Permeable Pavement as a Component of Water Sensitive Urban Design: A Mini Review

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Abstract

Rapid urbanization has led to an increase in runoff and pollution in urban waterways. Water sensitive urban design (WSUD) is a sustainable means of reducing the impacts of urbanisation on urban water cycle. Permeable pavement system (PPS) is a component of WSUD that can reduce both runoff volume and pollution. PPS is generally used in low-traffic areas such as car parks, pedestrian footpaths, cycle paths and driveways. In this paper, we present a review of PPS highlighting its major benefits and limitations and recommend areas of further research. It has been found that PPS has a number of benefits such as reduction of urban runoff volume, removal of pollutants from stormwater runoff, enhancement of groundwater recharge, and reduction of heat island effects. The major limitations are related to its maintenance, clogging effects, lifecycle cost analysis and strength and durability. The future research and development potentials of PPS are identified in this paper.

***Keywords*:** WSUD, Urban Design, Permeable Pavement, Water Quality, Permeable Pavement Systems

1. INTRODUCTION

Urbanisation increases runoff volume and reduces stormwater quality. Water sensitive urban design (WSUD) has been introduced recently to reduce the impact of urbanisation on urban water cycle. As a component of WSUD, permeable pavement systems (PPS) are used in a variety of residential, commercial, and industrial applications in urban areas. The typical layout of a PPS starts with layers of a permeable paver unit with a drainage cell, bedding layer, base, an optional geotextile and a native sub-grade. The optional geotextiles are added as a preventative layer to stop the sand entering into the base of the PPS. Scholz and Grabowiecki (2007) noted that the benefits of PPS include runoff reduction and stormwater treatment by removing pollutants such as hydrocarbons and heavy metals.

Numerous researchers [e.g. Rushton (2001), Brattebo and Booth (2003), Bean et al. (2007) and Roseen et al. (2012)] demonstrated that effluent from PPS has lower suspended solids and heavy metal concentrations than runoff from the traditional asphalt pavement. Legret and Colandini (1999) reported that, relative to a reference catchment, runoff from a porous asphalt pavement reduced suspended sediments, Pb, Cd and Zn concentrations by 59%, 84%, 77% and 73%, respectively.

Kamali et al. (2017) conducted a study to evaluate the temporal and spatial clogging of PPS. They constructed the PPS on sidewalks in a low impact development scenario to control the stormwater runoff and pollutant wash-off. The removal of total suspended solids (TSS) was found to be in the range of 23% to 100%, the removal rate for ammonium and phosphate was 'medium'; however, for nitrate the removal efficiency was negative. As noted by Sountharajah et al. (2017), PPS is not efficient in removing heavy metals from stormwater runoff. In their pilot study utilising zeolite or basalt as bed material in PPS, removal rates of 41–72%, 67–74%, 38–43%, 61–72%, 63–73% of Cd, Cu, Ni, Pb, and Zn, respectively were achieved for the PPS. Radlinska et al. (2012) found the TP removal of 94.3%. Haselbach et al. (2014) reported 90% and 87% removal efficiencies of PPS for Zn and Cu, respectively.

The objectives of this paper are (i) to present a review of PPS and identify its benefits and limitations and (ii) to recommend areas of further research to strengthen the applicability of PPS to achieve sustainable urban development.

2. PPS CONFIGURATION

PPS consists of a permeable layer at the top, and subsequent layers of sub-base as illustrated in Figure 1. The top layer gives the structural stability, hardness, and the visual appearance. Secondary layers of sub-base filters out pollutants and provide short term storage of surface runoff whilst supporting the top layer. Factors that influence the performance of PPS include properties of aggregates, layering structure, pollutant build up, rainfall characteristics (Brattebo and Booth, 2003). Material selection and layering are quite important in the design of PPS.

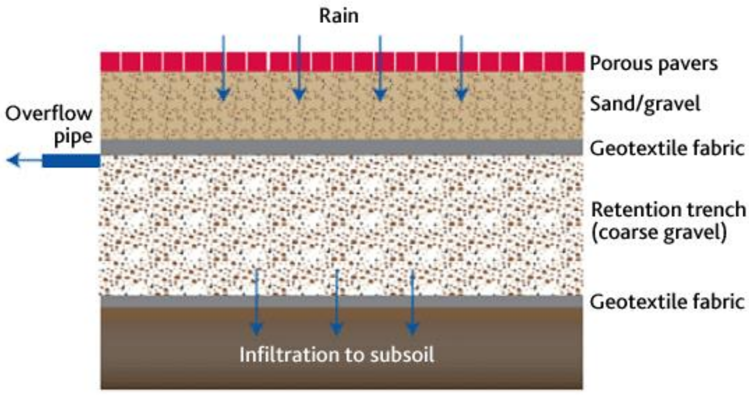

Figure 1. Typical configuration of PPS (Melbourne Water, 2017)

Figure 2 shows four different types of top surfaces in PPS. Jayasuriya and Kadurupokune (2010) observed 45-55% and 50-60% runoff reduction for type-c and type-d PPS compared with the conventional asphalt pavement, respectively. Monolithic porous asphalt generally demonstrates superior performance in removing suspended solid and nutrients in comparison to modular form (Huang et al. 2016; Gomez-Ullate et al., 2011). The modular form demonstrates higher infiltration capacity due to the presence of coarse aggregates between the concrete blocks (Argue and Pezzaniti, 2005; Jayasuriya and Kadurupokune, 2010), however, this type of PPS is more prone to clogging. Table 1 summarises the construction and application of various types of PPS

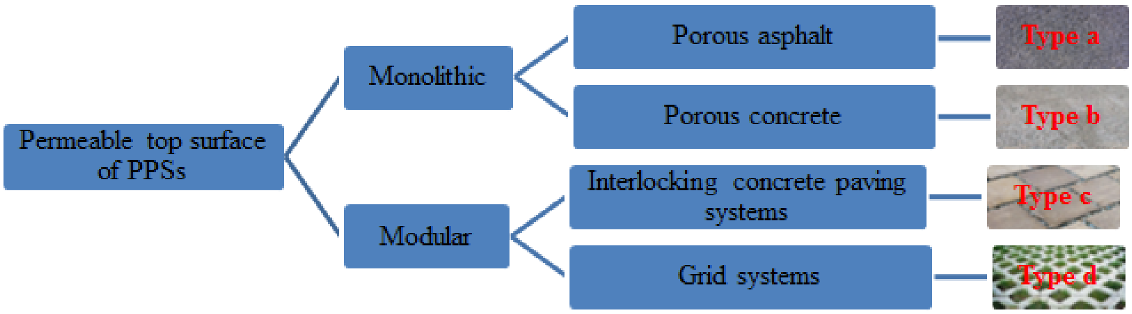

Figure 2. Categorisation of top surface in PPS (Jayasuriya and Kadurupokune, 2010)

Table 1. Construction and application of PPS (Gold Coast City Council, 2017)

Pavement type	Construction	Application
Porous concrete/asphalt	Open-graded concrete or asphalt with no or reduced fines mixed with a special binder that create voids when cured to allow water to infiltrate.	Commercial parking lots, perimeter/overflow parking, perimeter/light commercial, driveways, patios/other paved areas, sporting courts, industrial storage yards/ loading zones.
Interlocking concrete paving systems	Paving stones installed with keeping gaps between stones to allow water to infiltrate.	Commercial parking lots, perimeter/overflow parking, perimeter/light commercial, driveways, patios/other paved areas, industrial storage yards/loading zones, parking pads (e.g. caravan parks).
Grid systems/reinforced turf	Plastic or concrete grids filled with aggregate, sand or grassed soil so that water can infiltrate through.	Commercial parking lots, perimeter/overflow parking, parking pads (e.g. caravan parks).

3. CLOGGING OF PPS

Urban stormwater contains a range of solids, which are broken down into finer particles by traffic. These particles slowly fill and block void spaces within PPS. These accumulated particles create a hard crust in PPS, which slowly builds up with time and reduces permeability of PPS (Pratt et al., 1995). Yong et al. (2013) examined the clogging behaviour of PPS and developed a black-box model to predict clogging. The clogging of PPS was found to vary depending on the type of PPS. For example, porous asphalt clogged at its surface causing drainage to slow than that of Hydrapave, which clogged just above the geotextile layer. Hydrapave clogged deeper and its failure could not be noticed easily. Welker et al. (2013) examined material taken out of voids of PPS situated in a car park and found very little fine sediments in the deposited materials. They noted that pavement deterioration contributes mostly to the deposited materials in PPS. A number of researchers noted that clogging generally occurs on the surface or in the upper layer of PPS (e.g. Kayhanian et al., 2012); however, few other studies observed that particles can also clog the deeper layers of PPS (e.g. Chopra et al., 2010). Kia et al. (2017) presented a review on the clogging of PPS. They noted that particulates in stormwater are deposited in the pore spaces of PPS, which reduces the permeability of PPS that limits its service life. PPS needs regular maintenance by vacuum sweeping and pressure washing, which may not be practical in many situations. Kia et al. (2017) noted that clogging of PPS is linked to the tortuosity of the connected porosity and suggested that PPS should be poured on-site to achieve a pore structure with low level tortuosity.

4. LIFE CYCLE COST ANALYSIS

There have been only limited studies to compare the initial cost of construction between PPS and conventional pavements. For example, Wang et al. (2010) noted that initial costs are higher for PPS due to restrictive design and placements to attain proper voids continuity in PPS. The overall cost benefits of PPS should be evaluated by life cycle cost analysis; however, due to lack of field data, long-term performance and construction and maintenance cost data, there has been little success in this area (Chandrappa and Krishna, 2016). If environmental benefits provided by PPS (e.g. reduction of flood risk, improved runoff quality, increased groundwater recharge, reduction of heat island effects) are fully costed, the PPS will most likely outperform the conventional pavements for low-traffic areas.

5. FURTHER RESEARCH POTENTIALS

PPS is a relatively new technology and hence its full potentials are yet to be explored. Firstly, a better understanding of the correlation between laboratory experiments and field conditions needs to be developed since most of the previous studies on PPS focused on laboratory conditions. Secondly, an appropriate structural modelling technique of PPS needs to be developed since finite element model is unsuitable to PPS due to its discrete nature. Thirdly, the long-term performance and monitoring of PPS are needed to establish the maintenance needs and reduce the clogging problem of PPS. Fourthly, data on the capital and maintenance costs of PPS covering its design life, and other benefits of PPS need to be collated so that the life cycle costing of PPS can be fully undertaken to compare PPS with traditional pavements. Finally, research should be conducted to enhance the strength of PPS to reduce abrasion so that PPS can be used in different types of roads including highways.

6. CONCLUSION

The use of PPS in low-volume traffic applications (such as local streets, pedestrian walkways and driveways) has been gaining popularity around the globe as this can offer several benefits such as reduction of urban runoff volume thereby flood risk minimization, removal of pollutants from the stormwater runoff thereby resulting in cleaner urban waterways, enhancement of groundwater recharge, and reduction of heat island effects. Since this is a relatively new technology, further research is needed to enhance the applicability of PPS such as lifecycle cost analysis considering all the benefits of PPS, clogging mechanism of PPS and possible rectification, enhancement of the strength and durability of PPS. Also, a good understanding is needed between the results of laboratory experiments and field conditions of PPS as there are many laboratory experiments on PPS as compared to field observations.

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