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Performance of Inclined-Plate Settler and Activated Carbon Sponge-Cube Media Filter for the Treatment of Urban Stormwater Runoff from an Industrial Complexs

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ABSTRACT

Urban stormwater runoff contributes to the deterioration of water quality of urban waterbodies. Development of a cost-effective treatment system that renders the treated effluent suitable for the recharge of receiving waterbodies meeting stringent regulations is required. This study evaluated the performances of the inclined-plate settler (IPS) and activated carbon sponge-cube media filter (ASMF) in treating urban stormwater runoff from an industrial complex area. The stormwater runoff during the first hour of rainfall had significantly high concentrations of suspended solids (SS), chemical oxygen demand (COD), and total nitrogen. The IPS and ASMF bed with hydraulic retention times of 15 $\pm$ 5 and < 3 min showed the removal efficiency of 5.4 – 33.2% and 32.8 – 95.1% for SS, turbidity, COD, and TP including < 5 – 20% for TN. The combined IPS/ASMF or biofilm (BF)-ASMF system at filtration velocity of 10 m/h showed removal efficiencies of 46.7 – 99.2% for insoluble fractions such as turbidity, COD, TP and heavy metals including < 40% for TN. The ASMF or BF-ASMF bed coupled with IPS is a cost-effective option for the treatment of urban stormwater runoff, achieving an effluent quality suitable for industrial or multipurpose reuse and for the recharge of waterbodies.

1. Introduction

Unlike the control of point sources of pollution, the impact and control of nonpoint sources of pollution of urban rivers and waterbodies by stormwater runoff has not been adequately addressed (Pandey et al., 2014; Lu et al., 2020; Siddiqui et al., 2020). Urban stormwater runoff is widely regarded as the main transport medium for contaminants that enter urban waterbodies (Bjoerklund et al., 2018). The quality of stormwater runoff in an area can vary significantly depending on land-use characteristics surrounding it such as industrial, commercial, agricultural, and urban. Stormwater runoff contains significant concentrations of heavy metals, nutrients, suspended solids (SS), colloidal and volatile fractions of inorganic and organic particulates, and other anthropogenic compounds that contaminate waterbodies including rivers in coastal areas (Li et al., 2020; Muller et al., 2020). Many municipalities are concerned about implementing reclamation and reuse measures that can reduce pollution caused by urban stormwater runoff to recover the quality of receiving waterbodies and meet regulations that have become more stringent. In particular, such measures are more pertinent in the case of the reuse of contaminated urban stormwater runoff from industrial complexes to secure industrial or multipurpose water supply and protect receiving waterbodies from pollution. Typically, the major contaminants in the stormwater runoff can be removed easily through sedimentation or filtration (You et al., 2019; Nystrom et al., 2020; Okaikue-Woodi et al., 2020). However, conventional sedimentation or filtration beds are less effective in removing soluble contaminants such as nutrients and dissolved organic matter, and normally occupy large areas (Zhang et al., 2020). Conventional sedimentation using a gravity settler is widely used for the treatment of domestic and industrial wastewaters. The efficiency of solid–liquid separation of a gravity settler is directly related to the surface area available for settling. Compared to a conventional gravity settler, an inclined-plate settler (IPS) has a brief hydraulic retention time (HRT) because of its shorter settling distance, and in this case, the available settling area is dependent on the total area of the plates projected on to a horizontal surface. Hence, it is a preferred pre-

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treatment process for the filtration of urban stormwater runoff under limited space conditions (Salem et al., 2011). Conventional filtration systems are usually composed of sand, anthracite, and fiber. However, a variety of alternative sorbents such as zeolite, activated carbon, and compost can be incorporated into the filter media for the assimilation and transformation of organic, inorganic, and toxic constituents through processes such as infiltration, sorption, precipitation, and binding by organic colloidal material or adsorption of metal-ligand complexes to improve water quality (Davis et al., 2001). A coagulant is also used prior to the use of conventional media-filters to increase their filtration velocity and enhance removal efficiency of colloidal and suspended particles (Chua et al., 2003). In addition, the fiber filter has been studied as an alternative to the conventional filter. Previous studies showed that the conventional filters having a limited filtration velocity and a low filtration efficiency was an inappropriate in treating urban stormwater runoff. These have required for evaluating the possibility of applying the fibre filter as an alternative to the conventional filters for efficient treatment of urban stormwater runoff (Jeanmaire et al., 2007; Lee et al., 2010). Compared with the conventional granular media filters, the sponge-cube media (SM) filter having a high filtration velocity and a high filtration efficiency can achieve high performance in removing organic and particulate matters (Lee et al., 2010; Gao et al., 2012). Based on the above, we can expect that the SM filter coupled with IPS provides a cost-effective option for the treatment of urban stormwater runoff, achieving a quality of effluent that is suitable for industrial or multipurpose use and for the recharge of waterbodies. Therefore, the objectives of this study were to evaluate the performances of the IPS and activated carbon sponge-cube media filter (ASMF) and assess their potentials for the reclamation and reuse of urban stormwater runoff from an industrial complex area. IPS as a pretreatment process of ASMF was applied to enhance the removal of particulate matters. The effects of operating parameters such as packing density of filter media and filtration velocity on the effluent organic and inorganic contaminants and head loss were studied. The characteristics of particle removal throughout IPS and the filter bed were also evaluated. The rest of this article is organized as follows. In Section 2, we explain experimental apparatus and methods. Section 3 provides experimental results and discussion for the characteristics of urban stormwater runoff quality, performance of the inclined-plate settler, and filtration characteristics of sponge-cube media filter. Finally, the conclusions and recommendations are presented in Section 4.

2. Materials and Methods

2.1 Apparatus and Materials

Transparent acrylic contactors of the IPS (0.04 [D] × 1.2 [H] m) and ASMF (0.3 [L] × 0.2 [W] × 1.2 [H] m) were used for batch experiments. The bed volumes of IPS and ASMF with HRTs of 15 ± 0.5 min were 0.002 – 0.04 m^3. A pilot-scale plant (capacity of 1.5 m^3/d) consisting of units of screen, raw water storage tank,

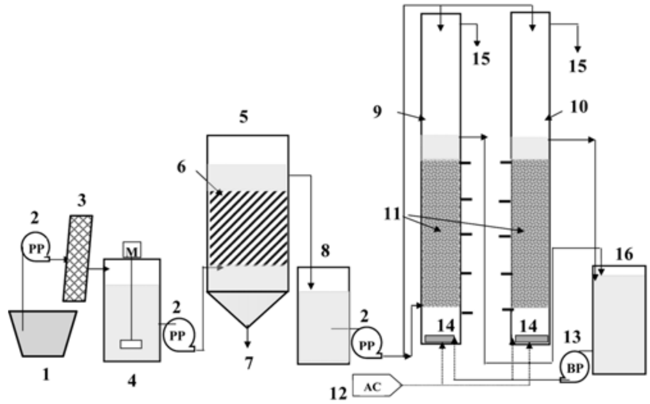

Fig. 1. Schematic Diagram of IPS/ASMF System for Treating Urban Stormwater Runoff (1. trench; 2. peristalic pump; 3. screen; 4. pre-filterated storage tank; 5. inclined plate settler; 6. inclined plate; 7. waste sludge; 8. storage tank; 9. ASMF bed; 10. BF-ASMF bed; 11. sponge-cube media; 12. sir compressor; 13. backwash pump; 14. air diffuser; 15. backwashed water; 16. finished water storage tank)

IPS tank (IPST), ASMF, and treated water storage tank for backwashing of the filter was used for continuous experiments (Fig. 1). The IPST is a pretreatment process that reduces SS load flowing into the ASMF. The screening tank, which pretreats the stormwater runoff was made of stainless steel (0.4 [L] × 0.6 [W] × 1.0 [H] m) and the pore size of the screen net was 0.3 mm. The IPST and ASMF were fabricated using an acrylic plate and their volumes were 0.18 m^3 (0.5 [L] × 0.3 [W] × 1.2 [H] m) and 0.012 m^3 (0.1 [D] × 1.5 [H] m), respectively. IPST was packed to 90% of the tank volume with a plastic plate (0.4 [L] × 0.2 [W] × 1.0 [H] m). Each filter was packed to 0.5 m with polyethylene sponge-cube media (6.5 [L] × 6.5 [W] × 6.5 [H] mm) coated with activated carbon with a specific surface area of 3,500 m^2/ m^3. Air diffusers were placed at 20 and 40 cm from the bottom of the filters for backwashing. The filters consisted of upper support net, filter media, and lower support net. The pilot-scale plant was equipped at the study area (5 km^2) located at an urban industrial complex area in Gyeongsang Province, Korea. The sampling site was approximately 10 m away from a retention pond that receives the urban stormwater runoff from a stream in the industrial complex area. The stream is 2 km long and 20 – 35 m wide. A trench was installed in a stainless-steel basin (1.0 [L] × 1.0 [W] × 1.5 [H] m) to collect the stormwater runoff.

2.2 Operational Conditions

Batch experiments were conducted to investigate the effects of IPS and ASMF with respect to their flow rates and filtration velocities on the removal of contaminants. A continuous experiment using the pilot-scale plant was conducted to evaluate the combined performance of the IPS/ASMF system. The settling experiment of IPS to determine the configuration of inclined plate was performed at a spacing of 1 – 4 cm and angles of inclination of 30° and 60°. The screening tank and IPST were also operated at flow rates of 0.96 and 0.72 m^3/d, respectively, corresponding to an HRT of 10 min. In order to determine the configuration of filter system coupled with IPS, the filtration experiment using the ASMF and biofilm-ASMF (BF-ASMF) were operated at packing density of 90 – 95 kg/m^3 and filtration velocities of 10 – 40 and 3 – 10 m/h, respectively. Piezometers located throughout the filter column were used to determine the head loss through the filter beds. The influents for the bench- and pilot-scale plants were fed through upflow into the upper 10 cm from the bottom IPST and through downflow into the upper 10 cm from the top of the ASMF, respectively. For ASMF and BF-ASMF beds, the distance between the upper and the lower support nets was 0.5 m during filtration, but was expanded up to 0.8 m during backwash. Backwashing of filter bed was conducted after reaching a head loss of 100 cm. Backwashing consisted of air scouring (5 – 7 L/min) and high-velocity wash at 30 – 40 m/h supplied by the water in treated water storage tank. Both water and air were introduced into the bottom of the filter. Backwashing duration was set at 3 – 5 min including the water rinsing for 1 min. The stormwater runoff used for this study was sampled during four wet weather periods. The collected stormwater runoff was pumped using a peristaltic pump to the screening tank and then the pre-filtrated water was fed using cross-flow into the first storage tank. The device was programmed to collect the stormwater runoff if the water level in the trench was above 10 cm. The pre-filtrated water was used as the raw water for the batch and continuous experiments.

2.3 Analytical Methods

Samples of influents and effluents of IPST and ASMF processes were collected and analyzed for the following parameters: pH, chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP). pH was measured using standard probes (Hach, USA). Turbidity was measured by turbidimeter (Hach, USA). The particle size distribution of the sample was measured using a laser particle counter (SPECTREX PC-2200, USA). COD, SS, TN, and TP were analyzed according to standard methods published earlier (APHA, 2001). TN and TP were measured using a spectrophotometer (Varian-Cary 50, Australia). Concentrations of metals (Fe, Mn, Pb, Cd, and Cr) were determined using an inductively coupled plasma spectrophotometer (Varian-ICP, Australia). Samples were stored in glass bottles at 4°C in the dark, and if necessary, filtered through 0.45-μm cellulose nitrate membrane filters.

3. Results and Discussion

3.1 Characteristics of Urban Stormwater Runoff Quality

Figure 2 represents the correlation coefficients of SS, COD, TN, and TP with the rainfall duration of 1 – 5 h. The contaminants concentrations in the stormwater runoff from the industrial complex such as SS, COD, TN, TP, Cd, Pb, and Cr were 32.5 – 298.7, 25.6 – 148.6, 3.062 – 17.608, 0.424 – 2.481, 0.017 – 0.258, 0.001 – 0.005, and 0.020 – 0.038 mg/L, respectively. The average particle size distribution was 73.1, 13.0, and 13.9% for < 9, 10 – 20, and 22 – 100 μm particles; this corresponds to average

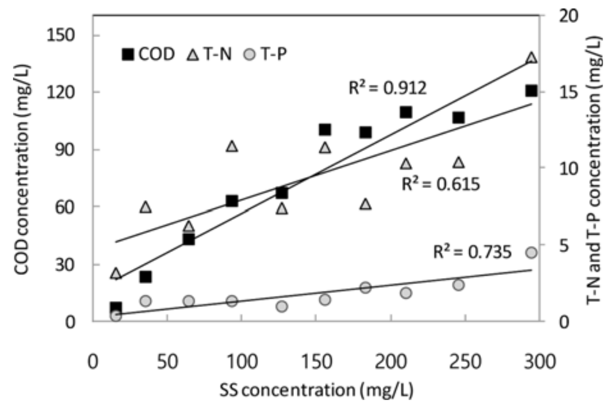

Fig. 2. Correlation between SS, COD, T-N, and T-P in Urban Stormwater Runoff during Rainfall Uration Time (1 h)

109.1 × 10^4 particles of 1 – 9 μm, 19.4 × 10^4 particles of 10 – 20 μm, and 20.8 × 10^4 particles of 22 – 100 μm. These results were similar to other reported results which stated that particles of < 5 μm accounted for more than 80% of number fraction while their mass fraction was about 12% (Yun et al., 2010). The stormwater runoff within the first 1 h of rainfall had significantly high concentrations of SS, COD, and TN, at 285.4 ± 13.3, 135.7 ± 12.9, and 16.263 ± 1.345 mg/L, respectively. A close relationship between SS and COD with correlation coefficients of 0.91 was observed. This value was similar to that reported a strong correlation of 0.8 – 0.9 between SS and COD for the runoff rainwater from an urban area (Andral et al., 1999; Lee et al., 2008). After 2 h of rainfall, these correlation coefficients decreased to 0.44 – 0.69, which were similar to findings of Li et al. (2005), who reported that the particle concentration decreased as the storm progressed and the number of large particles decreased more rapidly than the total number of particles. These results indicate that the reduction of organic loadings in the urban stormwater runoff depends on the removal of SS within the first hour of rainfall containing a high level of SS, which is caused by the wash-off from impervious surfaces and accumulated sediments during dry weather in sewers (Gnecco et al., 2006). Therefore, the treatment of urban stormwater runoff should include systems for the separation of particles and removal of dissolved contaminants to effect the multipurpose reuse of water and meet the recharge regulations of receiving waterbodies.

3.2 Performance of the Inclined-Plate Settler

The batch experiment using IPS but without chemical was performed to evaluate particulate matter separation, which is a pretreatment process for the filtration. In this experiment, inclined plates were set at inclination angles of 30° and 60° and spacings of 1, 2, and 4 cm for IPS with HRT values of 10 and 20 mins. Influent concentrations of SS, COD, TN, and TP were 61.2–65.6, 47.5 – 54.5, T-N 5.186 – 6.835, and 0.847 – 1.241 mg/L, respectively. Removal efficiencies for plates at 60° angle for SS, COD, TN, and TP were 30.6 – 33.2, 5.4 – 8.8, 3.9 – 4.9, and 8.9 – 16.0%, respectively (Fig. 3). At an HRT of 10 min, the plate

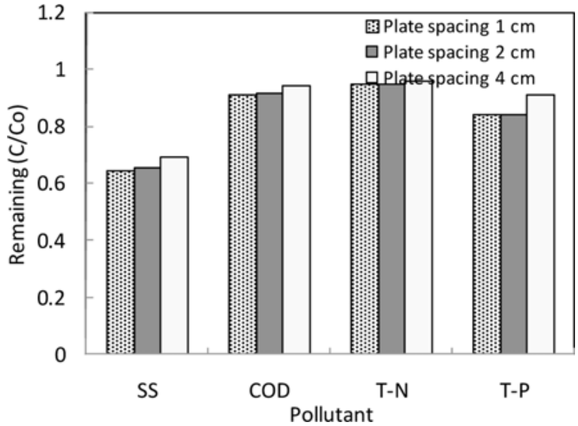

Fig. 3. Effects of Plate Spacing on Contaminants Separation of IPS with Inclined Angle of 60°

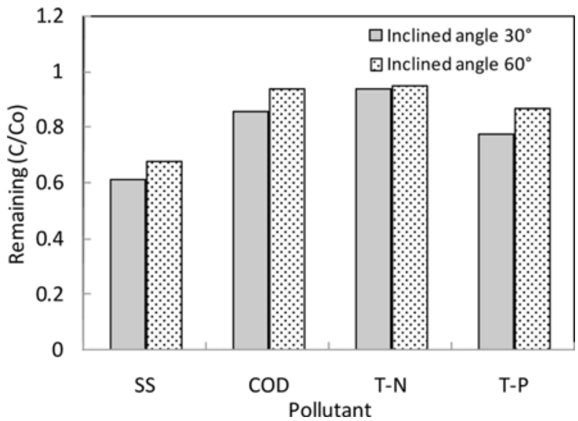

Fig. 4. Effects of Inclined Angle on Contaminants Separation of IPS (2 cm in plate spacing)

spacing of 2 cm achieved a 5% higher efficiency compared to that with a plate spacing of 4 cm. In particular, a lower spacing (< 2 cm) at a high flow rate can result in a relatively low deposition of particles on the plate due to increased hydraulic behavior between the plates (Salem et al., 2011). At the operating conditions of IPS in the batch experiment (operated at HRT values of 10 and 20 min and a plate spacing of 2 cm), the settling efficiencies of inclination angles 30º and 60º for SS, COD, TN, and TP were 32.0 – 38.8, 5.4 – 14.3, 5.1 – 6.3, and T-P 13.2 – 22.5%, respectively (Fig. 4). At an inclination angle of 30°, higher settling efficiencies of 5-10% were achieved compared to those at 60°. Contrastingly, the settling efficiency at an HRT of 20 min achieved a higher efficiency of 5 – 10% compared to that at an HRT of 10 min, regardless of the inclination angle of the plates. Notably, the settling efficiency at inclination angle 60° rapidly reduced at an HRT of 10 min. Fig. 5 shows the distribution of particle size in the influent and effluent of the IPS, which was operated at a plate spacing of 2 cm, inclination angle of 60°, and an HRT of 10 min. The average numbers of influent particles (number/mL) were 6.5 × 10^4, 5.1 × 10^4, and 5.7 × 10^4 for particle sizes of 10 – 12, 13 – 20, and 22 – 25 μm, respectively. As a result, the average particle removal rates were 17.2 – 30.1, 19.4 – 30.3, 29.4 – 56.1, and > 67.8% for particle sizes of 10 – 12, 13 – 20, 22 – 57, and 62 – 100 μm, respectively. Particles with sizes of < 30 μm were dominant, and those > 35 μm comprised approximately 30% of the total number of particles. These results reveal that appropriate increase in HRT and decrease in plate angle (< 60°) can improve the settling efficiency. In addition, steep angle (> 60°) and narrow spacing (< 1 cm) of plates are not required to enhance the settling efficiency of the IPS with a high flow rate (Yeh, 2001; Salem et al., 2011).

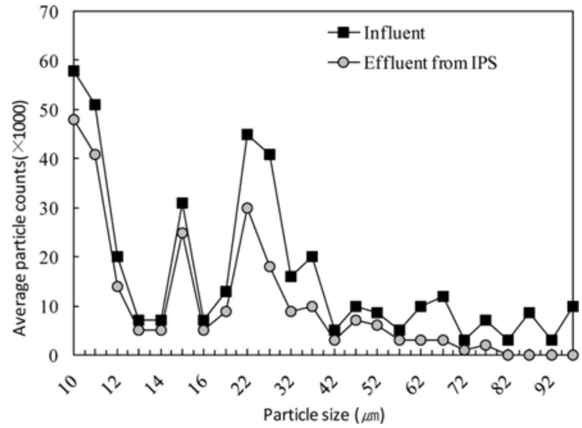

Fig. 5. Distribution of Particle Size in Influent and Effluent of IPS

3.3 Filtration Characteristics of Sponge-Cube Media Filter

3.3.1 Performance of High-Rate Filtration

Batch experiments of the ASMF were performed to evaluate the performance of high-rate filtration (HRF). Both filtration velocity and packing density (PD) are important factors that affect HRF. In this study, four filtration velocities (10, 20, 30, and 40 m/h) and two packing densities (90 and 95 kg/m^3) were applied to the ASMF bed. The concentrations of turbidity, COD, TN, and TP in the influent were 65.6 – 72.7, 59.3 – 66.5, 8.125 – 9.213, and 1.427 – 2.083 mg/L, respectively. When the filtration velocity was increased from 10 to 40 m/h, the removal efficiencies of the ASMF with a PD of 90 kg/m^3 for turbidity, COD, TN, and TP were 74.8 – 85.1, 27.8 – 37.3, 5.1 – 17.4, and 31.5 – 45.2%, respectively, as shown in Figs. 6(a) and 6(b). In addition, the filter with a PD of 95 kg/m^3 achieved a higher efficiency of 5 – 10% compared to that with a PD of 90 kg/m^3 in terms of COD and nutrient removal. The filtration performance of the ASMF bed with a PD of 90 kg/m^3 and a filtration velocity of < 20 m/h led to an increase of 5 – 14% in removal efficiency compared to that of > 30 m/h. Moreover, the cycle duration of filtration at a lower filtration velocity was longer due to even deposition of contaminants in the filter compared to that operated at a higher PD and filtration velocity. Similarly, the filtration performance of the ASMF bed with a PD of 95 kg/m^3 and filtration velocity of < 20 m/h led to a 10 – 20% increase in the removal efficiency compared to that of > 30 m/h. At a high filtration velocity (> 30 m/h), high PD achieved a better removal of organic matter and particle levels in the filtrate

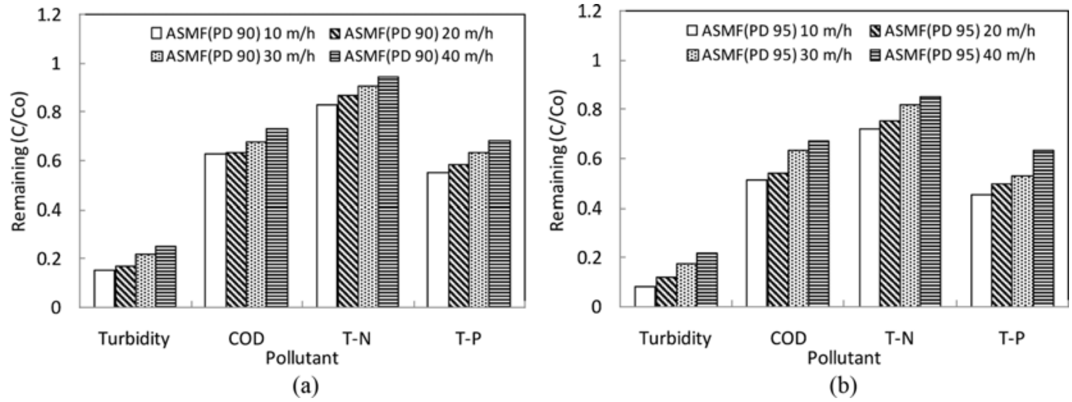

Fig. 6. Effects of Packing Density of ASMF Beds on Contaminants Filtration: (a) PD 90 kg/m^3, (b) PD 95 kg/m^3

water than those of the low PD of 90 kg/m^3, which was probably because of the loose packing of particles compared to that of the high PD. This phenomenon occurred during the initial operating period. In particular, higher filtration velocities with a short operating period accelerated compaction and ensured uniform density of the sponge-cube media filter, resulting in a good entrapment of particulate matter; however, during a longer operating period, increased turbid matter in the filtrate was attributed to the breakthrough occurrence in the filter bed (Gao et al., 2012). These results suggest that the ASMF bed with a low filtration velocity and PD is conducive to achieve optimal parameters of the filtrate and filtration cycle time (Lee et al., 2010). Shitu et al. (2020) reported that the enhanced interception of particles by sponge-cube media depends on porosity, space between sponge cubes, and pore sizes of sponge cubes. Thus, sponge-cube filter media offer a high surface area owing to their porous structure and ensure high efficiency and cost-effectiveness of filtration systems (Tanikawa et al., 2018). Compared to conventional dual layer filters with a filtration velocity of < 5 m/h and a flow rate of 120 L/d, the ASMF with a much shorter HRT and a higher flow rate of 392 –784 L/d achieves similar turbidity and TP removal rates (Hatt et al., 2006). Most of the particulate matter was also removed in the upper layer of the ASMF with a packed depth of 50 cm, which is similar to that in the top 30 cm of the fiber-ball filter bed and granular media filtration (Gao et al., 2012). During the initial filtration period, the removal of each contaminant was reduced in the immature ASMF bed, probably because of its relatively loose packing compared to that of the dual layer filter, which allows small particles to easily pass through. This resulted in a low specific gravity of the sponge-cube media compared to that of the granular media. In contrast, the head loss across the ASMF bed with a PD of 90 kg/m^3 and a filtration velocity of > 30 m/h was developed from 24.0 ± 1.3 to 70.5 ± 11.3 cm, which was 1.5 – 2.0 times faster than that at a filtration velocity of < 20 m/h, while the head loss across the ASMF bed with a PD of 95 kg/m^3 at a filtration velocity of > 30 m/h occurred 1.7 – 2.2 times faster than that at a filtration velocity of < 20 m/h. Thus, HRF using the ASMF bed has disadvantages such as the low reduction of organic matter and N and frequent backwashing cycle because of the presence of coarse material in the stormwater runoff resulting in blocking. Therefore, introduction of a pre-treatment facility prior to the HRF operation was needed to achieve better efficiency. The HRF should be operated with a filtration velocity of < 20 m/h for the efficient removal of organic and particulate matter and minimized power consumption because increased hydraulic loading leads to immature filter bed due to a stronger scouring of media surfaces (Kong and Wu, 2008).

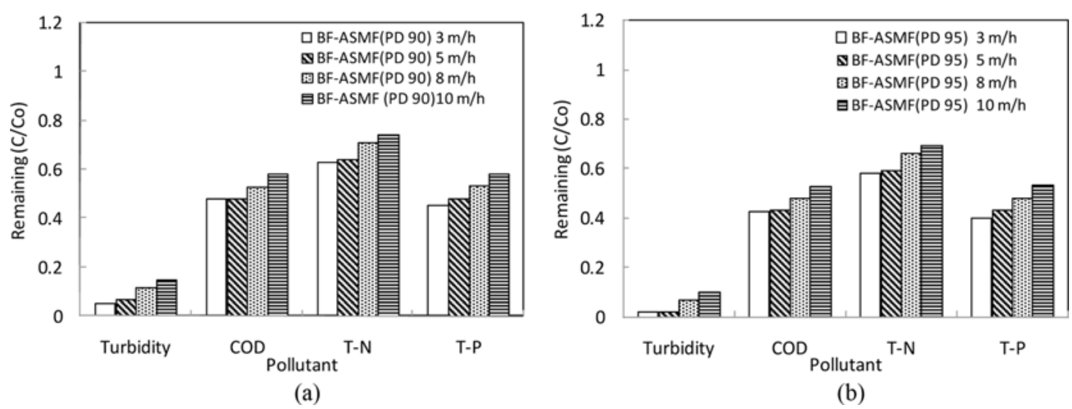

Fig. 7. Effects of Packing Density of BF-ASMF Beds on Contaminants Filtration: (a) PD 90 kg/m^3, (b) PD 95 kg/m^3

3.3.2 Performance of Biofiltration

Figures 7(a) and 7(b) present the biofiltration efficiency of the BF-ASMF with a PD of 90 – 95 kg/m^3 and filtration velocity of < 10 m/h, determined by the batch experiment results. In this study, filtration velocities of 3, 5, 8, and 10 m/h and PDs of 90 and 95 kg/m^3 were applied for the BF-ASMF bed after 30 d operation at a filtration velocity of 3 m/h to maintain a mature biofilter bed. Average influent concentrations of turbidity, COD, TN, and TP were 71.6 – 79.4 NTU, 54.3 – 58.5, 9.126 – 11.154, and 1.953 – 2.072 mg/L, respectively. When the filtration velocity was increased from 3 to 10 m/h, the removal efficiencies of the BF-ASMF with a PD of 90 kg/m^3 were 85.1 – 95.2, 41.7 – 52.3, 25.5 – 37.1, and 41.5 – 55.0% for turbidity, COD, TN, and TP, respectively. The biofilter with a of PD of 95 kg/m^3 achieved a 3 – 5% higher efficiency compared to that with a PD of 90 kg/m^3 in terms of COD and nutrient removal. The BF-ASMF bed with a PD of 90 kg/m^3 at a filtration velocity of < 5 m/h achieved a 5 – 10% higher removal efficiency compared to that of > 8 m/h. The filtration cycle duration of the biofilter operated at a filtration velocity of < 5 m/h was longer owing to an even deposition of contaminants caused by a relatively loose packing in the biofilter compared to that of the biofilter at a PD of 95 kg/m^3 operated at a filtration velocity of > 8 m/h. Likewise, the BF-ASMF bed with a PD of 95 kg/m^3 and a filtration velocity of < 5 m/h achieved a 5 – 13% higher removal efficiency compared to that of > 8 m/h. At a high filtration velocity (> 8 m/h), a high PD of 95 kg/m^3 achieved a better removal efficiency resulting in lower organic matter and particle levels in the filtrate water compared to those of the low PD of 90 kg/m^3. The high removal of COD and nutrients is caused by the sponge media, which provide better living spaces for various bacteria including nitrifying bacteria (Liu et al., 2019). Based on thin-biofilm growth and particle deposition, biofilters with PD values of 90 and 95 kg/m^3 and operated at a filtration velocity of > 8 m/h provided better filtrate quality and a shorter filtration cycle time owing to the faster clogging of the upper layer of the biofilter. In particular, this phenomenon was prominent in the BF-ASMF bed with a PD of 95 kg/m^3 compared to that with a PD of 90 kg/m^3 and the ASMF with PD values of 90 and 95 kg/m^3. These results indicate that the BF-ASMF with a longer contact duration leads to a greater reduction in organic matter (Halle et al., 2009) and a shorter filtration cycle duration (Mitrouli et al., 2008). A shorter contact duration leads to a lower reduction of organic content because of the high filtration velocity (> 8 m/h) and thus can remove loosely attached large microbial aggregates (Choi et al., 2007). In contrast, the head loss across the BF-ASMF bed with a PD of 90 kg/m^3 and a filtration velocity of > 8 m/h was developed from 25.5 ± 1.5 to 71.5 ± 10.6 cm, which was 1.5 – 2.0 times faster than that at a filtration velocity of < 5 m/h, while the head loss across the BF-ASMF bed with a PD of 95 kg/m^3 at a filtration velocity of > 8 m/h occurred 1.6 – 2.3 times faster than that at a filtration velocity of < 5 m/h. Higher filtration velocities accelerate compaction and facilitate uniform density of the sponge-cube media filter, thereby achieving significant entrapment of particulate matter and a lower removal of organic matter and nutrients; latter is attributed to the limited biofilm growth on the filter media due to the frequent backwashing of the biofilter and rapidly increasing head loss (Halle et al., 2009; Gao et al., 2012). Therefore, the BF-ASMF bed with a PD of 95 kg/m^3 should be operated at a filtration velocity of < 5 m/h to effectively remove dissolved contaminants in the stormwater runoff and ensure better filtrate quality and filtration cycle duration. Furthermore, instead of using conventional filter media such as granular media or sponge-cube media without activated carbon, use of filter media equipped with adsorption and biological activity is preferred.

3.4 Performance of Combined IPS/ASMF and BF-ASMF Systems

Continuous experiments of the combined IPS/ASMF and IPS/BF-ASMF systems with total HRT values of 23 and 26 min, respectively, were performed to evaluate HRF performance and reuse of urban stormwater runoff. IPS with an inclination angle of 30° and a plate spacing of 2 cm was operated at an HRT of 20 min. ASMF and BF-ASMF with a PD of 95 kg/m^3 were operated at filtration velocities of 10 and 5 m/h, respectively. Influent concentrations of turbidity, COD, TN, TP, Mn, Fe, Pb, Cd, and Cr were 76.4 – 81.6 NTU, 57.1 – 63.7, 10.235 – 12.327, 2.895 – 3.102, 0.045 – 0.055, 1.042 – 1.823, 0.002 – 0.004, 0.174 – 0.254, and 0.045 – 0.058 mg/L, respectively. As listed in Table 1, the removal efficiencies of the combined IPS/ASMF system for turbidity, COD, TN, TP, Mn, Fe, Pb, Cd, and Cr were 90.1 – 92.4, 40.2 – 48.3, 25.1 – 28.5, 48.1 – 52.2, 70.2 – 77.4, 75.2 – 85.1, 75.0 – 82.0, 78.2 – 86.1, and 79.1 – 85.8%, respectively. This combined IPS/BF-ASMF system achieved a 5 – 25% higher efficiency compared to that of the combined IPS/ASMF system with effluent concentrations of turbidity, COD, TN, and TP of 3.2 NTU, 5.6, 4.6, and 3.2 mg/L, respectively. Notably, the biofilter with biodegradation and biofiltration activity facilitated by a biofilm coated on filter media achieved a much lower concentration compared to that of ASMF bed without the biofilm. The biofiltration without chemical use showed an effluent turbidity (< 5 NTU) similar to that of the fiber-ball filter with coagulant (Lee et al., 2009; Gao et al., 2012). The effluent parameters of the IPS/ASMF system, except for COD, nearly met standards for reuse

Table 1. Comparative Results of ASMF and BF-ASMF Beds Coupled with IPS on Contaminants Removal

Parameter	Influent	IPS/ASMF	IPS/BF-ASMF
Turbidity (NTU)	79.0±3.7	7.1±0.8	2.7±1.5
COD (mg/L)	60.4±4.7	33.7±0.8	20.2±0.3
T-N (mg/L)	11.281±1.479	8.277±0.848	6.367±0.114
T-P (mg/L)	2.999±0.146	1.497±0.012	1.064±0.031
Fe (mg/L)	1.783±0.128	0.342±0.097	0.224±0.008
Mn (mg/L)	8.933±1.295	2.255±0.014	1.322±0.058
Pb (mg/L)	0.003±0.001	<0.001	<0.0004
Cd (mg/L)	0.214±0.067	0.037±0.002	0.031±0.002
Cr (mg/L)	0.052±0.009	0.009±0.001	<0.008

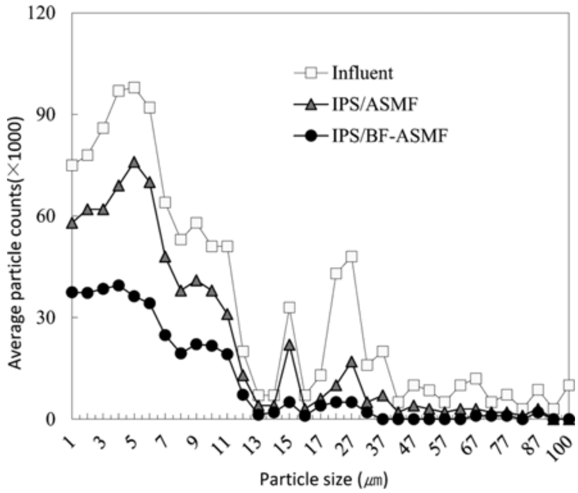

Fig. 8. Distribution of Particle Size in Influent and Effluent of ASMF and BF-ASMF Coupled with IPS

of industrial water and effluent quality for discharge into waterbodies. This indicates that the filtration velocity of the ASMF must be reduced to < 5 m/h to meet the standards for reuse and discharge, when the concentrations of contaminants of the urban stormwater runoff is more than that of the influent as listed in Table 1. The head loss across the combined IPS/BF-ASMF bed was comparable to the combined IPS/ASMF bed. Therefore, both filters coupled with IPS can achieve a higher removal efficiency of 10 – 20% and a lower head loss build-up of 10% compared to systems with both filters but without an IPS. Thus, IPS as a pretreatment process for both filters play an important role in enhancing the quality of effluent and mitigating head loss via effective reduction of particulate matter resulting in a longer filtration duration. Fig. 8 shows the distribution of particle size in the influents and effluents of the combined IPS/ASMF and IPS/BF-ASMF systems. In the influent, the average particle size distribution was 63.5, 17.6, and 18.9% for < 9, 10 – 30, and 37 –100 μm particles. Particle sized 52–100 μm were > 95% removed within < 10 min of ASMF operation and those > 37 μm were removed in 50 – 60 min; this corresponds to average 70.1×10^4 particles of 1 – 9 μm, 18.9×10^4 particles of 10 – 12 μm, 6.7×10^4 particles of 13 – 20 μm, 15.6×10^4 particles of 22 – 57 μm, and 5.7×10^4 particles of 62 – 100 μm. Bechet et al. (2006) reported that Cd and Pb were associated with fractions of > 0.45 μm and Zn, Cu, Ni, and Cr were present in fractions sized 3 – 5 μm in runoff waters. The distribution of particles removed by the combined IPS/ASMF system was as follows: 1 – 9 μm particles (20.5 – 29.3%), 10 – 12 μm particles (25.5 – 39.2%), 13 – 20 μm particles (33.3 – 57.1%), 22–57 μm particles (60.1–68.8%), and 62 – 100 μm particles (> 65.5%). The removal efficiency of the combined IPS/BF-ASMF system achieved a higher efficiency of 27.5 – 40.5% (< 9 μm particles) and 23.1 – 45.5% (10 – 20 μm particles) compared to the combined IPS/ASMF system for various particle sizes owing to its lower porosity caused by thin-biofilm growth on the ASM surface. Our results suggest that the ASMF or BF-ASMF coupled with IPS was considerably effective for particle separation and removal of dissolved contaminants in spite of its shorter HRT compared to the conventional filtration system (Hatt et al., 2006). Contaminant removal efficiency of the combined IPS/ASMF system with a PD of 95 kg/m^3 without chemical use was comparable to that of the fiber filter system with a PD of 115 kg/m^3 with coagulation–flocculation (Lee et al., 2009). These results suggest that the ASMF and BF-ASMF bed coupled with IPS should be operated under appropriate filtration velocities and backwashing frequencies to enhance filtration efficiency and mitigate head loss build-up for the reduction of contaminants from the urban stormwater runoff. Furthermore, the combined IPS/BF-ASMF system can be applied for treating the stormwater runoff regardless of the quality of influent; however, the IPS/ASMF system can be applied for treating the influent with much lower organic matter and nutrient contents.

4. Conclusions

The urban stormwater runoff from an industrial complex area within 1 h of rainfall showed significantly high concentrations of SS, COD, and TN and exhibited a close correlation (0.91) between SS and COD, except for nutrients. The contaminant removal efficient of IPS with an HRT of 10 min was < 30% for organic matter, nutrients, and heavy metals. Filtration velocity of < 10 m/h and < 5 m/h, respectively for the ASMF and BF-ASMF beds resulted in turbidity, TP, COD, TN, and heavy metal removal efficiencies of > 90%, 40 – 50%, 25 – 50%, 48 – 67%, and > 72%, respectively. Compared to conventional filters, the combined IPS/ASMF system with a much shorter HRT showed high removal efficiencies of insoluble fractions such as SS, heavy metals, and particulate COD. Moreover, a relatively high organic matter and nutrient removal was observed because of the adsorption by activated carbon coated on the filter media. Overall, the ASMF or BF-ASMF coupled with IPS without chemical use is a cost-effective option for the treatment of urban stormwater runoff that results in an effluent that can be used as industrial or multipurpose water and is suitable for the recharge of waterbodies.

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Not Applicable

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