Interaction between Ballasting Agent and Flocs in Ballasted Flocculation for the Removal of Suspended Solids in Water

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Abstract

The interaction between ballasted agent and flocs formed from coagulation/flocculation process is not well understood. This study sought to understand the interaction between ballasted agent and flocs by investigating the impact of ballasted agent on the flocs formation and subsequently the removal of suspended solids in water. Ballasted flocculation was conducted using jar tests where the dosage of flocculant and sand was varied at 1-4 mg/L and 2-8 g/L, respectively. The turbidity removal peaked (90%) at 2 mg/L of flocculant and 1 g/L of sand. It was observed that excessive dosing of sand resulted in the formation of premature flocs that settled quickly before having the chance to remove more suspended solids via sweep coagulation. This revealed that the ballasted agent would affect the coagulation-flocculation process and subsequently the removal of suspended solids. This study indicates that future research on the impact of the ballasted agent on different coagulation-flocculation mechanism should be explored to ensure the suspended solids could be removed with short settling time and without compromising the quality of treated water.

Keywords: Ballasted flocculation; Coagulation; Flocculation; Natural Organic Matter; Water Treatment

Highlights

- Coagulation process achieved higher turbidity removal but longer settling time.
- Ballasted flocculation accelerated the settling rate and formation of large flocs.
- Ballasting agent affected the flocs formation during sweep coagulation mechanism.
- Quick settling of flocs resulted in the slightly lower removal of suspended solids.
- The interaction between the ballasted agent and flocs formation is worth exploring.

1. Introduction

The issue of water scarcity is already a reality to more than 2 billion people, especially with growing populations and increasing water usage [1]. Natural organic matter (NOM) and suspended impurities are compromising with the clarity of water known as turbidity, and settling to the bottom and forming sludge beds [2]. Among numerous water and wastewater treatment technologies, coagulation-flocculation process is indisputably the most widely employed technology in water treatment plants [3], [4]. Coagulation-flocculation may be broadly described as the physicochemical process that injects coagulant to destabilize the particles prior to flocculant chemicals to form larger and heavier particle aggregates (flocs) that will settle rapidly for removal by subsequent clarification process [5]–[7].

Over the past few decades, land constraint has become one of the major issues in the construction of conventional wastewater treatment plants [8]. Hence, development of ballasted flocculation is of great interest to tackle this issue by reducing the system footprint and hydraulic retention time [9]. Ballasted flocculation involves the injection of a ballasting agent during the flocculation process to increase the size and density of the flocs [10]. Ballasting agent such as microsand typically has a high density that could significantly result in a higher settling velocity compared to non-ballasted flocs [11]. According to previous work done, ballasting agent has greater mass than the microflocs formed during the coagulation-flocculation process, which affecting the size of flocs after the aggregation between the former and the latter and increased settling velocity [12]–[14]. Also, ballasting agent has low surface charge density compared to colloidal particles in water. Hence, the addition of ballasting agent will not chemically disrupt the interaction between the coagulant/flocculant and colloidal particles [14].

Some of the main advantages of ballasted flocculation include reduced system footprint, elevated start-up time, higher settling rate, and minimized usage of coagulant and flocculant [15]. Furthermore, the quality of water produced has been reported to be equal to or better than the conventional coagulation-flocculation process [11]. Due to the advantages of the ballasted flocculation process, it was previously employed commercially for drinking water treatment and in recent years, has been further used for combined sewerage overflow (CSO) and wastewater treatment plants [16]. The treatment efficiently reduces hydraulic retention time and increases overflow rate [17]. For instance, ballasted flocculation enhanced water quality and reduced runoff volume from the wastewater treatment plant, which prevented the discharge of nutrients, organic matter and debris into local waterway [8]. As such, it was reported that injecting sand with cationic polymer could provide a higher phosphorus removal efficiency which is the main cause of eutrophication and algal growth in the river [18]. This was possible because ballasted flocculation significantly shortened the time for flocs clarification and sedimentation, allowing the treatment plant to receive more inflow water for treatment.

Some of the recent works reported on ballasted flocculation investigated the characteristics of flocs formed under various operating conditions [10], [19], [20]. For instance, Young et. al studied the influence of numerous factors affecting the efficiency of ballasted flocculation separately [14]. Ghanem et. al studied the mechanism of ballasted flocculation through different tests: bench scale observations, microscopic observations, density tests, and centrifugal settling tests [13]. Besides, Sieliechi et. al (2016) used pozzolana as the alternative ballasting agent in their study with attention given to the floc compaction in the presence of ballasting agent [12]. However, reports on the development of fundamental understanding about the interaction between the ballasting agent and polymer flocculant remain scarce. Such understanding could provide insight into the impact of the ballasted agent and polymer flocculant on the characteristics and formation of flocs. In this context, the objective of this study was to investigate the performance of ballasted flocculation in removing turbidity using different dosages of sand and polymer flocculant. Accordingly, the impact of ballasting sand on the coagulation-flocculation mechanism (formation of flocs) was investigated by observing the flocs formed during the ballasted flocculation process.

2. Materials and methods

2.1 Materials

The chemicals used in this study: humic acid, kaolin, ferric chloride ($FeCl_3$), calcium chloride ($CaCl_2 \cdot 2H_2O$), sodium bicarbonate ($NaHCO_3$), sodium chloride (NaCl), hydrochloric acid (HCl) and sodium hydroxide (NaOH) were of analytical grade and purchased from Sigma Aldrich, Malaysia. The polymer-based cationic flocculant (Zetag 8165) with a charge density of 40-50% was supplied by BASF, Singapore. The characteristics of Zetag 8165 was summarized in Table 1. The ballasting agent used in this study was silica sand with a mean diameter of 75 μm.

Table 1

Characteristics of Zetag 8165

Form	Powder
Odour	Odourless
Colour	Off white
pH	3.5-4.5

2.2 Preparation of synthetic water

All the solutions used in this study were prepared by using ultrapure (UP) water with a quality of 18 $M\Omega.cm^{-1}$. Humic acid and kaolin were used to represent NOM and suspended solids in water, respectively. The synthetic water was prepared by dissolving 0.1 g of humic acid powder in 10 ml of 0.1 M NaOH under continuous stirring for 1 hour. A salt mixture (80 ppm NaCl, 200 ppm $CaCl_2 \cdot 2H_2O$, and 170 ppm $NaHCO_3$) was then added to the humic acid solution to mimic the presence of minerals in the water. Sodium hydrogen carbonate was added to provide carbonate alkalinity similar to that of natural rivers [21]. UP water and kaolin were then added to alter the turbidity to 30 NTU. The pH of the prepared synthetic water was then adjusted to 7 by using NaOH and HCl. The zeta potential of the synthetic water was -29.9 mV.

2.3 Ballasted flocculation process

All experiments were conducted by using a jar test system (Model ZR4-6 Zhongrun Water, China) with 500 ml of prepared synthetic water for each run. The distance between the impeller and the bottom jar is 1 cm with total water depth of 7 cm. All experiments were repeated twice. Two control sets of coagulation processes: coagulation without flocculant and sand, and coagulation with flocculant but without sand, were carried out to provide benchmarking information for understanding ballasted flocculation process. The jar test setting for coagulation without sand and flocculant was rapid mixing at 100 rpm for 1 min and slow stirring at 30 rpm for 30 min. However, the jar test setting for coagulation with flocculant but without sand and also ballasted flocculation were rapid mixing at 200 rpm for 1 min and followed by a slow mixing at 30 rpm for 5 min.

The optimal coagulant ($FeCl_3$) dosage for all experiments was fixed at 22 mg/L, as determined in the previous study [22]. The dosage of flocculant (Zetag 8165) and sand was varied at 1-4 mg/L and 1-4 g/L, respectively. Coagulant was dosed into the solution instantaneously once the rapid mixing was started, followed by flocculant and sand according to the sequence described by Lapointe & Barbeau [10]. Pictures of the flocs and time for most of the flocs to settle down when entering the slow mixing period was recorded. After the sedimentation period, the supernatant water was then extracted for turbidity and zeta potential analysis.

2.4 Analytical methods

The quality of treated water was measured from the removal of turbidity using Turbidimeter (2100N, HACH, USA). The particle charge before and after the ballasted flocculation processes was evaluated based on the zeta potential value using a Zeta-Sizer (Malvern, UK).

3. Results and discussion

3.1 Performance of coagulation-flocculation process

In order to investigate the impact of sand as a ballasting agent on the formation of flocs, two control sets of coagulation-flocculation process without the addition of sand were conducted. For the first control experiment (with coagulant only), it has been observed that the flocs were gradually formed during the slow stirring period and grew larger with time (Fig. 1).

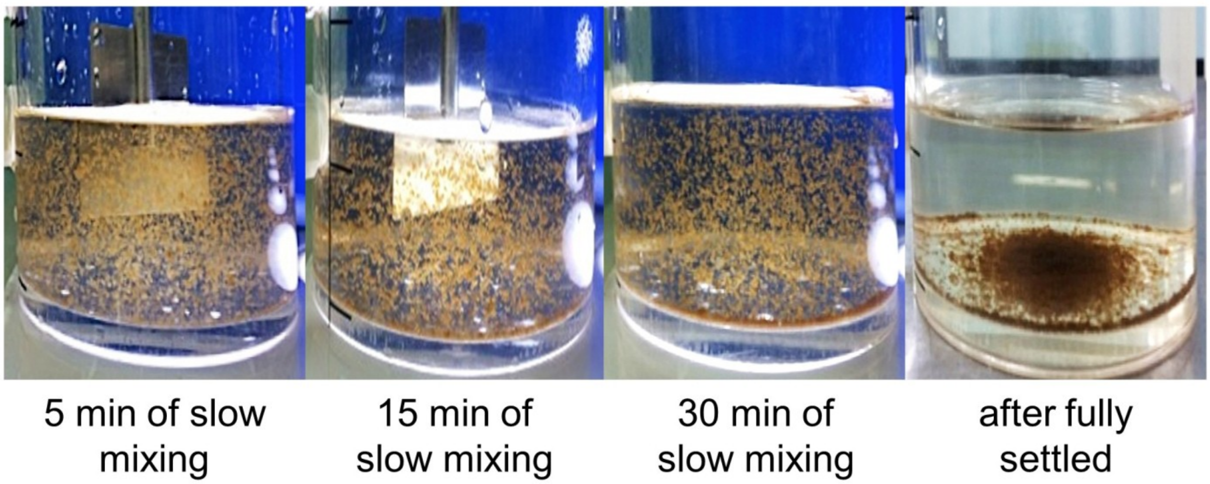

Fig. 1. Development of flocs with coagulant

This observation could be explained by sweep coagulation mechanism as supported by zeta potential value in Table 2. As explained in the previous study, iron-based coagulant hydrolysed to form positively charged ferric hydroxides that partially neutralized the negatively charged particles and bound them together to form flocs [6], [23]. During the slow stirring period, small flocs swept across the solution and captured the residual suspended solids particle. At the same time, the flocs collided with each other and coalesced into larger aggregates, as indicated by the growing size of flocs in Fig. 1. A similar observation was reported by Ang et al. [22] where the flocs became larger and heavier due to collision between positively charged ferric precipitates and negatively charged suspended solids particles through the sweeping mechanism. Both phenomena resulted in the removal of more suspended solids and formation of larger flocs for subsequent removal via sedimentation. The time taken for the majority of the flocs to settle was more than 5 min, as tabulated in Table 2.

In comparison, the addition of flocculant in the second control set reduced the settling time of the flocs to around 2 min with the formation of larger flocs. Fig. 2 shows the development of flocs with the addition of flocculant in the coagulation-flocculation process. It could be observed that the flocs in Fig. 2 are larger compared to the flocs without flocculant in Fig. 1. This is because the flocculant acted as a binder which bound the suspended flocs together, further increased the entanglement of flocs during the stirring period [24]. Therefore, this resulted in two consequences; lower turbidity removal and shorter settling time. It was postulated that larger flocs had less exposure to residual suspended solids in the solution due to its lower surface area and shorter suspension period in the solution. Hence, the turbidity of the treated water with flocculant (2.36 NTU) was subsequently lower compared to without flocculant (0.69 NTU) as presented in Table 2.

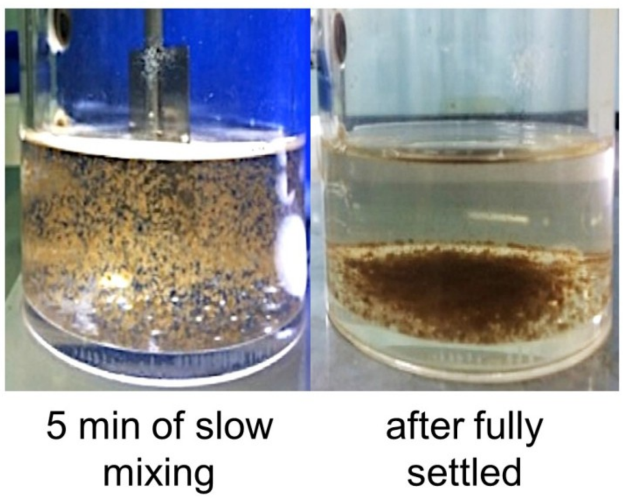

Fig. 2. Development of flocs with coagulant and flocculant

Table 2

Turbidity and zeta potential of control sets (with coagulant only, with coagulant and flocculant)

Synthetic water condition	Settling time (s)	Turbidity (NTU)	Zeta Potential (mV)
With coagulant only	> 300	0.69	-18.6
With coagulant and flocculant	> 120	2.36	-18.7

3.2 Effect of flocculant dosage

The flocculant used in this study was Zetag 8165, which is a positively charged polymer with zeta potential of 52.43 mV at pH 7. The success of the coagulation-flocculation process is heavily reliant on the destabilization of the negatively charged suspended solid particles with a high oppositely charged coagulant and flocculant [25]. The cationic polymer flocculant played a significant role in the formation of flocs by destabilizing the repulsion forces between the particles and interacted with the particles to form larger agglomerates [26].

Table 3 presents the turbidity of the supernatant under the influence of different flocculant dosage (1-4 mg/L) and sand dosage fixed at 1 g/L. From Fig. 3, it was observed that the turbidity removal increased from 35% to 90% with the dosage of flocculant increased up to 2 mg/L. However, a further increment of flocculant dosage (>2 mg/L) did not help with the removal of turbidity where the removal efficiency declined slightly (1-2 %). Indeed, as tabulated in Table 3, the final turbidity of the supernatant solution under these dosages are within in the same range (3-3.5 NTU). Hence, it could be concluded that the optimal dosage of flocculant in this case was 2 mg/L.

Table 3

Effect of flocculant dosage on settling time, turbidity, and zeta potential

Flocculant dosage (mg/L)	Settling time (s)	Turbidity (NTU)	Zeta Potential (mV)
1	4.01	19	-25.9
2	3.21	3.1	-21.1
3	3.55	3.32	-20.6
4	3.86	3.41	-19.9

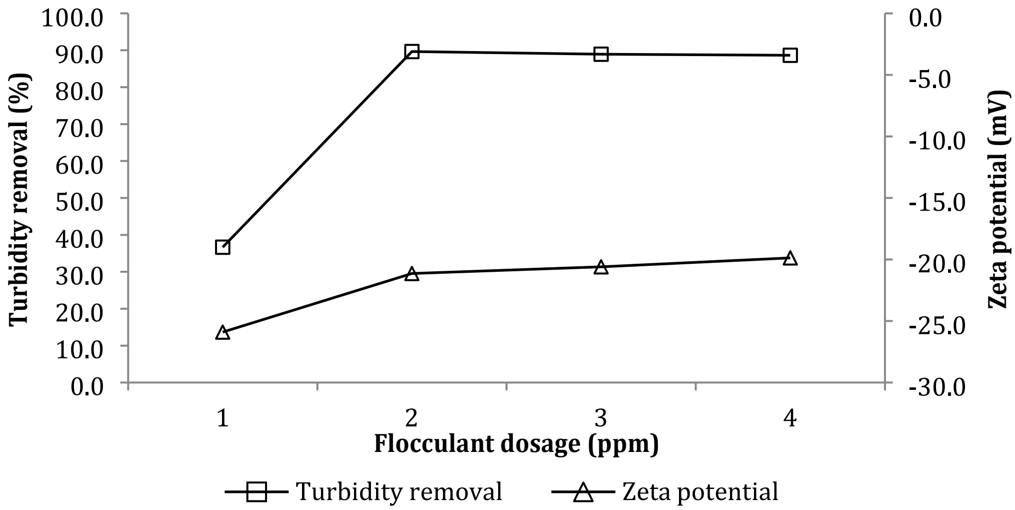

Fig. 3. Effect of different flocculant dosage on turbidity removal and zeta potential

Fig. 4 provides direct visual evidence on the quality of the supernatant after ballasted flocculation at different flocculant dosages. It is visible that with 1 mg/L dosage of flocculant, the supernatant appeared turbid with most of the suspended solids remained in the solution and only small number of flocs settled at the bottom (Fig. 4(a)). On the other hand, the supernatant solutions for flocculant dosage of 2-4 mg/L were much clearer with large flocs settled at the bottom (Fig. 4(b)-(d)). Such observation can be explained by the interaction between the flocculant and flocs during the ballasted flocculation process. In this case, the zeta potential was used to understand the interaction between the flocculant and suspended solids particles that eventually can be utilized to explain the observed performance [27].

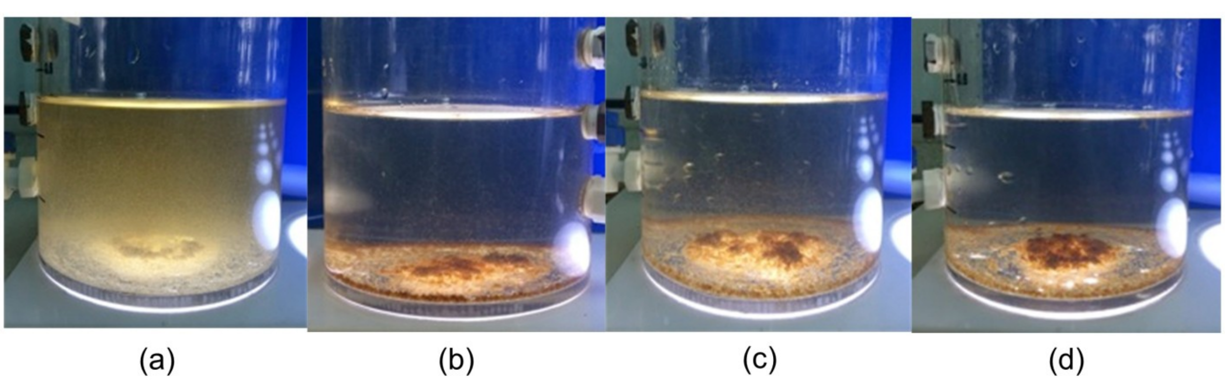

Fig. 4. Floc formations of different flocculant dosage after settling; (a) 1 mg/L (b) 2 mg/L (c) 3 mg/L (d) 4 mg/L

With the addition of coagulant only (as discussed in the previous section), the zeta potential of the supernatant was around -18.6 mV. After the addition of 1 mg/L of flocculant and 1 g/L of sand, the final zeta potential was -25.9 mV, which was more negative compared to the control set. It could be attributed to insufficient of flocculant dosage to weaken the charge repulsion and bind the particles together [28]. Consequently, most of the suspended solids were still present in the solution and resulted in a turbid supernatant, as shown in Fig. 4(a). Some flocs were formed in this ballasted flocculation process, but the size and amount were obviously smaller and lesser compared to other flocculation scenarios. The settling time for the majority of the flocs was around 4 seconds, which was not much different from the rest.

The zeta potential values for the ballasted flocculation process with dosages 2-4 mg/L were within the range of -20 mV. The more positively zeta potential charge showed that the cationic polymer flocculant played a role in the formation of flocs by weakening the repulsion charge (negatively charge) on particles and bound the particles together to form larger flocs [26]. The settling time for most of the flocs during the slow mixing period was within 3-4 seconds. It was considerably fast compared to the control sets without flocculant and sand (>300 seconds) and with flocculant only (>120 seconds). The incorporation of sand in the flocs had increased both its size and density, hence reduced its settling time [29]. This reflected the benefit of ballasted flocculation, which can significantly shorten the settling time for flocs sedimentation and clarification. However, the improvement in settling time had compromised the final quality of the supernatant, where the final turbidity for ballasted flocculation was around 3 NTU, slightly higher than 1 NTU when only coagulation process was employed. This is because the flocs embedded with sand in ballasted flocculation appeared to be much larger, thus reducing the collision rate with the residual turbidity due to faster settling rate and lesser contact frequency between the flocs. Fig. 4 shows that the size of the flocs grew larger with the flocculant dosage, corresponding well with the postulation where the larger flocs had lesser chance to capture the residual turbidity and resulted in lower turbidity removal.

In previous studies, it was reported that $FeCl_3$ coagulation process removed the NOM and suspended solids by sweep coagulation mechanism [6], [30]. Under this mechanism, the coagulant formed high positive charged hydroxides that captured the negative charged impurities. During the slow stirring period, the flocs swept across the solution, grew larger by enmeshing the other flocs, residual NOM and suspended solids present in the solution. Subsequently, the flocs became heavier due to the incorporation of sand and settled faster during the sedimentation period [10]. This is as in evidence by the large dark brown flocs settled at the bottom in Fig. 4 (b)-(d).

3.3 Effect of sand dosage

Following from the previous section, the optimal flocculant dosage was fixed at 2 mg/L while the sand dosage varied from 1-4 g/L. The incorporation of polymer flocculant assisted the sand to attach to the flocs due to the binding property of the polymer [11]. Fig. 5 shows that the turbidity removal decreased slightly from 90 % to 86 % with the dosage of sand. Such trend was also observed by Sieliechi et al. that a slight deterioration of the residual turbidity was noted with the increased dosage of pozzolana particles as ballasting agent [12].

The increased dosage of sand resulted in the formation of smaller, isolated, and heavy flocs. As observed in Fig. 6, the flocs settled at the bottom of the jars shows an interesting pattern. The flocs formed for the sand dosage of 2-4 g/L appeared to be smaller, unlike the flocs in Fig. 6(a), which were in large chunk form. In addition, a greater number of flocs formed at sand dosage 2-4 g/L compared to sand dosage at 1 g/L, in which the flocs covered larger area of the jars. This observation indicates the role and impact of sand in the formation of flocs that would directly influence the turbidity and suspended solids removal.

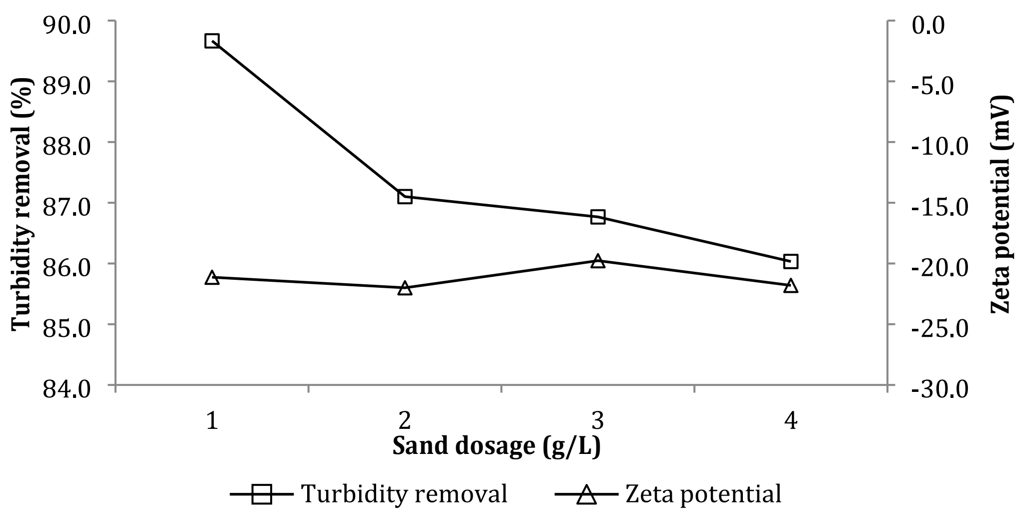

Fig. 5. Effect of different sand dosage on turbidity removal and zeta potential

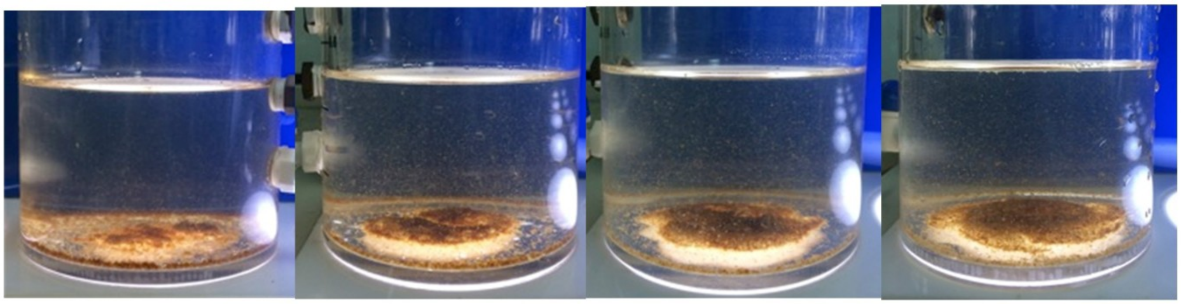

Fig. 6. Floc formations of different sand dosage after settling; (a) 1 g/L (b) 2 g/L (c) 3 g/L (d) 4 g/L

Table 4

Effect of sand dosage on settling time, turbidity, and zeta potential

Sand dosage (g/L)	Settling time (s)	Turbidity (NTU)	Zeta Potential (mV)
0	-	30	-29.9
1	3.21	3.1	-21.1
2	3.37	3.87	-22.0
3	3.81	3.97	-19.8
4	4.73	4.19	-21.8

Table 4 presents the zeta potential of the supernatant solution after the ballasted flocculation process. Generally, the zeta potential values fall in the same range regardless of the sand dosage. The result revealed that sand has no chemical interaction with the coagulant or flocculant as mentioned by Young et al. [14]. Instead, sand interacted physically with the flocs and resulted in the formation of flocs with a marked difference in size and quantity for the various dosage of sand. From the preliminary study, sand could not be embedded into the flocs without the dosing of flocculant. It was due to the binding property of flocculant that the sand could be incorporated into the flocs [11].

Based on the zeta potential value in Table 4, it could be deduced that sweep coagulation was the main mechanism for the removal of turbidity and suspended solids. This mechanism utilizes the presence of premature flocs to sweep across the solution and captures more impurities before settling down for subsequent removal [22]. The aggregation of larger flocs from premature flocs was due to van der Waals attraction that facilitated the sweep coagulation mechanism [31].

The addition of excessive sand (> 1 g/L) increased the presence of sand in the solution and thus enabled more sand to be embedded into the premature flocs. These flocs were small yet heavy due to the incorporation of sand. Consequently, the flocs tended to settle quickly, especially during the slow mixing period. With the diminishing of suspended flocs to sweep across the solution, the removal of residual particles was also reduced. Furthermore, the premature flocs also had lesser chance to collide with each other to form larger flocs as shown in Fig. 6(a). This is in good agreement with the result reported by Gasperi et al. that the addition of excessive sand dosage saturated the flocs and reduced particulate removal [17]. Hence, this explained the increased in final turbidity of the supernatant with sand dosage more than 1 g/L.

The settling time for the flocs is reported in Table 4. The settling time did not record any significant difference for all sand dosages. The slightly longer settling time (4.73 s) with 4 g/L of sand could be attributed to the remaining light premature flocs that did not have the chance to embed with the sand or collide with other flocs to form heavy agglomerates. Nonetheless, the time difference was too small to have any significant impact.

Overall, this study shows that the incorporation of ballasting agent has the potential to interrupt the efficiency of existing water and wastewater treatment (coagulation/flocculation) process. It was also noticeable that sweep coagulation mechanism required the flocs to sweep across the solution for a longer period in order to capture more suspended solid particles. The addition of sand increased the density of the flocs significantly and rapidly settled the flocs. With fewer flocs available to sweep across the solution, removal of impurities also declined. This indicated that the interaction between the ballasting agent and flocs should be considered during the design of ballasted flocculation process.

4. Conclusion

The results presented in this study provided understanding about the interaction between sand and flocs in the ballasted flocculation process. The optimal dosage for this study was 2 mg/L of flocculant and 1 g/L of sand that gave rise to 90% of turbidity removal. The settling time for the ballasted flocs was much shorter (3 seconds) compared to non-ballasted flocs due to the incorporation of sand that caused the premature flocs to become heavy and settle quickly. However, the turbidity removal efficiency was slightly compromised due to presence of lesser suspended flocs to enmesh the residual turbidity during sweep coagulation stage. The impact of ballasting agent on the flocs formation and impurities removal is worth further investigation for other different coagulation-flocculation mechanisms with different types of coagulants and flocculants.

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The authors declare no conflict of interest.