Modifications to permeable pavement structure to achieve improved heavy metal attenuation in stormwater runoff

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ABSTRACT

This paper reports a study conducted to investigate the influence of rainfall intensity and subbase materials on attenuation of heavy metals in stormwater runoff through permeable pavements. The porous structure of permeable pavements facilitates the attenuation of particulate heavy metals by filtration. However, the ability of permeable pavements to remove dissolved fractions of heavy metals is still largely at an experimental stage. The porous structure of permeable pavements is a favourable environment to promote adsorption of dissolved heavy metals. However, this capability is heavily dependent on rainfall intensity and duration, which can contaminate groundwater and underlying soil, by leaching heavy metals back to the infiltrate either due to altered flow conditions or after saturation.

In this study, a laboratory model of two permeable pavement columns have been tested for heavy metals attenuation with varying rainfall intensity. One column was constructed according to standards and the other one by maintaining a saturated zone, thin sand layer and providing a carbon source to investigate the influence of heavy metal attenuation by biosorption. Results confirmed the ability of the traditional permeable pavements to attenuate the total pollutant loads of Ba, Co, Mn, Ni, Cu and Zn under low and high rainfall conditions. During high rainfall intensity the attenuation of Al and Mo dropped by 50% compared to low rainfall intensity. During heavy rains, Cr can be leached back to the infiltrate. Results also indicated, maintaining a favourable environment for microbial growth improves the heavy metal attenuation even in high rainfall intensities. Findings of this study ebable to modify the permeable pavement subbase by incorporating a sand layer, a compost layer and maintaining a saturated zone in the subbase to obtain an improved heavy metal attenuation depending on the design rainfall condition, predictable pollutants and the structural requirements of the proposed site.

Keywords: adsorption, biosorption, heavy metals, permeable pavements, stormwater pollutants.

1 INTRODUCTION

Currently, with the sustainable stormwater management concepts, traditional storm drainage systems are being overpowered by more environmentally friendly alternatives. Permeable pavement systems (PPSs) are load bearing pavement structures explicitly designed to promote stormwater infiltration through the top permeable layer and its underlying structure. PPSs are capable of capturing water on the pavement surface, treat this water while passing it through aggregate layers, store and infiltrate this water into the groundwater systems. PPSs provide a combination of a hard surface and an infiltration and detention system; thus, reducing additional land requirements for detention facilities. This is especially important in urban areas with high land price and highly impervious sites with little or no space for stormwater detention.

Open literature proves the ability of PPSs to attenuate pollutants in stormwater. PPSs are generally regarded as being successful in removing stormwater pollutants by adsorption, filtration and biological decomposition. Brattebo and Booth [1] observed that concentrations of Zn, Cu and mineral oil were significantly small in stormwater infiltrated through PPSs. Pagotto et al. [2] demonstrated the ability of PPSs to reduce heavy metals by 20% Cu and 74% Pb. Melbourne Water [3] reports that correctly designed and maintained PPSs can retain up 70 % of heavy metals. However, in some instances, PPSs can contaminate groundwater and underlying soil, by leaching pollutants back to the infiltrate. In vegetated stormwater management systems such as biofilters, filtered substances are removed from the system by plant assimilation. However, in a PPS, pollutants removed by physical processes, especially heavy metals, may leach back to infiltrate either due to altered flow conditions or after saturation. These phenomena need to be further investigated.

Apart from physical adsorption and filtration, heavy metals can also be removed from aqueous solutions through biosorption . It is presumed that metal ions are converted to less soluble forms by oxidation or reduction of heavy metal ions or/and by metabolic actions of enzymes in microbial cells [4]. Research on bio-filtration has shown redox potential and dissolved oxygen decreases in the saturated zone, influencing the separation of metals between the solution and the solid phase [5]. Also, the addition of organic matter in the form of carbon provides an opportunity for enhanced metal uptake [6]. Above findings evidenced the importance of maintaining a saturated zone and providing carbon sources that can influence heavy metal attenuation. Though PPSs are proven to perform as bioreactors, no research can be found on biosorption processes for heavy metal treatment in PPSs. Thus, the effect of these factors and their interactions on metal treatment in PPSs cannot be readily estimated from the available literature.

In this study, a laboratory model of a PPS has been tested for heavy metals attenuation during different rainfall intensities and durations to investigate the treatment performance and likelihood of leaching metals back to the infiltration. Also this study is aimed to investigate the removal of heavy metals from the runoff by creating favourable conditions for biosorption. To achieve this aim a number of changes have been made to the subbase of the traditional PPS as below.

- An added compost layer as a carbon donor to provide opportunities for enhanced metal uptake.
- Maintained a saturated zone by providing required moisture reduced oxygen and increased retention time to influence the separation of metals between the solution and the solid phase.
- Added thin sand layers to limit oxygen transport.

2 MATERIALS AND METHODS

Two permeable pavement columns as presented in Figure 1 were constructed with different subbase configurations. Column 1 was constructed according to the standard PPS design guide. Column 2 was constructed with the ability to maintain a saturated zone, a thin layer of sand to restrict oxygen transfer and a compost layer to provide a carbon source. These modifications were offered to investigate the influence of heavy metal attenuation by biosorption. Columns were constructed with an opaque black material to simulate the natural conditions of PPS subbase. The column length (600 mm) and width (420 mm) were determined based on the Representative Elementary Volume (REV) for porous media [7]. Due to limitations associated with the use of real stormwater, synthetic stormwater was used to simulate rainfall.

All chemicals that comprised the synthetic stormwater solution were dissolved in tap water. Synthetic runoff was applied to permeable pavement columns continually for 4 hours varying the rainfall intensity. Experiments were carried out starting with a rainfall intensity between 19-21 ml/min. It was maintained for 1 hour and the average rainfall intensity was increased to 118-122 ml/min. The input stormwater was stored in a 300L fiberglass container and was well-mixed. During the experiment, stormwater was pumped into the columns from the top through weeper hose and outlet samples were collected from the bottom. Over 4 hours rain event, samples were collected at 15 minutes intervals and tested for metal components. Characteristics of synthesized runoff were chosen from literature data (average values in μ/L are Al-70, Cr-77, Cu–348, Mo-107, Sr-136, Ba-72, Co-35, Mn-72, Ni-83, Zn-86). The pH of synthetic runoff was maintained between 5.5 and 6.5. Percentage reductions of metal elements for both columns were calculated considering first and last hour during the 4 hours rainfall (Table 1). The experiment was repeated three times and average results were analysed.

Linear polyethylene bottles were used for sampling. Samples were preserved immediately after collection by acidifying with high purity concentrated nitric acid to pH < 2 (added 5 mL of HNO_3 to 1L of the sample) and stored at 4°C till they were analysed. Shimadzu inductively coupled plasma - optical emission spectrometry (ICP-OES) 710 was used for metal analysis.

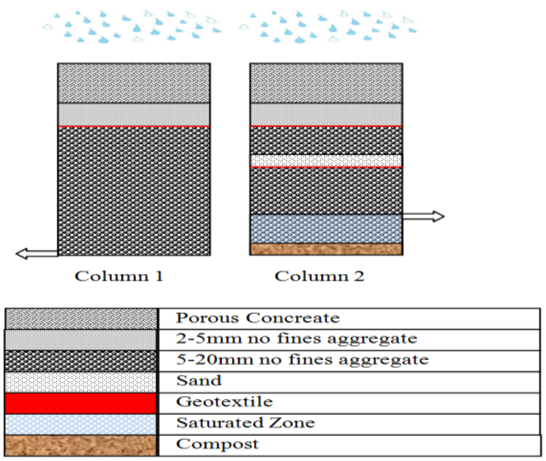

Figure: 1 Column cross-sections

3 RESULTS AND DISCUSSION

Figure 2 presents the outlet concentrations of heavy metals through the standard traditional PPS structure (Column 1) over 4 hours for low and high rainfall intensities. Results confirmed the ability of the traditional PPS (Column 1) to attenuate the total pollutant loads of Ba, Co, Mn, Ni, Cu and Zn under low and high rainfall conditions. During high rainfall intensity, the attenuation of Al and Mo has been dropped by about 50% compared to the low rainfall intensity. In case of Cr, it can be desorbed back to the runoff during heavy rain. Except at the transition from low to high-intensity rainfall, the reduction curves for all metal elements are very stable.

As presented in Figure 3, Column 2, which is upgraded to facilitate biosorption, has also shown a 100% reduction of Ba, Co, Mn, Ni, Cu and Zn under low and high rainfall conditions. When comparing Column 1 and Column 2, except for Al and Sr, during low rainfall intensity both columns showed similar results (Table 1). Reasons for leaching Sr from Column 2 is unknown and need to be further investigated. Column 2 has shown an improved metal attenuation even in high rainfall intensity, confirming favorable facilities for biosorption.

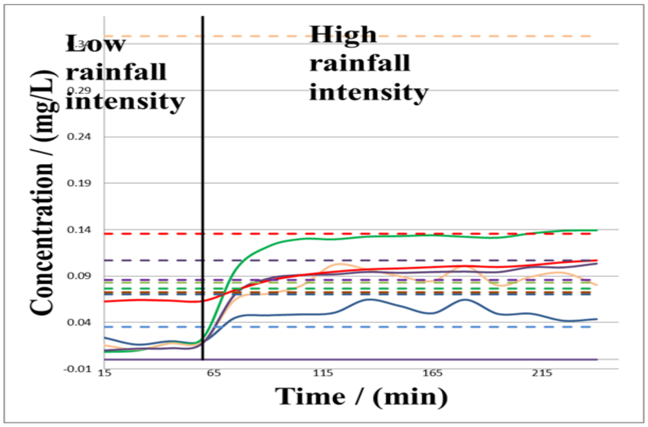

Figure: 2 Metal attenuation over time for Column 1

In case of Cr, Column 2 also has shown a negative percentage reduction which indicates the possibility of desorption of Cr back to the runoff during heavy rain. Results from Kayhanian et al. [8] also demonstrated dissolved Cr in leachate from concrete PPSs. Though, the desorption amount from Column 2 is only one-third of desorption from the standard traditional structure, as Cr is one of the most dangerous pollutants in terms of ecological toxicity [9] PPS structure needs to be further modified for Cr rich sites.

Pollutant	Average Percentage Reduction			
	Low-intensity rainfall		High-intensity rainfall	
	Column 1	Column 2	Column 1	Column 2
Al	71.98	59.87	34.47	72.31
Cr	80.82	81.35	-78.14	-21.79
Cu	95.50	92.42	75.40	93.89
Mo	87.93	83.39	7.18	21.96
Sr	53.29	-13.10	23.83	-11.42
Ba	100.00	100.00	100.00	100.00
Co	100.00	100.00	100.00	100.00
Mn	100.00	100.00	100.00	100.00
Ni	100.00	100.00	100.00	100.00
Zn	100.00	100.00	100.00	100.00

Table 1: Percentage reduction of metals via column 1 and 2

When considering the influence of rainfall duration on metal attenuation, except at the transition from low to high-intensity rainfalls, Column 1 shows stable outlet concentrations without much effect by rainfall duration. But Column 2 has shown a gradual increase in concentrations of heavy metals at the outlet over time during heavy rainfall. Metal attenuation through the standard traditional PPS structure was further investigated for the rainfall 40 mm/ 4 hrs, which is nearly the commonly adopted design rainfall for Sydney NSW, Australia.

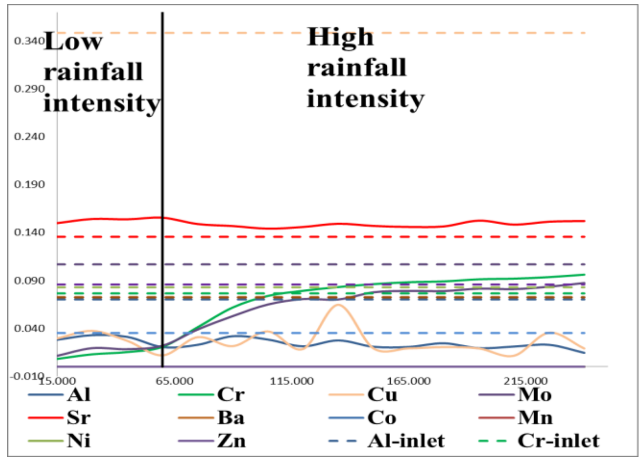

Figure: 3 Metal attenuation over time for Column 2

Except for Cr, Sr and Mo, the percentage metal attenuation was not much affected by the rainfall duration. Though Table 1 shows a 80% reduction of Cr during the first hour (i.e at 20 ml/min rainfall intensity) when the rainfall intensity was increased to 45 ml/min, the percentage reduction of Cr dropped to 56% during the first hour (Table 2) and it further dropped to 11% during the 4th hour. Likewise, the attenuation of Sr and Mo also dropped as presented in Table 2. This experiment was further extended by changing the inlet concentrations (0.1 mg/L – 1 mg/L) of heavy metals at 45 ml/min rainfall intensity for 4 hours rainfall duration. The behavior of outlet concentrations of metals over the rainfall duration was not affected by the inlet concentrations.

Metal element	Average Percentage Reduction			
	1st hour	2nd hour	3rd hour	4th hour
Cr	56.64	18.18	14.10	11.51
Mo	80.26	48.05	40.13	39.28
Sr	36.66	19.12	14.10	11.51

Table 2: Percentage reduction of metal elements through column 1 over 4 hours

Investigations on improving heavy metal attenuation in PPSs are limited to date. However, sorption media such as activated carbon [10]-[12], hydrous ferric oxide [13], natural zeolite [14], alumina, activated bauxsol-coated sand, bark, bauxsol-coated sand, fly ash, granulated ferric hydroxide, iron oxide coated sand, humic acid [14], and waste materials such as saw-dust [15], industrial waste [16], fly ash [17] and juniper fiber [18] have shown positive outcomes for heavy metal treatment in wastewaters. These sorption media can also be tested for PPSs. However, the ability of different materials to remove different pollutants is different and the quality of stormwater is site-specific. Thus, the PPS structure needs to be carefully designed considering the conditions of the proposed site, design rainfall, water quality guidelines and environmental needs.

4 CONCLUSION

It has been found that rainfall intensity affects attenuation of heavy metals such as Al, Cr, Cu, Mo and Sr through the traditional permeable pavement structure. Cr can be desorbed back to the runoff during heavy rain. Also, the attenuation of Mo has dropped to 7% during heavy rain. Rainfall duration also plays a significant influence on attenuation of metals such as Cr, Sr and Mo. These results suggest that traditional permeable pavement structure can transfer heavy metals in stormwater runoff to groundwater and surrounding surface water without treatment.

Biosorption of heavy metals can be promoted in PPSs by maintaining a saturated zone, thin sand layer and providing a carbon source in its subbase. In our experiment, this has reduced the desorption of Cr compared to the traditional structure and has improved the Al, Cu and Mo attenuation. However, this modification in subbase has negatively affected the Sr attenuation.

Thus, during the permeable pavement design stage, factors such as material selection and layer setting of the pavement structure need to be carefully considered to obtain the desired performance under the design rainfall condition of the proposed site. In future research, the utilisation of materials which can influence heavy metal attenuation as aggregates or in combination with aggregates needs to be investigated.

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