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A laboratory study on synthetic fiber filter for further treatment of turbid stormwater from construction sites

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Abstract. On the purpose of conform the more stringent government regulation for turbid stormwater from construction sites, the feasibility and availability of synthetic fiber placing after the conventional protection barrier were tested in this study. Initially, comparative work on the filtering performance of fiber media and conventional gravel filter was carried out, 27% higher filtration capacity was obtained under the similar operational conditions. The filter efficiency was about 20 to 52% with a varying filter depth of 5 to 15cm, presuming at extreme storm flow conditions (800-1500 m/day of filtration rates). Fiber filter was found to have a similar filtration prosperity as grain media; namely, the separation efficiency is directly and inversely proportional to filter depth and rate, respectively. The effects of filter aid (polyaluminium chloride) on filter performance was also investigated, it greatly affected the turbidity reduction at the dosage of 2 mg/L. At the time of breakthrough, a simple filter washing was carried out, herein, the solid recovery achieved over than 88% and greatly determined by operational parameters. Based on the operational data, the empirical models aimed for predicting filtration efficiency were established, which can effectively determine the required filter depth and filtration area in field.

Keywords: construction sites; fiber filter; stormwater; turbidity

1. Introduction

Construction site is considered as one of the main sources of diffuse pollutants that can result in water quality concerns in the receiving waters (Barrett *et al*. 1998, USEPA 2009). When rainfall occurs, soil particles from an unstabilized construction site can be detached by the individual raindrops and washed off within stormwater runoff. Once those particles were directly discharged into water body without any control, not only the visibility and photosynthetic activity in water can be declined but also deteriorate the ecological environment by numerous associated pollutants (USEPA 2007).

In order to manage the turbid runoff from building site, various abatement strategies and best management practices (BMPs) were applied around world to reduce quantities of water-borne particulates. However, most of stormwater managements in construction site are compromised, because they are effective to capture the larger particles (sands and silts), but are not valid on clay particles and finer soil matters (Trenouth *et al*. 2015a). The fine-sized fraction can be easily washed out from temporary basin which has been retrofitted with gravel, silt fence or sand bags, and the retention capacity of particulates is limited by pore spaces of filter medium (Yu *et al*. 2013). On the other hand, conventional BMPs can achieve a certain reduction of turbidity matters, whereas the performance can be impaired by the rapid flow and the occurrence of overflow. Furthermore, some facilities were effective to attenuate stormwater runoff, they have significant limitation for improving effluent quality.

In response to above problems, numerous management guidelines have been proposed to enforce the effluent quality from construction site up to the standard. The US Environmental Protection Agency permitted the discharge of stormwater runoff from construction site with less than 280 nephelometric turbidity unit (NTU) (USEPA 2009). In Korea, government requires the effluent turbidity from BMPs should not exceed 100 NTU (KEC 2008). Still, conventional media cannot reliably meet the lowering turbidity effluent limits in some circumstances. Hence, providing a further treatment unit for assuring the quality of yielding water are of great importance.

As a type of filter media recently developed, synthetic fiber filter has played a significant role in the separation of particles in water treatment (Borsi *et al*. 2012). Fiber filter is commonly made of polyamides, plexiglass, polypropylene (Niu *et al*. 2015, Gao *et al*. 2012, Kim *et al*. 2013), thereby having a great abrasion resistance and elasticity. Additionally, since the fiber filter has a larger porosity than grain media, it can be operated at high filtration speed (Lee *et al*. 2008). Therefore, in order to cope with the latest regulations for turbid runoff, a compact module packed with synthetic fiber media was established for the treatment of turbid stormwater at high filtration speed (800-1500 m/day). Its performance were investigated with various operational parameters, including filter

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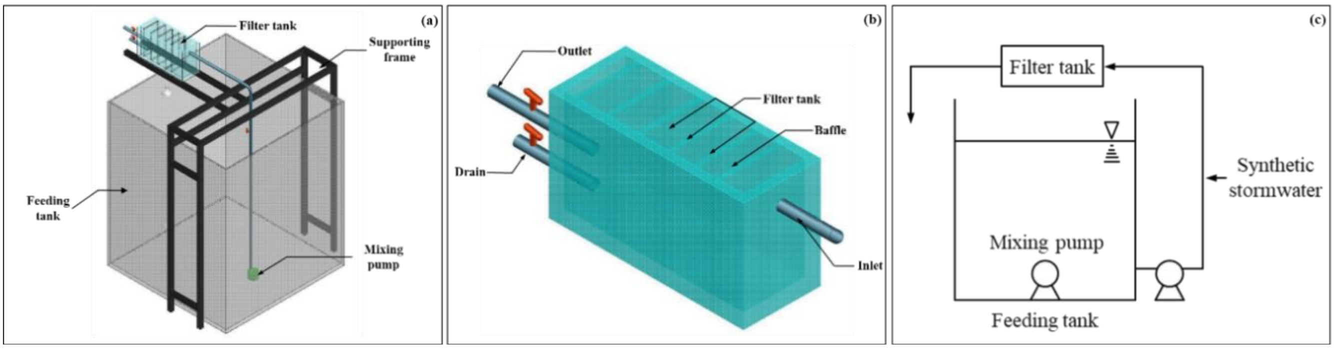

Fig. 1 Laboratory filter system ((a) feeding tank; (b) filter tank; (c) sketch diagram of experiment setup)

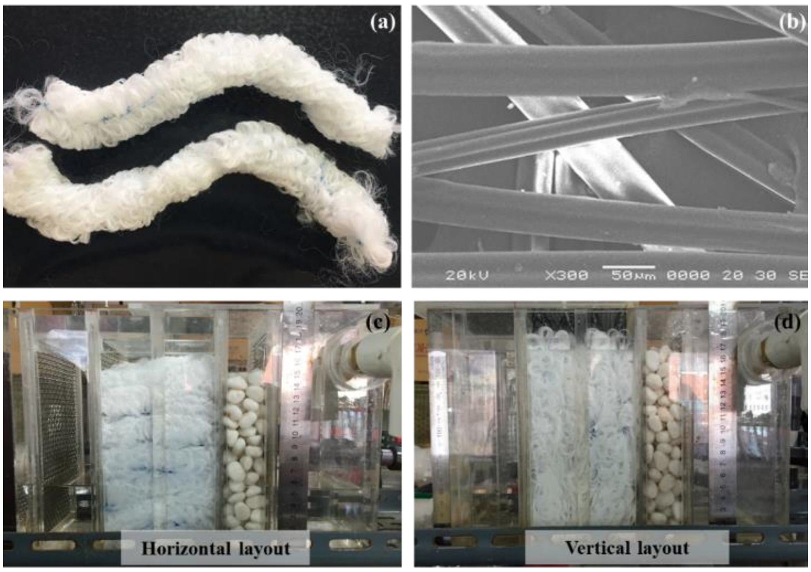

Fig. 2 (a) bundle-type synthetic fiber filter; (b) SEM image of synthetic fiber; (c) and (d) arrangement of fiber filter in module

configuration, filtration rates, filter depth and coagulant dose.

2. Material and methods

2.1 Lab-scale fiber filter

In order to accomplish the objectives, a laboratory-scale filter system was developed, consisting of a filter tank and feeding tank (Fig. 1). The dimensions of the feeding tank and filter tank were 0.7 × 1.0 × 1.0 m (width × length × height) and 0.12 × 0.20 × 0.32 m, respectively. The flume-type filter module, which is the core of the experimental device, was filled with gravel and fiber filter media. Grids were installed between the fiber and gravel media to ensure they could not be moved by the water flow. A baffle is installed in the top of the module to dissipate the impulsive force and homogeneously transfer the water flow.

2.2 Employed filters and synthetic stormwater

The employed fiber filter consisted of polyamide tied to a 5 mm diameter polythene core rope. The fiber was arranged in a linear non-woven bundle (Fig. 2 (a)), which means that it can be easily assembled and disassembled with regard to various drainage structures. The SEM image of employed fiber is shown in Fig. 2 (b). The polythene bundles had a nominal outer diameter of 45–50 mm, as well as a specific surface area of 1.0–1.6 m^2/m. Additionally, its porosity was in the range of 90–95%. Its arrangements in filter tank are exhibited in Fig. 2 (c) and (d). The surface of the synthetic fiber filter was negatively charged because of the natural property of polyamide. A small portion of gravels (D_{60} = 1.37 cm, U_c = 1.17 cm) packed before the fiber filter were to distribute the water flow.

In this study, the synthetic stormwater was made by mixing tap water with yellow soil, which is primary composed of clay and silt. According to the particle size distribution (PSD) of synthetic stormwater, the particles less 12 μm occupied over 80% of the volume fraction (Fig. 3). On the other hand, the latest standard for the construction site stormwater in Korea was required the effluent turbidity to be far less than 100 NTU (MOE 2014). In this aspect, the concentration of raw water was adjusted around 100 NTU, which is equivalent to the total suspended solids (TSS) of 340 mg/L.

2.3 Experiment design

A series of experiments were carried out to assess the filtration capacity under different conditions, including

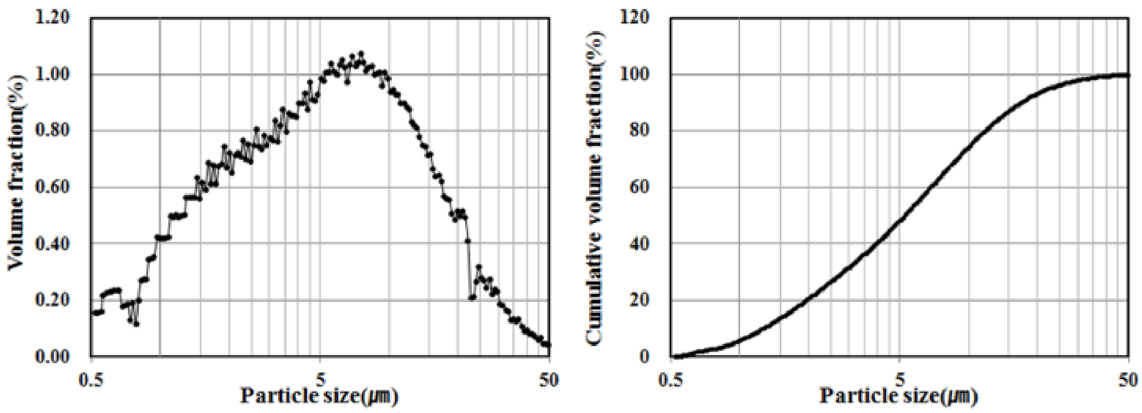

Fig. 3 Particle size distribution of feed water

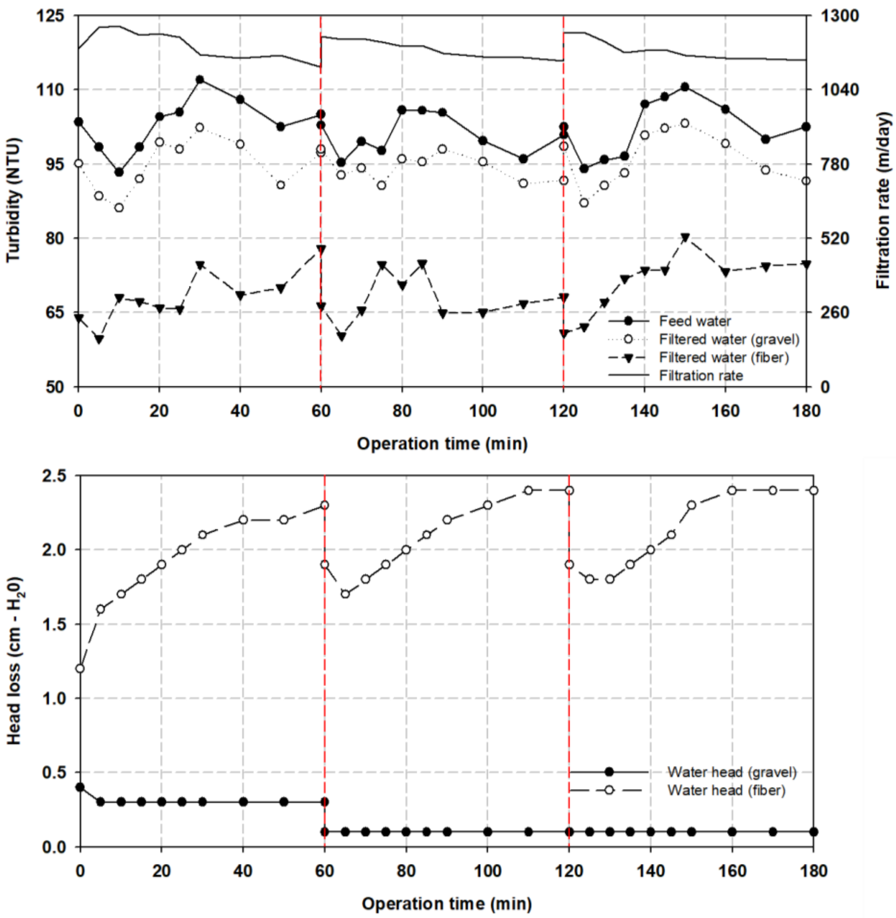

Fig. 4 Comparative operation of gravel and fiber filter (filtration rate = 1150 m/day, filter length = 10 cm)

filter configurations (horizontal and vertical layout), filter depths (5-15 cm), filtration rates (800-1,500 m /day) and dosages of filter aid (0-10 mg/L). In order to verify the reproducibility of the filtration performance, every experiment was performed in three runs for 60 min each. The inflow and outflow turbidity and TSS, flow rate and head loss were measured continuously within the entire experimental duration. The TSS was measured based on Standard Methods (APHA *et al*. 2005), while turbidity was measured using the Hach 2100N Turbidimeter. Herein, the samples taken from each 20 minutes were for the analysis of particle size distribution using the Accusizer™ 780 Particle Analyzer.

2.4 Filter cleaning

After 60 min of operation, the water in the filter tank was completely discharged. Thereafter, the filter materials were taken out and placed in a washing tank with running tap water. The adhered particulate matters on the filter surface were washed off by agitating them in washing water from side to side. The volume of the washed water was in range of 5-15 L, depending on the thickness of filter layer. The turbidity and TSS of washed water was measured to be able to determine the amount of washed-out solids by Equation 1.

$$\text{Solids Recovery (\%)} = \frac{\sum C \cdot V}{\sum \Delta_C \cdot Q \cdot \Delta_t} \times 100\% \quad (1)$$

where C = TSS concentration in washed water (mg/L), Δ_C = the concentration of captured suspended solids (mg/L), V = volume of washed water (L), Q = flowrate of synthetic stormwater (L/min), Δ_t = time interval (min).

3. Results and discussion

3.1 Comparative filtration of gravel and fiber filter

Generally, suspensions retention efficiency of BMPs was mainly related with runoff detention behind the filter barrier, not the filtration through the grain media (Barrett *et al*. 1998). When the further reduction on turbidity was required, filtration is considered as a measure necessary for effluent purification. Hence, the entrapment capacities of turbidity matters by conventional gravel filter and synthetic fiber media were examined and compared under same condition. Fig. 4 shows the operational data set of two filter media. Based upon the three consecutive filtrations with a velocity of 1150 m/day, the average efficiency of fiber and gravel filters media were around 33.7% and 6.7%, respectively. This can be accounted for the larger internal pore space in fiber filter.

By the analysis of PSD (Fig. 5), a significant decline in particle number was observed in the effluent from fiber filter, especially for the particles with a size of 0.5-5μm. As to the smaller-sized fraction, particles having a neutral or slightly positive charge can be intercepted by fiber filter since the electrostatic attraction. For the portion of large-sized particulates, small pore size and large void volume (over 90%) in fiber layer provided more chances for detaining them by straining and size exclusion. In terms of gravel filter, the greater interstices between grains and relatively lower porosity (42%) caused the suspended matters passing through. Overall, even the filtration capacity was accelerated by an average of 27% with the installation of fiber filter, its retention of fine particles still have a great potential to improve receiving water quality, on account of the strong affinity between fine particles and pollutants (Novotny and Olem 1994).

On the other hand, it was detected that the initial head loss of the fiber filter was 1.2 cm, which was higher than that of in the gravel filter (Fig. 4 (b)). Furthermore, during the filtration process, the head loss in the fiber filter gradually increased to 2.4 cm, whereas a small variation of water head was observed in the gravel filter. Due to the intricate filamentous structure, the pore size in fiber filter become smaller, and the distribution of void was serried. Therefore, more complicated flow field occurred in fiber layer, leading to clogging and head loss build-up.

3.2 Filtration performance with different operational conditions

Since a better filtration performance achieved by synthetic fiber filter, exploring the influential factors on filtering capacity is essential for scaling up the filter device in field. In this paper, the effect of selected operational

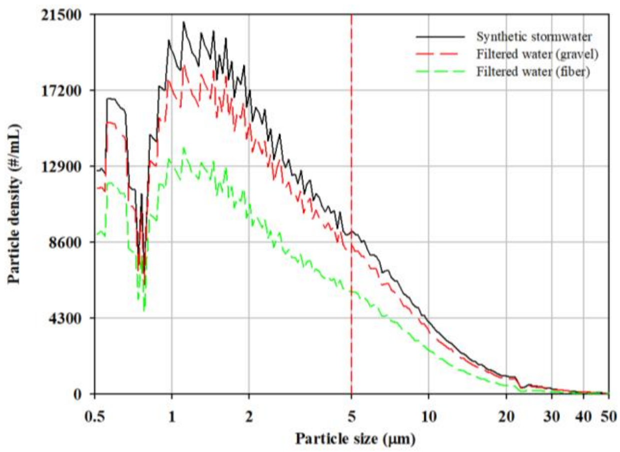

Fig. 5 Particle size distribution in synthetic stormwater and filtered water from gravel and fiber filter

factors on treatment performance of fiber filter are evaluated and the results are summarized in Fig. 6.

First, a preliminary experiment was carried to pursue the filter performance towards the arrangement of fiber in filter tank (Fig. 2 (c) and (d)). It was observed that the efficiency of turbidity removal in the vertical arrangement was slightly enhanced (Fig. 6 (a) and (b)), whereas it did not greatly change with that of from horizontal layout ($p > 0.05$). Theoretically, vertical arrangement was thought to produce a better filtering performance due to the occurrence of more complicated flow filed when the water flow transversely divided by the fiber bundles. However, the insignificant improvement was greatly related with the repelling force between fiber and inflow particles. As kind of natural property of nylon and particles from environment, negative charge distributes on their surface. Hence, the repulsion occurred when the particles moved towards the fiber. As a result, particles were predominantly removed by mechanical straining, wherein only the particles larger than the void space of fiber can be retained.

In terms of the effect of filtering speed, it can be seen that the increased velocity induced a decline of filter performance, whilst the water head was elevated under the fast flow condition (Fig. 6 (a) and (b)). Higher filtration velocity can accelerate the accumulation of turbidity matter in void space, whereafter the detachment occurred as the particulates filled up in pore space. Therefore, increasing velocity resulted in an increase in head loss, and decrease in filtration efficiency. Furthermore, the increased depth of filter layer played a more crucial role in trapping the detached particles from front layer as well as the influent individual turbidity matters. Thus, the entrapment of particulate matters were positively correlated with the filter depth.

In the case of the water head, the variation of filtration efficiency was more sensitive to the change in head loss for filter (Fig. 6 (c) and (d)) in horizontal arrangement. When the fiber arrangement was in accordance with flow direction, interstice between filters became the main pathway for turbid water passing through. In this case, the shortened fiber layer has less resistance on water flow resulting in a direct wash-out of suspesions, whereas it

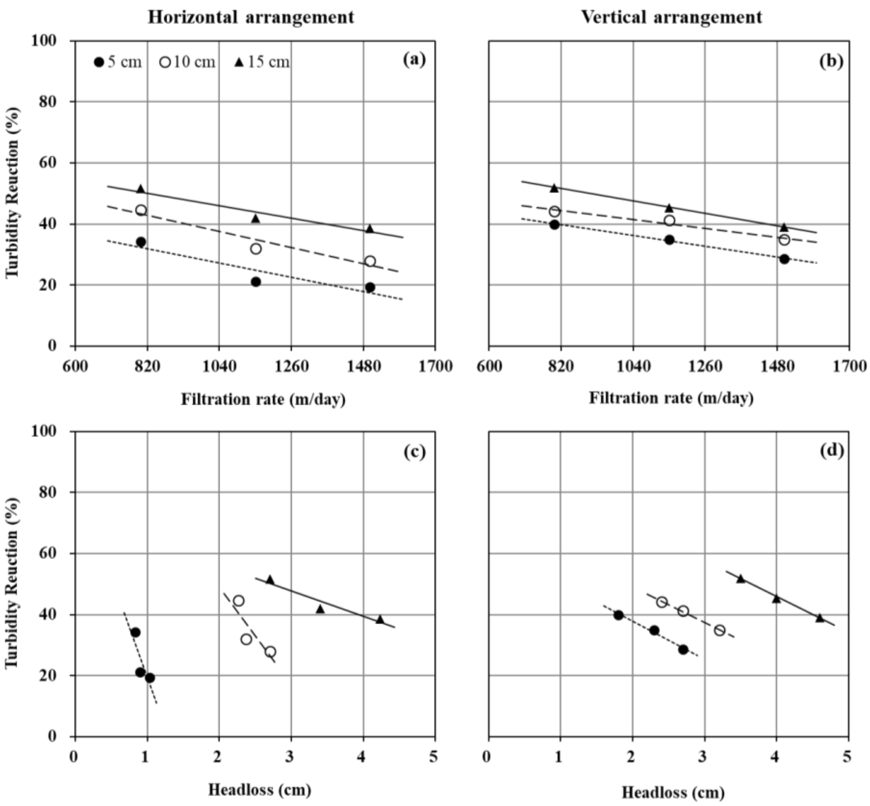

Fig. 6 Effect of various operational conditions on filter performance ((a) and (b) removal efficiency versus filtration rate at varying filter length; (c) and (d) removal efficiency versus head loss at varying filter length)

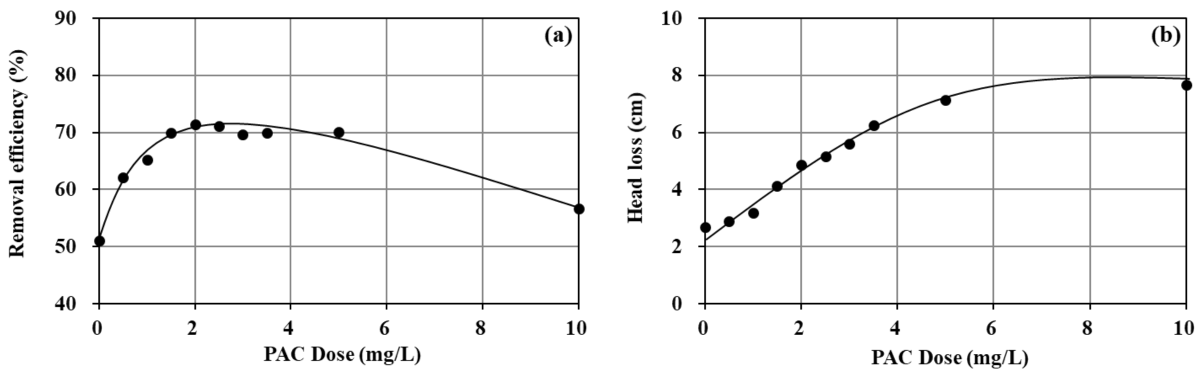

Fig. 7 Effect of PAC dosage on filter performances ((a) turbidity removal efficiency; (b) head loss)

dramatically decreases the hydraulic retention time. That is, the possibility of particle deposition was significantly decreased. Therefore, the slope of the performance curve decreased with increasing depth. Unlike the horizontal layout, the variations of efficiency with rising water head were similar in vertical arrangement. It was account for the greater buffering effect on water flow since the arrangement of fiber layer was perpendicular to the flow direction.

3.3 Filter performance with filter aid

Hydrolyzing metal coagulants, such as aluminum and ferric salts could strengthen the aggregation of suspended turbidity matters to improve filtrate quality (Gregory 2005). In present study, poly-aluminum chloride (PAC) was selected as a filtration aid, and different concentration of PAC were dosed (0–10 mg/L) to determine its effects on turbidity reduction and water head.

As exhibited in Fig. 7 (a), PAC resulted in an effective enhancement of reducing the influent turbidity when its concentration was less than 2.0 mg/L. When PAC was employed, it can be readily hydrolyzed in water, wherein the cations led to a destabilization of particles and subsequently form them into aggregation. Thus, the aggregated particulates can be easily detained by mechanical separation. Additionally, since the PAC is a cationic polymer, the electric charge of the particles in the water was changed from negative to neutral (Gregory 2005, Niu *et al*. 2014). Hence, the repelling force occurred between fiber and inflow particle was eliminated, whilst the electrostatic attraction on neutralized particles appeared. As those particulate pass through the fiber filter, they could be captured by more filtration mechanisms (e.g. interception and adhesion).

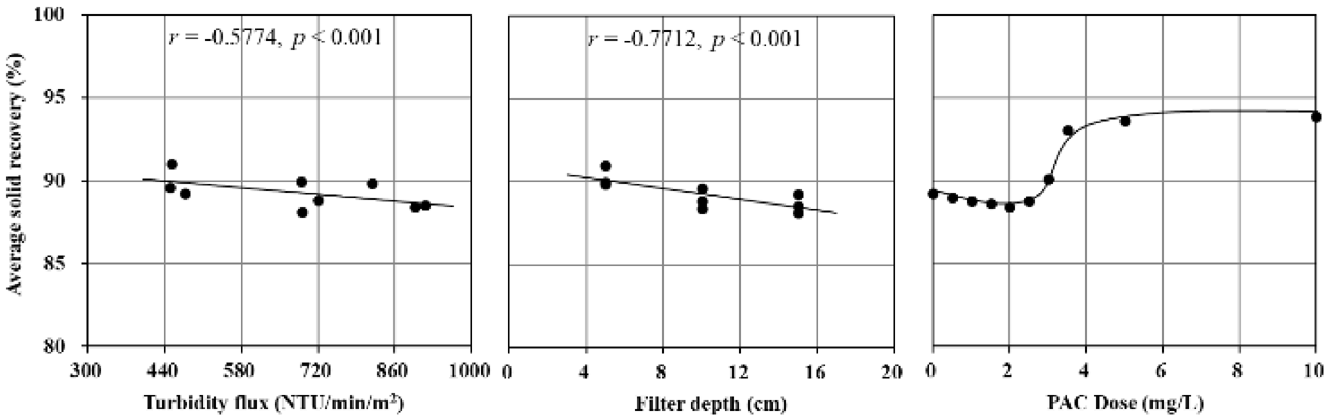

Fig. 8 Effect of different operational conditions on solid recovery

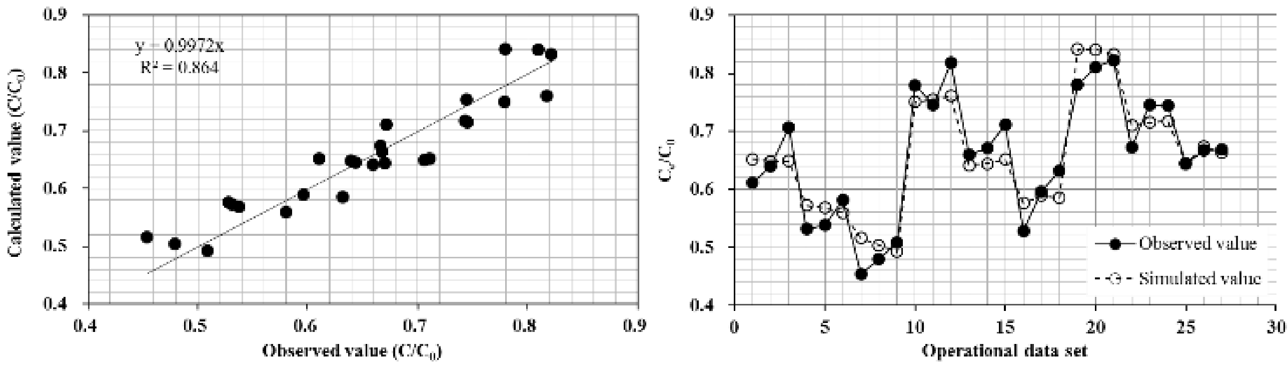

Fig. 9 Relationship between the observed and simulated turbidity of filtered water

However, the effluent turbidity decreased substantially with higher PAC dosages (> 2 mg/L). With the addition of high dosed coagulant, particulate started to restabilize and its surface charge can be reversed. In this circumstance, those particles can be more attracted by fiber filter due to the enhanced attraction between unlike charges, whereas the pre-deposited particles which have the same charge with free particles can repel them away from the filter. As a result, the repulsion appeared between particles resulted in more chances for particles discharged from filter system, accordingly, decreasing the removal efficiency.

In terms of the variation of water head, it was clearly observed that the head loss increased with incremental PAC dose (Fig. 7 (b)). As mentioned above, an incremental dosage can increase the amount of suspensions in the synthetic stormwater due to the formation of coagulations (Gregory 2005). Thus, rapid deposition of solids can occur in the void, resulting in head loss build-up. Consequently, PAC controlled the effluent turbidity within a small range at a minimal dose to neutralize charge and/or form bridges between suspensions. In contrast, a substantial dose had a negative effect on the improvement of filtration efficacy. Therefore, optimal PAC dosage was 2.0 mg/L for the turbid stormwater with a turbidity value of 100 NTU.

3.4 Filter washing and its affecting factors

At the end of filtration, a simple preventive maintenance was carried out to wash off the accumulated particulates from fiber filter. The efficacy of filter cleaning was estimated by the ratio between recovered and captured suspensions, and its results were summarized in Fig. 8. As can be seen, the particle recovered efficiency achieved over 88% in all the experiments, indicating that the majority of attached particles were subject to the intensive shearing action regardless of the complicated internal structure. Still, the performance of filter washing was affected by different operational parameters. As shown (Fig. 8 (a) and (b)), the averaged particle recovery significantly decreased with the inflow flux and thickness of filter layer due to the increasing opportunities for particulates into filter bed.

On the other hand, when coagulant was employed in filtration process, the physicochemical property of particles were changed, thereby defining as an influential factor tofilter cleaning process. As exhibited in Fig. 8 (c), it was observed that the averaged particle recovery was slightly declined with the increasing PAC dose. This is attributed to the electrostatic attraction occurred between the fiber and deposited particles since the surface charge was neutralized by additive, and subsequently reducing the detachment of particles in washing process. This result also confirmed the work by Guerra *et al*. (2014) and Niu *et al*. (2016).

However, the washing efficiency started to elevate as the coagulant concentration exceed 2.0 mg/L, and stabilized around 93% since the PAC dose was over 3.5 mg/L. This result can be closely related with the increased amount of large-sized coagulation. The higher concentration of coagulant can result in more particles to be formed into a greater aggregation (2005). During the filter washing process, the effect of shearing force on those particulates was enhanced, whilst the electrostatic force between fiber filter and particles was weakened. As a result, the solids recovery was raised with dosing high concentration of coagulant. Comparing to the previous studies on determining the effect of PAC dosage on filter washing efficiency, the variation of solid recovery shows a different trend in present study, which probably resulted by the larger range of PAC dose.

3.5 Model development for fiber filter

The prime objectives of modelling filtration processes is to improve their engineering design and obtain preferable separation of particulate matter from the water (Trenouth *et al*. 2015b) In this regard, the modelling work of granular filter performance has been previously carried out in many studies. However, the evaluation and prediction of performance on removing solid particulates using non-woven fiber media have been barely documented, especially for treating the runoff under the extreme storm flow condition.

In terms of performance prediction models for depth filtration, the model proposed by Hudson (1981) was applied in the present study to simulate the effluent turbidity from high-speed filtration system. The model including the filtration rate factor, filter media property factor, head loss factor and filter depth factor is shown as follows:

$$\frac{C_e}{C_0} \cong \frac{V d^3 p^4 HS}{L} \tag{2}$$

where C_e = turbidity in filtered water (NTU), C_0 = turbidity in raw water (NTU), V = filtration rate (m/day), d = effective size (mm), p = filter porosity, H = loss of water head through the bed (m water), S = surge amplitude in percent of head lost and L = thickness of the bed (m).

In the present study, since the head loss and surge amplitude were small, the effect on overall efficiency is negligible. Furthermore, the porosity and effective size of fiber filter were consistent in all the filtration experiments. Therefore, filtration rate (V) and filter depth (L) were the factors taken into account in model development, whilst the equation is amended as follows:

$$\frac{C_e}{C_0} \cong K_f \cdot \frac{V^a}{L^b} \tag{3}$$

where K_f, a and b are empirical filtration constant.

Total of 27 data sets was used for model calibration, and the following equations was obtained:

$$\frac{C_e}{C_0} \cong 0.02425 \cdot \frac{V^{0.39225}}{L^{0.22395}} \tag{4}$$

Zero-interception linear correlation of measured and calculated values (C_e/C_0) preformed by developed model was pursued (Fig. 9 (a)). As shown in the figure, the slope of the best-fit line is 0.99, whilst the significant relationship (R^2 = 0.864, p < 0.001) between the observed data and calculated data indicates that the concentration ratio between influent and effluent can be simulated based on the filtration velocity and filter depth. In addition, Fig. 9 (b) shows that the increases and decreases of predicted values are well correspond the observed concentration ratios, indicating a high accuracy of the developed empirical model. Once the equation has been evaluated for a given set of conditions, the results for other conditions can be evaluated.

In order to determine the thickness (L) of filter layer and filtration area (A) to achieve the designed efficiency, the equation (4) is transformed as follows.

$$L \cong \left(\frac{0.02425 \times V^{0.39225}}{C_e/C_0}\right)^{\frac{1}{0.22395}} \tag{5}$$

$$V \cong \left(\frac{C_e/C_0 \times L^{0.22395}}{0.02425}\right)^{\frac{1}{0.39225}} \tag{6}$$

Two methods are possible for designing the fiber filter, depending on the conditions of the drainage system from construction site. If the designed values (C_e/C_0) and the flow-through rate (V) are determined, the required thickness (L) of fiber filter can be calculated using Eq. (5). Meanwhile, as the target turbidity reduction and the filter thickness (L) were given, the filtration velocity (V) can be estimated by Eq. (6). Thus, the size of cross-sectional area where the fiber filter installed can be obtained based on the designed water quality flow (WQF).

Conclusion

In this study, a synthetic-fiber filter system was designed for purification of stormwater from the construction sites. By using synthetic fiber, the effluent turbidity can be dramatically reduced to a lower level as compared to that of from conventional gravel filter due to the preferable retention of small particle (< 5.0 μm).

The performance of lab-scale filter system was evaluated in terms of its capacity for turbidity removal under different operational conditions. It was found that the fiber filter thickness and filtration rate showed positive and negative effects on the removal performance, respectively, indicating that the fiber filter media act exactly like a granular media. In terms of the head loss, the studied fiber filter could provide a minor water head despite the extreme storm flow condition due to its highly porous structure.

In addition, the experimental results imply that using optimum dosage (2.0 mg/L) of filtration aid can greatly improve the efficiency. Thus, it could be an alternative as the specific treatment required. Furthermore, most of the trapped particles can be washed out by filter cleaning, and the efficacy of filter washing was found to be closely determined by inflow flux, filter thickness and PAC dosage.

According to the experimental work, an empirical model for predicting the performance of fiber filter was developed, and the removal efficiency can be well predicted even with two factors (filter layer thickness and filtration speed). Based on the established model, the required filter depth and the filtration area can be estimated by the given design parameters.

Acknowledgments

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