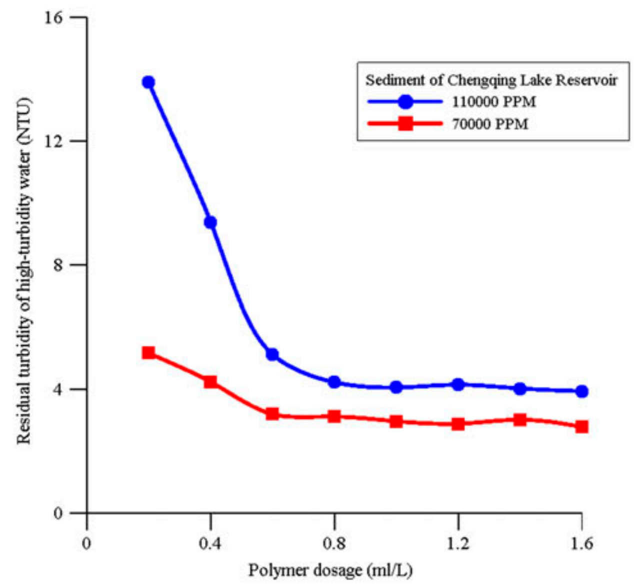

Fig. 7. The residual turbidity for sediment of Chengqing Lake Reservoir as a function of polymer dosage.

3.2. The influence of dosage

The Fig. 9 through Fig. 10 demonstrate that there is a negative correlation between dosage and residual turbidity. There is a limit to the minimum turbidity, referred as terminal turbidity, which the coagulants can reach that is independent of dosage.

Fig. 9 through Fig. 11 show that a dosage of 0.2 ml/L can reduce the turbidity from 110,000 ppm to 14 and 25 NTU for Chengqing Lake and Kaolin soil, respectively, which comply with the drinking water standard of 30 NTU during high turbidity periods. The curve pattern illustrated in the figures may be different, but the general trend is that more dosage results in better clarity of the treated water. A steeper slope appears between 30,000 and 60,000 ppm for Kaolin soil. This slope refers that the liquid of fine particles with sediment concentration of 30,000 ppm or smaller has better results in terms of water clarity. For standard sand, this pattern is not observed. The residual turbidity for the standard sand samples are below 6 NTU for all cases.

3.3. The influence of particle size

The particle size of Kaolin soil is smaller than the particle size of Chenqing Lake Reservoir. As can be seen in Figs. 9 and 12 with the dosage of 0.2 mg/L, the residual turbidity is below 15 NTU and below 25 NTU for the Chencing Lake Reservoir and Kaolin soil, respectively. Fig. 10 presents the result comparison between Chengqing Lake and the Kaolin soil samples. The residual turbidity is related to particle size and smaller particle size leads to higher residual turbidity. This characteristic can also be seen in Figs. 9, 12, and 11. Therefore, more dosage is needed to reach the same level of residual turbidity for small particle size.

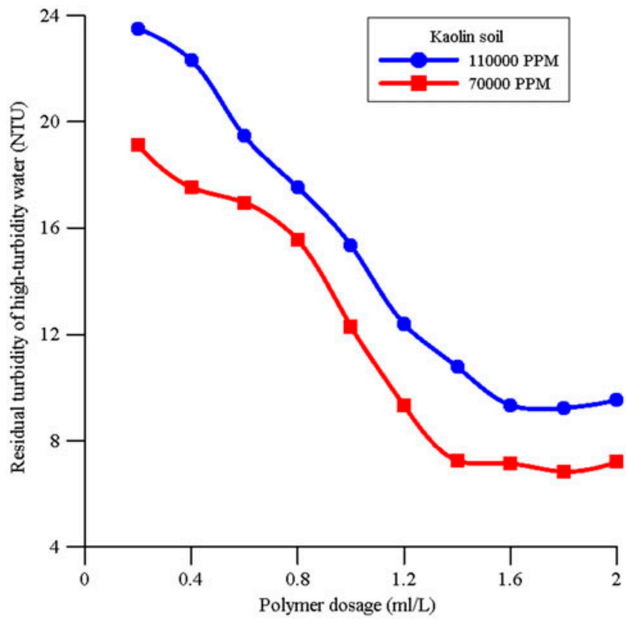

Fig. 8. The residual turbidity for sediment of Kaolin soil as a function of polymer dosage.

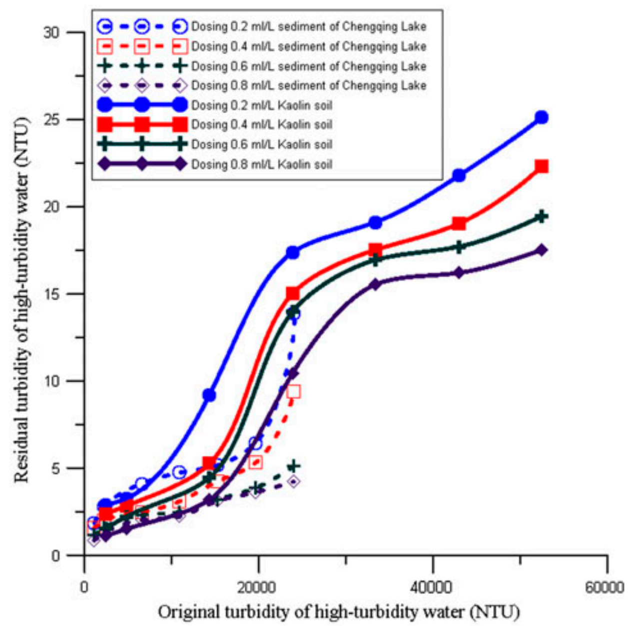

Fig. 10. The residual turbidity for sediment of Kaolin soil and Chengqing Lake Reservoir as a function of polymer dosage.

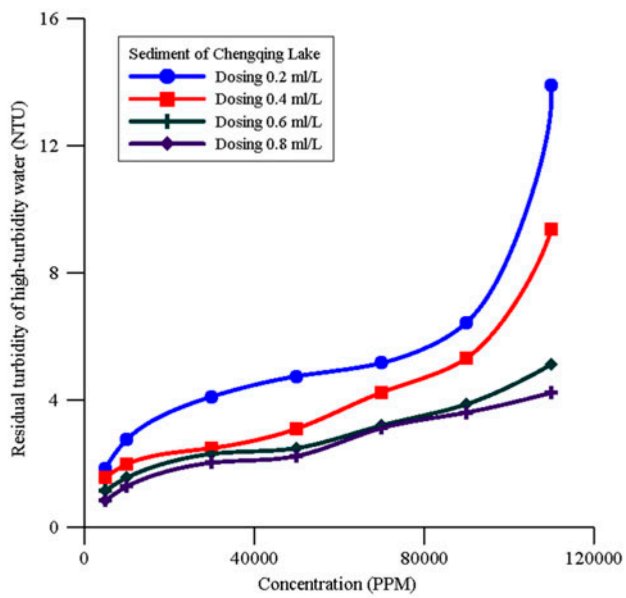

Fig. 9. The residual turbidity for sediment of Chengqing Lake.

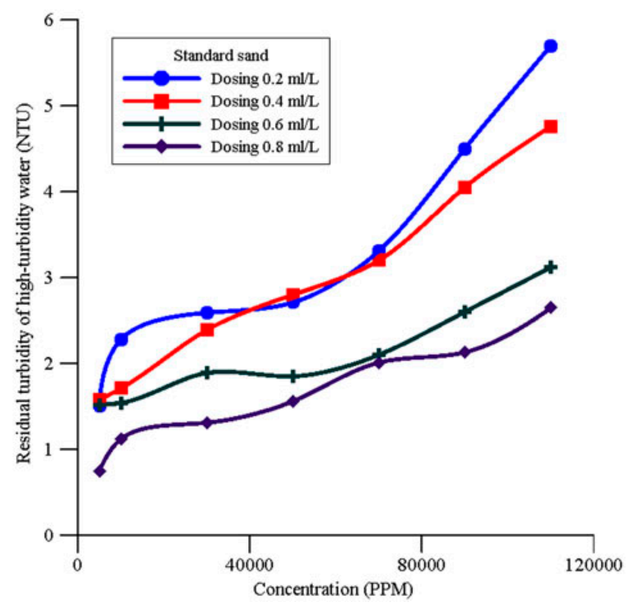

Fig. 11. The residual turbidity for standard sand.

3.4. The influence of mixing

The mixing method is an important factor that affects the finishing turbidity. Rapid then slow mix refers to mixing at a speed of 150 rpm for 1 min then 50 rpm for 5 min and slow mix refers to mixing at a speed of 50 rpm for 15 min. The mixing methods can (a) simulate the mixing procedures, flush mix and flocculation, in a water treatment plan; and (b) provide design criteria for treating water outside of a treatment plant. In Fig. 13, the residual turbidity has a flat profile between 30,000 and 90,000 ppm under slow mix condition. This flat profile is not observed when

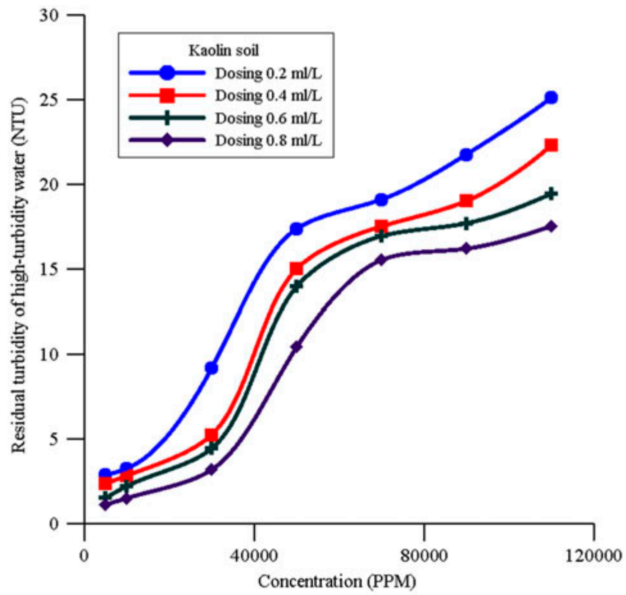

Fig. 12. The residual turbidity for Kaolin soil.

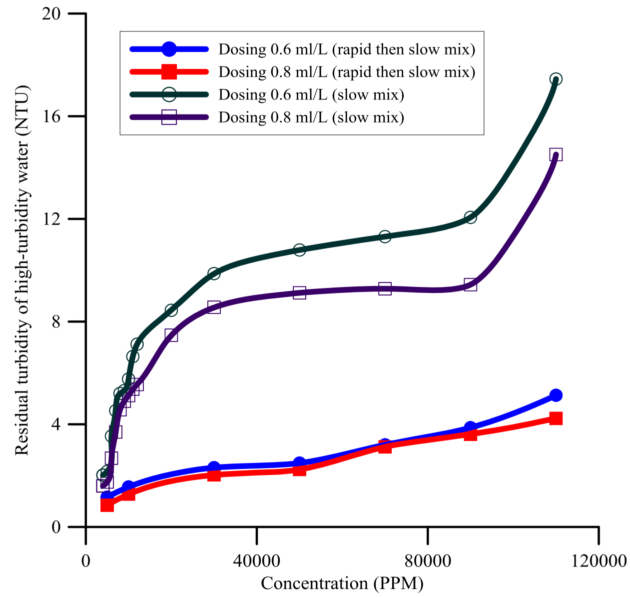

Fig. 14. Comparison of the mixing methods applied to the sediment of Chengqing Lake.

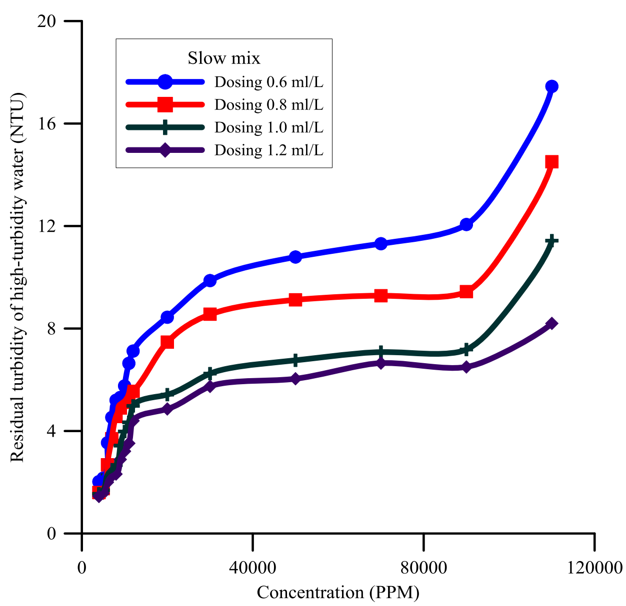

Fig. 13. The residual turbidity for sediment of Chengqing Lake (slow mixed).

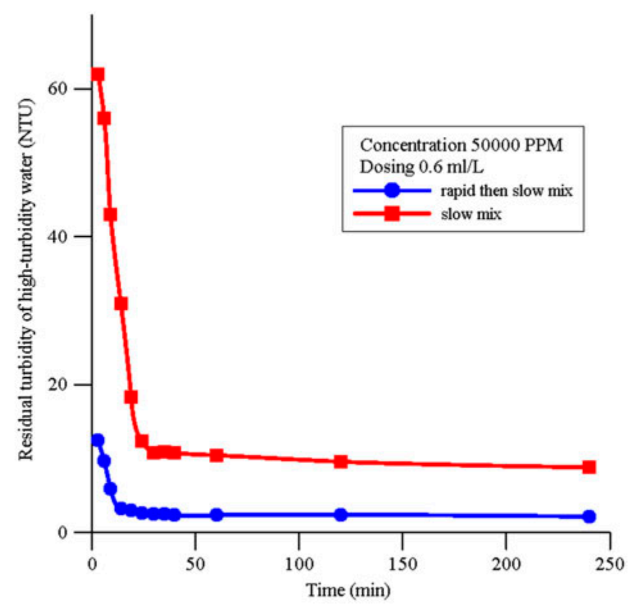

Fig. 15. The difference in the residual turbidity as a function of time for different mixing methods.

rapid then slow mix is applied (Fig. 14). The results show that the rapid then slow mix yields a better mixture of the fluid and further reduce the turbidity. This result may imply that rapid then slow mix provides better mixture.

3.5. The influence of settling time

The settling time is a critical factor for residual turbidity. Theoretically, if the settling time is long enough, the turbidity would reach clarity. Fig. 15 demonstrates the relationship between residual turbidity and time with comparison of two mixing scenarios.

For slow mix, the turbidity closely approaches the terminal turbidity at about 35 min. On the other hand, the reach time is about 20 min for rapid then slow mix. After this point in time, the residual turbidity is stable.

3.6. The residual turbidity and the terminal turbidity

The initial concentration directly influences the residual turbidity. The bandwidth of the finishing turbidity between different initial concentrations tends to be narrower along with lower initial concentrations. The terminal turbidity appears to be related to initial concentration and the particle size of the sediment where higher concentrations and/or smaller particle size tend to increase the terminal turbidity.

3.7 Comparison of results with an existing study

Chatterjee et al. [36] studied the effectiveness of Chitosan as a coagulant for treating soil suspensions in water. The percentage of suspended soil removed in their study was compared to the results of sediment of Chengqing Lake Reservoir, Fig. 16. The percentage removed was 86% for the water sample used in Chatterjee et al. [36] and 99.9% for the sediment of Chengqing Lake Reservoir after 120 min of sedimentation. The result shows that the Chitosan has very good performance in Taiwan's reservoir environment. Some of the reasons for the difference removal rates are: (1) the initial concentration of the water sample used in Chatterjee et al. [36] and this study are 5,000 and 50,000 ppm, respectively. The extremely high initial concentration could result in higher reduction rates; (2) the pH value of the water sample used in Chatterjee et al. [36] and this study are 6 and 7 respectively, which may influence the effectiveness of Chitosan; (3) the soil texture used in Chatterjee et al. [36] is sandy loam, containing 48.6% sand, 48.2% silt, and 3.2% clay with a high organic matter content of 12.9%. The high organic matter may reduce the effectiveness of Chitosan.

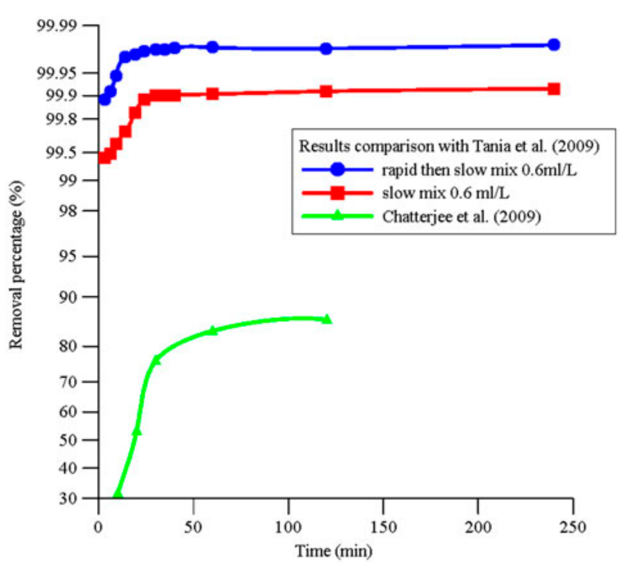

Fig. 16. The removal percentage compared with results from Chatterjee et al. [36].

4. Summary and conclusions

This study proposes a new thinking of turbidity reduction for situations where there are extreme turbidity levels that result from storm events. The proposed methodology and coagulants can stabilize the water supply during these extreme periods. It is proposed that Chitosan, a non-toxic, biodegradable material, is used as a bio-polymer for the turbidity reduction. Three types of water samples are studied: (1) real samples from Chengqing Lake Reservoir in Taiwan, (2) Kaolin soil, and (3) Ottawa standard sand. These three samples represent the range from coarse sand to fine silt/clay.

The results demonstrate that the bio-polymer can reduce the turbidity from extremely high turbidity to low turbidity using a very low dosage with less concern of health risk. The residual turbidity, in fact, meets the water supply standards. Several factors that may affect the residual turbidity are observed in the experiments: (1) dosage, (2) initial concentration, (3) particle size, (4) mixing method, and (5) settling time.

To reach lower residual turbidity, we can increase dosage, reduce the initial concentration, increase the particle size, increase the efficiency of mixing, or increase the settling time. In addition, the results show that a terminal turbidity may exist for the residual turbidity, which indicates an optimal dosage exists for a specific condition of water sample. The optimal dosage should be a function of those five factors affecting the residual turbidity and can be found via a jar test.

With the initial SS concentration of 50,000 ppm and dosage of 0.6 ml/L, slow mix with 50 rpm for 15 min could reach the terminal turbidity at 10 NTU within settling time of 35 min. On the other hand, rapid then slow mix with 150 rpm for 1 min and 50 rpm for 5 min, could reach the terminal turbidity at 2 NTU within 20 min. Choosing proper mixing procedure could dramatically reduce the cost in terms of reduction of the dosage, retention time, and retention space. Chitosan was found to be effective for coagulation of soil suspensions in Taiwan Reservoir environment.

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