Journal of Modern Materials
ISSN: 2456-4834
Volume 7, Issue 1, pp. 37-44, 2020
DOI: https://doi.org/10.21467/jmm.7.1.37-44

RESEARCH ARTICLE

Removal of Heavy Metals from Stormwater Using Porous Concrete Pavement

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Received: 26 May 2020 / Revised: 18 June 2020 / Accepted: 08 July 2020 / Published: 09 July 2020

ABSTRACT

This study aimed to investigate the heavy metals, i.e. Cu, Pb, Ni and Zn removal efficiency from stormwater runoff of a porous concrete pavement (PCP). A model of PCP was designed with the porosity and co-efficient of permeability of the pavement were 27.2% and 1.83 cm/sec, respectively. Artificial stormwater containing heavy metals are passed through the pavement at a constant rainfall rate to mimic the stormwater rainfall-runoff condition. The artificial stormwater infiltrated through the pavement were then collected at two different pavement layers at different time instances. From the experimental investigations, it is observed that Cu, Pb, Ni and Zn concentrations are significantly reduced in the treated stormwater. At the first collection point which is located below the sub-base layer and coarse sand layer of the pavement, the concentrations of Cu, Pb and Zn reduced 56%, 67% and 93% respectively compared to their initial concentration, Ni concentration reduced only 20%. At the second collection point which is located below the coarse and fine sand layers beneath the pavement, the concentrations of Cu, Pb, Zn, and Ni are reduced 92%, 89%, 100%, 100%, respectively.

Keywords: Porous concrete pavement, heavy metal removal, stormwater, Pavement layers, artificial rainfall

1 Introduction

This study focuses on the Porous concrete pavement (PCP) application to reduce heavy metal contaminated stormwater. PCP is a feasible alternative to reduce stormwater runoff and can remove various heavy metals, such as, Zn and Cu significantly [1]. Porous concrete is an open-graded material with zero-slump, comprises with coarse aggregate, cement, water and contains few or no fine aggregates, i.e. sand. It is also known as "no-fines" concrete. PCP usually has interconnected void space of 15%-25% and a surface permeability of 300 to 2000 inch/h [2]. It captures rainwater by allowing water to seep into the ground, recharges groundwater, reduces stormwater runoff, ensure efficient usage of land and lower overall impervious surfaces. Although the porous concrete has high water permeability and lower compressive strength, lower durability compared to conventional concrete, but it has enough strength for use in parking lots, roof tops and driveways. As a rule of thumb, 150 mm of Porous concrete pavement can carry the same light traffic that would normally be carried by 100 mm of conventional concrete pavement [3].

Since water quality maintenance and sanitation infrastructure do not cope up with rapid urbanization and population growth, the pollution of heavy metals in water is a major concern in many developing cities. Sources of heavy metals can be natural and artificial. Artificial sources of heavy metal include direct disposal of untreated industrial waste, mining effluent containing heavy metal contamination and runoff of pesticides, fertilizer used in the agricultural fields. Heavy metals can accumulate in human body, non-degradable in nature, resulting in damage to internal organs and nervous system [4]. It is recognized that heavy metal such as Cu, Zn, Pb and Ni can prevent biological system of ecosystem.

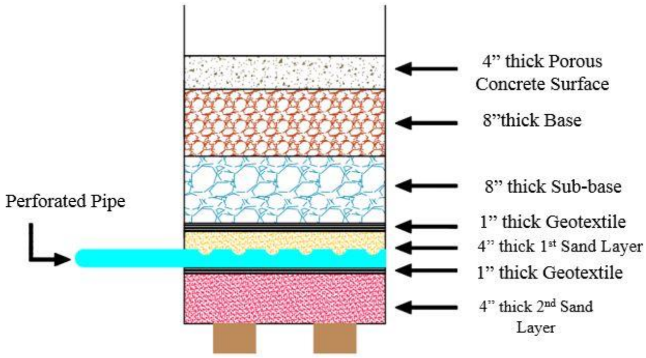
A considerable amount of studies have been performed on the removal effectiveness of porous concrete pavement systems for hydrocarbons, nutrients, fecal coliforms, metals, and various contaminants [5-7]. The advantages of PCP systems are reduced runoff, improved water quality, sediment filtering, pollutant removal and increased infiltration of rainfall [8]. Recent studies related to porous concrete pavement includes, application of PCP in Municipal waste treatment [9] and blending Geo-polymer with porous concrete to remove heavy metals [10].For environmental ecosystem protection it is essential to removed or reduced heavy metal pollutant. Remove heavy metal-contaminated wastewater pollutant is very difficult and costly. If porous concrete pavement used to remove pollutant the pavement is made by local materials. It made easily and economic and no bad effect on environment.

The aim of the study is to assess the efficiency of Porous concrete pavement (PCP) for removal of heavy metal in stormwater pollutants at different layers. PCP is a viable alternative to reduce stormwater runoff in the urban stormwater management. The study determines the stormwater quality before infiltration and compares the percent removal of heavy metals concentration in stormwater by PCP. The main challenge of this study is to investigate the heavy metal removal efficiency of PCP from stormwater in context of Bangladesh and access its applicability.

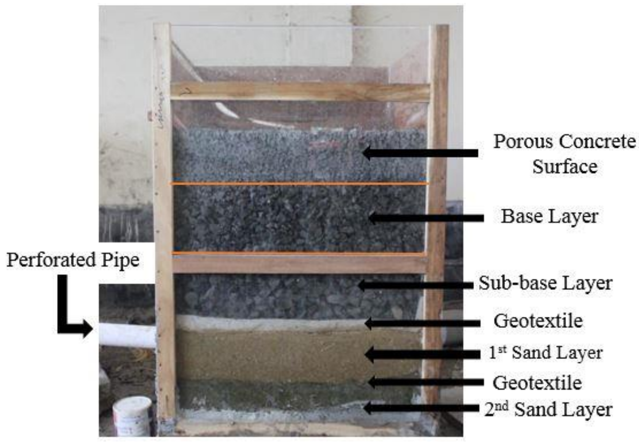
2 Research Methodology

2.1 PCP Model Preparation

The porous concrete pavement (PCP) consisted with 7 layers, i.e. surface layer, base layer, sub-base layer, coarse sand filter layer, fine sand filter layer and two layers of Geotextile. The PCP model was designed as per AASHTO, 1993 [11] guideline and followed typical layer thickness used for porous concrete pavements [10]. In this study, we used thickness of 4”, 8”, 8”, 4” and 6” for surface layer, base layer, sub-base layer, coarse sand layer and fine sand layer respectively (Figure 1). The model of porous concrete pavement had a cross-section of 2 ft × 2 ft and a height of 2.5 ft.



(a)



(b)

Figure 1: Porous Concrete Pavement in (a) Schematic View and (b) Model

2.1.1 Surface Layer

This layer consists of porous concrete. The proportion of the mixture is (cement) 1: (coarse aggregate) 4. This ratio is optimum for porosity and permeability [12]. In this study, we used gradation of aggregate shown in Table 1. Usually, the water cement (w/c) ratios between 0.27-0.30 are used with admixtures [13].

***Table 1**: Gradation of Aggregate of Porous Concrete Mix*

Sieve No. (mm)	Weight (gm)	% Weight
12.5	9	0.45
9.5	93	4.65
4.75	1671	83.55
2.36	223	11.15
1.18	3	0.15
Pan	1	-
Total	2000	

2.1.2 Base and Sub-base Layer

In this study, open-graded aggregate used as a base. We used aggregate sizes from 19 mm (20mm) to 9.375 mm (10mm). A single sub-base layer was used in this study. A coarse layer used which comprised of smaller sized aggregate above the sub-base and sand filter layers used for water quality improvement. We used aggregate sizes from 19 mm to 38 mm.

2.1.3 Sand Filter Layer

In the study, we used two sand filters below the sub-base. One sand filter used as coarse sand and another is fine sand. 1st sand filter used as coarse sand and 2nd sand filter as fine sand. Natural sand was used for cushion layer. The fineness modulus (FM) of the coarse sand and fine sand are 2.56 and 1.67 respectively. The 1st sand and 2nd sand filters in square model were packed in layer 4" and 6" thickness respectively with preparatory tamping and was not in the state of fully compacted.

2.1.4 Geotextile Layer

A geotextile layer increases the pollutant attenuation capabilities [14], reduces the heavy metal, suspended solids and enhance fine particle retention capacity [6, 15, 16] within the porous concrete pavement system. In this study, plastic geotextile was set in two layers, one between sub-base and coarse sand layer and another one between coarse sand and fine sand layer. Plastic geotextile consist of 2% black carbon, which help to removal of heavy metal.

2.2 Porosity and Permeability Test for Surface Layer

2.2.1 Porosity Test

The effectiveness of porous concrete are determined by volumetric method [8]. In this method, a cylindrical test specimen is used where, a mass of water to fill a sealed test is compared with an equivalent volume of void to measure the porosity. The effective porosity is calculated by the Equation 1:

$$P = [\frac{M_1 - M_2}{\rho_w V}] \times 100 \quad (1)$$

Where, P = Total porosity of the test specimen (%), M_1 = Weight of the test specimen air-dried for 24 hours (gm), M_2 = Weight of the test specimen submerged in water (gm), V = Volume of the test specimen (cm^3) and ρ_w = Density of water (gm/cm^3)

The porosity of porous concrete within 15%-30% are acceptable usually [17, 18]. In this study, the porosity value is 27.2%, which is in the acceptable range.

2.2.2 Permeability Test

Permeability defines the flow of water through the material structure. Concrete mixture proportioning have influence on porosity and permeability of porous concrete [19]. Permeability test of PCP in this study have been conducted by constant head permeability method [20, 21]. The coefficient of permeability k as given:

$$k = \frac{QL}{Aht} \quad (2)$$

Where, k = Coefficient of permeability(cm/s), Q = Quantity of flow through the test specimen (cm^3), L = Specimen length (cm), A = Cross sectional area of the test specimens (cm^2), h = Water head (cm) and t = Time (s)

The porous mixtures had permeability values between 1 to 2 cm/s, which is recommended to be used as a drainage layer of pavement system [19]. In this study, the co-efficient of permeability is 1.83 cm/s, which is acceptable for good drainage.

2.3 Rainfall Data Analysis

We collected last 5-years rainfall data from a rain gauge station at Dhaka city from Bangladesh Metrological Department (BMD). The average total rainfall for a year is 1910.8 mm. In this study, we were experiment for 100 mm/hour (5% of 1910.8) rainfall intensity.

2.4 Stormwater Quality Test

Porous pavements can reduce pollutant loads by filtering, chemical degradation, adsorption and biological activity [8]. Copper (Cu) is found in surface water, groundwater, seawater, Zinc (Zn) is an essential mineral that is naturally present in some foods and available as a dietary supplement. Lead (Pb) is a heavy metal that is denser than most common materials. Nickel (Ni) is generally considered to be one of the most toxic metal found in environment. Higher concentration of Ni is harmful for human body. It causes cancer of lungs, nose and bone.

2.4.1 Synthetic Stormwater Preparation

In this study, we prepared synthetic stormwater in the laboratory. We analysis Pb, Cu, Ni and Zn these heavy metals which exist in stormwater. We took standard solutions of Cu, Pb, Ni and Zn. The standard solution was added within 35 liters tap water. Then was well mixed using stirrer. After proper mixed, was collected some amount of sample for testing in laboratory. After testing we have been knowing about correct concentration of Cu, Pb, Ni and Zn. Finally, synthetic stormwater is prepared for experiment.

2.5 Experiment Procedure

Experimental setup of the porous concrete pavement is shown in Fig. 2. Total synthetic stormwater tank was placed beside the pavement, which above of the pavement surface. A water pipe connected one end with the tank and another end with shower. The water flow through the pipe average 2.7 liter/min. The water infiltrated through the pavement, then we collected sample from two points. 1st point located at 24" below the porous concrete pavement surface and 2nd point located at 30" below the porous concrete pavement surface, which shown the Fig. 2. The water samples were collected at 3 minutes, 6 minutes, 11 minutes and 16 minutes from the start of the test session from each point. The tank was empty within 13 minutes. Label of the collected 8 samples with respect to the time represented in the Table 2. The collection time 3 min, 6 min, 11 min and 16 min corresponding to 1st collection point (2nd collection point) were labeled as 1-1 (2-1), 1-2 (2-2), 1-3 (2-3) and 1-4 (2-4) respectively. The volume of each sample was about 500 ml.

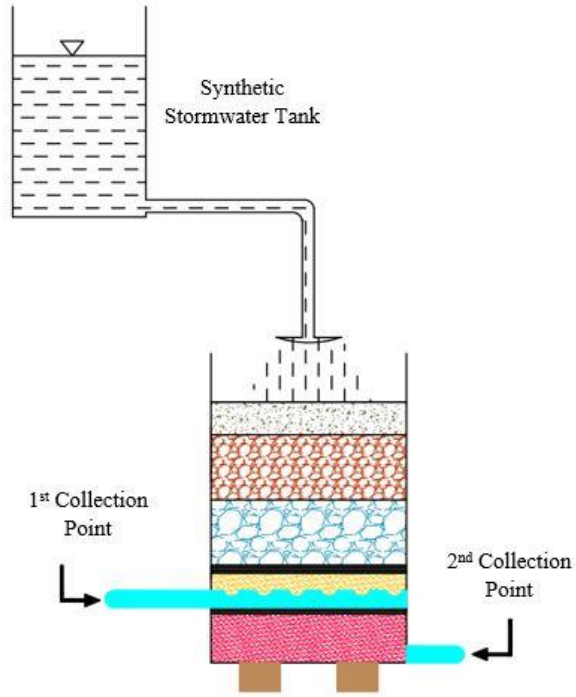


Figure 2: Schematic View of Experimental Setup in this Study

Table 2: *Test results of heavy metal concentration at different layers of the porous concrete pavement at various sampling time*

Test Parameter		Cu (ppm)	Pb (ppm)	Ni (ppm)	Zn (ppm)
Initial		0.2153	0.5231	0.2136	0.0152
At 1st Collection Point	3 min.	0.2119	0.3851	0.2121	0.0019
	6 min.	0.2112	0.2785	0.1921	0.0015
	11 min.	0.1168	0.2763	0.1713	0.0012
	16 min.	0.0953	0.1751	0.1711	0.0011
At 2nd Collection Point	3 min.	0.0923	0.2015	0.1151	0
	6 min.	0.0781	0.2003	0.0983	0
	11 min.	0.0315	0.1963	0	0
	16 min.	0.0181	0.0561	0	0

2.6 Heavy Metals Test Results in Laboratory

Heavy metals (Copper, Lead, Nickel and Zinc) were analyzed by atomic absorption Spectrophotometer (AAS). For digesting, 2.5 ml diluted HNO_3 acid (1:3) and 7.5 ml diluted HCl acid (1:3) were added to 100 ml of synthetic stormwater sample. Then, the acidified samples were kept overnight. The digested for two hours under reflux conditions. After the cooled samples were filtered and the filtrate volume was adjusted

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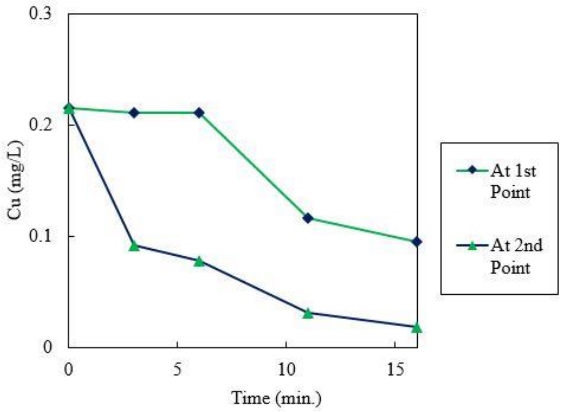
to 100 ml by de-ionized water. The sample was then ready for analysis through the Atomic Absorption Spectrophotometer (AAS) Model AA-7000. The Test results of the heavy metals Cu, Pb, Ni and Zn concentration are summarized in Table 2.

3 Discussion

3.1 Heavy metals in synthetic stormwater

The maximum amount of Cu concentration has reduced by the sand layers and geotextile layers (Figure 3a). The amount of decrease of Cu concentration not varies on using of the coarse sand layer or fine sand layer. The maximum amount of Pb concentration has reduced by the coarse sand layers and geotextile layers. Also, Pb was removed by the fine sand layer but it is relatively low (Figure 3b).



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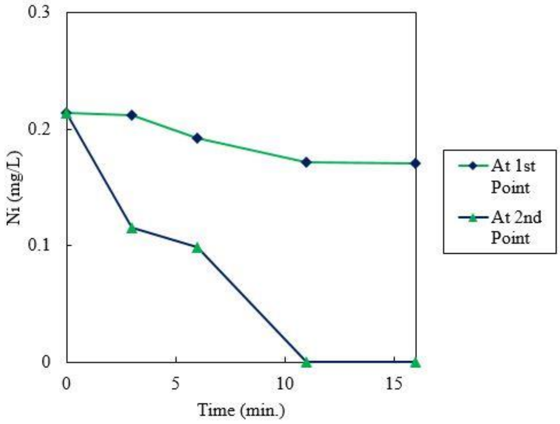

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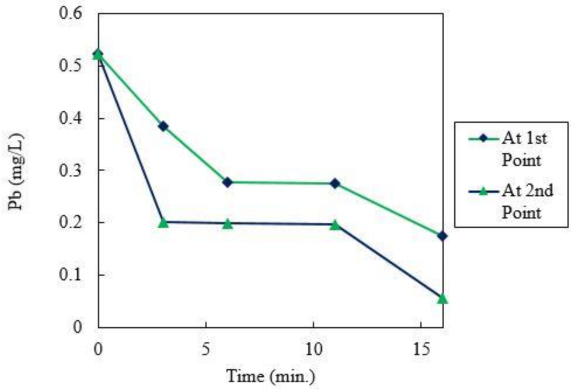

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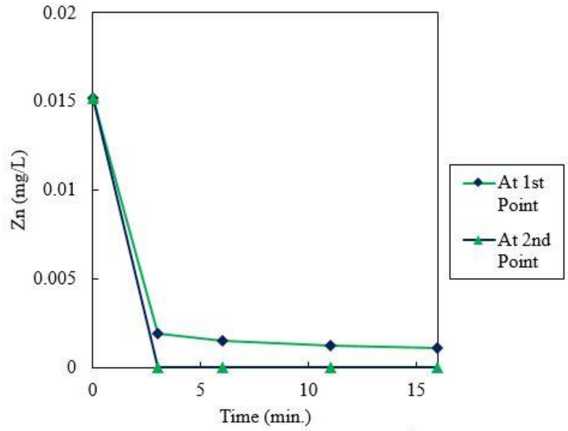

(d)

Figure 3: Concentration of (a) Cu, (b) Pb, (c) Ni and (d) Zn with respect to the time at 1st collection point and at 2nd collection point

Less amount of Ni concentration reduced by the coarse sand layer (Figure 3c). Relatively, maximum amount of Ni concentration has reduced by using of fine sand layer. In synthetic stormwater, initial Zn concentration was 0.0152 ppm. Zn concentration gradually reduced in synthetic stormwater with time. Total concentration has removed by the two sand layers and geotextile layer, which consist of one coarse sand layer and another is fine sand layer (Figure 3d).

3.2 Removal Analysis

From the Table 3 we observed that, after 3 minutes maximum percentage of Zn concentration was removed in the 1st collection point. But, other parameters were reduced very small amount. After 6 minutes, Pb concentration was removed about 50%, but for removed about 50% Cu concentration required time was 11 minutes. At the end of 16 minutes Cu, Pb and Zn

ISSN: 2456-4834
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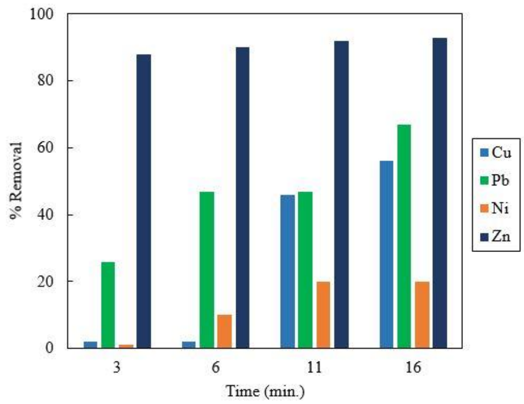
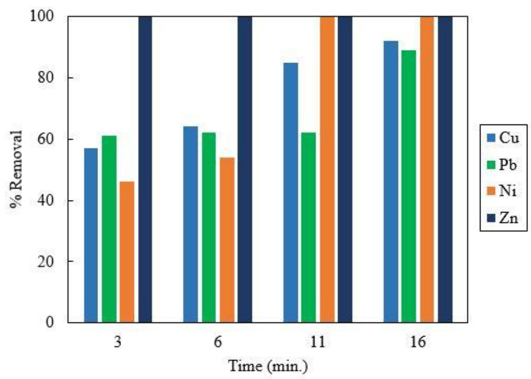
concentration were removed of 56%, 67% and 93% respectively, but Ni concentration was removed only of 20% shown in Fig. 4(a).

Table 3: *Percentage removal of Cu, Pb, Ni and Zn by the porous concrete pavement*

Collection point	Time (min.)	Cu (%)	Pb (%)	Ni (%)	Zn (%)
1st	3	2	26	1	88
	6	2	47	10	90
	11	46	47	20	92
	16	56	67	20	93
2nd	3	57	61	46	100
	6	64	62	54	100
	11	85	62	100	100
	16	92	89	100	100



(a)



(b)

Figure 4: Percentage (%) removal of Cu, Pb, Ni and Zn with respect to the time at (a) 1st collection point and (b) 2nd collection point

From the Table 3 we observed that, after 3 minutes Zinc (Zn) concentration was removed 100% in the 2nd collection point. But other three parameters were gradually reduced with respect to time. For removed of 100% Nickel (Ni) concentration required time was 11 minutes. At the end of 16 minutes Cu and Pb concentration were removed of 92% and 89% respectively, shown in Figure 4(b).

When water pass through the 4-inch porous concrete pavement layer, 8-inch porous base layer, 8-inch porous sub-base layer, 4-inch coarse sand layer and 1-inch geotextile layer, then Copper and Lead concentration has removed of 56% and 67% respectively. But when water passes through another 6-inch fine sand layer and 1-inch geotextile, then Cu and Pb concentration has removed of 92% and 89% respectively shown in Figure 5.

When water pass through the 4-inch porous concrete pavement layer, 8-inch porous base layer, 8-inch porous sub-base layer, 4-inch coarse sand layer and 1-inch geotextile layer, then Nickel and Zinc concentration has removed of 20% and 93% respectively. But when water passes through another 6-inch fine sand layer and 1-inch geotextile, then Ni and Zn concentration has removed of 100% shown in Figure 5.

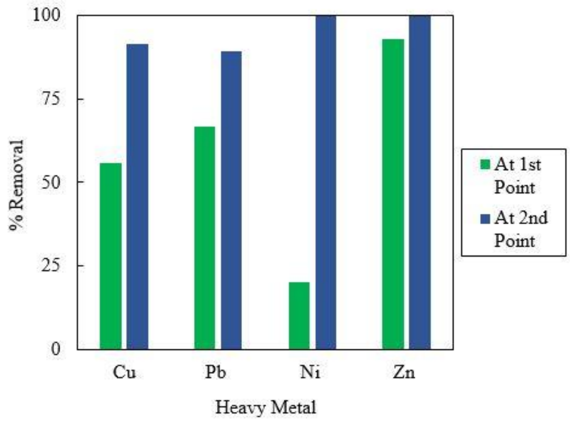


Figure 5: Percentage (%) removal of heavy metal

The results showed that the average removal efficiency of Ni concentration is higher by the fine sand layer. The average removal efficiency of Zn concentration is maximum by the coarse sand layer. Removal efficiency of Zn concentration is 100% from first time to last time.

Legret et al. [15] used 6 cm porous asphalt, two 10 cm porous asphalt stabilized graded aggregates, 35 cm thickness of crushed materials and woven geotextile laid on the formation level and found reductions of 79% and 72% for Lead and Zn respectively during three-month runoff on the surface. Hogland and Niemczynowicz [23] found 62% reduction of zinc, 42% reduction of copper, 50% reduction of lead for a porous pavement system receiving snowmelt runoff. Some prior studies used porous reactive concrete [24] and geo-polymer with PCP [1] to remove heavy metal from stormwater. In this study, we have used locally available materials, which are low cost and removal efficiency of Zn, Pb and Cu are higher than some prior studies [15, 23]. Therefore, our proposed lab scale PCP model can be experimented for the future practical application in the field.

4 Conclusions

This study evaluated the porous concrete pavement structures in order to assess their capability to reduce the concentration of heavy metals from stormwater. Synthetic stormwater quality analyses, after the passage through the model, by coarse sand layer and geotextile layer are reduced the concentration of Cu, Pb and Zn are 56%, 67% and 93% respectively, but reduce Ni concentration 20%. Since the atomic mass of Ni is relatively less than Cu, Zn and Pb. So, the atomic crystal size of Ni is less. When fine sand layer and geotextile layer are added below the coarse sand layer, then 100% reduced the concentration of Zn and Ni, also about 90% reduced the concentration of Cu and Pb. Coarse and fine sand layers can remove the heavy metal, because of it have maximum adsorption capacity. The plastic geotextile can remove the heavy metal, because of it consist of black carbon. So the pavement improved stormwater quality by removing heavy metals. This infiltrated stormwater can use as groundwater recharger or water treatment plant. This research work has opened up new possibilities for further works to improve the metal removal efficiency of PCP. Additional studies are required to observe clogging effect of porous concrete pavement. Further study can determine efficiency after long time flow on the pavement. The study can be extended for recycling materials, determine efficiency at various metal concentration stormwater and considering various water cement ratio.

5 Declarations

5.1 Acknowledgements

The authors would like to acknowledge Department of Civil Engineering, Dhaka University of Engineering and Technology (DUET) for providing funds to conduct this research.

5.2 Competing Interests

There is no potential conflict of interest exists in this publication.

How to Cite this Article:

K. Rahman, S. Barua, M. S. Anwar, M. Z. Hasan, and S. Islam, “Removal of Heavy Metals from Stormwater Using Porous Concrete Pavement”, *J. Mod. Mater.*, vol. 7, no. 1, pp. 37-44, Jul. 2020. doi:10.21467/jmm.7.1.37-44

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