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Development of a stormwater treatment system using bottom ash as filter media

Joan B. Gorme, Marla C. Maniquiz-Redillas, Lee-Hyung Kim*

Department of Civil & Environmental Engineering, Kongju National University, 275 Budaedong, Cheonan, Chungnamdo 331-717, Korea, email: leehyung@kongju.ac.kr (L.-H. Kim)

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ABSTRACT

This study investigated the applicability of bottom ash as filter media for a stormwater treatment facility. Filtration test experiments were conducted in a 30 × 15 × 15 cm transparent acrylic test reactor using a synthetic run-off, prepared from run-off collected from a wetted impervious road. The reactor designed as a stormwater treatment system and incorporated bottom ash as filter media was tested for three flow regimes (i.e. 200, 400, and 800 mL/min) to investigate the treatment performance of the system at various intensities during rainfall events. Based on the findings, the bottom ash media was able to reduce 70% of total suspended solids and more than 50% of iron, zinc, and lead from the synthetic run-off. A design guideline was developed which recommended a facility surface area to catchment area ratio of 0.007–0.015 for the effective treatment of 5, 7.5, and 10 mm design rainfall.

Keywords: Bottom ash; Design application; Filter media; Nonpoint source; Stormwater treatment

1. Introduction

Urban stormwater run-off has been identified as critical non-point source pollution to receiving water systems. Stormwater contains heavy metals that come from a variety of sources such as building materials and traffic-related sources, which include brake linings, tire wear, and auto-catalysts [1]. The discharge of these heavy metals is an environmental concern due to their toxicity, ubiquitousness, and non-biodegradability. In Korea, the government had implemented the use of stormwater best management practices (BMP) to deal with the storage, infiltration, and treatment of stormwater run-off. BMPs commonly employed for run-off control include, constructed wetlands, filtration, and infiltration systems, bioretention swale, modular pavements, and rain garden.

In an aquatic environment, heavy metals are either dissolved or are bound to particulates which tend to settle out of the water column and accumulate in sediments [2]. Filtration treatment systems are one of BMPs applied to reduce heavy metals in stormwater, provided that an effective filter media is used. Various materials such as sand, peat, zeolite, anthracite, and activated carbon have already been used as possible filter media for removal of heavy metals from stormwater run-off [3–5].

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*Corresponding author.

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The rising generation of coal-burning power plants in Korea has resulted in an increased disposal of the associated by-products, such as boiler slag, fly ash, and bottom ash. These coal-fired power plants have generated about five million tons of coal bottom ash [6]. This growing amount of bottom ash requires large disposal areas, which may eventually become a source of pollution. Therefore, alternates for the utilization of these by-products have to be developed. Currently, bottom ash has already been used as structural fill, and construction and road base materials. Also, several studies have investigated the possible utilization of bottom ash as an adsorbent for the removal of various heavy metals from wastewater. The particle size, inherent large surface area (SA), and high porosity of bottom ash make it a good choice for use as a low-cost adsorbent [7–10].

The main objective of this research was to investigate the applicability of using bottom ash as filter media for a stormwater treatment facility. Since bottom ash is a waste product, a series of preliminary tests were conducted to determine the physical, chemical, and leaching characteristics of bottom ash to evaluate the safety of the material to be reused as filter media. Batch adsorption experiments were performed to assess the potential of bottom ash to adsorb heavy metals. To simulate the behavior of a bottom ash filtration system, a lab-scale test reactor was designed and assembled which was subjected to different hydraulic loading rates and pollutant loadings. The stormwater pollutants measured and analyzed for this research were suspended solids and heavy metals. The research aims to find out how much these pollutant loads will be reduced by the design treatment system and to determine the factors that affect the treatment efficiency. Based on the results of the laboratory test experiments, a design guideline was developed for the application of bottom ash filter media treatment system in an actual environment based on the parameters such as design rainfall, treatment efficiency, and aspect ratio.

2. Materials and method

2.1. Characterization of bottom ash

2.1.1. Physical and chemical composition

Bottom ash samples were obtained from a coal incinerator in Korea. Bottom ash is a granular material with a continuous grain size distribution depending on the incineration process. Fig. 1 shows the broad particle size distribution of bottom ash, which has an effective media size range of 1.0–8.2 mm. The bottom ash samples were grouped into four size ranges (i.e. 1.0–2.0 mm, 2.0–4.75 mm, 4.75–9.0 mm, and 9.0–12.0 mm) for the analysis of its leaching and adsorption characteristics. The elemental composition and mineral composition of bottom ash were analyzed using the scanning electron microscopy-energy dispersive spectroscope (SEM-EDS, MIRA II LMH by Tescan USA Inc.) and X-ray diffractometer (XRD, MIRA II LMH by Tescan USA Inc.).

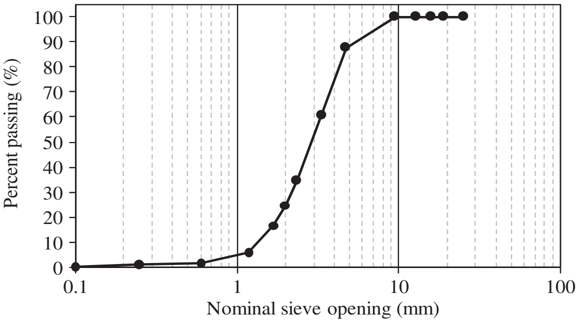

Fig. 1. Particle size distribution of bottom ash.

2.1.2. Leaching and adsorption capacity

A good adsorbent material is considered safe and efficient when it can effectively remove heavy metals without releasing potentially hazardous substances. The leachability of the heavy metals from the bottom ash was assessed according to the Korean Standard Leaching Test. Meanwhile, the adsorption capability of bottom ash was carried out through a 1:1 adsorbent/adsorbate ratio, having lead (Pb) as the primary pollutant with an initial concentration of 2.5 mg/L. The mixtures were vigorously shaken (100 rpm) in a water bath shaker at a constant temperature of 20˚C. Small samples of the solution were taken out at a predetermined time intervals to measure the evolution of the adsorbate concentration. All metal concentrations of the samples obtained from the leaching and adsorption tests were analyzed using an inductively coupled plasma (ICP) atomic emission spectroscopy (ICPS-7510 by Shimadzu Co., Japan).

2.2. Application of bottom ash in a lab-scale test reactor

2.2.1. Design of the lab-scale test reactor

The filtration test experiments were conducted in a 30 × 15 × 15 cm transparent acrylic test reactor. The schematic of the test reactor was shown in Fig. 2. The test reactor was divided into two main treatment regions which consist of a sedimentation tank, which

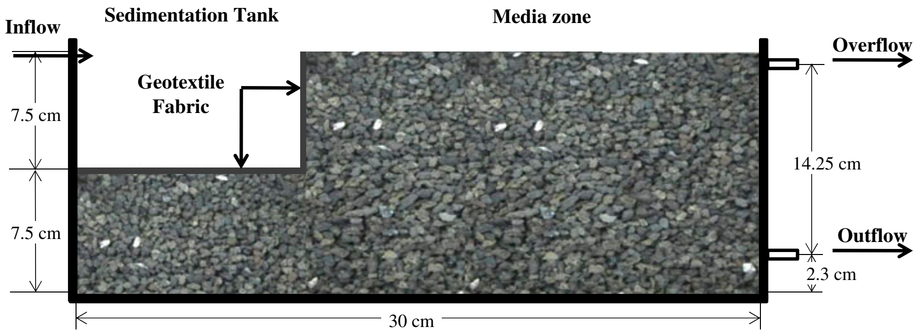

Fig. 2. Schematic of the test reactor.

allows pre-treatment and limits the entrance of coarse sediments and debris into the system; and a media zone composed of bottom ash which provides an area for filtration and adsorption of pollutants. The particle size group which obtained the highest adsorption capacity from the adsorption test will be used as the filter media for the lab-scale test experiment.

2.2.2. Experiment parameters and data collection

Stormwater BMPs are commonly designed by considering the water quality volume (WQV) during storm events. The WQV is the catchment area (CA) of the BMP multiplied by the design run-off volume (first flush) expressed in depth per drainage area. Three different rainfall intensities (RI) were selected representing the minimum, average, and maximum amount of rainfall during storm events, which is draining from a 6.0 m^2 CA. Run-off simulation was performed during two hours to represent the first flush run-off duration since it was during the early period of storm events where the concentration pollutants and amount of run-off volume was at its highest [11]. Table 1 shows the summary of the calculated test flow rate (Q) based on the WQV design criteria.

The influent used in the experiment was a synthetic run-off which was collected on an impervious road after wetting it with tap water. The purpose of using this type of influent was to simulate the actual pollutant characteristics of stormwater run-off from a real catchment. The collected run-off was stored in a tank equipped with a mixer to prevent the settlement of particulate matters at the bottom of the tank. The influent was introduced into the reactor through a pump which operates in a controlled rate depending on the desired flow rate. Water quality samples were collected at the inflow and outflow units with the interval of 0, 5, 15, 30, 60, 90, and 120 min after the flow started. The total suspended solids (TSS) and turbidity of the collected samples were measured and the total heavy metal content such as Pb, cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), nickel (Ni), and zinc (Zn) were analyzed using the ICP.

2.2.3. Data analysis

The pollutant concentration entering and leaving the test reactor for each test run were calculated based on the event mean concentration (EMC). According to a reference [11], EMC is the total constituent mass divided by the total run-off volume, expressed as:

$$\mathrm{EMC} = \frac{\int_0^t C(t) \cdot Q(t)dt}{\int_0^t Q(t)dt} \tag{1}$$

where, $C(t)$ = pollutant concentration, mg/L; $Q(t)$ = flow rate discharged at time t. The pollutant removal efficiency was calculated to estimate the pollutant reduction from the inflow to the outflow of the lab-scale test reactor. The removal efficiency (%) is presented as:

Table 1
Hydraulic parameters of the lab-scale test reactor

Flow regime	No. of test run	Q (mL/min)	RI (mm/h)	CA (m^2)	Water depth (cm)
Minimum	9	200	2	6	4.0
Average	8	400	4	6	9.0
Maximum	9	800	8	6	13.0

Note: Q = flow rate; RI = rainfall intensity; CA = catchment area.

$$\text{Removal efficiency}(\%) = \frac{\text{Average influent EMC} - \text{Average effluent EMC}}{\text{Average influent EMC}} \quad (2)$$

3. Results and discussion

3.1. *Characteristics of bottom ash*

3.1.1. *SEM-EDX and XRD analyses*

The elemental composition of bottom ash is shown in Fig. 3. The results showed that oxygen (O), silicon (Si), aluminum (Al), carbon (C), and magnesium (Mg) were the major elements found on the surface of bottom ash. It was in conformity to the XRD test results where it was found that bottom ash was composed mainly of quartz (SiO2) and mullite (Al6Si2O13). Based on the diffraction pattern, no crystalline compounds were detected indicating that bottom ash was an amorphous material. The significant amounts of Si and Al found on the bottom ash identified that the material was a good adsorbent of heavy metal ions from water and wastewater. The same elements were also found in zeolite, one of the effective adsorbent material for metals, indicating that bottom ash may also be a good adsorbent for removing heavy metals from water [12].

3.1.2. *Leaching and adsorption capacity*

The results from the leaching test is shown in Table 2 which revealed that all metal concentrations from the four particle size groups were less than 0.3 mg/L, thereby passing the Korean regulatory limit and safe to be reused as filter media. Constituent elements of heavy metals were present in bottom ash because these metals were captured in coal combustion by-products, which were incorporated into the silicate minerals constituting the bulk of the bottom ash. The ability of bottom ash to adsorb Pb is shown in Fig. 4. The adsorption phenomenon consisted of two phases: an initial rapid phase where adsorption was fast and a gradual second phase whose adsorption was relatively small, until it reaches equilibrium. Of the four particle size ranges, the 1.0–2.0 mm size range obtained the highest amount of Pb adsorbed (95.2%) and the fastest to reach equilibrium, which was attained after 60 min of contact time. The adsorptive capacity of Pb increased significantly with the decrease in the particle size of bottom ash. Since adsorption was a surface phenomenon, the higher adsorption rate, and metal adsorption by smaller particles were attributed to greater accessibility to pores and larger SA for adsorption per unit weight of the adsorbent at equilibrium [13]. Based in the adsorption test results, the 1.0–2.0 mm size range of bottom ash was used as media in the lab-scale filtration test experiment.

Table 2
Leaching concentration of soluble heavy metals in bottom ash (mg/L)

Size range	Cr	Cu	Cd	As	Pb
1.0–2.0 mm	0.129	0.125	0.122	0.112	0.102
2.0–4.75 mm	0.129	0.126	0.121	0.109	0.098
4.75–9.0 mm	0.129	0.123	0.121	0.110	0.096
9.0–12.0 mm	0.129	0.124	0.121	0.111	0.095
Limit	1.5	3.0	0.3	1.5	3.0

3.2. *Application of bottom ash in a lab-scale test reactor*

3.2.1. *Water balance and hydraulic retention rate*

The lab-scale test reactor was tested with three different flow rates to determine its response when subjected to low, average, and high amount of rainfall. Fig. 5 shows the percentage of outflow, storage, and overflow volume with respect to the total inflow

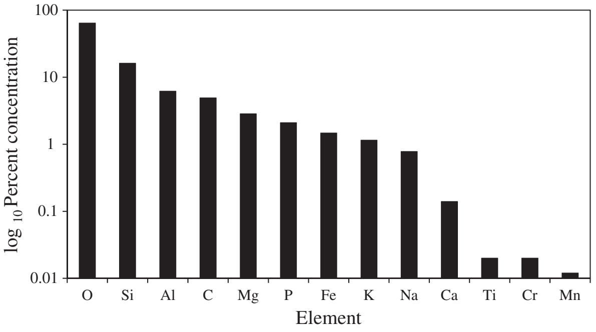

Fig. 3. Elemental composition of bottom ash.

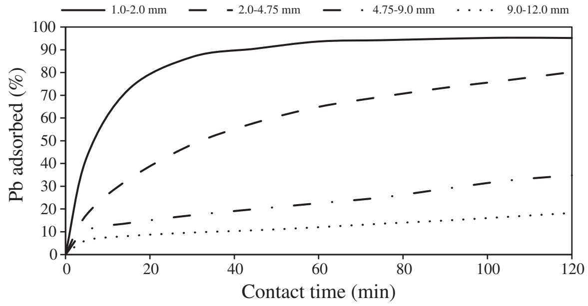

Fig. 4. Amount of Pb adsorbed by bottom ash.

volume. Based on Fig. 5, the reactor was able treat 90–98% of the total inflow in which 5% of it was retained inside the reactor. During high flows, an overflow (9%) occurred which happened during the initial 60 min of inflow. Since the test experiments were performed at constant flow rate throughout the run-off duration, the period in which the inflow and outflow rates reached equilibrium occurs at 25, 15, and 5 min for $Q = 200$, 400, and mL/min, respectively. For $Q = 200$ and 400 mL/min, outflow was relatively stable throughout the run-off time until 100–120 min in which it stopped shortly after the inflow stopped. After inflow was stopped, outflow was suddenly reduced to 30% for $Q = 200$ mL/min and 75% for $Q = 400$ mL/min. On the other hand, the outflow rate for $Q = 800$ mL/min becomes unstable when overflow occurred after 100 min decreasing the outflow rate to 31%. The reactor has a hydraulic retention time (HRT) of 3.3, 1.7, and 1.3 min for $Q = 200$, 400, and 800 L/min. Overall, the average HRT of the reactor was 2.1 min. Since bottom ash is a coarse media, HRT is faster. The bottom ash filter can flush out previously captured pollutants until the filter is aged and more permanently retain pollutants.

3.2.2. Water quality characteristics

The concentration of TSS, turbidity, and the total heavy metals during each test run were calculated by means of the EMC. Table 3 summarizes the mean inflow and outflow EMC for the different test flow rates. A wide range of concentration of pollutants was observed for each test runs because the influent used in the test experiments was a run-off from a wetted road. Based on the data, pollutants with high concentration such as TSS, turbidity, Tot-Fe, Tot-Zn, and Tot-Pb were observed to have high reduction rate compared to pollutants with low initial concentration. Among the parameters, TSS constituted the greatest amount of concentration because TSS serves as surrogate carriers for other constituents such as metals, nutrients, and organics. Heavy metals in stormwater run-off exist in a form of significant quantities of dissolved metal elements, particulate-bound metal elements, and suspended, colloidal and volatile fractions of particulates [14].

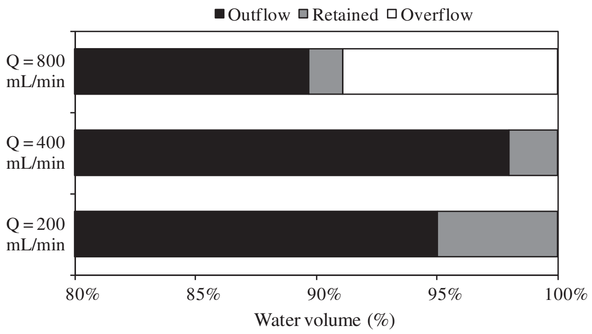

Fig. 5. Water balance in the reactor at different flow rates.

The particulate-bound and soluble forms of heavy metals in the influent used in test experiments are presented in Fig. 6. Based on the figure, all heavy metals were predominantly particulate-bound metals since the ratio of the particulate-bound to the soluble metal was high. Fe, Zn, and Pb were the metals that were strongly attached to sediment (70–99%) while significant portions of Cd, Ni, Cu, and Cr were in soluble phase (53–94%). When heavy metal was primarily particulate-bound, filtration can be an effective removal mechanism. For soluble metals, the best treatment mechanism is adsorption to media [15].

3.2.3. Overall pollutant removal efficiency

The overall pollutant removal efficiency of the test reactor at different test flow rates is shown in Fig. 7. Of the three flows, $Q = 200$ mL/min attained the highest removal efficiency for all pollutants. It obtained the highest pollutant removal because slower flow rate provided a longer HRT, giving more opportunity for the pollutants to settle down, be filtered, and be adsorbed onto the media. As the reactor was subjected to more test runs, more pollutants were brought and accumulated inside the reactor. In some instances, when velocity was fast, pollutants that were retained inside the system were disturbed causing some of it to move along with the flow and out of the reactor.

As shown in Fig. 7, TSS obtained the highest removal efficiency (70%) followed by Tot-Fe (69%), Tot-Zn (67%), turbidity (64%), and Tot-Pb (51%) while the remaining pollutants were found to have low treatment efficiency with Tot-Cd (6%) as the lowest. The metals with high reduction were the metals that were strongly bounded with the particulates which were filtered and adsorbed by the bottom ash media. Tot-Cu, Tot-Cr, Tot-Ni, and Tot-Cd obtained lower removal efficiencies (5–30%) because a major portion of these metals were in soluble phase and that the remaining particulate-bound metal concentrations were associated with smaller particulates which passed more easily through the bottom ash media. Overall, the main treatment process occurring in this treatment system was the sedimentation of the suspended solids and associated pollutants at the pretreatment system, and the filtration and adsorption by the bottom ash media.

Table 3
Mean inflow and outflow EMC per flow rate

		$Q = 200$ mL/min		$Q = 400$ mL/min		$Q = 800$ mL/min	
Parameter	Unit	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
TSS	mg/L	453	29	612	128	466	253
turbidity	NTU	347	32	219	87	452	261
Tot-Cr	mg/L	0.175	0.135	0.229	0.179	0.271	0.250
Tot-Fe	mg/L	19.159	1.584	24.800	4.622	17.284	9.685
Tot-Ni	mg/L	0.130	0.112	0.172	0.148	0.222	0.210
Tot-Cu	mg/L	0.170	0.105	0.247	0.168	0.211	0.172
Tot-Zn	mg/L	1.185	0.132	1.588	0.365	0.963	0.506
Tot-Cd	mg/L	0.084	0.081	0.115	0.111	0.138	0.133
Tot-Pb	mg/L	0.239	0.072	0.324	0.137	0.279	0.200

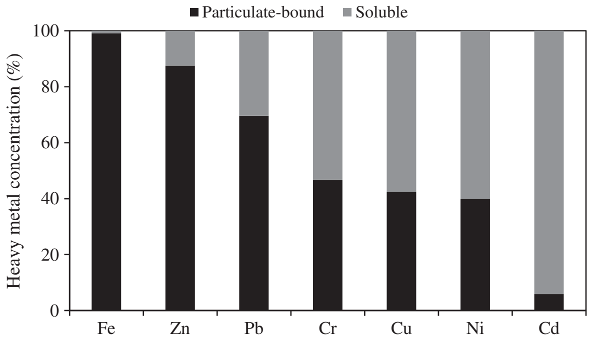

Fig. 6. Fractional distribution of heavy metals.

3.2.4. Design application

In Korea, the guidelines for the design and installation of stormwater BMPs explains that the first flush phenomenon in a storm event is best represented by a maximum rainfall depth of 5 mm [16], 7.5 mm [17], and 10 mm [11]. Considering the first flush run-off gives a more effective design of any stormwater treatment facility since it employs only the capture and treatment of the most polluted run-off, with the subsequent run-off being directly diverted to the system as bypass [18].

Polynomial regression plots were constructed by plotting the TSS pollutant removal rate against the calculated facility surface area to catchment area (SA/CA) ratio for various design rainfall based on the flow rates and estimated run-off coefficient of 0.8. The limit of the SA/CA ratio was noted as the SA/CA ratio corresponding to the maximum removal efficiency with design rainfall. Fig. 8 shows the relationship between the SA/CA ratio and TSS removal efficiency. Based on the figure, the optimum SA/CA ratios having 95% removal efficiency at 5, 7.5, and 10 mm rainfall were 0.007, 0.0108, and 0.015, respectively. Ratio that was lower and higher than the optimum SA/CA ratio showed lower treatment efficiency. The SA/CA ratio is important to calculate the size of the treatment facility depending on the desired CA. Either

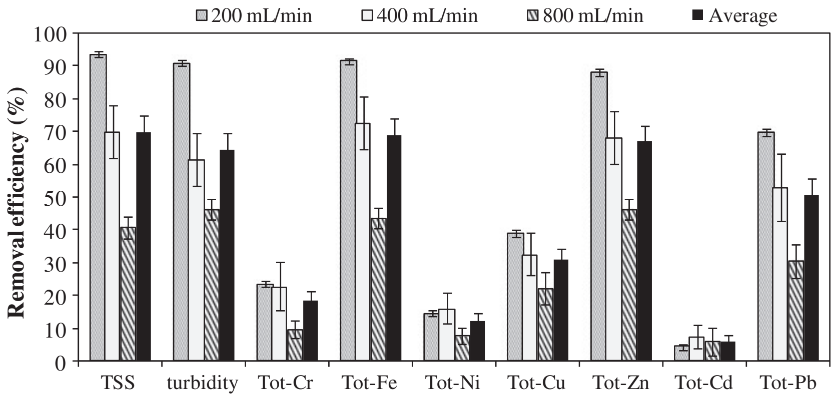

Fig. 7. Pollutant removal efficiency of the lab-scale reactor.

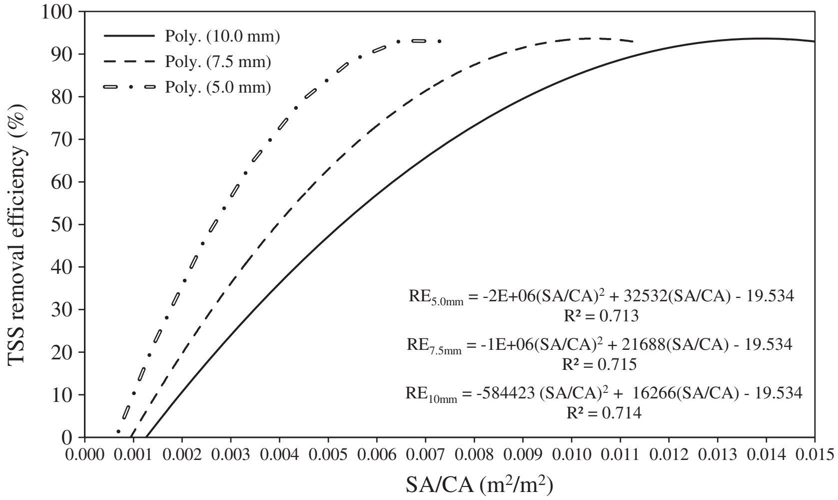

Fig. 8. Facility SA/CA ratio with respect to the design rainfall and TSS removal efficiency (RE).

Table 4
Aspect ratio of the bottom ash media treatment system

Parameter	Unit	Aspect ratio
W:L	m/m	1:2
W:D	m/m	1:1
PA:SA	m^2/m^2	1:3
MA:SA	m^2/m^2	1:1.5

Note: L = length of the facility; W = width of the facility; D = depth of facility; SA = surface area of facility; PA = surface area of sedimentation tank; MA = surface area of media layer.

of the design rainfall can be used to design the bottom ash filtration system. The design criteria provided techniques for application of the design based on functionality, effectively, economical, and necessity. Other features of the treatment system can be calculated by using the aspect ratio provided in Table 4.

4. Conclusions

This research was conducted to develop a stormwater treatment system using the bottom ash as filter media. A preliminary test was conducted to evaluate its safety to be reused as a filter media and a lab-scale test was performed to investigate the treatment efficiency of the designed filtration system. Based on the results of the preliminary tests, bottom ash was found to have significant amount of silica and aluminium on its surface making it a good adsorbent for heavy metals while the leaching test results passed the Korean limit for safe disposal. The batch adsorption test showed that smaller bottom ash particles (i.e. 1.0–2.0 mm size range) obtained the highest adsorption capacity compared to the bigger size ranges. Based on the lab-scale test experiment results, the test reactor obtained the highest removal of TSS (70%) followed by Tot-Fe (69%), Tot-Zn (67%), turbidity (64%), and Tot-Pb (51%) while the remaining pollutants were found to have low treatment efficiency with Tot-Cd (6%) as the lowest. Tot-Fe, Tot-Zn, and Tot-Pb showed the highest reductions among other metals since these were the metals which showed high correlations with TSS. A large fraction of these metals was strongly bounded with the particulates that were filtered and adsorbed by the filter media. A design guideline was developed for the application of bottom ash filter media treatment system in an actual environment based on the parameters such as design rainfall, design treatment efficiency, and aspect ratio.

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References

[1] H. Genç-Fuhrman, P.S. Mikkelsen, A. Ledin, Simultaneous removal of As, Cd, Cr, Cu, Ni and Zn from stormwater: Experimental comparison of 11 different sorbents, Water Res. 41(3) (2007) 591–602.

[2] J. Sansalone, D. Glenn, Metal distributions in soil receiving urban pavement runoff and snowmelt, Water Environ. Res. 79(7) (2007) 736–752.

[3] R.H. Al-Anbari, K.P. Wootton, S. Durmanic, A. Deletic, T.D. Fletcher, Evaluation of media for the adsorption of stormwater pollutants, Proceedings of the 11th International Conference on Urban Drainage, Edinburgh, Scotland, 2008.

[4] B. Urbonas, Design of a sand filter for stormwater quality enhancement, Water Environ. Res. 71(1) (1999) 102–113.

[5] J. Gironás, J.M. Adriasola, B. Fernández, Experimental analysis and modeling of a stormwater perlite filter, Water Environ. Res. 80(6) (2008) 524–539.

[6] N.I. Um, J.W. Ahn, G.C. Han, K.S. You, S.J. Lee, H.C. Cho, Characteristic of magnetic-substance classification from coal bottom ash using wet magnetic separator, Proceedings of the 2009 World of Coal Ash Conference, Lexington, KY, USA, 2009.

[7] S.Y. Kim, N. Tanaka, T. Matsuto, Solubility and adsorption characteristics of Pb in leachate from MSW incinerator bottom ash, Waste Manage. Res. 20(4) (2002) 373–381.

[8] Y.S. Shim, Y.K. Kim, S.H. Kong, S.W. Rhee, W.K. Lee, The adsorption characteristics of heavy metals by various particle sizes of MSWI bottom ash, Waste Manage 23(9) (2003) 851–857.

[9] Y.S. Sim, W.K. Lee, Preparation of adsorbent from MSWI ash. J. Korean Soc. Environ. Eng. 23(8) (2003) 379–388.

[10] W.L. Sun, Y.Z. Qu, Q. Yu, J.R. Ni, Adsorption of organic pollutants from coking and papermaking wastewaters by bottom ash, J. Hazard. Mater. 154 (2008) 595–601.

[11] L.H. Kim, S.M. Jeong, S.O. Ko, Determination of first flush criteria using dynamic EMCs (event mean concentrations) on highway stormwater runoff, Water Sci. Technol. 55(3) (2007) 71–77.

[12] R.M. Barrer, Zeolites and Clay Minerals as Sorbents and Molecular Sieves. Academic Press, London, 1978.

[13] W. Zou, R. Han, Z. Chen, Z. Jinghua, J. Shi, Kinetic study of adsorption of Cu(II) and Pb(II) from aqueous solutions using manganese oxide coated zeolite in batch mode, Colloids Surf., A 279(1–3) (2006) 238–246.

[14] S. Clark, P. Johnson, R. Pitt, S. Gill, M. Pratap, Filtration for metals removal from stormwater. Proceedings of the 10th International Conference on Urban Drainage, Copenhagen, Denmark, 2005.

[15] J.J. Sansalone, S. Buchberger, S. Al-Abed, Fractionation of heavy metals in pavement runoff, Sci. Total Environ. 189–190(190) (1996) 371–378.

[16] Ministry of Environment, Republic of Korea (MOE). Manual for the BMPs Installation, Management and Maintenance, Ministry of Environment, 2008.

[17] Ministry of Construction and Transportation, Republic of Korea (MOCT), Guidelines for the Friendly Road Construction. Ministry of Construction and Transportation, Seoul, Korea, 2007.

[18] E.J. Lee, M.C. Maniquiz, J.B. Gorme, L.H. Kim, Determination of cost-effective first flush criteria for BMP sizing, Desalin. Water Treat. 19 (2010) 157–163.