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Research article

Evaluation of permeable pavement responses to urban surface runoff

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ABSTRACT

The construction of permeable pavement (PP) in sidewalks of urban areas is an alternative low impact development (LID) to control stormwater runoff volume and consequently decrease the discharge of pollutants in receiving water bodies. In this paper, some laboratory experiments were performed to evaluate the efficiency of a PP subjected to sediment loadings during its life span. Simple infiltration models were validated by the laboratory experiments to evaluate the trend and extend of PP infiltration capacity throughout the life of the pavement operation. In addition, performances of the PP in removing total suspended solids (TSS) and selective nutrient pollutants such as NO_3^-, NH_4^+ and PO_4^{-3} from the surface runoff have been investigated. Experimental data showed that the PP was completely clogged after seven hydrological years. The model revealed that the ratio of horizontal to vertical hydraulic conductivity is 3.5 for this PP. Moreover, it was found that 20% reduction in hydraulic conductivity occurred after three hydrological years. The PP showed 100%, 23% and 59% efficiencies in sediment retention (TSS removal), (PO_4^{-3}), and $N-NH_4^+$ removal during the entire study, respectively. However, the removal efficiency of ($N-NO_3^-$) was −12% and we suspect the increase in effluent ($N-NO_3^-$) is due to the nitrification process in subsurface layers. This study demonstrated that when PPs are annually cleaned, it is expected that PPs can function hydraulically and be able to remove particulate pollutants during their life span by a proper maintenance.

1. Introduction

Urban development increases impermeable surfaces such as pavements and buildings that diminish water infiltration to the ground and increase runoff volume (Finkenbine et al., 2000; Nie et al., 2011). This runoff that was induced by impermeable surfaces, washes out pollutants from urban areas and carries them to waterbodies (Davis et al., 2001). Urban runoff has been known as a primary pollutant source. About 46% of surface water pollution is attributed to urban runoff (Chai et al., 2012; USEPA, 1996). Therefore, controlling urban runoff quantity and quality seems vital to properly maintain watercourses. Among several practices developed to obviate the abovementioned issues, the PP is known as a LID that can mitigate first flush impacts and decrease volume of runoff as well as treatment costs (Sansalone and Teng, 2005; Andersen et al., 1999).

Several researches have investigated infiltration rates of PPs in sidewalks using double ring infiltrometer tests (e.g. Qin et al., 2013; Valinski and Chandler, 2015); however as far as authors' knowledge permits, literature lacks studies that cover the hydraulic performances of a sidewalk PP under clogging. Therefore, the authors present the literature that has studied the clogging process of PPs with the most similarity to our experimental setup. Several investigations have been performed to evaluate the performance of PPs for water quality and some representative example studies are examined here. For instance, TSS contain attached heavy metals, which remarkably prevent aquacultural growth (Brown et al., 2009). PPs have revealed acceptable performances for TSS removal from runoff. Morquecho et al. (2005) showed that a PP can reduce TSS, turbidity and total phosphorus more than 50%. Tota-Maharaj and Scholz (2010) reported that TSS, $N-NH_4^+$ and $P-PO_4^{-3}$ removal efficiencies for a PP were 91%, 84.6% and 77.5%, respectively. In another study, Collins (2007) asserted that a PP noticeably decreased $N-NH_4^+$ and increased $N-NO_3^-$ effluent concentrations compared to the asphalt pavement. Although PPs have shown acceptable performances in TSS and some other pollutant removal, the poor PP construction and maintenance lead to sediments accumulation into the PP structure, which causes

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clogging. This clogging reduces PP popularity when compared to the other practices (Bean et al., 2007). Several studies have been investigated to assess clogging behaviors of PPs (Coleri et al., 2013; Kayhanian et al., 2012a). Types of sediments as well as methods of applying sediments to PPs vary in literature. Sediments introduced to a PP might be real samples during urban runoff campaigns or can be artificially provided (Siriwardene et al., 2007). Further, sediments can be applied to PPs either manually (Castro et al., 2007; Coleri et al., 2013), or by precipitation (Pezzaniti et al., 2009); however, the pavements in sidewalks are frequently cleaned and majority of the sediments are entered through surface runoff; therefore, applying the sediments by runoff is a more realistic experimental setup.

From the literature review and some of the aforementioned studies, generally the PP performances were evaluated under unrealistic conditions. For instance, the simulated rainfall and applied sediments were not in accordant with real sediment loads and precipitation conditions. Therefore, experimental observations might differ from field observations. Pezzaniti et al. (2009) assessed the effective life of a PP in both laboratory and field works. Their results showed that in the field, clogging happened at a faster rate compared to the laboratory work. Our study was performed by conducting experiments through applying clean simulated rainfall (no suspended solid) from the top of the PP (representing rainfall) and simulated runoff with sediments that was flown from a side. In addition to this unique experimental setup, we developed a model to understand the water flow in this PP structure. This approach was used to evaluate the temporal and spatial clogging trends in this PP and hence to find the vulnerability of the PP to sediment loadings during rainfalls. We defined clogging in terms of the accumulation of silt within the pavement structures that corresponds to a decrease in the hydraulic conductivity of the PP (Castro et al., 2007). Castro et al. (2007) related the clogging due to the reduction in hydraulic conductivity to the entrapments of particles in the upper surface layer as well as the accumulations of particles on the geotextile fabric. Recognizing susceptible spots for clogging in PPs would help to locate the failed locations and to properly clean it through an optimum maintenance schedule. One other important feature of our investigation was addressing the pattern of water flow through the PP as a porous media to determine the fraction of the total water that enters the PP and horizontally flows for sizing the drainage system in PPs.

This study aims at examining performances of a PP, used in sidewalks, during a flow of runoff that contains sediment loads. We present the clogging steps as a runoff was exposed to the PP using specific sediment samples that were collected from some streets in Tehran, Iran. Using our experimental measurements, a simple model was developed to find out the capacity of the PP, the chronological clogging trend and its age (we defined the age of the PP as the time before runoff overflows the PP). Although evaluating the PP clogging by sediments was taken as the primary objective of this study, the performances of the PP in removing some pollutants such as TSS, PO_4^{-3}, NH_4^+ and NO_3^- removal were also investigated.

2. Methodology

2.1. Experimental setup

Fig. 1 displays the schematic diagram of the experimental setup used to evaluate the performance of our PP under different laboratory conditions. Several important features of the experimental setup are described below.

2.1.1. PP module

The schematic diagram of a PP module is depicted in Fig. 1a. The experimental area of this PP was about 2 m^2 (2 m by 1 m) and pavement was constructed at 2% slope. The experimental PP module comprised of three different layers: (1) top layer includes concrete blocks with 4 cm height and 0.5 cm gaps between the two adjacent blocks; the gaps were filled with granular gravel size ranging from 2.36 mm to 4.75 mm, (2) middle layer that consists of 5 cm granular filter, which is comprised of granular gravel in the range of 2.36–4.75 mm, and (3) the bottom subbase pebble gravel layer with 12 cm height and granular particle size between 4.75 and 20 mm. In addition, a geotextile fabric was installed in the bottom of the granular filter (second layer) and subbase layer (third layer). The top geotextile layers were installed to prevent downward flow of particles into the subbase layer. The bottom geotextile layer was added to prevent particle upflow movements from subbase soil into the subbase layer.

Using the rainfall records from the nearest weather station in Tehran (Mehrabad weather station, about 2.5 km far from the studied streets) as well as design method suggested by the Iowa stormwater management manual for pavement systems (Iowa Stormwater Management, 2009), we estimated the depth of reservoir layer to be about 25 cm. According to this manual, curve number, ratio of impermeable pavement to permeable pavement, void ratio of aggregate base, and design rainfall event were assigned 98, 3, 0.4, and 30 mm, respectively. However, due to limitations in the PP modular dimension and weight, the depth of 12 cm was considered. The 13 cm reduction in depth was mostly associated with the subbase layer that might be more significant for PP design with higher traffic speeds as well as load applications and will be insignificant for clogging investigations in sidewalks. For example, it has been documented that pavement failure due to clogging is mostly associated with particles trapped in surface or upper subsurface of PP pavements (Teng and Sansalone, 2004; Kayhanian et al., 2012a; Coleri et al., 2013), which is usually independent of bottom layer depths. Therefore, the proposed depth in our experimental setup is justified in accordance with the study objectives.

2.1.2. Rainfall and sediment simulator setup

A schematic diagram of the rainfall and sediment loading simulator is shown in Fig. 1b. Different setups were examined to find the highest uniformity in the rainfall applied to the PP. In order to achieve the highest uniformity, the number of nozzles and their heights with respect to the surface of the PP were changed. The best experimental setup, whose uniformity was high, had a 2 m height from the PP surface and 3 nozzles in one row. With some limitations in our experimental set up, we calibrated the intensity of the rainfall simulator and found to be 36 mm/h, which is fairly close to the average rainfall intensity in Tehran (Tehran's mean annual rainfall = 240 mm with majority of rainfall events last about 6 h and therefore the average hourly rainfall intensity is equal to 40 [=240/6] mm/hr). In order to meet the annual rainfall, the system worked for 6.67 h (=240/36) in each hydrological year. The rainfall simulator was operated with clean tap water and applied on top of the PP and let the water flow downward through different pavement layers.

In addition to applying clean rainfall from top, an artificial surface runoff was also introduced to the PP from one side (see Fig. 1b). This type of PP is planned to be implemented in pedestrians of Tehran. It will convert impermeable surfaces, which have three times greater surface area than permeable surfaces, to permeable pavements. Thus the flowrate of runoff was three times larger than rainfall intensity to be consistent with real conditions. This applied runoff containing sediments in some of the experiments allowed us