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Jiang, W, Sha, A, Xiao, J et al. (2 more authors) (2015) Experimental study on filtration effect and mechanism of pavement runoff in permeable asphalt pavement. Construction and Building Materials, 100. pp. 102-110. ISSN 0950-0618

https://doi.org/10.1016/j.conbuildmat.2015.09.055

Experimental Study on Filtration Effect and Mechanism of Pavement Runoff in Permeable Asphalt Pavement

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Abstract: In this study, self-developed laboratory apparatus was devised to investigate filtration effects of permeable asphalt pavements (PAP) and their mechanisms. The filtration effect of PAP is specified by measuring 16 pollutant indices in influent and effluent samples. Results show that the PAP is highly effective in removing copper (Cu), zinc (Zn), lead (Pb) and Cadmium (Cd), and relatively less effective on petroleum pollutants (PP), animal & vegetable oil (AVO), biochemical oxygen demand (BOD), chemical oxygen demand (COD) and ammonia nitrogen (NH_4-N). The effect on removing total phosphorus (TP), chloride (Cl^-) and total nitrogen (TN) is marginal. Influences of sampling time on pollutant concentrations were investigated as well, which indicates that the increases of sampling time reduce the pollutant concentrations to some extent. The decreases of pollution concentrations can be attributed to the interception and physisorption of porous materials used in the PAP.

Key words: permeable asphalt pavement, porous asphalt concrete, pavement runoff, filtration effect, filtration mechanism

1 Introduction

Permeable Asphalt Pavement (PAP), in which water on the pavement surfaces can enter the pavement structures and finally infiltrate into underground, consists of porous asphalt concrete (PAC) and open graded stones[1, 2]. Compared with conventional impervious asphalt pavements, PAP can effectively recharge groundwater, thereby alleviate water table sinking and land subsidence caused by over-exploitations of groundwater. Furthermore, PAP can adjust atmospheric humidity, which benefits plant growing and mitigates urban heat island effect. Therefore, PAP is known as a breathability pavement [3-5]. PAP can reduce the stresses on urban drainage systems by decreasing the peak flow during rainstorms. Additionally, it can reduce tire noises and enhance driving safety [6-8]. In general, PAP has attracted more and more attentions in pavement engineering due to its extraordinary benefits in ecological and environmental fields.

However, pavement runoff could permeate into subgrade through pavement structures with large amount of pollutants. Heavy metal, nitrogen, phosphorus and oil found in these pollutants are difficult to degrade in the environment. Once these pollutants infiltrate into subgrade, they may cause groundwater contamination. Since it is difficult to restore water quality after groundwater contamination, domestic water and ecological environment will be severely affected [1, 9-12]. Therefore, the quality of the water permeating into the subgrade needs to be carefully assessed, especially for the road sections with heavy traffic and potentially high concentrations of pollutants (e.g. urban permeable pavements).

Many studies have identified permeable pavements are effective to retain pollutants and preserve the natural hydrologic functions [13-15]. Rushton B T [16] compared the pervious paving and impervious paving of parking lot at the Florida Aquarium in Tampa, USA. Results indicated that pervious paving with a swale reduced the pollutant loads by at least 75% for metals and total suspended solids (TSS) compared to asphalt paving without a swale. Pagotto C et al. [17] reported that porous asphalt exfiltrate contained lower lead (Pb) and copper (Cu) concentrations than conventional asphalt based on the results of the field investigation. Brown C et al. [18] investigated the solids removal abilities in two types of permeable pavement: porous asphalts and open-jointed paving blocks. Results illustrated that both types of pavement were capable of removing suspended solids with an elimination ratio ranging from 90% to 96%. Barrett M E [19] assessed the effects of Permeable Friction Courses on the filtration of highway runoff. Concentration reductions were observed for TSS, Pb, Cu, and zinc (Zn).

There have also been studies outlining the potential water quality improvements of interlocking concrete permeable pavement and other type permeable pavements. Nitrogen removal effect and applications of four permeable pavements: permeable interlocking concrete pavements (PICP), pervious concrete（PC）, concrete grid pavers (CGP) filled with sand and dense-graded asphalt pavements were compared[20,21]. Lower concentrations of Zn, ammonia nitrogen (NH_4-N), total nitrogen (TN) and total phosphorus (TP) were observed in permeable pavements than dense-graded asphalt pavements. Drake J et al. [22] compared the water quality of effluent from two Interlocking Permeable Concrete Pavements, a pervious concrete pavement with runoff from a control asphalt pavement. The results showed that the permeable pavement provided excellent stormwater treatments to petroleum hydrocarbons, TSS, Cu, iron (Fe), manganese (Mn), Zn, TN and TP by reducing mean concentrations (EMC) and total pollutant loadings. Brattebo B O et al. [23] evaluated the performance of four permeable pavement systems，including two types of flexible plastic grid systems, a concrete block lattice and a small concrete block. Results showed that the infiltrated water contained less Cu, Zn and motor oil as compared with direct surface runoff. Gilbert J K et al. [24] compared the quality and quantity of stormwater runoff among a dense-graded asphalt pavement, an interlocking concrete permeable pavement and a crushed-stone permeable pavement. It was found that the permeable pavements runoff have lower concentrations of suspended solid (SS), TN, nitrate-nitrogen (NO_3-N), NH_4-N, TP, Zn, Pb and Cu than dense-graded asphalt pavements runoff.

Previous studies conducted to evaluate the PAP filtration effect of pavement runoff were mainly concentrated on the permeable interlocking concrete pavements and porous concrete. The filtration effect of PAP which consists of PAC, open graded stones and natural sand is not well considered. Besides, previous researches were mainly based on the field investigation. Among the available data about PAP filtration effect of pavement runoff, the majorities were focused on certain types of pollutants and there is no comprehensive study for water quality. For this purpose, a laboratory apparatus was developed in this study to simulate the filtration process and gather the infiltrated water from the PAP structure. Concentrations of 16 pollutants in the influent and effluent water samples were assessed to study the filtration effect by the PAP on different pollutants. Furthermore, the removal mechanisms of pavement runoff in the RAP were analyzed. The developed test apparatus can be used in future study, to investigate the filtration effects of PAP with different layer configurations and materials to optimize the PAP design.

2 Pollutants in urban pavement runoff

2.1 Sources and types

The sources of pollutants in urban pavement runoff can be from vehicle and pavement themselves, or from exposed surface of surrounding pavements, which include urban pavement runoff after rain shower.

On one hand, pollutants in urban pavement runoff come from the vehicle and pavement themselves [25-27]. For instance, the additions of cadmium salt and zinc into tires and lubricating oil make the tire abrasion and lubricating oil burning the main sources of zinc and cadmium pollutants in urban pavement runoff. Besides, zinc-bearing dusts caused by the wide use of galvanized automobile sheets aggravate the zinc pollutants in urban pavement runoff [28]. Heavy metal pollutants such as Cu, Pb, Cr and Cd, are generated by the abrasions of vehicle brake pads and body metal components [29-31]. Petroleum pollutants (PP) coming from seeping of bitumen and volatilizing of bitumen components at high temperature are not negligible [32]. In cold regions, chlorine salts in snow-dissolving agents is a source of pollutant [33].

On the other hand, the pollutants may come from surrounding natural and built environment. Adjacent buildings, greenbelts and plants around pavements accumulate to the atmospheric pollutants in dry climates. These pollutants blend into the pavement runoff through rain shower and eventually infiltrate into the subgrade [34]. The applications of waterproof materials, metallic materials and drainage pipelines to buildings result in some heavy metal pollutants (such as Cu, Pb, Zn) and PP. Organic matters and nitrogen & phosphorus nutrients produced by fallen leaves, animal waste and pollen, as well as applying chemical fertilizer and pesticides are treated as pollutants as well.

Generally, the ingredients and concentrations of pollutants in pavement runoff are closely related to pavement locations (residential, commercial, industrial and suburb), climates (temperature, humidity, rainfall and catchment area) and traffic conditions (traffic volume and type).

2.2 Pollutant Indexes

Based on the above discussions, 16 pollutants are selected for the comprehensive evaluation of water quality in this study, including physicochemical indexes (pH value, turbidity, SS), nutrient and organic pollution indexes (COD, BOD, NH_4-N, TN, TP, PP, animal & vegetable oil (AVO)), heavy metal pollutant indexes (hexavalent chromium (Cr^{6+}) , Cu, Zn, Pb, Cd and chloride (Cl^-)).

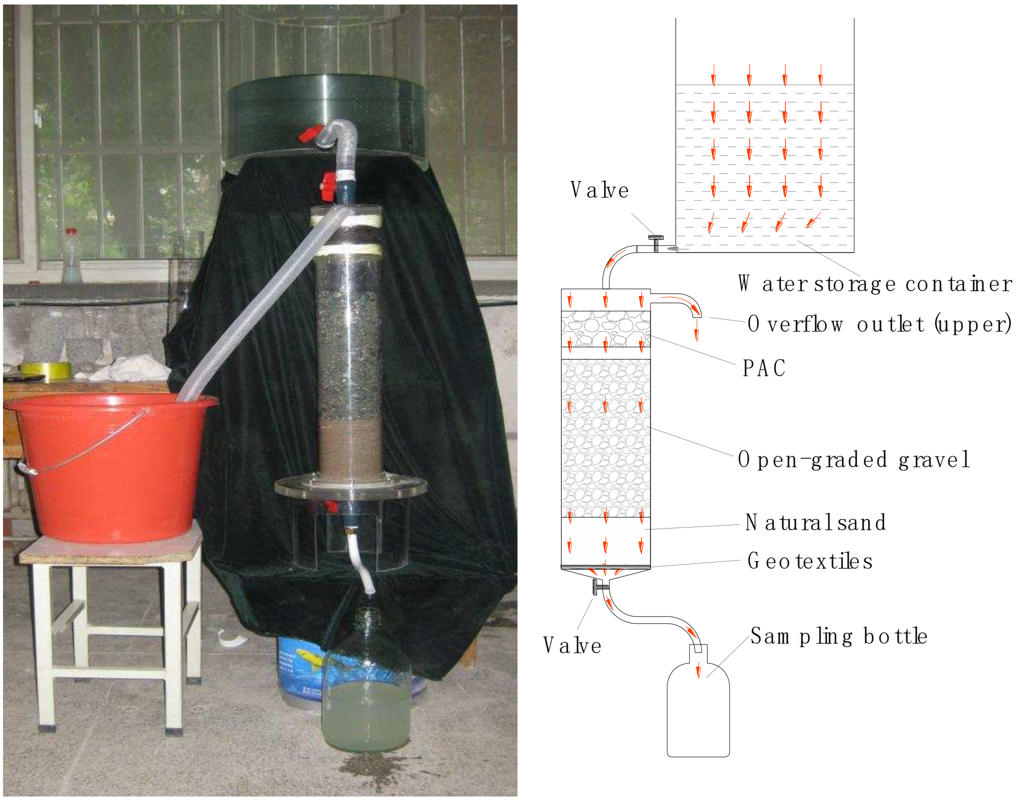
3 Test equipment and scheme

3.1 Permeable pavement infiltrate apparatus

The developed laboratory apparatus is shown in Fig.1. A 60L water storage container (40cm in diameter and 50cm in height) and a long cylinder (10cm in inner diameter and 52.5cm in height) are used. A layer of geotextile is paved at the bottom of the long cylinder to prevent the erosion and infiltration of fine particles. The top of cylindrical tube is connected to a PAC Marshall specimen (without removing the mold).

The water storage container is connected to the long cylindrical tube by a flexible pipe with valve. When the valve is open, the water in the storage container flows into the PAC Marshall specimen, and then permeates into the pavement materials inside the long cylindrical. The water eventually seeps from the bottom of the long cylindrical tube into a sampling bottle (2.5L) via another flexible pipe with a valve.

In order to eliminate the effects of water pressure on the penetration process, an overflow outlet is set on the top of the long cylindrical tube to ensure the water head remains unchanged during the whole test.



a) Test apparatus b) Schematic

Fig.1. Permeable pavement infiltrate apparatus

The apparatus can be used to imitate permeable pavement infiltrate with combination of different thickness and pavement material. The water seeping from the bottom of the long cylindrical tube can be collected for analysis. Additionally, other materials could also be tested for their filtration effect as well as permeation rate by this apparatus.

3.2 Materials

3.2.1 Porous Asphalt Concrete (PAC)

The PAC specimen used in this study is mixed by bitumen with a penetration grade of 60/80, crushed diabase aggregates, limestone powder, and high viscosity bitumen modifiers (TAFPACK-SUPER, 12% TPS). Mixtures were prepared by Marshall compaction (50 blows per side). According to the D3203 of ASTM [35]，the void content of the PAC specimen is controlled at around 20.1%. The gradation of the PAC is presented in Table 1.

Table 1 Gradation of PAC for testing

Mixtures	Passing (by Mass) under different sieve size (mm) /%										Binder content (%)
	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	
PAC-13	100.0	90.1	61.3	23.4	14.8	12.7	10.8	8.3	7.0	5.0	4.6

3.2.2 Open-graded gravel

Crushed diabase aggregates were used as the open-graded gravel. In consideration of the long cylindrical tube dimensions, the maximum aggregate size of open-graded gravel is 9.5mm. The gradation of the open-graded gravel is presented in Table 2. Open-graded gravel filled in the long cylinder were packed in layers of 5cm thickness each with preparatory tamping. Because of restriction of further compaction in the long cylinder, the open-graded gravel was not in the state of fully compacted. The air void content is 39% with stacking state in accordance with Chinese specification JTG E42—2005 [36].

Table 2 Gradation of open-graded gravel for testing

Sieve Size (mm)	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing (%)	100	40.5	27.1	16.9	10.8	4.4	2.2	0.8

3.2.3 Natural sand

Natural sand was used for the cushion layer. The gradation of the natural sand is presented in Table 3. The fineness modulus of the natural sand is 2.316 and the mud content is 0.64%. The bulk specific gravity is 2.598g/cm^3. Natural sand filled in the long cylinder was packed in layers of 5cm thickness each with preparatory tamping. Because of restriction of further compaction in the long cylinder, natural sand was not in the state of fully compacted. Air voids content is 41.1% with stacking state in accordance with Chinese specification JTG E42—2005 [36].

Table 3 Gradation of natural sand for testing

Sieve Size (mm)	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing (%)	100.0	95.3	87.3	82.5	66.3	17.6	1.9	0.4

3.2.4 Geotextiles

Geotextiles, for permeability and separation purpose, was set underneath the natural sand cushion layer. On the one hand, the geotextiles could prevent the loss of the fine particles in the natural sand under the scouring of flowing water. On the other hand, the geotextiles could avoid voids blocking caused by the soil particles in subgrade entering the upper pavement structure under capillary actions. The main properties of geotextile are listed in Table 4.

Table 4 Properties of geotextiles

Properties	Test result	Testing methods
Mass per unit area , g/m^2	120.2	ISO 9864
Thickness, mm（Under pressure of 2kpa）	1.203	ISO 9863
Tensile strength, kN/m	9.3	ISO 10319
Rate of elongation, %	43	ISO 10319
CBR bursting strength, N	1575	ISO 12236
permeability, mm/s	8.9	ISO 11508

3.3 Urban pavement runoff collection

The rainfall and pavement runoff samples used in this study were collected at round 22:00 on 6th August 2014 after 2 hours light rainfall. It should be noted that the half-month continuous dry weather with high temperature before this rainfall makes the pollutants concentration of the pavement runoff extraordinarily high.

Three collection sites were selected near Chang'an University, Xi'an, China, as shown in Fig.2. The first site locates at the intersection of Southern 2nd Circular Road and Wenyi Road. This site was selected since the southern 2nd Circular Road is a city expressway with 100 000 vehicles per day, which means the pollutants mainly come from the traffic. The second site locates in the Wenyi South Road surrounded by pets and plants markets. In this site, pavement runoff pollutants are mainly from animal and plant organic matters, domestic sewages and plant decays. The third site is located at the intersection of Yucai Road and Cuihua Road with lots of chophouses surrounded. Apart from the pollutants from traffic, domestic sewages and eatery offal are the main pollutants at this location.

Dustpans were used for runoff collection 20 minutes after rainfall. The collected pavement runoff from these sites was stored in three 50L plastic buckets clearly marked for laboratory analysis.

Fig.2. Three pavement runoff collection sites

3.4 Test scheme

In order to maximize the types of pollutants in the water sample, the pavement runoff samples collected from three sites were mixed in equal volumes. The mixed water sample was filtered by a 0.15mm sieve to remove the plant leaves and large particulates, thereby reducing the probability of apparatus being clogged.

About 60L of water sample was poured into the water storage container. An electric mixer was used to avoid pollutants sediment during the test, as shown in Fig.3. As a result, the water sample between upper layer and lower layer maintained a uniform color during the whole test. After the test, no sediment was found at the bottom of the water storage container, which means no evident sedimentation or separation occurred in the water storage container.

a) Electric mixer **b) pavement runoff water**

Fig.3. Electric mixer and pavement runoff water in the water storage container

The PAP specimen consists of a 6.3cm thick PAC layer, a 30cm thick open-graded gravel layer and a 15cm thick natural sand layer. Water sample was collected directly form the outlet of water storage container at the beginning and designated as S1. Then open the valve of the water storage container and the bottom valve of the long cylindrical tube and start to collect initial seeped water from the outlet of the long cylindrical tube (designate the collected sample as S2). Then, the seeped water samples were collected under various infiltrate time varying from 10min to 70min and designated as S3 to S6 (Table 5). The total test time is determined by the capacity of the water storage container. In consideration of larger changes of pollutant concentrations at the early stage， the sampling time interval is relatively short (e.g. 10mins)and as the test continue, the sampling time interval is increased (e.g. 30mins). Finally, the remaining water in the water storage container was collected and designated as E1. All the water samples (2500ml for each) were stored in sampling bottles and temporarily placed in a sink filled with 0°C ice water. The pollutant concentrations of these samples were assessed within 24 hours.

Table 5 Designation and illustration of water samples

Designation of water samples	Illustration of water samples
S1	Collected directly form water storage container at beginning of test
S2	Initial seeped water sample collected form outlet of long cylindrical tube
S3	After 10 min seepage, collected form outlet of long cylindrical tube
S4	After 20 min seepage, collected form outlet of long cylindrical tube
S5	After 40 min seepage, collected form outlet of long cylindrical tube
S6	After 70 min seepage, collected form outlet of long cylindrical tube
E1	Remaining water in the water storage container

4 Test results and discussion

4.1 Uniformity evaluation of test water

As shown in Table 6, the pollutants concentration of S1 and E1 are similar, indicating that the runoff water in the water storage container was uniform under the agitation of electric mixer.

Table 6 Pollutants concentration of S1 and E1

Test index	S1	E1
pH Value	7.17	7.16
Turbidity, NTU	9750	10600
SS, $mg \cdot L^{-1}$	785	796
COD, $mg \cdot L^{-1}$	532	501
BOD, $mg \cdot L^{-1}$	218	228
NH_4-N, $mg \cdot L^{-1}$	0.929	0.948
TN, $mg \cdot L^{-1}$	10.3	11.6
TP, $mg \cdot L^{-1}$	0.39	0.408
PP, $mg \cdot L^{-1}$	0.87	0.77
AVO, $mg \cdot L^{-1}$	6.69	6.08
Cu, $mg \cdot L^{-1}$	0.06	0.05
Zn, $mg \cdot L^{-1}$	0.46	0.44
Pb, $mg \cdot L^{-1}$	0.0427	0.0411
Cd, $mg \cdot L^{-1}$	0.00219	0.00192
Cr^{6+} , $mg \cdot L^{-1}$	0.036	0.036
Cl^{-}, $mg \cdot L^{-1}$	37.7	36.2

4.2 Filtration effect of PAP on pavement runoff

Pollutant concentrations in the pavement runoff samples before and after the PAP filtration are listed in Table 7 against different sampling time between 10min to 70min.

Table 7 Pollutants concentration of pavement runoff before and after infiltrated in PAP with different sampling time

Test index	S1	S2	S3	S4	S5	S6
pH Value	7.17	7.18	7.13	7.14	7.17	7.18
Turbidity, NTU	785	110	107	96	91	77
SS, mg·L^{-1}	9750	2500	2000	1900	1500	1250
COD, mg·L^{-1}	532	258	240	235	226	226
BOD, mg·L^{-1}	218	111	106	95.7	93.4	92.8
NH_4-N, mg·L^{-1}	0.929	0.96	0.638	0.611	0.608	0.602
TN, mg·L^{-1}	10.3	10	10.6	10.7	10.9	10.6
TP, mg·L^{-1}	0.39	0.371	0.326	0.307	0.297	0.271
PP, mg·L^{-1}	0.87	ND0.04[a]	ND0.04	ND0.04	ND0.04	ND0.04
AVO, mg·L^{-1}	6.69	3.86	3.78	3.13	2.46	2.32
Cr^{6+} , mg·L^{-1}	0.036	0.035	0.033	0.029	0.021	0.02
Cl^-, mg·L^{-1}	37.7	38.2	37.4	36.2	36.2	35.2
Cu, mg·L^{-1}	0.06	ND0.05	ND0.05	ND0.05	ND0.05	ND0.05
Zn, mg·L^{-1}	0.46	ND0.05	ND0.05	ND0.05	ND0.05	ND0.05
Pb, mg·L^{-1}	0.0427	ND0.001	ND0.001	ND0.001	ND0.001	ND0.001
Cd, mg·L^{-1}	0.00219	0.00100	0.00092	0.00065	0.00056	0.00038

a：ND represents Not Detected. The number after ND is the limit value that can be detected.

4.2.1 pH value

From Table 7, the water specimen shows no significant changes in the pH values before and after infiltrating through PAP.

4.2.2 Suspended solid (SS)

Fig.4 shows SS concentration of pavement runoff before and after infiltrated in PAP with different sampling time. It was found that the SS concentration of pavement runoff decreased sharply by 86.0% after initial infiltrate in PAP, and continued to decrease but very slightly over sampling time. The total reduction was 90.1% with the sampling time at 70min. This is due to the fact that SS in pavement runoff mainly refers to the particle with grain size larger than 0.45μm. In the process of infiltrate, these particles were easy to be intercepted and adsorbed by PAP materials.

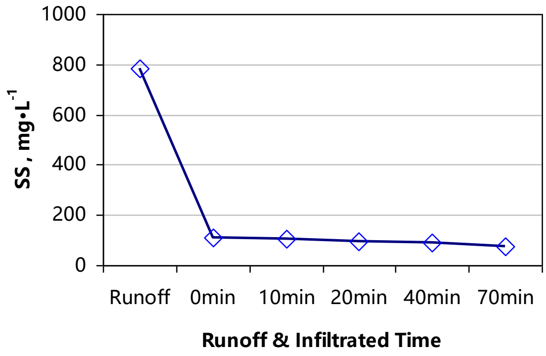


Fig.4. SS concentration of pavement runoff before and after infiltrated in PAP with different sampling time

4.2.3 Turbidity

Turbidity is the cloudiness or haziness of a fluid caused by large number of individual particles that are generally invisible to the naked eyes. The unit of turbidity from a calibrated nephelometer is called Nephelometric Turbidity Units (NTU). Generally, high concentration of SS indicates great turbidity of the fluid. Thus, similar tendency to the SS concentrations was observed for turbidity as shown in Fig.5. A sharp decrease of turbidity (74.4%) was observed from original runoff sample (S0) to the initial seeped water (S1). With the increase of the sampling time, the turbidity shows a slight downwards tendency and reached 87.2% of the original value (i.e. turbidity of S0).

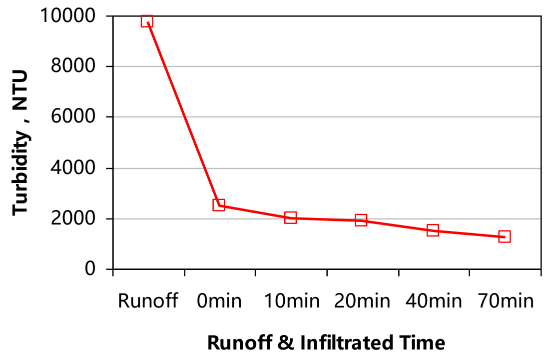


Fig.5. Turbidity of pavement runoff before and after infiltrated in PAP with different sampling time

4.2.4 Chemical Oxygen Demand (COD) & Biochemical Oxygen Demand (BOD)

COD is the amount of organic compounds in water, which indicates the mass of oxygen consumed per liter. The higher the value of COD the heavier pollution of the water. BOD is the amount of dissolved oxygen needed by aerobic biological organisms in water body to break down organic materials, which indirectly indicates the relative amount of organic matter. Fig.6 shows the COD and BOD in pavement runoff with various sampling time.

The results illustrate that the COD and the BOD decreased significantly after the runoff was infiltrated through the PAP, and largely remained stable with the increase of sampling time. The decreasing amplitudes of COD and BOD were around 50% for S2, and around 55% for S6. The decreases of COD and BOD can be attributed to the interception and adsorption of porous materials used in the PAP.

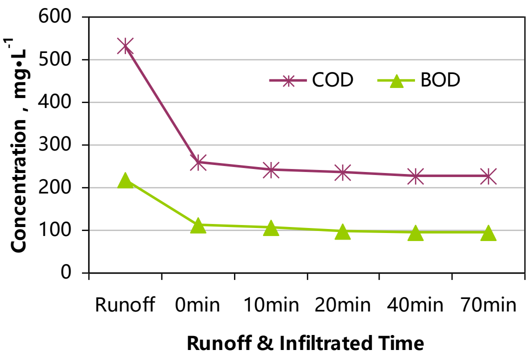


Fig.6. COD and BOD of pavement runoff before and after infiltrated in PAP with different sampling time

4.2.5 Total nitrogen (TN) & ammonia nitrogen (NH_4-N)

Nitrogen in pavement runoff usually comes from industrial emissions and sewage decomposition, and mainly exists in the form of organic nitrogen and NH_4-N. The pollutant index TN is analyzed by considering both of these two forms. Generally, the organic nitrogen concentration of pavement runoff is remarkably higher than the concentration of NH_4-N.

It is found from Fig.7 that the NH_4-N concentration of pavement runoff decreased by 34% with the sampling time increase from 20min to 70min. The results suggest that, on one hand, only a small amount of NH_4-N could be removed because of the interception and adsorption by PAP materials; on the other hand, NH_4-N removal efficiency is low which may be caused by short infiltrate time or weak adsorption ability of the PAP materials. It is interesting that NH_4-N concentration has a slight increase with the sampling time at 0 min. This increase is owing to the existence of nitrogen in the cushion layer constructed by natural sand containing sediments of animal and plant waste.

As shown in Fig.7, the PAP has very limited effect on the TN removal. The possible reason is that the NH_4-N concentration is less than 10% of TN (concentration of TN is 10.3 mg/L, and concentration of NH_4-N is 0.929 mg/L), which means the majority of nitrogen in the pavement runoff is organic. The way of removal of organic nitrogen is largely by ammoniation which takes place in the aerobic environment under a certain amount of microorganism. Based on the above, there are no conditions of ammoniation for organic nitrogen during the infiltrate process in PAP.

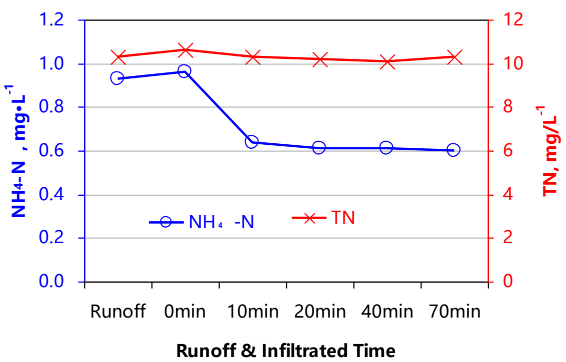


Fig.7. NH_4-N and TN of pavement runoff before and after infiltrated in PAP with different sampling time

4.2.6 Total phosphorus TP

Fig.8 gives the TP concentrations in the samples collected under different sampling time. The TP concentration obviously decrease after the water specimen infiltrated through the PAP and shows a downward tendency with the increase of sampling time. The decreasing amplitude varies from 5% to 87.2% with the sampling time increasing from 0min to 70min. The TP is normally removed by the adsorption and filtration of the PAP materials, as well as the precipitin reactions of phosphate and calcium ions in PAP materials.

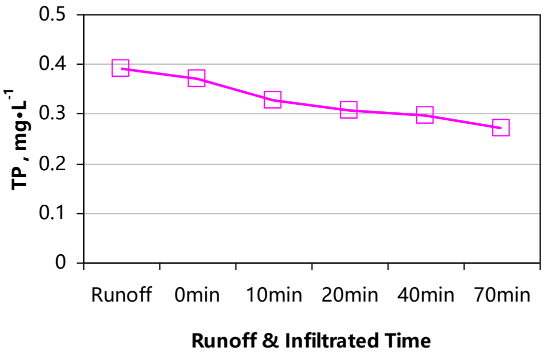


Fig.8. TP of pavement runoff before and after infiltrated in PAP with different sampling time

4.2.7 Petroleum pollutants (PP) and animal & vegetable oil (AVO)

The concentrations of PP and AVO in the water samples are illustrated in Fig.9. It can be seen that the PP concentration of the initial seeped water (S1) decreases below the limit value (0.04 mg/L) and cannot be detected with the increase of sampling time, which means the PAP has a good effect on PP removal. In terms of AVO, the decreasing amplitude of AVO changes from 42% to 65% when the sampling time increase from 0min to 70min. PP and AVO are removed by the physisorption of the PAP materials, which is closely related to the Van der Waals force. Generally, the larger molecular weight results in greater Van der Waals force, greater polarity and therefore larger physisorption ability. Compared with AVO, the larger molecular weight of PP enables the PAP to remove it more efficiently.

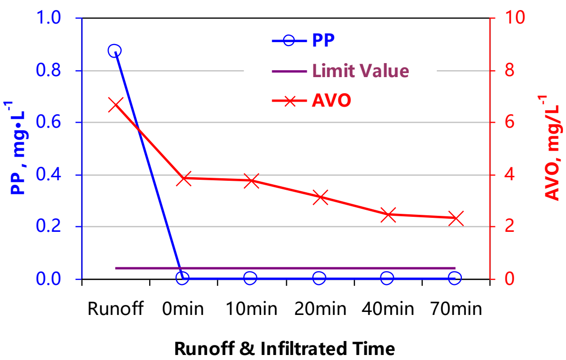


Fig.9. PP and AVO of pavement runoff before and after infiltrated in PAP with different sampling time

4.2.8 Heavy metals

From Table 7, it can be seen that the concentrations of Cu, Zn and Pb decrease dramatically below the limit value for S1, and tend to be smaller with the increase of sampling time. The concentration of Cd in S0 is 0.00219 mg/L, while decreases to 0.00100 mg/L in S1 and 0.000380 mg/L in S6. The decreasing amplitude is about 54.3% for S1 and 82.6% for S6, as shown in Fig.10. Test results show that the PAP has a good effect of Cu, Zn, and Pb removal. This confirms with previous findings that the Cu, Zn, Pb and Cd are adsorbed on the suspension colloids and can be removed along with the suspended particles by PAP materials [37-40].

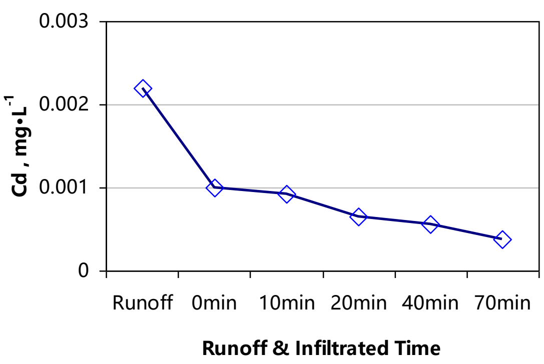


Fig.10. Cd of pavement runoff before and after infiltrated in PAP with different sampling time

Fig.11 shows Cr^{6+} of pavement runoff before and after it was infiltrated by the PAP with different sampling time. Compared with S0, the Cr^{6+} concentration in S1 shows a slight decrease (2.8%) and the decreasing amplitude increases to 44.4% when the sampling time increases to 70 min (for S6). It can be seen that the Cr^{6+} removal efficiency for PAP is relatively lower compared to other heavy metal pollutions of Cu, Zn, Pb and Cd. Cr^{6+} mainly exists in the forms of $CrO^{2-}{}_4$ and $Cr_2O^{2-}{}_7$, which are stable and soluble in water. On the other hand, $CrO^{2-}{}_4$ and $Cr_2O^{2-}{}_7$ (with negatively charged) are difficult to be adsorbed by minerals and organic matter. Thus, Cr^{6+} in pavement runoff with strong mobility is difficult to be removed. However, as the sampling time goes on, the Cr^{6+} can transform into Cr^{3+} by reacting with some inorganic matters, microorganisms and humus intercepted, thereby leading to a more significant Cr^{6+} removal with the increase of sampling time.

Fig.11. Cr^{6+} of pavement runoff before and after infiltrated in PAP with different sampling time

4.2.9 Chloride (Cl^-)

The concentration of Cl^- in pavement runoff is illustrated in Fig.12 against different sampling time. It seems that the PAP does not have very significant effect on the removal of Cl^- in pavement runoff with only 6% Cl^- being removed in the water sample collected after 70min seepage. The water-solubility of Cl^- is one of the main reasons of the low removal rate. Additionally, even though the Cl^- can react with some metallic ions, the products of reaction are difficult to precipitate. Generally, electrostatic attractions rather than physical absorption are recommended to be used to remove the Cl^-.

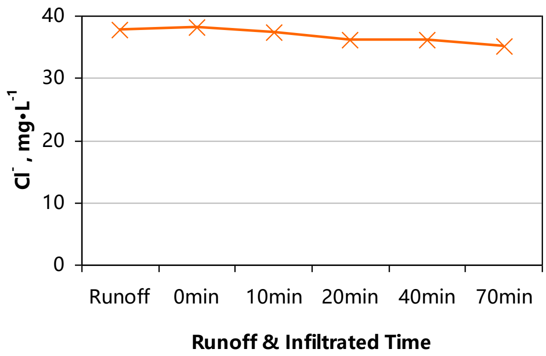


Fig.12. Cl^- of pavement runoff before and after infiltrated in PAP with different sampling time

It's worth noting that pollutants concentration of the pavement runoff samples after infiltrated in PAP was closely related to the materials and structure of PAP. In other words there were close relationships between materials composition, thickness, cleanliness and pollutants concentration of the pavement runoff samples after infiltrated in PAP. Therefore, the pavement runoff filtration effect was not merely affected by one layer, but the combination of layers.

In practice, the pollutants intercepted by the PAP materials could be removed by special vacuum air sweeper vehicles [41,42]. Recent studies have revealed the usefulness of washing permeable pavements with clean, low-pressure water, followed by immediate vacuuming. Combinations of washing and vacuuming techniques have proved effective in cleaning both organic clogging as well as sandy clogging [43].

5 Summary and conclusions

Permeable asphalt pavement can reduce the stresses on urban drainage systems by decreasing the peak flow in during rainstorms. However, the rainfall-runoff could permeate into subgrade through pavement structures with large volume of pollutants; the quality of the water permeating into the subgrade needs to be carefully assessed. Laboratory studies were conducted to investigate the filtration effects and their mechanisms of permeable asphalt pavement. The filtration effect of PAP is specified by measuring 16 pollutant indices in influent and effluent samples with self-developed laboratory apparatus. Based on the results from the study, the following conclusions can be made:

(1) The self-developed apparatus developed is adequate to model the permeable pavement infiltration process. The water samples collected from the apparatus can be used for pollutant concentration analysis and study of the filtration ability of PAP. Additionally, other materials could also be tested for the filtration effect as well as permeation rate by this apparatus.

(2) PAP has very high removal efficiency on heavy metal pollutions, such as Cu, Zn, Pb and Cd.

Similarly, it can remove AVO, BOD, COD, NH_4-N and TP effectively. However, PAP is incompetent with the removal of Cl^- and TN.

(3) Pollutions concentrations are reduced to different degrees as the sampling time goes on. On the one hand, the pollutions contained in PAP materials themselves would be removed by the scouring action of the seepage water at initial stage; On the other hand, the removal efficiency for PAP would be improved by the inorganic matter, microorganism and humus intercepted.

Because of the restriction on compaction in the long cylinder, the open-graded gravel and natural sand were not in the state of fully compacted. Therefore, air voids of the two materials are larger compared with the real condition used in the pavement. Based on the filtration mechanism of PAP, it can be expected that the materials with small air voids will have better filtration effect.

Further work can be conducted to improve the modeling of the filtration effect, such as using special tool and device to compact the materials filled in the long cylinder. Meanwhile, the different thickness and materials combination can be tested to simulate different in situ construction details. Besides, the relationship between laboratory and field test results can be explored.

Acknowledgements

This project was supported by the National Natural Science Foundation of China (Grant No. 51208049), Natural Science Basic Research Plan in Shaanxi Province of China (Grant No. 2015KJXX-23), China Postdoctoral Science Foundation (Grant No. 2014T70898), and by Construction Technology Project of Ministry of Transport of China (Grant No. 2013318221150).

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