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Article

The Influence of Geotextile Type and Position in a Porous Asphalt Pavement System on Pb(II) Removal from Stormwater

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Abstract: Porous asphalt (PA) pavement systems with and without a geotextile layer were investigated in laboratory experiments to determine the impacts of the geotextile layer on processes leading to lead ion (Pb^{2+}) removal from stormwater runoff. Two types of geotextile membranes placed separately at upper and lower levels within the PA systems were tested in an artificial rainfall experiment using synthetic rainwater. The effect of storage capacity within the system on Pb^{2+} removal was also investigated. Results indicated that the use of a geotextile layer resulted in a longer delay to the onset of effluent. The non-woven geotextile membrane placed below the reservoir course improved the Pb^{2+} removal rate by 20% over removal efficiency of the system using a woven geotextile placed just below the surface but before the choker course. Pb^{2+} ions were reduced by over 98% in the effluent after being held for 24 hours in reservoir storage. Results suggest that temporary storage of stormwater in the reservoir course of a PA system is essential to improving Pb^{2+} ion removal capability.

Keywords: porous asphalt pavement system; stormwater; stormwater runoff; heavy metals removal; geotextile membrane

1. Introduction

Impervious surfaces in urban areas can lead to stormwater related problems including urban flood events, natural water quality degradation, groundwater level decline, etc. The impacts are becoming more and more severe due to the rapid urbanization that many regions are experiencing, which lead to large increases in impervious surface [1,2]. In particular, stormwater runoff generated by an urban impervious surface has been regarded as an important contributor to the degradation of receiving aquatic systems because it carries contaminants accumulating between storm events in the urban environment. These pollutants include suspended solids, organic matter, nutrients, heavy metals, oils and even polycyclic aromatic hydrocarbons (PAHs) [3,4]. To mitigate these negative effects, and potentially start using stormwater as a resource instead of a waste product, low impact development (LID) options such as permeable pavement systems (PPS), are seeing an increase in implementation in low-traffic areas in place of impermeable surfaces [5-7].

PPS are comprised of various pavement layers of porous media resulting in a high infiltration capacity that allow surface stormwater runoff to pass freely into a reservoir structure for temporary storage, which may be harvested for later reuse or released slowly into the underlying soil or receiving water bodies or drainage systems. Throughout this process, the stormwater is being treated through mechanical filtration, physical sorption, chemical sorption, nutrient transformation, degradation and chemical precipitation [8-10]. In this way, PPS not only significantly decreases the surface stormwater runoff volumes and peak flow rates, but effectively removes pollutant, such as total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP) and heavy metals (Pb, Cu, Zn).

PPS commonly consists of a permeable surface (common examples are porous asphalt (PA), porous concrete (PC), permeable interlocking grid pavers (PICPs), etc.), overlying a bedding course for PICPs and a choker course for PA and PC, and then a reservoir structure for stormwater temporary storage (also referred to as base course, which can involve an open graded aggregate bed with varying depths depending on water storage requirements and frost depth) [11,12]. Permeable geotextile membrane is traditionally used at one or two levels within the PPS to separate the layers and prevent migration of stones and gravel, as well as for strengthening purpose [4,6,13,14].

Various studies have confirmed that a standard PPS incorporated with any geotextile layer will improve stormwater quality. Dietz et al. [15], Legret et al. [16] and Boving et al. [17] recognize that the presence of a geotextile layer at the choker course or gravel reservoir in a PA system was effective in helping to improve stormwater quality by retaining chloride, organic and selected heavy metals (Pb, Cu, Cd and Zn) from stormwater runoff, respectively. Pratt et al. [18] reported that a PICP system containing both upper and lower geotextile membranes performed as an effective system for retaining and degrading oil. Nnadi et al. [6], and Tota-Maharaj and Scholz [19] performed laboratory-based experiments and found that PICP systems incorporating a geotextile layer at the bedding course increased the removal efficiency of selected metals (Cd, Cu, Pb, Ni, Fe and Zn), ammonia and ortho-phosphate. Brown et al. [20] proposed using a geotextile at the base course in both the PICPs and PA systems and indicated that the “sieving action” occurring primarily at the geotextile was important for TSS removal. Mullaney et al. [13,14] conducted a field study using PICPs systems with and without a geotextile at the upper sub-base and concluded that the PICPs containing an upper geotextile had a better performance for removing lead, copper and cadmium from stormwater over the long-term.

These studies have indicated that commonly used PPS with an upper and/or lower geotextile layer will provide suitable conditions for trapping pollutants, such as heavy metals, oil, nutrients, TSS and chloride, from stormwater runoff; however, very few research studies have been directly concern with the impact of the geotextile material itself on stormwater runoff quality. Only one of the studies produced directly comparable observations and results of PPS with or without a geotextile layer. There are a plethora of geotextile materials available for pavement construction that vary in thickness and thread density. When a research study is conducted, the type of geotextile is given secondary consideration if at all. To the Authors’ knowledge, no study has considered the impact of different geotextile types on the treatment. Greater evidence and data is needed to understand the role of geotextile membranes within PPS and to better recommend their usage in designs leading to better stormwater quality performance.

In this study, the influence of the type and position of geotextile layer on the removal of Pb^{2+} ions is investigated in PA pavement systems. The objectives of this paper are to: 1) assess the role of geotextile layers within a PA system for removing dissolved lead from stormwater runoff; 2) investigate the differences in the removal of Pb^{2+} ions in stormwater runoff by PA systems incorporating a non-woven or woven geotextile membrane place at the choker course or at the base of reservoir structure; and 3) examine the influence of a PA system working under different water detention capacities on the removal of Pb^{2+} ions in stormwater runoff. This study compares the system performances under artificial rainfall events of 120 min duration and monitoring several water quality parameters over a period of 24 hours.

2. Materials and Methods

The experiment was conducted in two stages: the first stage was to monitor the Pb^{2+} ion removal efficiency by PA systems during artificial rainfall event 1; the second stage involved a temporary storage period (24 hours) of the stormwater generated by artificial rainfall event 2 and stored within

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the reservoir course to analyze any changes in removal efficiency and estimate whether the stormwater discharged from the PA systems could be reused as irrigation water.

2.1. Materials

2.1.1. Models of Porous Asphalt Systems

Five model PA systems were constructed. Each contained three main courses (as shown in Table 1), including a 10 cm-thick surface of PA mixture with a void ratio of 22 %, a 10 cm-thick choker course of large stone porous asphalt mixture (LSPM) with 23 % void content, and a 40 cm-thick base reservoir of 13.2 cm of crushed limestone gravel with 35 % void space; all of which were designed in accordance with the Technical Specifications for Permeable Asphalt Pavement (CJJ/T 190-2012) [21] and other related standards in China. A non-woven or woven permeable geotextile membrane was placed either at an upper level, that separates the PA surface from the choker courses, or a lower position at the reservoir base (see Figure 1).

Table 1. Details of the PA system models paved in test rigs

Test Rig	Mixtures or Materials for the pavement layers				
	Surface course	Choker course	Upper geotextile	Gravel reservoir	Lower geotextile
A	PAC-16 [1]	LSPM-25 [1]	-	Limestone	-
B1	PAC-16	LSPM-25	Non-woven	Limestone	-
B2	PAC-16	LSPM-25	Woven	Limestone	-
B3	PAC-16	LSPM-25	-	Limestone	Non-woven
B4	PAC-16	LSPM-25	-	Limestone	Woven

[1] According to the Technical Specifications for Permeable Asphalt Pavement (CJJ/T 190-2012) in China, PAC-16 and LSPM-25 are two of common aggregate gradations for surface course and choker course that are designed with maximum particle size of 16 mm and 26.5 mm crushed gravel, respectively.

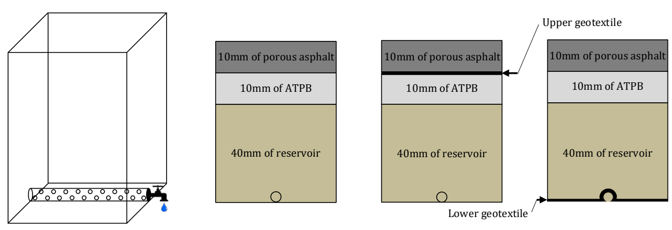

Figure 1. (**a**) Test rig for paving PA system model; (**b**) PA system without a geotextile; (**c**) PA system with an upper geotextile; (**d**) PA system with a lower geotextile.

The physical characteristics of the materials for the three pavement layers and the hydraulic demands for providing a sufficient storage volume for infiltrated stormwater runoff during a rainfall event, were determined based on the average annual precipitation in the 2011~2016 period in the City of Nanjing, China. PA mixtures were manufactured by using a rolling wheel compactor. Aggregate materials were thoroughly washed and dried prior to installation in the test rigs in order to minimize the occurrence of fine sediment in the experiment.

2.1.2. Test Rigs for Assembly of Pavement Models

Each test rig was made of acrylic with a 5 mm wall thickness and having a dimension of 30 cm (length)×30 cm (width)×65 cm (depth), as shown in Figure 1(a). Acrylic is chosen because of its stable chemical properties and it provides a clear view. A perforated PVC pipe (a diameter of 5 cm) with a tap was installed at the bottom of the test rig to convey effluent drainage and facilitate sample

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collection. The sections of PA systems with and without a geotextile layer are shown in Figures 1(b), (c) and (d).

2.1.3. Preparation of Synthetic Rainwater

Synthetic rainwater was used to supply a consistent water quality in the experiment. Pb(Ⅱ) was selected as a target pollutant because it is one of the highest heavy metal ions in both road-deposited sediment (RDS) and stormwater runoff that poses an environmental risk in China [22,23]. It was reported that the RDS is one of the greatest contributors to heavy metal pollution in urban stormwater runoff [23,24]. On this basis, a concentration of 10 mg/L of Pb^{2+} ions was determined to create the synthetic rainwater due to the level of total Pb in RDS measured by the authors (results shown in Table 2) and local historical rainfall events data from 2011 to 2016, Nanjing.

Table 2. Pb concentration in RDS sample

Sampling date	Dry period (hours)	The mass of RDS per unit area (g/m^2)	Concentration (mg/g)
04-20-2016	232	225	0.598
07-23-2016	96	225	0.384
09-14-2016	124	225	0.461
12-08-2016	210	225	0.648

2.1.4. Desgin of Rainfall Event

In this study, an artificial rainfall event with a total precipitation, average intensity, rainfall duration and return period of 82.3125 mm, 0.6310 mm/min, 120 min and 5 years, respectively, were determined using the Rainstorm Intensity Formula of Nanjing. The well-known Chicago method [25] was used to design the pattern of simulated rainfall event. The application of the rainfall event with a total duration of 120 min, time step of 5 min, return period of 5 years and $\gamma = 0.40$ is shown in Figure 2.

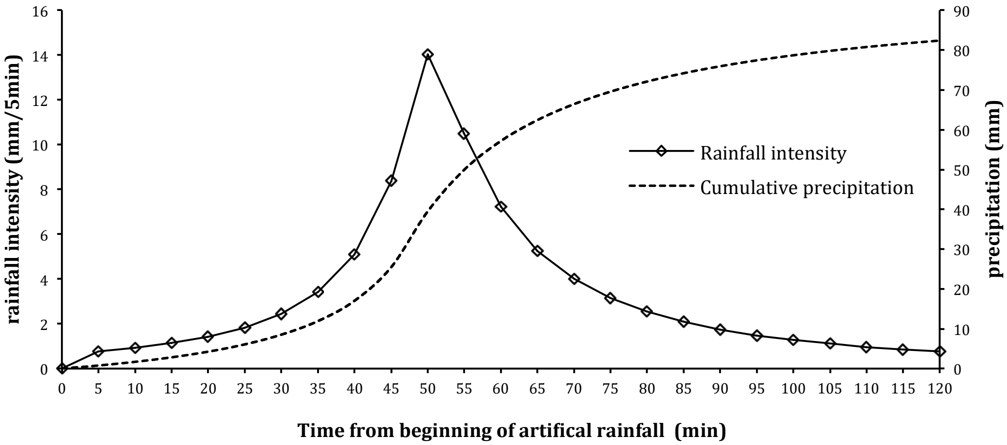

Figure 2. Design of an artificial rainfall event

2.1.5. The Artifical Rainfall System

Synthetic rainwater was applied on each of the test rigs through an artificial rainfall system that involved a tank, a pump, a dripper system, an electronic flow meter and a flow controller. A primary pipe with a diameter of 2.5 cm was used to connect the pump in the tank to the dripper system. The dripper system consisted of 6×6 mini drippers connected by flexible tubing. The flow rate of simulated rainfall was measured and controlled by a flow meter and a flow controller, respectively, which were both installed on the primary pipe.

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2.2. Methods

2.2.1. Experimental Procedure

Following the preparation of the pavement models and the synthetic rainwater, two separate rainfall events were simulated by the lab-made rainfall system. All five PA system models were tested during the first artificial rainfall event, but only the model that demonstrated the best performance in terms of Pb(Ⅱ) removal was tested in the second rainfall event. The tap was open during the first rainfall test but kept closed for 24 h during the second rainfall test except when sampling. A 7.41 L volume of synthetic rainwater was applied directly to the surface of each model to simulate the rainfall event. To maintain consistency in the comparison, the pavement model used in the second rainfall simulation, was washed with slow flowing deionized water for 2 h followed by a drying period of 5 days.

Timing commenced immediately when the artificial rainfall began. The first stormwater sample was collected when the initial flush effluent occurred in order to assess the initial effects of the PA system on the Pb^{2+} removal. Subsequent samples were collected every 5 min until the end of the first rainfall test, and every hour for up to 24 h in the second rainfall test.

At each sampling event, effluent samples were acidized with nitric acid immediately, and then stored in a refrigerator at 4℃. Pb^{2+} content in the synthetic rainwater and effluent samples were determined using Microwave Digestion and Inductively Coupled Plasma Atomic Emission Spectrometric (ICP-AES) method. Measurements of temperature, pH and conductivity followed Chinese standard methods.

2.2.2. Water Quality Data Analysis

Data obtained for the analysis were used to determine the efficiency ratio of Pb^{2+} removal the PA systems with and without a geotextile layer, as follows:

$$R_i = \frac{(C_0 - C_i)}{C_0} \times 100\%, \quad (1)$$

where: R_i is the removal rate of Pb^{2+} at sampling time i (%); C_i is the concentration of Pb^{2+} in the effluent sample collected at time i (mg/L); and C_0 is the concentration of Pb^{2+} in the synthetic rainwater (mg/L).

To evaluate the potential reuse of infiltrated stormwater as an irrigation water source in China, water quality parameters including Pb^{2+} concentration, pH, conductivity and the temperature of effluent from the PA system that provided a 24 h stormwater storage within its reservoir structure, were compared with standards for irrigation water quality (GB 5048-2005) [26] in China.

3. Results

3.1. Initial Effects

The measured and calculated results, sampling time, Pb^{2+} concentration and removal efficiency of Pb^{2+} of the stormwater runoff that infiltrated through the five test rigs during the first of the two artificial rainfall events are shown in Table 3. There was a 5 min delay in the timing of the onset of effluent between test rig A and group B (test rigs B1, B2, B3 and B4), with the latter producing a 5 min of delay before the occurrence of outflow as compared with A that did not have the geotextile layer.

The results also showed a remarkable reduction in Pb^{2+} level in the initial effluent. The mean concentration of Pb^{2+} in the initial infiltrated stormwater samples was 7.2 mg/L, which was 29 % lower than the synthetic rainwater of 10 mg/L. This suggests that the PA system has the capability to remove Pb^{2+} from the first flush effluent, regardless of whether or not the system contains a geotextile layer.

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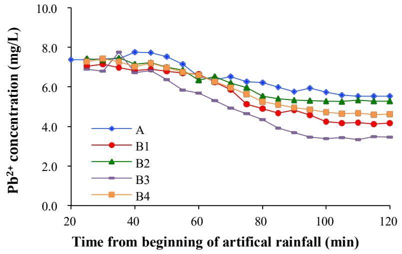
Differences were also observed in the Pb^{2+} removal rate between B and A, ranging from -0.4 % to 5.0 %. B2 using a woven geotextile at the upper level resulted in a slightly lower removal rate than A without a geotextile; and B3, which included a non-woven geotextile at the lower level resulted in the best performance. The results suggest that a non-woven geotextile membrane used at the lower level within the PA system is likely to produce a higher removal rate of Pb^{2+} from the initial effluent stream from the system.

Table 3. Experimental data of initial effluent

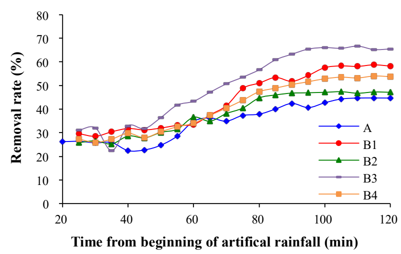
Test rig	Design parameters	Sampling time (min)	Pb^{2+} concentration (mg/L)	Removal rate (%)
A	No geotextile	20	7.378	26
B1	Non-woven, upper level	25	7.039	30
B2	Woven, upper level	25	7.421	26
B3	Non-woven, lower level	25	6.880	31
B4	Woven, lower level	25	7.267	27

3.2. Removal process of Pb(Ⅱ) during a rainfall event

Stormwater infiltrating through the test rigs were collected every 5 minutes during the first rainfall event test and observed concentrations and removal rates of Pb^{2+} are shown in Figure 3. Figure 3(a) shows that the concentration of Pb^{2+} in the effluent samples collected from A and group B decreased gradually with sampling time. Moreover, changes in Pb^{2+} levels with sampling time had similar trends. The concentration of Pb^{2+} decreased slowly in the first 50~55 min, followed by a marked reduction, and then remained relatively stable in the last 30 min. Particularly, Pb^{2+} concentration was quite a bit lower in group B than that observed in A. By contrast, there was a difference in the removal percentage of Pb^{2+} between rig A and group B, and this difference widened in the second half of the rainfall event as shown in Figure 3(b). The average removal rate of Pb^{2+} in group B was 9% higher than A. At the end of the rainfall, B1, B2, B3 and B4 removed Pb^{2+} from the stormwater with an efficiency of 58%, 47%, 66% and 54%, respectively, which were greater than A. These results validate the ability of a PA system to effectively remove Pb^{2+} from stormwater during a rainfall event, with or without a geotextile layer. The tests did not seem to suggest that the presence of a geotextile membrane within a PA system is necessary for Pb^{2+} removal; however, the results do suggest that a geotextile layer in PA system can improve the removal efficiency of Pb^{2+} during the rainfall process.



(**a**)



(**b**)

Figure 3. Results of the first artificial rainfall event: (**a**) Graph of concentration of Pb^{2+} versus time; (**b**) Graph of Pb^{2+} removal rate versus time.

A difference in removal rates between the test rigs with a geotextile layer positioned at different levels was observed. Overall, the concentrations of Pb^{2+} in the infiltrated stormwater samples collected from B3 and B4 were generally lower than that from B1 and B2, respectively. Moreover, the differences in the Pb^{2+} concentrations between B3 and B1 and between B4 and B2 increased over time. After 120 minutes of simulated rainfall, B3 and B2 had the best and worst performances for PA systems with a lower and upper geotextile layer, respectively. This result suggests that test rigs that include a lower geotextile layer are more efficient in removing Pb^{2+} from stormwater as compared

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with a geotextile layer positioned higher in the system. It also suggests that the use of a geotextile membrane at the lower level separating the reservoir structure from the sub-grade is advantageous for a PA system for Pb^{2+} removal from stormwater runoff.

For the test rigs with a geotextile layer placed at the same level but of different types, the data showed differences in performance between B1 and B2 and between B3 and B4; with the differences increasing over time. With the except of some individual sampling points, overall, the concentrations of Pb^{2+} in the water samples from B1 and B3 were found to be lower than those from B2 and B4, respectively. The average removal rate of Pb^{2+} by B1 and B3 was about 12 % higher than that average of B2 and B4 at the end of the rainfall event. The results suggest that rigs that include a non-woven geotextile layer can retain Pb^{2+} from stormwater runoff better than those containing a woven geotextile layer. In addition, the retention increases with the time regardless of its position.

3.3. Removal of Pb(Ⅱ) with a temporary storage

The results in Figure 3 show that B3, which has a non-woven geotextile at the lower level with direct runoff drainage, had a better Pb^{2+} removal performance than the other rigs, during the simulated rainfall. To understand fully the performance of this PA system that provides temporary storage for stormwater in the reservoir, parameters including temperature, pH, conductivity and Pb^{2+} concentration of the stored stormwater were monitored for 24 h during and after the second artificial rainfall. The results are shown in Figure 4. Throughout the 24 h of stormwater storage, the temperature of the effluent samples fluctuated from only 20.1℃ to 22.4℃. Both the pH and conductivity levels increased with sampling time, but at different rates. The pH levels of effluent increased faster in the first 10 hours and remained relatively stable in the later stages, to 8.2 by the end of the experiment. By contrast, the conductivity levels increased significantly with sampling time and reached up to 111.5 μg/cm after 24 h, which was almost 3.5 times the value for first water sample (Figure 4(a)).

Because the intensity, duration and pattern of the second artificial rainfall event was the same as the first event, the time of initial outflow occurrence and the concentration of Pb^{2+} in the first flush effluent was roughly similar to that collected from artificial rainfall event 1. The concentration of Pb^{2+} in the initial effluent was slightly higher than that measured in the rainfall event 1, but nearly equivalent to the mean concentration of group B. However, there was a greater change in the Pb^{2+} concentration throughout the 24 h of storage as compared with the 120 min of simulated rainfall (as shown in Figure 4(b)). Overall, the Pb^{2+} concentration in stormwater decreased markedly in the initial 7 h, then continuously decreased with increasing detention time, and finally remained relatively stable in the last 4 h. More than 98% of the Pb^{2+} ions were removed from the stormwater runoff after 24 h storage in reservoir. The result indicates that the Pb^{2+} removal efficiency by the B3 providing a temporary storage of stormwater is much higher than that if the design did not provided storage - by nearly 33 %.

The regression between the removal rate and the sampling time were further analyzed and the results showed that there was a significant logarithmic correlation between them. Equation (2) is the logarithmic formulae.

$$R_{Pb} = 14.57\ln(t) + 57.33\ (R^2 = 0.90), \tag{2}$$

where: R_{pb} is the predicted removal rate of Pb^{2+} at sampling time t (%); and t is the residence time of stormwater runoff in the reservoir structure of PA system (hour).

This result indicates that the Pb^{2+} removal percentage is strongly dependent on the residence time, the longer the residence time is, and more Pb^{2+} ions can be removed.

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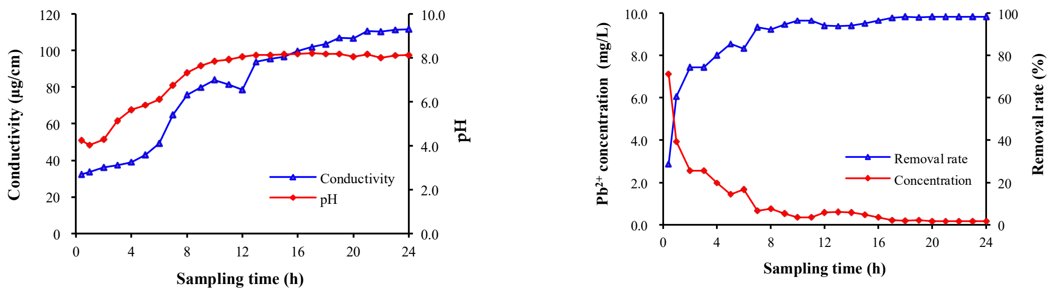

(**a**) (**b**)

Figure 4. Results of the later artificial rainfall event: (**a**) Conductivity and pH values of the water samples; (**b**) Graph of concentration and removal rate of Pb^{2+} versus time.

4. Discussion

4.1. Difference in initial effects between PA systems with and without a geotextile

The 5 min delay in the timing of initial effluent discharge between PA systems with and without a geotextile layer suggests that the presence of a geotextile membrane in the PA system has a direct effect on its hydraulic performance because of the lower permeability of the geotextile layer as compared to other pavement layers. The difference in the Pb^{2+} removal efficiencies between PA systems with and without a geotextile is small, but B3 has the highest removal rate. This may be caused by the different geotextile types and by the different levels of placement of the geotextile, but is likely due in larger part to the relatively short period of residence time. Based on the results, it is recommended that for highly efficient removal of Pb^{2+} from the initial runoff, PA system using a non-woven geotextile membrane at the lower level separating the reservoir from the sub-grade may be appropriate. But it should be noted that the Pb^{2+} removal rate in this case is not as high as the result reported by Zhao et al. [8] (but they used synthetic stormwater that combined metals organics).

4.2. PA systems offering direct drainage of stormwater

4.2.1 Influence of a geotextile layer

A similar varying tendency in the Pb^{2+} concentration over time for both groups suggests that the use of geotextile layer within PA system is not able to change the basic tendency of removal Pb^{2+} from stormwater runoff as compared to that without a geotextile layer during rainfall. The only difference in the comparison for the PA systems is that the system with a geotextile layer is producing generally lower Pb^{2+} concentrations in the effluent at each sampling point. This implies that some water quality benefits are gained by a PA system incorporating a geotextile layer. This is consistent with Mullaney et al. [13] in which they applied a total of 10 years of metals to their system, although the mechanism for removal was not made obvious.

According to the previous studies that explored the use of natural limestone and porous asphalt surfaces for the removal of heavy metals from stormwater runoff or aqueous solutions [27-31] and the pavement models used herein, the reduction of Pb^{2+} concentration in the effluent samples observed in this study is possibly due to several processes occurring within PA system: (1) the adsorption onto materials at the air voids within pavement layers including the bitumen in the porous asphalt mixture and limestone gravel in the reservoir; (2) the precipitation between the lead actions and the mineral in the limestone within the reservoir; and (3) the retention of Pb^{2+} by the geotextile layer.

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4.2.2. Influence of the geotextile position

During 120 min of artificial rainfall, the removal rates of Pb^{2+} by the test rigs containing a geotextile placed at the lower level are generally higher overall than those including a geotextile at the upper level. This result indicates that the position level of placement of the geotextile within the PA system is important to Pb^{2+} removal. The better removal performance of B3 and B4 may be attributed to a buffering function by the lower geotextile layer to the stormwater stored in the reservoir.

When the stormwater flows through the reservoir and then through the geotextile, a sharp reduction in the flow rate of stormwater occurs above the surface of the geotextile, which is a result of its much lower infiltration rate than the gravel reservoir with 35 % void space. This extends the residence time between the stormwater and the limestone gravel in the reservoir before the stormwater discharge. Because of the extension of residence time, the interactive reaction of Pb^{2+} ions and limestone gravel in the reservoir is promoted. Based on the findings given by previous researchers [27-29,32], for the PA system containing a lower geotextile layer, the adsorption processes of Pb^{2+} occur with the dissolution of limestone surfaces at the mineral-stormwater interface within the reservoir. This leads to the formation of lead-containing crystals growing on the surface of the calcite (the main component of limestone) and in the pores of the limestone gravel resulting in the decrease of Pb^{2+} concentration in the outflow. By contrast, the upper geotextile layer in the PA system located between the base course and the reservoir do not result in improving the system removal capacity because the residence time for stormwater and limestone within the reservoir may not be affected - even through the upper geotextile can effectively slow the stormwater flow velocity in the base course as well.

4.2.3. Influence of the geotextile types

The difference in Pb^{2+} removal efficiencies between the PA systems containing a non-woven geotextile and those of a woven geotextile is a reflection of the suggestion that various types of geotextile membranes used in PA systems can directly affect the system removal capacity of Pb^{2+}. Cook and Scholz note in their studies [4,33] that non-woven geotextile is the preferred geotextile type for permeable paving applications because of its better filtration and separation properties than woven geotextile. But no specific experimental data is presented for its removal capacity of heavy metals from stormwater or aqueous solutions. The results therefore, indicate that use of a non-geotextile membrane within a PA system is more appropriate than a woven geotextile for both the hydraulic properties and pollutant removal performance.

On the basis of the above results, it can be suggested that the use of a non-woven geotextile membrane at the lower level separating the reservoir structure and the sub-soil is more appropriate for PA systems in order to improve performance for removing Pb^{2+} from stormwater runoff during a rainfall event. Note that the concentration of Pb^{2+} in the discharge from B3, containing a non-woven geotextile at the lower level resulted in the best Pb^{2+} removal performance after 120 min rainfall - but this does not meet the Standard for Irrigation Water Quality (GB 5084-2005) [26] in China. This means the stormwater runoff discharged from PA system with a perfect geotextile layer is still too toxic for use as irrigation water after a rainfall event, unless it is further treated by more advanced processes.

4.3. PA system providing a temporary storage of stormwater

4.3.1. Influence of residence time on the pH and conductivity

When viewing the curves of pH and conductivity during the second artificial rainfall in Figure 4(a), it can be clearly seen how the pH and conductivity increase with residence time (or sampling time). Because the stormwater penetrated into the PA system is stored in the reservoir, the increase in the pH and conductivity in the effluent samples is possibly attributed to the surface dissolution

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growth process of limestone gravel, as well as the formation of lead-containing precipitates. Under acidic conditions, the surface limestone dissolution in stored stormwater supplies a number of ions, such as Mg^{2+}, Ca^{2+}, OH^- and CO_3^{2-}, which increase the conductivity. Meanwhile, adsorption and precipitation processes between limestone and Pb^{2+} ions form lead-containing products that therefore, increase both the conductivity and pH value of the stormwater. This has been investigated and described by previous works [27,29,34]. Moreover, Karageorgiou et al. [35] found that the dissolution of calcite is a fast process that initiates the reaction of metal cations and the limestone, so that both the conductivity and pH increase quickly in the early stages of the experiment.

4.3.2. Influence of residence time on the Pb(Ⅱ) removal

The removal performance of B3 when providing direct stormwater drainage was not as good as the performance of the same system when providing the stormwater with temporary storage. In addition, a strong logarithmic correlation between the Pb^{2+} removal rate and the residence time was observed, indicating that the residence time directly influences the removal process of Pb^{2+} ions. These apparent changes are probably due to the sorption processes of Pb^{2+} ions occurring in the reservoir. Various researchers [27-29,34,36] have confirmed that the removal of Pb^{2+} ions from aqueous solutions by natural limestone is mainly due to both the adsorption and chemical precipitation that is closely related to the dissolution of the solid surface.

This work suggests that the dissolution of surface limestone in stormwater under an acidic condition (initial pH = 4.2) constitutes the first step for Pb^{2+} removal and this leads to a rapid increase in pH and conductivity in stormwater. The removal of Pb^{2+} ions below pH 5.3 may be attributed to the possible ion-exchange reactions between the Pb^{2+} ions in the stormwater and Ca^{2+} ions of limestone, as well as through the formation of lead-containing precipitates (perhaps lead-hydroxide) [28]. Also, the removal rate increases with increasing pH value. The enhanced removal of Pb^{2+} ions above pH 5.3 can be attributed to the precipitation of lead carbonate, which leads to a higher removal capacity of the system [34,37]. Thus, the removal process is predominantly governed by the precipitation of lead carbonate since the stormwater pH remains above 5.3 for more than 20h of the 24h storage period.

Moreover, the findings by Németh et al. [28] verified that the precipitation forms both on the surface and in the pores of minerals. In addition, Sdiri et al. [38] pointed out that lead carbonate is more stable above pH 6.0. This perhaps is the reason why the removal amount of Pb^{2+} ions increases with longer residence time created with storage, and why the removal rate increases more quickly in the initial stages, but more slowly (eventually stabilizing) at a higher level in the later stages.

4.3.3. Evaluation of stormwater quality

With rapid urbanization in China, irrigation water quality has become a serious issue and heavy metal contamination in particular, presents a great risk for irrigation water because of the potential threat to living organisms and humans [10,29] if left untreated. In this study, the PA system containing a non-woven geotextile layer at the lower level and a temporary storage is suggested as an efficient technology for the treatment of dissolved lead in stormwater runoff. But it is essential and important to determine an appropriate storage time for stormwater runoff when considering the possibility reusing the discharge as irrigation water. The acceptable levels of temperature, pH and lead concentration for irrigation waters in China (GB 5084-2005) are 35 ℃, 5.5~8.5 and $\leq$ 0.2 mg/L, respectively. It should be note that these standards refer to a total, or aggregate value for maximum levels of pollutants in irrigation waters.

Throughout the time in storage, the temperature of the effluent was between 20 ℃ and 23 ℃, which is well below the limit indicated; the pH values did not exceed the limited range of 5.5~8.5 after 4 hours of storage; and the Pb^{2+} concentration did not exceed the limit of 0.2 mg/L after 20h. These results recommend that the stormwater runoff drained from the tested PA system is appropriate for use as irrigation water at least after 20h of storage in the reservoir.

5. Conclusions

Laboratory studies were designed to study the removal of Pb^{2+} ions in stormwater runoff from porous asphalt pavement systems with and without a geotextile layer, two different geotextile types, and two position levels within the pavement structure. In addition, the experiments included an additional design parameter dealing with stormwater detention in which observations were made when direct drainage of stormwater was allowed, and again when the system was constrained to provide temporary stormwater storage.

The decrease in concentration of Pb^{2+} ions in the initial effluents suggest that the use of a geotextile layer in PA system has only a small effect on the removal efficiency of Pb^{2+} ions from initial stormwater runoff, but it does provide a longer delay to the onset of discharge. Similar tendencies in Pb^{2+} ion removal rates over the sampling period were observed by the systems with or without a geotextile layer, and nearly 45~65 % Pb^{2+} ions were successfully removed after 120 min of rainfall. It indicates that the presence of a geotextile layer within PA system does not necessarily change the basic tendency for Pb^{2+} removal over time, but is able to improve the removal rate effectively overall. Moreover, different geotextile types and their position in PA system can directly affect the removal rate of Pb^{2+} ions. It is therefore recommended that for high Pb^{2+} removal rates, using a non-woven geotextile membrane at a lower level within PA system is appropriate.

The higher removal capacity of Pb^{2+} ions by a PA system with a non-woven geotextile layer at the lower level and with 24 hours of residence time in temporary storage suggests designing with a temporary storage for stormwater in the reservoir is important to a PA system's performance, as an effective LID technology for stormwater management. Stormwater quality analysis suggests that the stormwater runoff discharged from a PA system with a lower positioned non-woven geotextile layer that provides at least 20 hours of storage in the reservoir course may be used as irrigation water.

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