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Laboratory study on the clogging potential of a hybrid best management practice

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ABSTRACT

A hybrid BMP (best management practice) is a technology that incorporates several functions, such as infiltration, filtration, and retention in a single system. Nevertheless, such functions are still prone to clogging and may require frequent maintenance. Clogging due to the deposition of sediments over time reduces the porosity and infiltration rate during monitoring despite being a well-designed system. The objective of this study was to determine the clogging potential of a hybrid BMP. The clogging tests using filter media columns were undertaken to determine the physical clogging processes and the factors that affect clogging. Based on the results, hydraulic loading and sediment mass loading influenced the generation and duration of clogging in the filter media. Early development of premature clogging was observed at the initial 25% of the depth due to the retention of sediment particle sizes ranging between 50 and 250 μm. It was suggested that scraping of the first 25% depth of the media can be performed to maintain the hydraulic capacity of the stormwater filters. Although laboratory studies do not entirely demonstrate the actual field conditions, insights from this study can provide valuable understanding on how such system would perform over time.

Keywords: Clogging; Filter media; Hybrid BMP; Maintenance; Sediment

1. Introduction

Despite the capability of best management practices (BMPs) to remove, reduce, retard, and prevent targeted stormwater runoff quantity and quality from reaching receiving water bodies, certain BMPs solely function for a specific purpose and treatment of some pollutants seems [1]. A hybrid BMP is a technology that incorporates several functions, such as infiltration, filtration, and retention in a single system [2]. Nevertheless, the long-term performance and sustainability, particularly the potential for clogging of such systems are still uncertain [3,4]. Clogging is a process common to all types of water filters due to sediment accumulation and deposition when water percolates through it [5]. It evolves from continuously filling the void spaces with fine particles carried in suspension [6].

Several factors affect the rate of clogging in filter media such as hydraulic loading, sediment loading, and sediment particles sizes. According to recent studies, clogging was influenced by the combination of

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hydraulic and sediment loading [7–10]. It was found that when minimum, low flows, and variable flow magnitudes were maintained the filter media can have improved filter performance and prolonged life span. In terms of clogging generation, clogging depth and rate of clogging depend on particle sizes [7,11,12]. Smaller particle sizes cause faster clogging which usually take place at the interface of the filter media and underlying soil. However, it was also observed that clogging can occur at the upper layer of the filter media. Once clogging was reached, it was proven that pollutant removal did not vary with clogging [3,8,9,13].

Substantial importance must be given to clogging treatment systems because it can lead to more frequent overflows, extended ponding time, reduced treatment capacity, and it can create a highly polluted layer on top of the filter media [4,9]. The objective of this study was to determine the physical clogging potential under radial flow conditions of a hybrid BMP through a laboratory based approach. Clogging on varying inflow rates and concentrations was investigated. Furthermore, impact of clogging on the water quality, behavior of sediment accumulation, determination of the clogging layer, and potential manner for maintenance were identified.

2. Materials and methods

2.1. Filter columns

Non-vegetated columns were prepared from a 5 cm diameter acryl with a 2.5 mm hole at the end to test the clogging potential of filter media utilized in an infiltration hybrid BMP. Small dimensions were utilized since these columns represented the inlet segment of each tank of the hybrid system. Two filter types representing the infiltration and retention function of the hybrid BMP were prepared and tested. Infiltration columns have a filter depth of 25 cm composed of 17.5 cm top sand layer and 7.5 cm bottom gravel layer. Retention columns were composed of 3 cm top sand layer, 10 cm middle bottom ash, and 7 cm bottom gravel layer which make a total filter depth of 20 cm as shown in Fig. 1(a). It has to be emphasized that the hybrid BMP was shallow and actual media heights were used in this study. Also, intentional difference in filter media height was made to consider the hybrid function of the system. The hybrid system was designed in a way that when infiltration function fails to receive all input stormwater runoff, the excess volume will be directed to the retention function through the difference in tank height. In total, eight columns were prepared for the clogging test with four replicates for each media configuration. The characteristics of the filter media is provided in Table 1.

2.2. Synthetic stormwater and flow regime

Artificial stormwater runoff was prepared in a tank using collected sediments from highways with total suspended solids (TSS) concentrations ranging from 100 to 500 mg/L which was similar to the target TSS concentration (8–300 mg/L) of several studies [6–8]. The choice of choosing synthetic stormwater runoff was primarily to ensure consistency of concentrations. Inflow concentrations and flow rates for the retention column were lower compared to the infiltration columns. The difference was attributed to the design

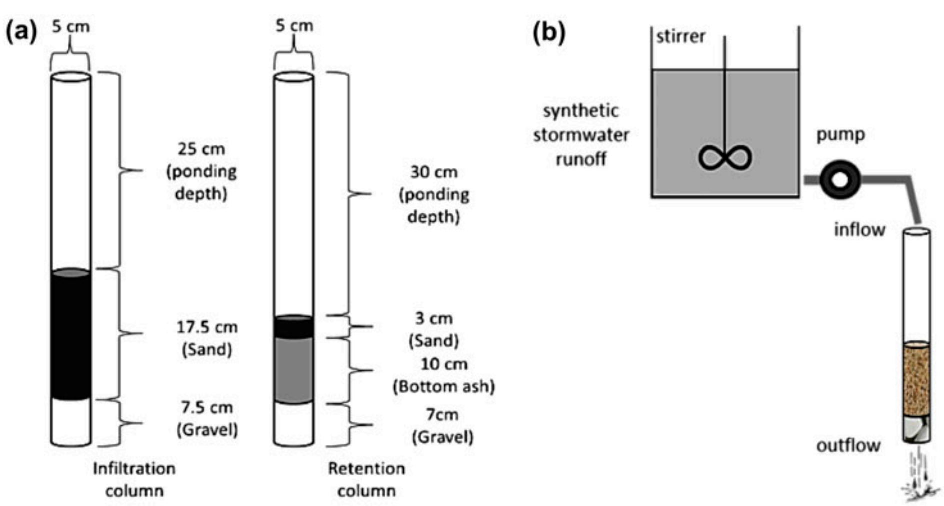

Fig. 1. (a) Infiltration and retention column and (b) experimental setup schematic.

Table 1
Filter media characteristics

Media	Size (mm)	Porosity (%)	Specific gravity	Uniformity coefficient	Permeability (cm/s)
Sand	2–5	40	2.53	1.7	1.32
Gravel	20–30	46	2.62	1.7	2.16
Bottom ash	1–2	37	2.43	1.5	1.03

of the hybrid BMP. It was assumed that inflow concentration and flow rates of the retention tank were reduced in effect of the infiltration function. The synthetic stormwater runoff was stored in a tank with a stirrer to provide even concentrations and was introduced to the columns using a pump for controlled flows as shown in Fig. 1(b). Two flow conditions were utilized representing the average (6 mm/h) and high (10 mm/h) rainfall intensities in Korea based on a reference [14]. The summary of the filter media characterization and flow regimes were shown in Table 2. The filter media was represented by SG and SBG (S—sand, G—gravel, and B—bottom ash) for the infiltration and retention functions, respectively. Adjacent to SG and SBG were two letters which correspond to the flow condition and inflow TSS concentration. Average and high flow conditions were represented by A and H while low and high inflow TSS concentrations were represented by L and H.

2.3. Sampling collection

Constant continuous flows without drying sequence were simulated in this study. Water flux or hydraulic loading rates were measured and monitored every 15 min and sediment flux changes were monitored hourly until clogging develops with the use the following equations:

$$\Delta\text{Water flux} = \left.\frac{Q\left(\frac{\text{m}^3}{\text{h}}\right)}{\text{SA}(\text{m}^2)}\right]_{in} - \left.\frac{Q\left(\frac{\text{m}^3}{\text{h}}\right)}{\text{SA}(\text{m}^2)}\right]_{out} \tag{1}$$

$$\Delta\text{Sediment mass flux} = \left.\frac{\text{TSS}_{concentration}\left(\frac{\text{mg}}{\text{l}}\right) \times Q\left(\frac{\text{m}^3}{\text{h}}\right)}{\text{SA}(\text{m}^2)}\right]_{in} - \left.\frac{\text{TSS}_{concentration}\left(\frac{\text{mg}}{\text{l}}\right) \times Q\left(\frac{\text{m}^3}{\text{h}}\right)}{\text{SA}(\text{m}^2)}\right]_{out} \tag{2}$$

where ΔWater flux is the change in flux between the inflow and outflow, ΔSediment flux is the change in mass flux between the inflow and outflow, Q is the inflow and outflow rates, and SA is the surface area of the filter column. In this study, complete clogging was defined and suspected to have occurred when the outflow was reduced to 15–20% of the initial outflow,

Table 2
Summary of the filter columns, flow condition, and inflow concentration

Function	Column	Inflow rate (10^{-6} m^3/s)	Flow condition	Target inflow TSS concentration (mg/L)	Inflow concentration condition[b]
Infiltration	SG-AL	1.6–1.7	Average	190–225	Low
	SG-AH	1.6–1.7	Average	500–600	High
	SG-HL	3.2–3.3	High	190–225	Low
	SG-HH	3.2–3.3	High	500–600	High
Retention	SBG-AL	1.3–1.4	Average[a]	100–150	Low
	SBG-AH	1.3–1.4	Average[a]	150–200	High
	SBG-HL	2.5–2.6	High[a]	100–150	Low
	SBG-HH	2.5–2.6	High[a]	150–200	High

Notes: SG-AL—sand, gravel-average, low; SG-AH—sand, gravel-average, high; SG-HL—sand, gravel-high, low; SG-HH—sand, gravel-high, high; SBG-AL—sand, bottom ash, gravel-average, low; SBG-AH—sand, bottom ash, gravel-average, high; SBG-HL—sand, bottom ash, gravel-high, low; SBG-HH—sand, bottom ash, gravel-high, high.
[a]Assumed to be 78–81% of infiltration inflow.
[b]Low and high values were compared based only on concentration.

ponding, and overflow while premature clogging was characterized only by ponding that would later result to overflow without attaining the 15–20% reduction in initial outflow. Water samples at the inlet and outlet were collected at the start of the simulation and every hour until clogging occurs. Water samples were limited only to hourly collection due to small flow rate inputs. Nevertheless, three replicates were taken within the hour for TSS and particle size distribution analysis (PSD). Simulations in each column were done continuously and were stopped at the instant when overflow occurs.

2.4. Analytical methodology

Collected water samples were analyzed for TSS in accordance to the standard method and PSD using Beckman Coulter LS230 Laser Diffraction Particle Size Analyzer with small volume module plus [15]. At the end of simulations, where clogging was suspected to have occurred, the columns were carefully dismantled. Determination of sediment accumulation was performed by drying and weighing the filter media (difference between the clean media and media with accumulated sediment). The sediment retained in the media of each column was also analyzed for PSD.

3. Results and discussion

3.1. Influence of inflow rate and concentration on clogging formation

It was observed that only premature clogging occurred in all simulations since reduction of final outflow to 15–20% of initial outflow was not achieved before ponding and overflow occurred. The maximum reduction in the initial outflow was observed in HL (high flow and low concentration) condition where it was reduced to 35 and 44% of the initial outflow rate for the infiltration and retention columns, respectively. Thus, generation of premature clogging was influenced by the inflow rate and concentration. Fig. 2 shows the duration of the clogging test, the hydraulic rate changes or water flux changes, as well as the mass loadings or sediment flux in the infiltration and retention columns. For the infiltration columns with high flow conditions, premature clogging was achieved sooner compared to average flow conditions regardless of the inflow TSS concentration as shown in the figure. Total accumulated changes in water flux were 3.99, 4.95, 24.72, and 16.87 m^3/m^2-h for SG-AL, SG-AH, SG-HL, SG-HH, respectively. This suggests that for average flow condition, small reduction in outflow rates can be expected when premature clogging occurs. On the other hand, high flow conditions were more at risk to reduced outflow rates during premature clogging. The similar results were observed in the retention columns with the same trend in accumulated changes in water flux.

As for the sediment flux changes, that reduction in sediment content in the water increased over time. Sediment removal over time gradually increased especially at high mass loading rates at the infiltration column, brought by aggregation of sediment and/or enhanced sedimentation which would result to formation of a cake layer in the media [13,16]. However, distinct trends were observed at the infiltration and retention columns. The high flow–low concentration regime was higher compared to the average flow–high concentration regime for the retention column that is apparently in contrast with the infiltration column. Addition of bottom ash layer in the filter media of the retention column may have attributed to the difference in results.

3.2. Spatial distribution of sediment

3.2.1. Sediment removal in water when clogging developed

Last water samples collected were analyzed for PSD and compared with the inflow water sample to determine the possible effect of clogging on the effluent water quality when clogging occurs. Fig. 3 shows the particle removal efficiency between the inflow and the final outflow water sample in distinct particle size ranges. Negative removal efficiencies (−50 to −78%) in 0–25 μm particle sizes were observed in infiltration columns but the values increased along with increasing particle sizes. Moreover, highest removal was attained by SG-HH with 100% removal efficiency for 100–250 μm sized particles. It can be therefore assumed that particles larger than 50 μm were completely trapped in the sand and gravel filter while smaller particles (<50 μm) were pushed out when clogging occurred. Regardless of hydraulic and mass loadings, this increasing trend in sediment removal was consistent and similar between the infiltration columns. Increasing trend was also noted in the retention columns but 100–250 μm particles apparently have negative removal efficiency for all columns. Negative removal efficiency for 0–25 and 100–250 μm particles may suggest the release of previously trapped pollutants and can be detrimental since the smallest particles (<50 μm) has the highest concentration of metals in highways [17]. Moreover, according to reference [18] TN and TP in stormwater samples are attached to sediments between 11 and 150 μm.

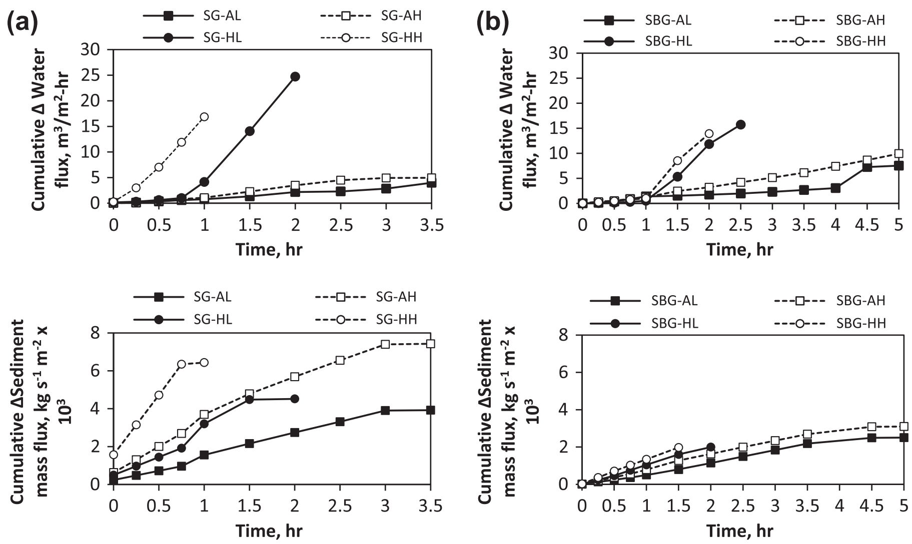

Fig. 2. Cumulative change in flux and cumulative change in mass flux of the (a) infiltration and (b) retention columns.

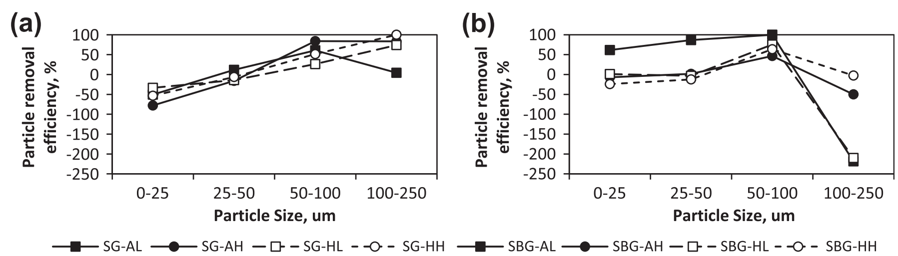

Fig. 3. Particle retention efficiency between the inflow and final outflow water samples in (a) infiltration and (b) retention columns.

Therefore, it may be possible for the filter media to become a pollutant source since significant amounts of pollutants were already trapped in the filter media.

3.2.2. Total sediment accumulation

Accumulation of sediment did not vary along the depth of the filter media despite the flow regimes and media configuration. Fig. 4 illustrates that sediment accumulation was highest at the initial 25–50% of depth then gradually decreased until it reached the bottom. Clogging layer formed at the first 25% of the infiltration and retention media. Correspondingly, clogging layer generates at the first 0–6 cm depth of the media according to related studies [11,19]. Among the infiltration columns, SG-AH column has the most accumulated sediment at the initial 5 cm depth with 347 kg/m^{3}d. This suggests that SG filter media has more clogging resistance when the flow regime was average ($1.6–1.7 \times 10^{-6}$ m^3/s) accompanied by high sediment loading (500–600 mg/L). Among the flow regime for the retention column, SBG-AH with average flow ($1.3–1.4 \times 10^{-6}$ m^3/s) and high concentration of TSS (150–200 mg/L) was observed to have more potential resistance to clogging.

3.2.3. Influence of sediment particle size on clogging formation

The degree and position of clogging is greatly influenced by suspended solids size [12]. In response, accumulated sediments along the depth of the filter media was analyzed for PSD. The clogging layer, which was previously identified to form at the upper part of the media, was mostly made up of 50–100 and 100–250 μm sediment particle sizes for both the infiltration and retention columns as shown in Fig. 5. Majority of particles with diameter 0–25 and 25–50 μm were retained at the lower part of the media and was more evident at the retention columns. Retention of

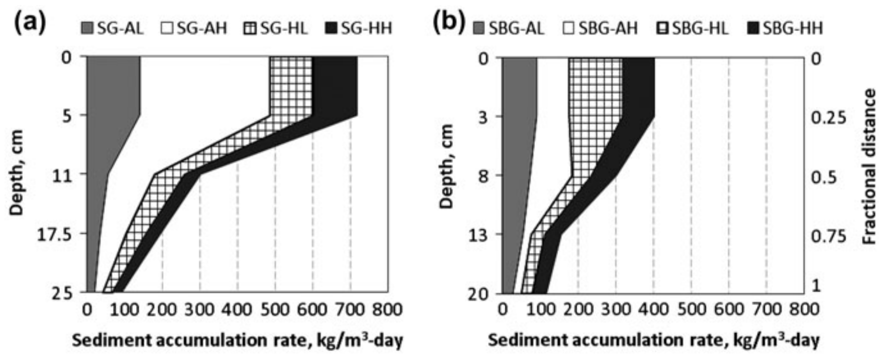

Fig. 4. Sediment accumulation with respect to the depth in the (a) infiltration and (b) retention column.

particle sizes ranging in 50–100 and 100–250 μm seemed to be uniform along the depth until before it reaches the bottom. On the contrary, particles with 0–25 μm diameter increased in sediment concentration fractions as it reaches the bottom of the filter media. This trend also agrees with a reference [13] wherein accumulation of 0–25 μm particle diameters increases with depth.

3.3. Implications for filter design and application

Laboratory scale experiments do not entirely demonstrate how field or actual condition of treatment systems would operate. However, insights from the laboratory scale can be valuable and can provide information which enables better understanding on how such systems would perform over time. Table 3 shows the summary of the results in this study. Comparing the sand–gravel and sand–bottom ash–gravel filter media, it was observed that the two filter types can perform better when the flow regime was average or lower despite the TSS inflow concentration. It suggests that maintaining these conditions can prolong the lifespan of the filters. Moreover, premature clogging on both filter types was attributed to the retention of sediment particle sizes ranging from 50 to 250 μm at the initial 25% of the depth. Apparently, premature clogging occurred at the sand filter layer for both infiltration and retention media. It has been known that sand filters have the poorest performance in terms of rapid declination of hydraulic capacity induced by sediment accumulation [20]. Nevertheless, the simplest manner that can be executed is scraping of the top layer of the filter media may be recommended maintenance for both the infiltration and retention columns. Based from the results, the total rainfall depth the filters can treat before reaching premature clogging was 1148–1163 mm. Therefore, it can be suggested that maintenance activities may be done after the summer season (end of September) since summer has the most occurrence of rainfall in Korea [21].

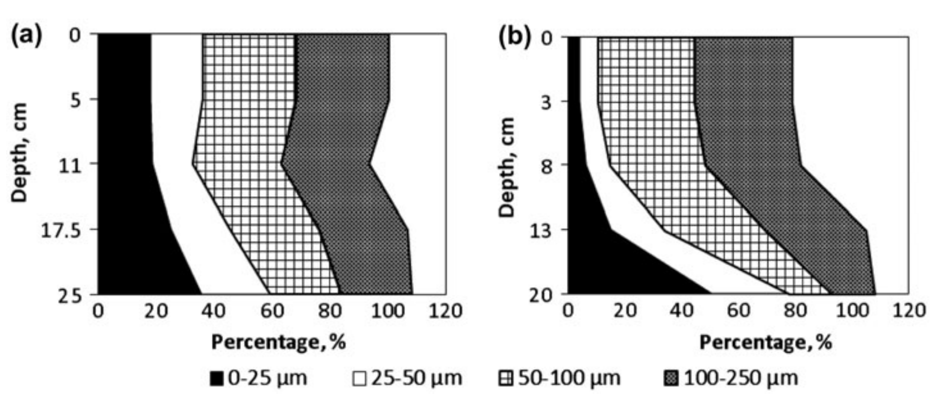

Fig. 5. Fraction of sediments trapped along the depth of the (a) infiltration and (b) retention column.

Table 3
Summary of desirable condition, water flux, rainfall depth, and maintenance frequency for the two filter media configuration

Media configuration	Desirable flow regime	Desirable TSS concentration condition	Max. Δwater flux (m^3/m^2h)	Clogging layer formation (% of depth)	Total rainfall depth (mm)	Suggested frequency of maintenance (days)
SG	Average	Low/high	24.72	0–25	1,163	130–410
SBG	Average	Low/high	15.72	0–25	1,148	150–410

Notes: SG—sand, gravel; SBG—sand, bottom ash, gravel.

4. Conclusions

The ultimate objective of this study was to determine the physical clogging potential of the filter media used in a hybrid BMP system under radial flow conditions through a laboratory-based approach. It was evident that sand filters can retain suspended particles well. However, good treatment capacity can also indicate shorter lifespan. In this study, the sand–gravel and sand–bottom ash–gravel media configuration showed similarities in results as premature clogging develops. Both media configurations have more resistance to clogging when the flow condition was lower regardless of the sediment mass loading. The clogging layer for both media configuration was identified to have occurred at the initial 25% of the depth caused by particle sizes ranging from 50 to 250 μm. Dissimilarities in results, however, may have been caused by the addition of bottom ash media between the sand and gravel layer. Release of previously trapped particle sizes ranging from 0 to 25 μm was observed in sand–gravel filter while 100–250 μm sizes were observed in sand–bottom ash–gravel media. Overall, it can be concluded that two and three layered filters showed similar performance when premature clogging occurred. The results of this study can assist in the improvement of the design of the hybrid BMP and filter media for stormwater filtration.

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