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Experimental study on filtration effect and mechanism of pavement runoff in permeable asphalt pavement

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HIGHLIGHTS

- Self-developed apparatus was devised to investigate filtration effects of PAP.
- 16 pollutant indices of runoff before and after infiltrated in PAP are tested.
- Removal mechanisms of pavement runoff in the RAP are analyzed.
- Influences of sampling time on pollutant concentrations are investigated.

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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.

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).

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Many studies have identified permeable pavements are effective to retain pollutants and preserve the natural hydrologic functions [13–15]. Rushton [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 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 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 [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 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 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 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 60 L water storage container (40 cm in diameter and 50 cm in height) and a long cylinder (10 cm in inner diameter and 52.5 cm 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