Pilot-Scale Microsand-Ballasted Flocculation of Wastewater: Turbidity Removal, Parameters Optimization, and Mechanism Analysis

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Abstract

The flocs formed during microsand-ballasted flocculation (MBF) have attracted much attention. However, few studies have reported on comprehensive process parameters of MBF and its mechanism is still not well understood. Jar test and pilot-scale continuous experiments were here conducted on two kinds of simulated wastewater, labeled S1 (21.6-25.9 NTU) and S2 (96-105 NTU). Results revealed the hydraulic retention time ratio in the coagulation cell, injection & maturation cell, lamella settler of pilot-scale MBF equipment was 1: 3: 7.3. The optimum poly aluminum chloride doses for Samples S1 and S2 were 0.875 g/L and 1.0 g/L. Besides, the optimum size of microsand was 49-106 µm and the optimum dose was 1.0 g/L. Under aforementioned conditions, the effluent turbidity of S1 was below 0.47 NTU, lower than the Chinese drinking water standard; that of S2 was below 1.7 NTU, meeting the Chinese recycled water standard. Turbidity removal ranged from 98.0% to 98.8% for S1 and 98.5% to 99.5% for S2 when microsand was added. Therefore, microsand addition enhances MBF performance, where microsand serves as an initial core particle. Some microsand core particles bond together to form a dense core structure of micro-flocs by the adsorption bridging of inorganic polymeric flocculant. Moreover, the size of the largest micro-flocs may be controllable as long as the effective energy dissipation $\theta_0$ is adjusted appropriately through specific stirring speeds. This work provides comprehensive pilot-scale process parameters for using MBF to effectively treat wastewater and offers a clearer explanation of the formation mechanism of microsand-ballasted flocs.

1. Introduction

With increasing water pollution and fresh water shortages, wastewater treatments and reclaiming technologies have been developing rapidly in recent years. Ballast flocculation (BF) has become a commonly used separation process for coarse dispersion and colloidal substances in industrial and urban wastewater treatment applications (Lapointe and Barbeau 2016). This is due to its high efficiency, small footprint, high impact load, and low doses (Liu et al. 2020; Wang et al. 2020). The BF process has been applied in many countries and regions of the world, such as the application of the largest sewage treatment plant in Europe: the Seine Aval plant near Paris, France (Gasperi et al. 2012). The BF process is complicated and involves aggregation, fragmentation, repacking, remineralization, deposition, and eventually resuspension (Li et al. 2019). BF is also an enhanced clarification process that involves the addition of a high-density particle additive (ballasted media) to coagulant or non-coagulant water or wastewater to increase the size, density, and settling velocity of flocs (Ghanem et al. 2007; Zafisah et al. 2020). The ballasted media may consist of kaolin (aluminum silicate hydroxide $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$) (Qasim et al. 2020; Qasim et al. 2020), the hybrid of ferric chloride ($\text{FeCl}_3$) (Nadella et al. 2020; Ribera-Pi et al. 2020) and magnetite (Murujew et al. 2020), cationic polyacrylamide (CPAM) (Musa et al. 2020), mill scale (Chhuon et al. 2020), microsand, and so on.

Among the types of BF, microsand-ballasted flocculation (MBF) has recently become the focus of much research (Wei et al. 2018). Due to its higher density, the microsand ballast increases the size and density of flocs, significantly improves settling speed, and reduces residence time (Zafisah et al. 2020). Organic
or inorganic polymer coagulants/flocculants (Liu ZM et al. 2012; Sang et al. 2008) are usually utilized as bridging agents between flocs and microsand (Desjardins et al. 2002) in MBF systems. Besides, the level of the microsand dose has an obvious effect on flocculation performance (Gasperi et al. 2012; Zafisah et al. 2020). The MBF system has already been used for the treatment of eutrophied urban landscape water (Su et al. 2013) and the polluted water of Nanitar Lake in India (Kumar et al. 2018).

The most popular and efficient MBF technologies are Densadeg® from Degrémont/Suez and Actiflo® from Veolia Water Group. Densadeg® combines sludge concentration and stratified separation in compact modular packaging to provide fast, efficient, and high-quality water purification (2003). Besides, the Densadeg® extreme rate clarifiers (XRC) from Suez were selected by Skanderborg Water and Wastewater Utility of Denmark for its expanded treatment plant (2019). Actiflo® technology was developed in the early 1990s and used primarily for tap water production and wastewater treatment. The improved ACTIDisc process, which is a combination of the Actiflo process and Veolia’s Hydrotech Discfilter surface filtration system, was used in a secondary effluent reuse trial at Castellon de la Plana in Spain (Sanz et al. 2007). Veolia Water Technologies installed two 12.5 MGD Actiflo® systems for phosphorus removal upgrade in Warwick, Rhode Island, USA (2015) and installed Actiflo® Turbo technology for primary clarification at Northumbrian Water’s Horsley water treatment works in the UK (2016). Judit et al (Ribera-Pi et al. 2020) proposed an on-site water-reclamation scheme using five different technologies, including Actiflo®-based physicochemical pre-treatment. Furthermore, the equipment of an Actiflo® clarifier was optimized and applied in Johannesburg, South Africa (Kallon et al. 2020).

Although the MBF technique has engineering applications all over the world, it is mainly limited to Densadeg® and Actiflo®, which cannot satisfy diverse global needs. Few reports in the literature have been published on comprehensive process parameters and the mechanism of the MBF process is not well understood. In this paper, we manufactured pilot-scale MBF equipment (Chinese patent: ZL201620444575.7) and used it to treat two types of wastewater with high and low turbidities. The effects of flow rate, poly aluminum chloride (PAC) dose, and microsand size and dose were analyzed using jar test and pilot-scale continuous experiments to determine the optimum values of each parameter. Additionally, we analyzed the formation mechanism of microsand-ballasted flocs.

### 2. Materials And Methods

#### 2.1 Reagents and wastewater samples

For these experiments, we used PAC (chemical grade, Zibo Purifying Agent Co., Ltd.) and kaolin (industrial grade, Beijing Xudong Chemical Plant). Simulated wastewater S1 was diluted from actual landfill leachate (2 L landfill leachate + 1000 L tap water, with a turbidity of 21.6-25.9 NTU), while S2 was a mixture of tap water and kaolin (with a turbidity of 96-105 NTU). Besides, the density of the microsand was 2,650 kg/m³, which is much higher than the density of the sewage and initial flocs.

#### 2.2 Experimental equipment
A schematic diagram and product photo of the pilot-scale MBF equipment is presented in Fig. 1. Wastewater samples were pumped by an influent pump into the coagulation cell, injection cell, maturation cell, and lamella settler in sequence, then the purified effluent was discharged. Coagulants were added to the coagulation cell, while polymer flocculants (PAC) were added to the injection cell. The sludge-microsand mixture was discharged from the bottom of the lamella settler and separated by the hydrocyclone. Finally, the separated microsand was recycled and re-injected into the injection cell.

### 2.3 Experimental procedures

#### 2.3.1 Jar test experiments

The optimum flocculant dose was determined in *Jar test experiment (I)*, by comparing treatment effects and sludge settling performance at different doses. Different volumes of 10 g/L PAC solution were added by pipettes to beakers containing a 200 mL wastewater sample, closely followed by 1 min rapid stirring, 10 min slow stirring, and 15/30 min steady settling. The supernatants were taken out by needle tubing to analyze their turbidities.

*Jar test experiment (II)* was conducted to determine the optimum microsand parameters, by comparing treatment effects at different microsand doses and sizes. We added 0.875 g/L PAC and various amounts of microsand into beakers containing a 400 mL wastewater sample. Subsequently, the wastewater underwent 1 min rapid stirring, 10 min slow stirring, and 30 min steady settling, and then the supernatants were extracted by needle tubing for turbidity analysis.

#### 2.3.2 Continuous experiments

These tests to assess continuous performance included experiments at different flow rates without flocculants or microsand (Section 3.2), optimum PAC dose without microsand (Section 3.5), and optimum PAC dose with different microsand doses (Section 3.6). As for the experiment in Section 3.2, turbidity removal was investigated at 200, 300, and 400 mg/L. In the other two trials, the MBF equipment was continuously run at an inflow rate of 200 L/h and a total hydraulic retention time (*HRT*) of 157.4 min. The matching flowrate relationship of the dosing pump (*q*) and the influent pump (*Q*) were adjusted in real-time. When the total *HRT* time had passed, the effluents were sampled every 30 min and their turbidities were analyzed. All data presented were the average results of three repeated experiments. The *HRT* for the experiment was also calculated and was equal to the effective volume *V* divided by the flow rate *Q*.

### 2.4 Analytical methods

Reagents and microsand were weighed using a BT423S electronic balance produced by Sartorius Scientific Instruments (Beijing) Co. Ltd. The turbidities were analyzed by a 2100N turbidity meter manufactured by Hach Company, USA.

### 3. Results And Discussions
3.1 Determination of actual HRT in each cell

The roles of the different cells vary, so their volume and HRT are not consistent. The total HRT can be used to determine the time interval between entering the influent inlet and reaching the effluent sampling point. Besides, the HRT of each cell was measured by recording the time interval between inflow start and cell overflow at certain flow rates. Results indicated that the HRT ratio in the coagulation cell, injection & maturation cell, lamella settler was 1: 3: 7.3. Besides, the total HRT at 200, 300, 400, 500, and 600 L/h were 157.4, 124.5, 78.7, 70.6, and 70.6 min, respectively.

3.2 Continuous performance at different flowrates without flocculants and microsand

Flow rate has a significant influence on the size, density, and growth of flocs. With no addition of flocculants or microsand, turbidity removal of S2 was explored at 200, 300, and 400 L/h. For each flow rate, effluent sampling began once the time of the total HRT had passed, and the sampling interval was 15 min.

As Fig. 2 illustrates, turbidity removal increased as the flow rate fell from 400 to 200 L/h. This is because lower flow rates result in longer HRT, denser flocs, and better aggregating/settling performance of suspended particles. Although neither flocculant nor microsand was added, wastewater turbidity declined substantially by 48.1%-57.7% at 200 L/h, which is probably due to the aggregation of existing solids and settling.

3.3 Jar test performance at different PAC doses

Lower doses of PAC lead to incomplete aggregation between colloids and flocculant, making it difficult to form larger and denser flocs. Conversely, higher doses of PAC result in a reduction in pH, especially if the water has low alkalinity. This consequently results in poor performance, because flocs will simply not form. Jar test experiment (I) was conducted to determine the optimal PAC dose for turbidity removal and floc settling performance.

3.3.1 Jar test experiment (I) for sample S1

The volume of Sample S1 was 200 mL and its turbidity was 24.6 NTU. Fig. 3 (a) presents the results of Jar test experiment (I) with S1. Turbidity removal increased rapidly when PAC doses were adjusted from 5 to 25 mL, indicating the significant influence of PAC dosing. Turbidity removal was much higher (96%-99%) when the PAC doses were between 25 and 45 mL, which is similar to the results of Chen et al (Chen et al. 2020).

To further understanding the internal mechanism of turbidity removal, it is necessary to investigate settling performance. Given the higher turbidity removal when using PAC doses between 35 and 45 mL, the settling performance of flocs was determined at the doses of 35, 40, and 45 mL. After rapid stirring for 1 min and slow stirring for 10 min, the wastewater was poured immediately into a 500 mL measuring
cylinder for steady settling. During this time, the sludge volume (SV%) was measured once every 5 min, which demonstrated a trend of continuously decreasing with time at three doses, as shown in Fig. 3 (b). Significantly, the sludge settling performance at the PAC dose of 35 mL was superior to doses of 40 and 45 mL. Considering turbidity removal and floc settling performance, we determined the optimal dose as 35 mL PAC per 400 mL wastewater, namely 0.875 g/L, since the concentration of PAC is 10 g/L.

### 3.3.2 Jar test experiment (I) for sample S2

Sample S2 had a volume of 200 mL and turbidity of 96 NTU. Results of Jar test experiment (I) with S2 are shown in Fig. 4 (a). Turbidity removal increased only slightly when steady settling increased from 15 to 30 min may because most of the suspended particles had already settled within the initial 15 min. Besides, turbidity removal exceeded 95% at PAC doses above 10 mL. Turbidity removal was extremely high (99.1%-99.4%) at PAC doses of 20-30 mL, but turbidity removal dropped sharply at PAC doses above 30 mL. This trend may be related to the settling performance of flocs.

Subsequently, the settling performance of flocks at doses of 20, 25, and 30 mL were investigated. First, rapid stirring for 1 min then slow stirring of 10 min were performed. Next, we poured the wastewater into a 500 mL measuring cylinder for steady settling, and the SV% was measured once every 3 min. As Fig. 4 (b) reveals, the sludge settling performance was worst at a PAC dose of 30 mL, while a PAC dose of 20 mL produced the best results and the most rapid settling velocity. Thus, the optimal dose for turbidity removal and floc settling performance was established at 20 mL PAC per 200 mL wastewater, which equates to 1.0 g/L since the PAC concentration is 10 g/L.

### 3.4 Jar test performance at different microsand sizes and doses

Using Sample S1 with a turbidity of 24.6 NTU, we carried out Jar test experiment (II) under different sizes (25-48 µm, 49-61 µm, 62-80 µm, 81-106 µm, and 107-120 µm) and doses (0.25 g/L, 0.5 g/L, 0.75 g/L, and 1.0 g/L) of microsand. Results of the experiments are presented in Fig. 5.

The effluent quality with 25-48 µm-sized microsand was the worst, and the effluent turbidity was higher than with other microsand sizes. Regarding the particle sizes of 49-61 µm, 62-80 µm, 81-106 µm, and 107-120 µm, effluent turbidity remained mostly stable and increased only slightly at larger particle sizes. This indicates that a broad spectrum of microsand sizes (49-106 µm) is effective. Such a value is lower than the effective microsand sizes reported in the literature of 150 µm for wastewater (Li TQ 2009) and about 100-150 µm for engineering application conditions (Li WJ et al. 2010). However, it is similar to the recommended microsand size of 40-125 µm and the ideal microsand size of 40-74 µm (Lu GJ et al. 2004). The difference between the optimal microsand size in this paper and the literature may result from the different source, surface properties, and floc-binding capacity of the microsand.

Furthermore, effluent turbidity declined with increasing microsand doses from 0.25 g/L to 1.0 g/L. High doses of microsand tend to form small, isolated, and heavy flocks compared to low doses of microsand (Zafisah et al. 2020). However, there was a negligible difference between the performance of the 0.75 g/L
and 1.0 g/L doses, which indicates that improved performance is not dependent on simply increasing the microsand dose. According to our observations, when the microsand dose reached 1.0 g/L, a small amount of uncombined microsand sank to the bottom of the beaker during stirring and did not move upward along with the water flow and the flocs. Higher doses of microsand increase operating costs and sand circulation loads, and superfluous microsand may not combine, thus becoming ineffective. Therefore, we established an optimum microsand dose of 1.0 g/L, which is more than the 0.5 g/L reported by Sieliechi et al (Sieliechi et al. 2016), but lower than the 1.5 g/L used in the Actiflo® process by Cailleaux et al (Cailleaux et al. 1992).

3.5 Continuous performance at optimum PAC dose without microsand

The performance of the continuous process at optimum PAC dose without microsand is illustrated in Fig. 6. The turbidity of S1 decreased from 23.5-25.9 NTU in the influent to below 0.75 NTU in the effluent, demonstrating a removal rate of 97.1%-98.8% (Fig. 6 (a)). For the S2 sample, the turbidity fell from 93.5-106 NTU to less than 3 NTU, indicating 97.5%-99.0% turbidity removal (Fig. 6 (b)). The S1 sample had better effluent quality than S2 because the latter was a highly stable colloid of ultrafine kaolin powder, which was challenging to separate. Concerning S2, turbidity removal here was much better than the 48.1%-57.7% removal rate without PAC (Fig. 2).

3.6 Continuous performance at optimum PAC dose with microsand

3.6.1 Microsand-Injected experiment for sample S2

For this test, the flow rate was 200 L/h, the doses of PAC and microsand were both 1.0 g/L, and the microsand size was 49-106 µm. The sludge pump and sludge scraper were turned on for 2 hours to recycle the microsand. Fig. 7 (a) indicates that turbidity removal was above 99% during the initial 3 hours, but then dropped sharply. The supernatant in the lamella settler became muddy and its color gradually became milky-white, similar to the color of the raw wastewater. The reason for this may be that the motion of the sludge scraper disturbed the water flow and affected separation ability. Therefore, the sludge scraper should be intermittently turned on only when the settled sludge accumulates to a certain level.

The second microsand-injected experiment for Sample S2 was conducted with the sludge scraper turned off. From the results displayed in Fig. 7 (b), turbidity removal was 98.5%-99.5%, yielding an effluent turbidity of less than 1.7 NTU. This is lower than the Chinese recycled water standard of 5 NTU stipulated by The reuse of urban recycling water – Water quality standard for urban miscellaneous use (GB/T 18920-2020, valid from Feb. 1st, 2021). By comparing Fig. 7 (b) and Fig. 6 (b), the turbidity removal rate with microsand was higher than without microsand, indicating that microsand enhances flocculating performance. More effective flocs are formed by adhesion and binding between the microsand and
suspended solids. Besides, incorporation of the polymer flocculant promotes microsand attachment to flocs, due to the binding properties of the polymer (Desjardins et al. 2002).

### 3.6.2 Microsand-Injected experiment for sample S1

Here, the flow rate was 200 L/h, the doses of PAC and microsand were 0.875 g/L and 1.0 g/L, respectively, and the microsand size was 49-106 µm. The continuous performance at optimum PAC is presented in Fig. 8 (a). The effluent was very clear and its turbidity was reduced to below 0.47 NTU, indicating a removal rate of 98.0%-98.8%. This meets the requirements of the Chinese drinking water standard of 1 NTU, set by the Standards for Drinking Water Quality document (GB 5749-2006, implemented on July 1st, 2007), and is much lower than the aforementioned Chinese recycled water benchmark of 5 NTU. Fig. 8 (b) reveals that the turbidity removal rate with injected microsand was higher than without microsand, which confirms the enhanced performance of MBF.

### 4. Mechanism Analysis Of Floc Formation And Ballasted Flocculation

The MBF process is divided into two stages: micro-floc formation at higher flow velocity gradients and pelleting cohesion at lower flow velocity gradients. As Fig. 9 illustrates, the pelleting flocs are formed over three steps (Zafisah et al. 2020): micro-floc formation, core structure formation, and pelleting floc growth.

When the PAC is added, it is rapidly dispersed by the higher flow velocity gradient in the wastewater stream to combine with the initial particles (microsand), which have a lower surface charge density (Ghanem et al. 2007; Lien and Kruzic 2006; Nadella et al. 2020). Several microsand particles bridge together by macro-molecular adsorption, under the influence of the PAC, to form the core floc structure. Next, the growth of pelleting flocs in the lower velocity gradient is essentially a combination between remaining (unbridged) microsand particles and the core structures, as well as the contact and capture of larger-sized core structures in microsand particles (Zafisah et al. 2020). A floc-suspended layer of a certain concentration appears when the system becomes stable. The remaining microsand particles pass through the suspended layer and are continuously captured, resulting in the further growth of pelleting flocs.

The core structure of a pelleting floc is its framework. Microsand particles of roughly the same size are absorbed onto the surface of core structures, preventing large amounts of pore water from entering the pelleting flocs. As a result, pelleting flocs are dense in structure and fundamentally different from random flocs (Zafisah et al. 2020). Therefore, the injection of high-density insoluble microsand particles accelerates the growth and settling performance of MBF flocs (Qasim et al. 2020).

### 5. Conclusion

The results from this study indicate that the hydraulic retention time ratio in the coagulation cell, injection & maturation cell lamella settler is 1: 3: 7.3. Besides, the optimal PAC dose for Samples S1 and S2 are 0.875 g/L and 1.0 g/L, respectively, while the ideal microsand particle size is 49-106 µm and the most
favorable microsand dose is 1.0 g/L. At these optimum conditions, MBF reduced S1 turbidity from 21.6-25.3 NTU to below 0.47 NTU, easily meeting the standard of 1 NTU for Chinese drinking water (GB 5749-2006). Additionally, the MBF process lowered S2 turbidity from 95-105 NTU to 1.7 NTU, which is much lower than the Chinese recycled water standard of 5 NTU (GB/T 18920-2020). Microsand-injected turbidity removal rates of 98.0%-98.8% for S1 and 98.5%-99.5% for S2 were much higher than the removal rates without microsand. This demonstrates the enhanced performance of MBF, where the microsand serves as an initial core particle.

In the microfloc-formation stage, we may be able to control the largest size a microfloc can attain, provided the effective energy dissipation $\tilde{\varepsilon}_D$ is managed properly by adjusting the stirring speed. With the assistance of adsorption bridging from inorganic polymeric flocculant PAC, microsand particles bond together to establish core structures, which in turn form dense microflocs. This study provides comprehensive pilot-scale process parameters for MBF to effectively treat wastewater and it creates a strong foundation for establishing the forming mechanism of microsand-ballasted flocs.

**Declarations**

**Ethics approval and consent to participate** Not applicable

**Consent for publication** Not applicable

**Availability of data and materials** Not applicable

**Competing interests** Not applicable

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Taotao Lu: Experiment, data analysis, paper editing.

Xianchun Lu, Shuguang Wang, Yanhe Han: Writing - review & editing.

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Lili Li: Experiment.

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Taotao Lu: Experiment, data analysis, paper editing.

Xianchun Lu, Shuguang Wang, Yanhe Han: Writing - review & editing.

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References

1. (2003) Integrated sludge thickening and lamellar separation performance in Scottish water applications. Filtration & Separation 40 (9) 22-23. https://doi.org/10.1016/S0015-1882(03)00924-8

2. (2015) Kruger upgrades Rhode Island plant with ACTIFLO. Pump Industry Analyst 2015 (5) 3. https://doi.org/10.1016/S1359-6128(15)30142-7

3. (2016) Veolia to install Actiflo technology at UK WTW. Filtration + Separation 53 (5) 7. https://doi.org/10.1016/S0015-1882(16)30185-9

4. (2019) Clarifiers to reduce phosphorus discharge into Danish lake. Filtration + Separation 56 (3) 9. https://doi.org/10.1016/S0015-1882(20)30094-X

5. Cailleaux C, Pujol E, Dianous F, Druoton J C (1992) Study of weighted flocculation in view of a new type of clarifier. 41 18-27.

6. Chen F M, Liu W, Pan Z B, Wang Y L, Guo X Y, Sun S H, Jia R B (2020) Characteristics and mechanism of chitosan in flocculation for water coagulation in the Yellow River diversion reservoir. Journal of Water Process Engineering 34 101191. https://doi.org/10.1016/j.jwpe.2020.101191

7. Chhuon R, Shahid M K, Kim S, Choi Y (2020) Mill scale as a ballasted flocculant for enhancing the settleability of activated sludge. Journal of Environmental Chemical Engineering 8 (5) 104237. https://doi.org/10.1016/j.jece.2020.104237

8. Desjardins C, Koudjonou B, Desjardins R (2002) Laboratory study of ballasted flocculation. Water Research 36 (3) 744-754. https://doi.org/10.1016/S0043-1354(01)00256-1

9. Gasperi J, Laborie B, Rocher V (2012) Treatment of combined sewer overflows by ballasted flocculation: Removal study of a large broad spectrum of pollutants. Chemical Engineering Journal 211-212 293-301. https://doi.org/10.1016/jcej.2012.09.025

10. Ghanem A, Young J, Edwards F (2007) Mechanisms of Ballasted Floc Formation. Journal of Environmental Engineering-asce - J ENVIRON ENG-ASCE 133 https://doi.org/10.1061/(ASCE)0733-9372(2007)133:3(271)

11. Kallon D V V, Maquina P, Baloyi K N, Ledwaba M D, Pillay P (2020) Effect of Loading on Stiffener Configurations for an Actiflo Clarifier. Procedia CIRP 91 776-780.
12. Kumar S, Kazmi A, Ghosh N, Kumar V, Rajpal A (2018) Urban stormwater runoff treatment of Nainital Lake's catchment: An application of ballasted sand flocculation technology. Water Science and Technology: Water Supply 19 https://doi.org/10.2166/ws.2018.148

13. Lapointe M, Barbeau B (2016) Characterization of ballasted flocs in water treatment using microscopy. Water Research 90 119-127. https://doi.org/10.1016/j.watres.2015.12.018

14. Li TQ (2009) Introduce to the design of Actiflo® microsand-ballasted flocculation as a high-efficiency precipitation process. Water & wastewater Engineering 35 (4) 11-13. https://doi.org/10.13789/j.cnki.wwe1964.2009.04.003 (in Chinese)

15. Li WJ, Tang XL, Ping WK (2010) Introduction and application of Actiflo® rapid settle with Microsand. China Water & Wastewater 26 (6) 55-57. https://doi.org/10.19853/j.zgjsps.1000-4602.2010.06.019 (in Chinese)

16. Li Y, Xia W, Wen B, Xie G (2019) Filtration and dewatering of the mixture of quartz and kaolinite in different proportions. Journal of Colloid and Interface Science 555 731-739. https://doi.org/10.1016/j.jcis.2019.08.031

17. Lien C-A, Kruzic A (2006) The Role of Activated Sludge Solids in an Actiflo® System. Proceedings of the Water Environment Federation 2006 6748-6759. https://doi.org/10.2175/193864706783761626

18. Liu C, Gao B, Wang S, Guo K, Shen X, Yue Q, Xu X (2020) Synthesis, characterization and flocculation performance of a novel sodium alginate-based flocculant. Carbohydrate Polymers 248 116790. https://doi.org/10.1016/j.carbpol.2020.116790

19. Liu ZM, Sang YM, Tong ZG, Wang QH, Sun TC (2012) Decolourization performance and mechanism of leachate secondary effluent using Poly-aluminium(III)–magnesium(II) sulphate. Water and Environment Journal 26 https://doi.org/10.1111/j.1747-6593.2011.00266.x

20. Lu GJ, Huang ZH, Duan JH (2004) Principle and application for a new method of high effective strengthen flocculation. Journal of Tsinghua University (Science and Technology) 40 (S1) 114-116. (in Chinese)

21. Murujew O, Geoffroy J, Fournie E, Socionovo Gioacchini E, Wilson A, Vale P, Jefferson B, Pidou M (2020) The impact of polymer selection and dose on the incorporation of ballasting agents onto wastewater aggregates. Water Research 170 115346. https://doi.org/10.1016/j.watres.2019.115346

22. Musa M, Wolf J, Stephens E, Hankamer B, Brown R, Rainey T J (2020) Cationic polyacrylamide induced flocculation and turbulent dewatering of microalgae on a Britt Dynamic Drainage Jar. Separation and Purification Technology 233 116004. https://doi.org/10.1016/j.seppur.2019.116004

23. Nadella M, Sharma R, Chellam S (2020) Fit-for-purpose treatment of produced water with iron and polymeric coagulant for reuse in hydraulic fracturing: Temperature effects on aggregation and high-rate sedimentation. Water Research 170 115330. https://doi.org/10.1016/j.watres.2019.115330

24. Qasim M, Park S, Kim J-O (2020) The role of ballast specific gravity and velocity gradient in ballasted flocculation. Journal of Hazardous Materials 399 122970. https://doi.org/10.1016/j.jhazmat.2020.122970
25. Qasim M, Park S, Moon Y, Kim J-O (2020) Developing a model to determine the settling velocity of ballasted flocs. Journal of Environmental Chemical Engineering 8 (6) 104515. https://doi.org/10.1016/j.jece.2020.104515

26. Ribera-Pi J, Badia-Fabregat M, Arias D, Gómez V, Taberna E, Sanz J, Martínez-Lladó, X Jubany I (2020) Coagulation-flocculation and moving bed biofilm reactor as pre-treatment for water recycling in the petrochemical industry. Science of The Total Environment 715 136800. https://doi.org/10.1016/j.scitotenv.2020.136800

27. Sang YM, Gu QB, Sun T C, Li S (2008) Colour and Organic Compounds Removal from Secondary Effluent of Landfill Leachate with a Novel Inorganic Polymer Coagulant. Water science and technology : a journal of the International Association on Water Pollution Research 58 1423-32. https://doi.org/10.2166/wst.2008.446

28. Sanz J, Guerrero L, Ortega J M, Ferrer C, Miguel D, Martínez F (2007) Application of the new solution ACTIDisc® on secondary effluent reclamation in Castellón de la Plana. Desalination 204 (1) 189-197. https://doi.org/10.1016/j.desal.2006.03.539

29. Sieliechi J, Lartiges B, Skali-Lami S, Kayem J, Kamga R (2016) Floc compaction during ballasted aggregation. Water Research 105 361-369. https://doi.org/10.1016/j.watres.2016.09.015

30. Su Z, Li X, Yang Y, Zhou Z, Wu Y (2013) Ballasted Flocculation of Micro-Sand/Magnetic Powder for Landscape Water Treatment. Advanced Materials Research 777 56-59. 10.4028/www.scientific.net/AMR.777.56

31. Wang S, Li E, Li J, Du Z, Cheng F (2020) Preparation and coagulation-flocculation performance of covalently bound organic hybrid coagulant with excellent stability. Colloids and Surfaces A: Physicochemical and Engineering Aspects 600 124966. https://doi.org/10.1016/j.colsurfa.2020.124966

32. Wei H, Gao B, Ren J, Li A, Yang H (2018) Coagulation/flocculation in dewatering of sludge: A review. Water Research 143 608-631. https://doi.org/10.1016/j.watres.2018.07.029

33. Zafisah N S, Ang W L, Mohammad A W, Hilal N, Johnson D J (2020) Interaction between ballasting agent and flocs in ballasted flocculation for the removal of suspended solids in water. Journal of Water Process Engineering 33 101028. https://doi.org/10.1016/j.jwpe.2019.101028

Figures
Figure 1

(a) Schematic diagram and (b) product photo of pilot-scale MBF equipment 1: Flowmeter; 2: Influent pump; 3: Drainage pipe; 4: PLC controller; 5: Hydrocyclone; 6: Fast mixer; 7: Slow mixer; 8: Sludge scraper; 9: Dosing pump

Figure 2

![Graph showing turbidity removal over running time at different flow rates]
Continuous performance of S2 sample at different flow rates without flocculants or microsand (sampling interval: 15 min)

Figure 3
(a) Jar test (l) performance and (b) floc settling performance for S1 at different PAC doses (sample volume: 200 mL; raw turbidity: 24.6 NTU)

Figure 4
(a) Jar test (I) performance and (b) floc settling performance for S2 at different PAC doses (sample volume: 200 mL; raw turbidity: 96 NTU)

Figure 5

Jar test (II) performance for S1 with different microsand sizes and doses (sample volume: 400 mL; raw turbidity: 24.6 NTU; PAC dose: 0.875 g/L)
Figure 6

Continuous performance at optimum PAC dose without microsand (a: S1, PAC dose: 0.875 g/L; b: S2, PAC dose: 1.0 g/L; flow rate: 200 L/h; HRT: 157.4 min)

Figure 7
Continuous performance at optimum PAC dose with microsand for S2 (a: sludge scraper turned on; b: sludge scraper turned off; flow rate: 200 L/h; HRT: 157.4 min; PAC dose: 1.0 g/L; microsand dose: 1.0 g/L; microsand size: 49-106 µm)

Figure 8

Continuous performance at optimum PAC dose with microsand for S1 (a: performance with microsand; b: comparison of turbidity removal with and without microsand; flow rate: 200 L/h, HRT: 157.4 min; PAC dose: 0.875 g/L; microsand dose: 1.0 g/L; microsand size: 49-106 µm)
Figure 9

Floc-forming process of MBF: Diffusion of polymer in water and interaction with initial particles; Core structure formation of pelleting flocs; Growth of pelleting flocs; Friction between pelleting flocs in motion; Further growth of pelleting flocs.