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Treatment of particulates and metals from highway stormwater runoff using zeolite filtration

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ABSTRACT

Highways are stormwater-intensive land uses, since they are impervious and have high pollutant mass emissions from vehicular activity. Vehicle emissions include pollutants such as heavy metals, oil and grease, particulates from sources such as fuels, brake pad wear, tire wear, and litter. The presence of heavy metals in highway stormwater runoff is of concern, as they are very toxic due to enhanced bioavailability, and have the potential not to degrade in the environment. Therefore, this research was carried out to understand the characteristics of metal pollutants in stormwater runoff from highways in Korea and to treat that runoff using zeolite filtration. The filtration facility was constructed on Korea Highway number 251 (Gaeryong I/C). The facility was operated during storms with durations of 0.3–4.8 h, and the influent treatment rate was varied from 3.60 to 17.34 m^3/day. The first flush phenomenon for metal pollutants was observed in all of the storm events. The average removal efficiency was determined to be 62.5% for TSS, 73.7% for Cu, 61.8% for Pb, and 67.3% for Zn.

Keywords: Highway; Metals; Runoff; Vehicle; Zeolite

1. Introduction

Urbanization changes a hydrologic cycle by reducing the degree of infiltration and increasing the volume of runoff. Developments such as roads, parking lots, and single family dwellings change the imperviousness, slope, and amount of depression storage. Development can also change the cycle by changing evapo-transpiration through the removal of vegetative cover, and by reducing the travel time to a receiving body of water through the construction of efficient drainage systems. The transformation of a watershed from natural to urban conditions produces several major changes in the hydrologic characteristics of streams. Increased flow volume, decreased detention time, and increased peak flow usually occur. The increase in flow volume primarily reflects changes in imperviousness. The transformation of vegetated areas into streets, sidewalks, and parking lots reduces hydraulic roughness and imperviousness, which increases the velocity and volume of overland flow. Together these changes increase peak discharge rates [1–3]. Runoff is affected by storm intensity, duration, antecedent dry days, land use types, and site characteristics such as slope, slope type, and imperviousness [1, 4]. In developed areas, the capacity to retain rainfall is reduced; in fact, highly impervious land use (e.g., parking lots, freeways) may produce conditions where nearly all rainfall becomes runoff. The result of the reduced capacity to retain rainfall is that storms of short duration and low intensity produce

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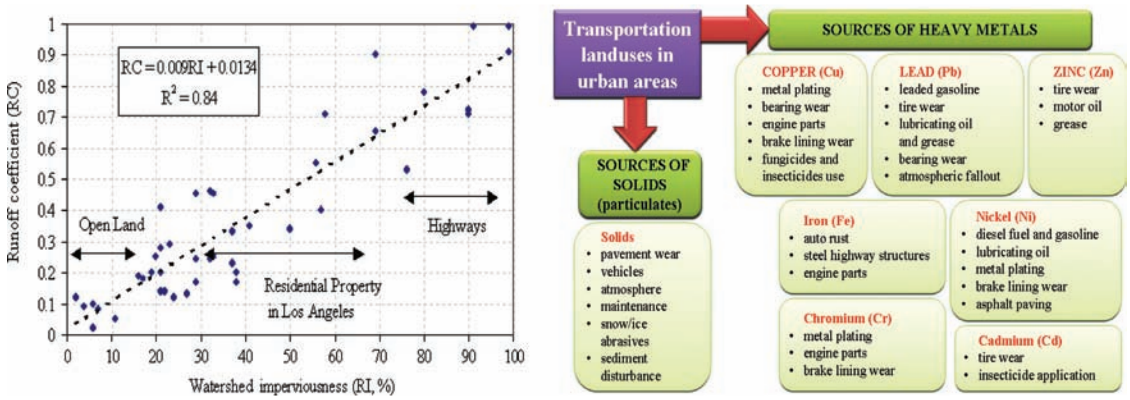


(a) runoff coefficient with watershed imperviousness

(b) source of TSS and Metals

Fig. 1. Runoff coefficients and sources of TSS and metals.

runoff. An important characteristic of land use is the expected stormwater runoff rate. Figure 1(a) shows that runoff coefficients correlate with site imperviousness. The increased surface runoff and discharge of polluted stormwater resulting from urbanization have a negative impact on the receiving waters. Pollutants originating from these nonpoint sources are a big issue world wide. In Korea, pollutants washed off from urban areas are especially of concern. In Korea, the contribution of non-point source (NPS) pollution is predicted to increase from 20 to 40% in 1998 to up to 60% in 2020 [5]. As a result, the Ministry of Environment (MOE) established the Comprehensive Measures for NPS Pollution Management in 2004, fulfilling the Total Maximum Daily Load (TMDL) programs.

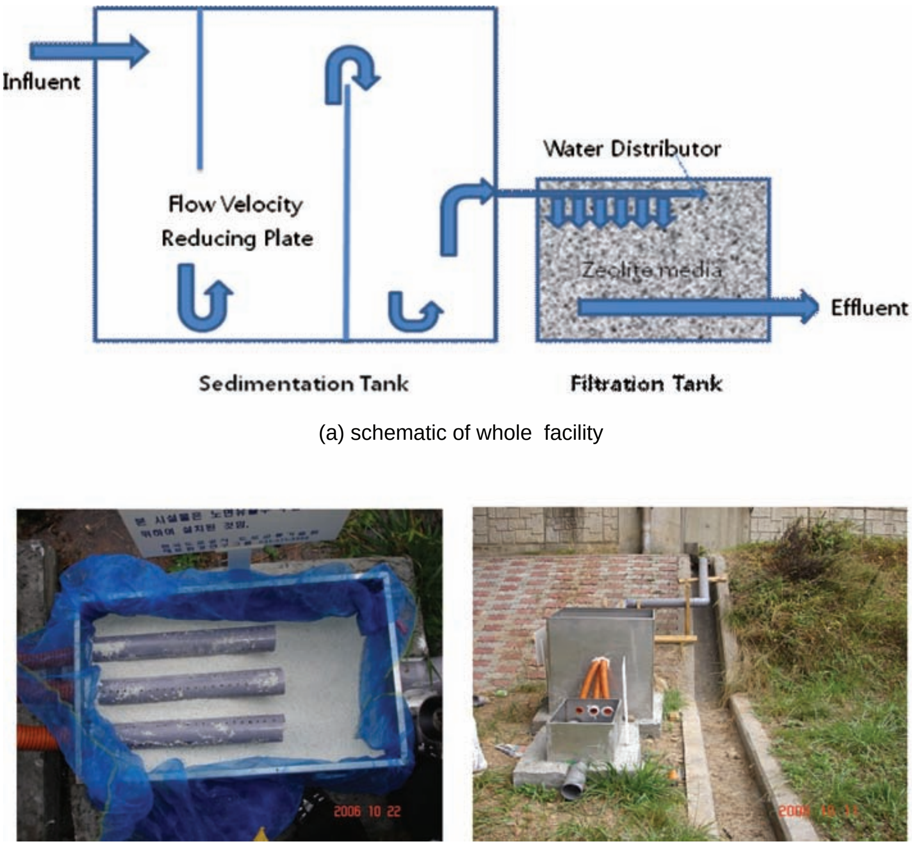
Of the various pollutant sources, highways are stormwater intensive land uses, since they are impervious and have high pollutant mass emissions from vehicular activity. Vehicle emissions include different pollutants, such as heavy metals, oil and grease, particulates from sources such as fuels, brake pad wear and tire wear, and litter, as shown in Fig. 1(b). The metal pollutants are a particularly big issue, and they are washed off with sediments as particulate or soluble status. The presence of heavy metals in urban runoff is of concern, as they are most toxic due to enhanced bioavailability and the potential not to degrade in the environment. Most impervious cover in many communities is related to the transportation system. Pollutants that accumulate on paved surfaces during dry weather are washed off during a storm. Bannerman et al. [6] found that streets contain the highest pollutant loads in most land use categories. Runoff quality or pollutant concentrations are a function of land use. The mass emission of pollutants from NPS in urban areas can be as large as or greater than point source discharges. In Korea, NPS discharges to four major large rivers contribute approximately two-thirds of the BOD input [5]. In an urban setting including highways, best management practices (BMPs) either address the source of the problem or attempt to treat the stormwater. Source controls are practices that keep chemical pollutants or litter from entering the runoff. Treatment control BMPs refer to devices that remove pollutants from the runoff. Examples include vegetated swales and buffers strips, infiltration, filtrations, detention basins, and catch basin inserts.

In this study, a zeolite filtration facility was installed in Gaeryong I/C of Korea highway number 251. It is a test-bed size, and has a sedimentation tank and zeolite filtration tank. This BMP facility was designed to remove the fine sediments, suspended solids, particulate pollutants, petroleum hydrocarbons, heavy metals, and nutrients from stormwater runoff. The facility is comprised of two devices in sequence. The first is responsible for the removal of sediments, free-floating oil, and debris by the mechanism of sedimentation. In this tank, the flow-velocity-reducing plate is placed to increase the sedimentation rate of particulates by reducing the flow velocity. The influent is then distributed inside the filter bed and allowed to permeate through the zeolite filter media.

2. Materials and methods

2.1. Design and installation of treatment facility

This treatment facility is a test-bed used before full-scale application on a highway. The treatment facility is located on Gaeryong I/C of Korea highway number 251.



(a) schematic of whole facility

(b) water distributers

(c) photo of the facility

Fig. 2. Design and installation of treatment facility.

The facility has two tanks in series: a sedimentation tank with a volume of 0.72 m^3 and a filtration tank with a volume of 0.11 m^3. The flow velocity is important to increase the settling rate of particulate materials in the sedimentation tank. Accordingly, two baffles that prevent short-circuiting were installed in the sedimentation tank as shown on Fig. 2. The zeolite medium was filled in the filtration tank with porosity of 0.4, and three water distributors were installed inside the media.

2.2. Monitoring and determination of event mean concentrations (EMCs)

A total of 6 events were monitored from 2007 to 2008 storm seasons to evaluate the pollutant removal efficiency of the BMP in treating stormwater runoff from the highway. Continuous flow measurements were performed and rainfall data were collected to obtain a relatively unbiased approximation of the mass loads of pollutants. The total sampling time was adjusted to approximate the time during which the "first flush" was processed [7]. Typical water quality parameters were measured, including particulate matter, organic matter, nutrients, heavy metals, and oil and grease. Analyses of the parameters were performed in accordance with Standard Methods [8]. Paved surfaces such as highways and streets in urban areas are *storm water intensive* land uses, since they are highly impervious and have pollutant mass accumulation from vehicular activity. The EMC is defined as the pollutant load washed off by a storm event divided by the event runoff volume. The EMC is one of the important factors in predicting the total pollutant load, which has made the EMC the critical parameter for estimating the contribution of runoff to receiving waters [9–12].

2.3. Evaluation of removal efficiency

The Summation of Loads (SOL) Method [13] has been utilized in BMP monitoring studies to evaluate efficiency. The SOL Method is based on the ratio of the summation of total incoming loads to the summation of total outgoing loads. The SOL equation is given below.

$$\text{Removal (\%)} = \frac{\sum \text{Inlet loads} - \sum \text{Outlet loads}}{\sum \text{Inlet loads}}. \quad (1)$$

3. Results and discussion

3.1. Event table and visual appearance of treated waters

The details of monitored events and operating conditions are provided in Table 1. The table included antecedent dry days (ADD), total rainfall, mean influent and effluent, operating time, and influent and effluent durations. The ADD ranged from 2 to 10 days, while the total rainfall varied from 8 to 19 mm. Fifty percent of the monitored events were performed under less than 10 mm rainfall. The mean flow rates ranged from 3.6 to 17.3 m^3/day for influent and from 2.7 to 29.2 m^3/day for effluent. The operation time of the facility ranged from 0.5 to 4.0 h.

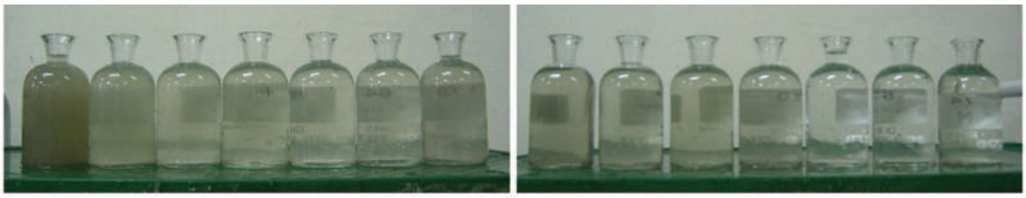
Figure 3 shows the visual appearances of influent and effluent waters. The first flush phenomenon for parti culates and metal pollutants were observed in all of the storm events. Mostly, the first flush effect was finished in 30 min of storm. Most of the particulate materials and adsorbed metals were captured in the sedimentation tank. The fine particles were filtered in the zeolite media layers, and soluble metals were adsorbed on the surface of the zeolite particles.

3.2. Operation of zeolite filtration facility

Figure 4 shows the concentrations of influent and effluent waters at the treatment facility for selected

Table 1
Monitored events and operating conditions of the treatment facility.

Event No.	Event date	ADD (day)	Total rainfall (mm)	Mean influent (m^3/day)	Mean effluent (m^3/day)	Operating time (h)	Influent duration (h)	Effluent duration (hs)
Event 1	2007-07-19	2	8.0	17.3	8.5	1.8	2.0	1.8
Event 2	2007-09-14	8	9.5	14.4	29.2	0.6	0.5	0.3
Event 3	2007-11-24	3	10.0	9.3	8.6	0.3	1.5	0.3
Event 4	2008-05-18	5	15.5	12.8	10.6	2.5	2.8	2.0
Event 5	2008-06-17	10	19.0	11.4	10.5	2.8	2.5	1.3
Event 6	2008-06-28	7	9.0	3.6	2.7	4.8	4.0	3.0



(a) Event 2

(b) Event 3

(c) Event 6

Fig. 3. Visual appearance of influent (left) and effluent (right) water.

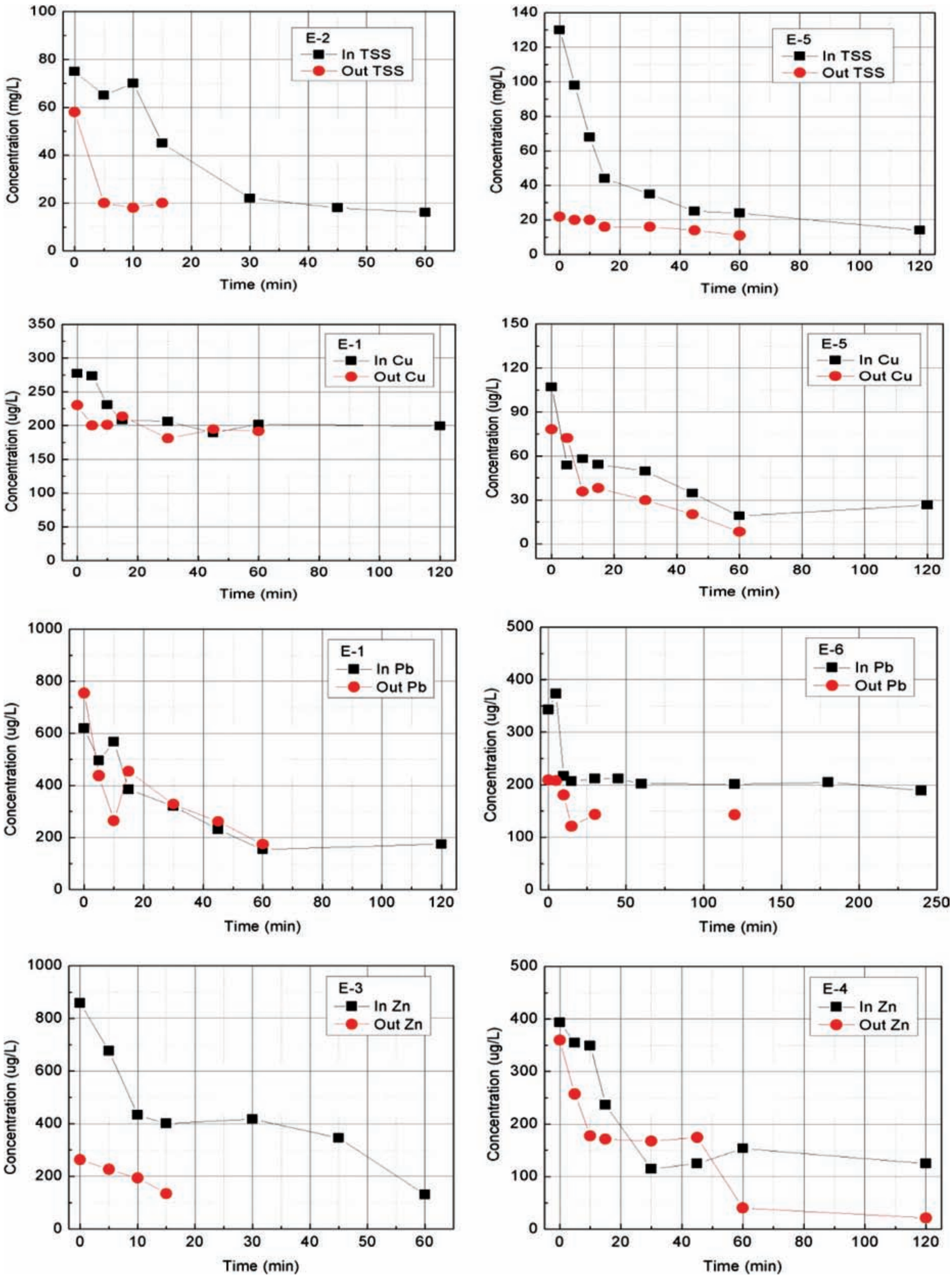


Fig. 4. Concentrations of influent and effluent waters.

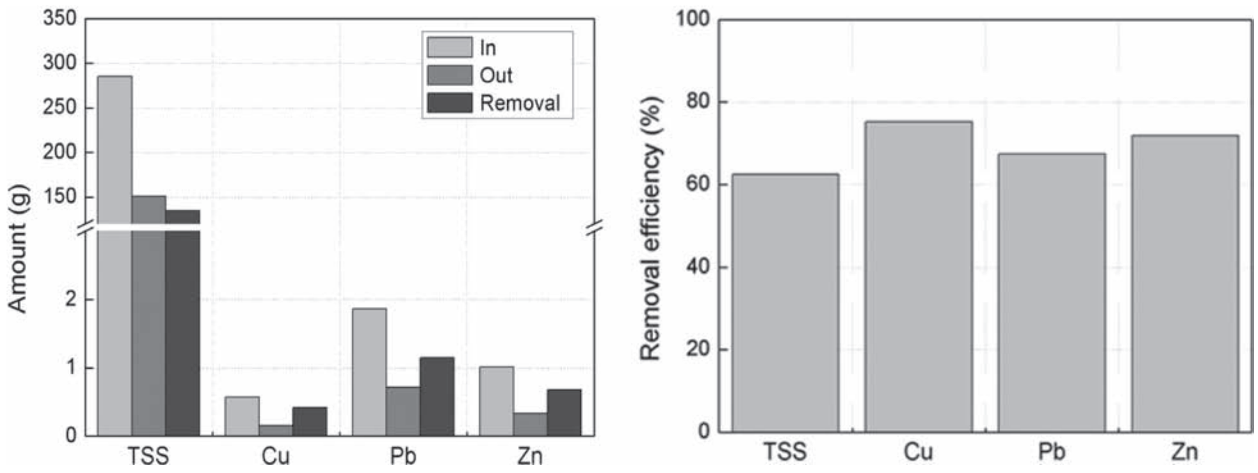


Fig. 5. Reduced mass and removal efficiency by the SOL method.

events. The ranges of TSS concentrations are measured from 6.0 to 434.1 mg/L for influent and 5.0–305.0 mg/L for effluent, giving a significant removal during the first 30 min. For high flow rates or rainfall intensity, the effluent concentrations increased because of excessive influent volume. The vehicle activities release metal pollutants that accumulate on highway surfaces during dry days.

There are many types of metals found in storm water runoff. The monitoring showed that the dominant metals were Cu, Pb, and Zn from fuels, brake pad wear, and tire wear, respectively. Some metals were washed from the highway surfaces by adsorbing on particulate materials. The treatment facility captured a high percentage of the particulates in the sedimentation tank. The baffles that prevent short-circuiting effectively increased the sedimentation rate at the tank. The ranges of Cu concentrations detected were 30.0–341.2 μg/L for influent and 20.0–230.2 μg/L for effluent. In the case of Pb and Zn, the influent concentrations ranged from 75.1 to 1430 μg/L for Pb and 38.5–858.3 μg/L for Zn. The effluent concentrations for these metals were measured from 75.1 to 816 μg/L for Pb and 10.0–394 μg/L for Zn.

3.3. Removal efficiency of particulates and metals

The SOL method was used to determine the pollutant removal efficiency of the treatment facility. Because the BMP facilities for NPS treat the intermittent flow during rainfall, it is not appropriate to use the efficiency ratio (ER) method, which is defined as the average removal efficiency of pollutants for each storm event by concentration alone. The SOL method can usually be applied effectively to determine the removal efficiency in this case. In order to determine the influent pollutant mass for the SOL method application, the flow rate volume and pollutant EMC had to be determined. The TSS EMCs ranged from 19.9 to 104.8 mg/L for influent and 6.2–64.2 mg/L for effluent. The Cu EMCs were 10–204.2 μg/L for influent and 5–195.2 μg/L for effluent. The influent EMCs for Pb and Zn were 195.9–430.4 μg/L for Pb and 58.6–350.0 μg/L for Zn. The effluent EMCs for these pollutants were 146.1–457.7 μg/L for Pb and 5.0–208.1 μg/L for Zn. Figure 5 shows the reduced pollutant mass and removal efficiency at the facility. The treatment facility showed the high particulates and metal removal efficiencies, which were mostly greater than 60%. The figure shows that the baffles that prevent short-circuiting in the sedimentation tank and that zeolite in the media layers could be used to effectively remove the particulate and metal materials.

3.4. Relationships of pollutant removal efficiency and rainfall characteristics

All of the BMP facilities had treatment capacities based on the characteristics of rainfall and their respective sites. The removal efficiency was largely affected by rainfall characteristics such as ADD, total rainfall, and average rainfall intensity. However, the BMP facility installed on the site for this research was a pilot plant for testing the technology. Thus, it was not easy to find the relationships of pollutant removal efficiencies and rainfall characteristics as shown in Fig. 6.

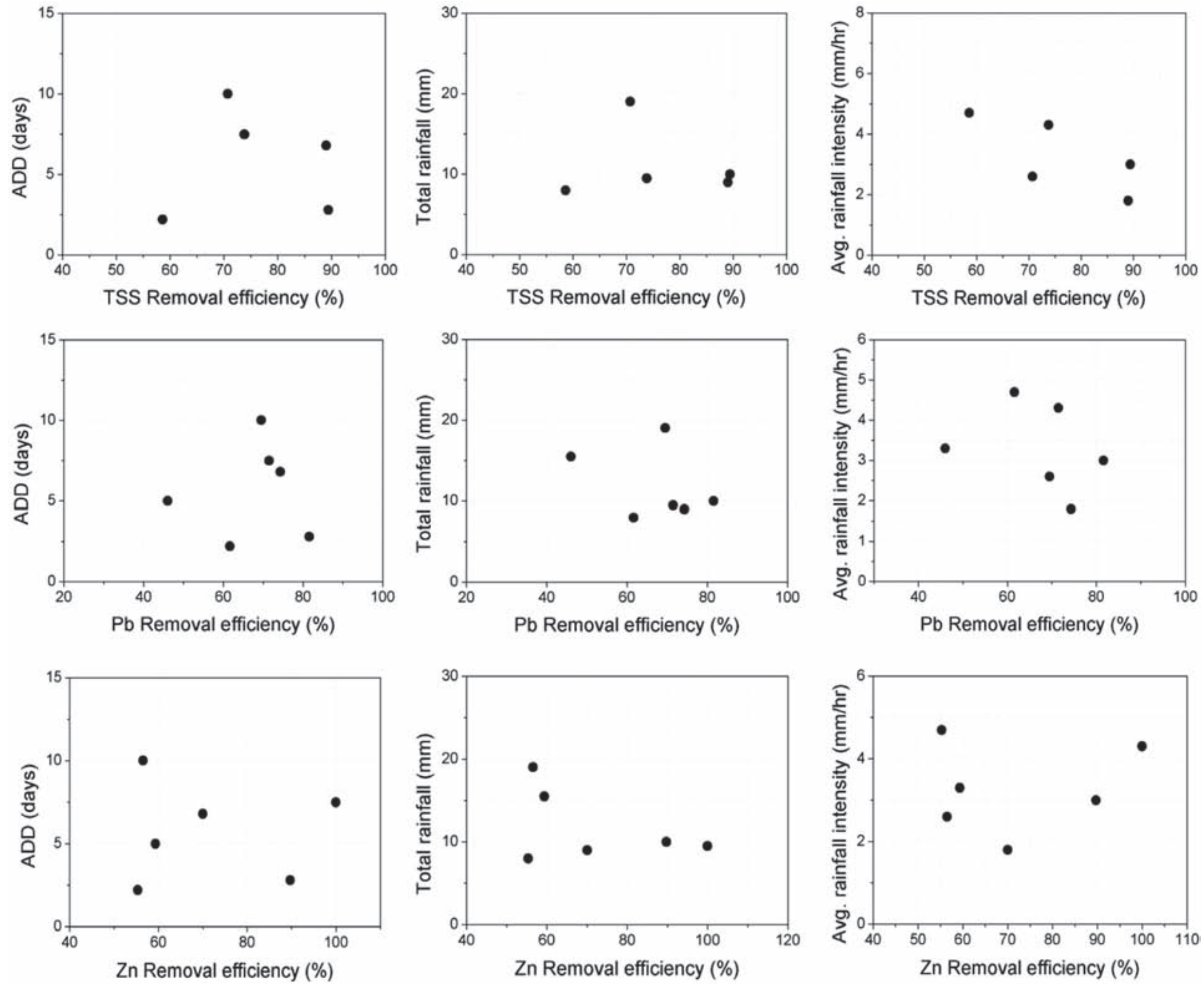


Fig. 6. Relationships between rainfall characteristics and removal efficiency.

4. Conclusions

The performance of the filtration type BMP was monitored during 2007 through the 2008 storm seasons to evaluate its performance in treating stormwater runoff from a highway. The pollutant removal efficiency was evaluated using the SOL method. The major findings are as follows:

1. The first flush phenomenon was observed in all of the storm events, and was finished in 30 min of storm. The dominant metals in highway stormwater runoff were Cu, Pb, and Zn, because of fuels, brake pad wear, and tire wear.
2. The EMCs from highway stormwater runoff were 19.9–104.8 mg/L for TSS, 10–204.2 μg/L for Cu, 195.9–430.4 μg/L for Pb, and 58.6–350.0 μg/L for Zn.
3. The zeolite filtration facility showed high particulate and metal removal efficiencies of mostly greater than 60%. The baffles that prevent short-circuiting were effective for increasing the sedimentation rates of particulates in the sedimentation tank. The zeolite was also effective for removing the particulate and metal materials.

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