A review on green pavement hydrological design and recommended permeable pavement with detention storage

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Abstract. This paper reviews innovation of green pavement technology for storm water management in an urban environment. This can be related with hydrological performance and assessments of the permeable pavement. Features of the typical permeable pavement are presented and discussed. Topics covered include recognizing important of permeable pavement, stormwater management benefit and detailed hydrological properties and design. The information in this paper provides stakeholders with an overview of research and development of green pavement. In particular, it discussed the benefit and advantages of the green pavement in current use. On the other hand, the permeable pavement with subsurface detention namely StormPav is presented. The hydrological design modification and innovation, as well as hydrological design and stormwater management benefits have been summarised. Therefore provided another option for green pavement infrastructure series to be used in roadworks.

Keywords: Stormwater management, green pavement infrastructure, permeable pavement, hydrological design, hydrological assessments

1. Introduction

Urban development affects land-use changes and thereby influences the natural hydrological cycle [1]. Percentage of land covered by impervious surfaces varied significantly with the changes of land use Arnold et al. [2] to cause a depletion in groundwater recharge, reduction in infiltration rate, creation of more runoff and thereby increasing the flood events [3,4]. Surface-water flooding in urban areas has become a critical issue due to the changing of precipitation patterns, congestion of the stormwater drainage system, expanding of urban areas and aging of drainage infrastructure [5]. The conventional approaches in stormwater management were mainly designed to reduce the peak flow but not the runoff volume. Consequently, it may lead to the occurrence of flood at downstream areas due to the excessive runoff. This is primarily a major issue in stormwater conveyance systems. It was normally addressed by enlarging the hydraulic capacity of the systems [6] and expanding existing urban drainage systems [4]. However, enlargement of the existing system had been proven its ineffectiveness in terms of economy and sustainability [4]. As a result, sustainability has appeared as the main concern while designing the stormwater management infrastructure since 1990s.

In past, there are numerous attempts to embrace sustainability in the design of stormwater intercourse [7-10]. Among the efforts, source control of stormwater with green infrastructure (GI) or...
low impact development (LID) applications is a promising alternative for flood mitigation. GI practices had been established and widely employed as a promising solution to the problems, such as aging of water infrastructure, urbanisation, climate change and water shortage [11,12]. Barszcz [13] reported a reduction in runoff depth and peak flow rate, recorded at 50.0 and 38.5% respectively, in urbanized sub-catchment through their study on the characteristics of surface runoff/outflow with 4 different types of LID. Ahiablame and Shakya [14] found that, under a condition of 50-100% permeable pavement and 100% rain, the rate of flood reduction of the garden areas and the parking lot areas varied from 45.5 to 54.5% for major floods; 28.8–40.8% for action floods, and 36.4% for major floods; 21.6% for action floods, respectively. Rodríguez-Rojas et al. [15] showed an average water volume reduction of over 41% in a LID application. Meanwhile, Eaton [16] found a different reduction rate under various conditions, where it reaches 35-55% for individual land uses and 23-42% for the entire watershed of a low-density residential area in New York City. Meanwhile, via the recent study conducted by Matos et al. [17], it was reported a peak discharge reduction of 76% while applying the LID combinations with green roofs, as well as at parking lots, sidewalks, secondary roads and primary roads with permeable pavement.

2. Green Pavement
The implementation of green infrastructure practices, especially green pavement, can significantly improve the rainfall-runoff responses and thereby minimise the occurrence of flood hazards, which may lead to uncountable economic losses [18]. Jaffe [19] reviewed the online economic model developed by the Center for Neighborhood Technology (CNT) through its application on construction costs, maintenance costs and component life spans (e.g. divert millions of gallons of stormwater). They found that the green infrastructures include permeable pavement, provided substantial economic benefits than the gray infrastructures. Permeable pavement (PP) has been widely used in stormwater management practices due to its environmental advantages, such as reducing the runoff [20], recharging the groundwater [21], mitigating the heat island effect and removing the pollutants [22].

Porous or pervious concrete, which was known and used for about 50 years ago in Europe and United States, is a type of concrete that contains little or no fines (i.e. sand). It is mostly composed of aggregate and cement paste. Its history started in the mid of 1940s as simple concrete turf blocks, which is a modular system to address flooding issues in the large cities of United States. In 1970s, due to the development of the turf blocks in plastic version, which provides the advantage in terms of cost-effectiveness, permeable pavement has become a more and more popular choice [23], while drawing the stormwater management strategies since 1980s in the United States, Canada, Europe and Japan. It was mostly applied to parking lots, low-density traffic lanes and pedestrian pathways [24]. Rowe [25] defined pervious and porous surfaces as “open to passage” and “full of openings ( pores)”, respectively. Meanwhile permeable surface was known as “capable of being passed through.” In general, the term “pervious” is used to describe permeable concrete as it allows the water passage, while “porous” is used to label permeable asphalt because of the void spaces. Permeable pavement (PP) is a paving system that allows water to infiltrate to the underground. Therefore, it is suitable for a wide variety of residential, commercial and industrial applications.

PP can be generally categorised according to the surface type, such as pervious concrete (PC), porous asphalt (PA) and permeable interlocking concrete pavers (PICP). Figure 1 illustrates examples of different permeable pavement types and properties. PC and PA are permeable variations of concrete or asphalt where the binding agent coats the aggregate particles without filling the voids between the particles [26]. Meanwhile, PICP consists of modular units separated by the joints filled with open-graded aggregate [27]. PICP introduce numerous surface designs of pavers such as precast grid, concrete block paver, plastic grid, grid paver and etc. The PICP is growing in popularity due to the modularity of precast block paver design. It is well-established with the provision of design guidelines and various case studies [28-30]. Overall, the designed thickness of permeable pavement can be more than 200mm to 600mm with aggregate sizes of about 2 mm to 76mm, void capacity up to 15% to 40% and pore space between 0.5 mm to 50 mm.
Permeable block paver, thickness: 40-80mm, void porosity 15-25%
Bedding, thickness: 50-100mm, void porosity: 15-25%
Base, thickness: 100mm & maximum void of 40%
Subbase, thickness: 100-450mm & maximum void of 40%

Porous concrete/asphalt, thickness: 20-40mm, void porosity 15-25%
Base, thickness: 70-150mm, maximum void of 40%
Subbase, thickness: 100-250mm, maximum void of 40%

**Figure 1.** Permeable pavement types and properties.

**Table 1.** PP development and research achievements.

| Researcher | Outcome |
|------------|---------|
| **1990s**  |         |
| [23,35]    | Planning and Design |
|            | • Experimental and laboratory studies in small scale on the structural and hydrological design. |
|            | • Determination on effectiveness in stormwater management. |
|            | - e.g. Studies on manufactured permeable pavers, field experiment to observe runoff subjected to different slopes and infiltration capacities. |
| **2000s**  |         |
| [20, 21, 26, 33, 36-69] | Implementation and Application |
|            | • Full scale studies on hydrological performance and structural requirements. (e.g. determination on optimal structure materials and thickness, preparation of the synthetic stormwater quality samples and selection of parameters for model verification) |
|            | • Field and laboratory studies on stormwater quality, stormwater infiltration techniques and pollutant removal efficacy. |
|            | • Investigation of parameters establishment (structural and hydrological) with modelling tools to aid in assessment. (e.g. development of stormwater management model and the code feasibility of the Storm Water Management Model (SWMM)) |
|            | • Introduction to various types of concrete grid pavers, laboratory monitoring, development and construction. |
|            | • Case studies and application of the newest types of permeable pavers and implementation of software. |
|            | • Published standard and guidelines of PPs. |
| **2010s**  |         |
| [70-97]    | Interpretation and Modification |
|            | • Many related studies on clogging and water quality performance of PP. |
|            | • Wider application and model establishment (e.g. SWMM, PCSWMMP, HYDRUS-2D). |
|            | • Modification and introduction to new modification, technology and materials of PPs to enhance strength and durability for higher load, optimise hydrology benefit and stormwater management and removal efficiency etc. |
|            | • Field application, case studies and stormwater quantity and quality assessments. |
3. PP research development

The PP has been widely used since the 1990s in Australia, Europe and Japan, and earlier in United States in 1984 [24]. The recent development of permeable pavement (PP) can be divided into three major time periods. In the 1990s, the PP system was introduced to the users. Most of the research studies were aimed to investigate the stormwater management benefits of the PP in reducing the peak runoff and its volume, as well as increasing the infiltration rate. Several prototypes had been constructed for the property and characteristic determinations via laboratory studies and field tests. The main concern of the analyses was the measurement of stormwater management benefits. Towards 2000s, the main focus of most of the research studies was on the applications aspect, which compared the designed PP with the existing road pavement or the pre- and post- conditions for the PP applications. Several modelling tools had been commonly used to assist the studies and applications of PP [31]. The permeable pavers, acting as the most successful pervious system had been seen for its wider application. This is because a number of design products, case studies benefits and standard guidance had been established [32,33]. From 2010s until recently, the main direction has changed to implementation and modification. Different modifications had been introduced, such as the adding of high strength materials with sufficient void to improve both structural and hydrological benefits, the modification of pavers surfaces with unique and aesthetic looks, etc.

Nevertheless, no matter how the modifications were implemented, the most important thing was the designed pavement must meet the standards and guidelines, especially to fulfill the structural and hydrological considerations. Of course, the point of view from the aspects of sustainability, economy and society have become more and more important. In addition, the optimal combination of low impact development (LID) practices or green infrastructure techniques has become the main concern in order to achieve the maximum benefit in stormwater management [34]. The chronology of PP development and researcher involved is simplified in table 1.

4. PP as green pavement

The PP has been proven its effectiveness in infiltrating stormwater runoff [13], reducing runoff volume [93,97] and peak flow [98]. Weiss et al. [84] discovered that the resulting variability on peak runoff and infiltration rate was mainly due to differences in PP, such as construction materials, mix designs, construction techniques, maintenance received, etc. As shown in table 2, many research on PP had been conducted. The PP had shown its potential to reduce the runoff to more than 40%, decrease the peak to at least 50-90% and improve the infiltration rate from 4-11 cm/h. Almost all studies agreed that permeable pavements, when constructed well and maintained regularly, could have the ability to reduce peak runoff and infiltrate a significant fraction of runoff volume. Ferguson [99] stated that, if the runoff coefficient that has been measured on the properly built porous pavement is zero, it meant there is no runoff due to the high surface permeability. On the other hand, numerous studies had been conducted on the new design materials used for different layers in permeable pavement system, with the objectives to find out the best combinations to minimise the clogging issues and optimise the permeability, whilst still can provide a good result in structural strength.

On the other hand, Bentarzi et al. [104] suggested a new eco-material, comprising a mixture of construction wastes (crushed concrete) and organic matter (compost) to produce permeable pavement. The crushed concrete was mainly for the structural support, while the compost was specifically for the retention and biological treatment of stormwater. Li et al. [105] used to overcome the issues such as low strength, high likelihood for clogging and inconvenient maintenance (as depicted in figure 1). Based on table 2, PP in PICP formed is the popular choice among the designers. This is due to the modular character, countless types of pavers block, surface materials, joints materials, layers and thicknesses, which provide opportunity of more research studies. Moreover, in term of the maintenance, Marchioni and Becciu [106] introduced a maintenance method to involved the removal of joint material and bedding layer. The other method for maintenance purposes is to remove the entire system, but the frequent replacement is impractical and expensive [102]. Thus, permeable pavement of PICP types becomes the preference, while selecting the type of pavement due to its modular interlocking concrete block characteristic that smoothens the remediation work [70,99].
Table 2. Researchers and types of PP used.

| Sources                                                                 | Types of PP used                                                                 |
|------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| [36,40,46,51,52,53,61,62,63,66,76,77,80,93,94,100,101]                  | PICP types: paving stones, pavers with infiltration joints, porous concrete pavers with \filter layer, and greened porous pavers, interlocking concrete block pavers, Rocla-Ecoloc pavers. Concrete grid pavers (CGP), block paver, permeable pavement with impervious paver blocks and enlarged joint spacing, porous concrete (PC), concrete grid pavers (CGP) filled with sand, and permeable interlocking concrete pavers (PICPs) with gravel fill, C&M Ecotrihex pavers and Atlantis turf, porous concrete block paving with different surface and layers and thicknesses, Impermeable rectangular concrete modules (Priora), grass paver, plastic geocells, Spaced modular, grass grid and gravel grid pavements, permeable interlocking concrete paving system (PICP), which comprised a maximum joint width. |
| [24,50,56,88,93,100]                                                   | Porous Asphalt and Porous Concrete, porous asphalt and pervious concrete with different void contents |
| [96,102,103,104,105]                                                   | New design materials used for different layers in permeable pavement system: PICP at maximum joint width (5-6mm), a special aggregate, consisting of waste materials, new eco-material-(mixture of construction wastes (crushed concrete) and organic matter (compost)), reactive powder concrete with high strength pervious concrete as pores pavement. |

5. PP design limitations
A typical PP is designed with layer of bases and connected through the pore spaces and interconnection between void. Permeable pavement invented with voids and porosity properties acts as stormwater management structure is prone to clog due to the blocking of debris, sediment and fine particles in the pore spaces, which disconnected the system [95,107,108]. Besides, the layered characteristics with open-graded materials were opened for particle build-up block, which connected capillary pores, accumulated in void spaces of permeable pavements and clogged the system [65,90]. Clogging is a result of fine particles accumulating in void spaces and thus affecting the rate of infiltration of stormwater and causing the ponding of surface water over the pavements. Clogging can happen within three or four years of installation due to sediment in runoff water and collapsing pores resulting from vibrations caused by traffic [109]. Imaging studies showed that the top 25mm of pervious concrete is mostly subjected to clog. Numerous studies have reported clogging on permeable pavement with reduced permeability and infiltration rates over time [18,107,110].

On the other hand, it was sometimes for the permeable pavement to equip with underground detention storage. The concept of storing water in an underground carriageway could help to significantly reduce drain size and peak runoff, greywater usage and water harvesting. Such design has been applied in the University of South Australia, and in Gresham, Oregon. There also commercial products by integrating an underground retention and detention such as Permavoid® (Product of Permavoid Limited, Warrington, UK), StormCapture® and PermeCapture™ (Product of Oldcastle Infrastructure, UK), geo-cellular sub-base replacements and SingleTrap® and DoubleTrap® (Product of StormTrap, LLC, US). The products are large underground detention systems for water storage and groundwater recharge. This design might require big-scaled machinery and equipment for the construction. In addition, it faced numerous problems associated with the under road systems, such as water supply pipes, sewer pipes, cables and trees roots. Therefore, it is of interest to develop an innovative design for a micro-scale on-site detention pond permeable pavement to avoid potential conflict with the existing systems under roads besides having the ability to detain water with minimize clogging and recharge groundwater for sustainability development.
6. StormPav, innovation in green pavement

Previous researches on permeable pavement system were typically focused on its hydrological performance, the capability of handling traffic volume, materials and mix design, as well as handling, maintenance and safety measures. Nevertheless, among the recent studies that had been reviewed in this paper, it was found the absence of permeable pavement with a micro-detention pond system. The idea is mainly from the PICP design of the modular character, which allows quick and easy installation. To achieve improvement in terms of clogging the new system eliminates layer characteristics of PICP, where the large precast underground detention structure is replaced with a micro-detention hollow precast system that acted as base and water storage, figure 2a. This empty space enhances void storage for water retention and provides a longer time for infiltration to the ground.

StormPav as green pavement main features is a product of precast honeycomb structure that enhance self-interlocking, rain water holding micro-detention pond and self-drying through side and bottom seepage of water in comparison with conventional PP, figure 2b. It have features of modularity, adaptability, portability and self-interlocking. It is actually a hollow cylinder covered with the top and bottom plates, reinforced with two layers of steel and optionally covered with a geotextile layer. The system is constructed on the flat subgrade soil and dry-stacked to form an interlocking paver that has the ability to provide structural support and durability which in turn yielding benefits in terms of permeability in stormwater management. The permeability of the system is accomplished through the under drainage system of the hollow cylinder/vessel residing beneath the subsurface of the pavement. According to Shackel [70], a paver with dentate shape performed better than the rectangular paver. Thus, the StormPav is designed to have a hexagonal shape in order to achieve better performance from the perspective of hydrological design and structural durability. Acting as the open passage for stormwater inflow and infiltration respectively, both the top and bottom layers comprises a central hole with 40mm diameter and six grooves as interlocking keys.

![Figure 2. StormPav (a) single unit (b) cross-section of PICP with comparison to StormPav](image)

This product ensures cost-effective as dry-stacked with reduce installation time and manpower. The aesthetics value is its enduring beauty as honeycomb structure and user-and environmental-friendly product. The new micro detention permeable pavement, StormPav consists of three layers of modular set: hexagonal shape top surface, micro detention pond hollow cylinder tank in between, hexagonal bottom and an optional geotextile layer, constructed on a flat subgrade native soil. The thickness of top and bottom layers and micro detention pond hollow cylinder tank is 75mm and 300mm respectively. The top and bottom layer of StormPav is a flat, concrete interlocking set. Each plate is reinforced by
two layers of steel. A 0.04 m diameter hole in the centre and joint lines in the interconnection between sets characterize the open passage. The top cover functions as road pavement with an inflow to drain stormwater whilst the bottom cover functions as an outflow that allows infiltration. As for the horizontal flow, the micro detention pond hollow cylinder tank has two openings of 0.04 m diameter hole opposite to each other, which are placed close to the bottom of the cylinder. The micro structure promises easy and rapid installation which can be lifted manually, or using simple mechanical devices. In addition, the design comes with more percentage of an open surface area capable of providing a large amount of infiltration into the soil and with longer time of clogging. Instead of having a layer of open aggregates surface, base and sub-base, the StormPav is fabricated with a hexagon shape top and bottom layers with 40mm diameter hole and micro detention hollow cylinder tanks structure in between as a detention storage. The hollow cylindrical feature in StormPav has an empty space of 0.19 m³/m² (30 L/unit) and about 70% void of the pavement area. It drains the surface water at a rate of 8400 mm/hr.

Table 3 presents a series of research studies on StormPav since the development in 2013. The development of StormPav is also following the chronology in table 1. The StormPav is design to apply as stormwater management infrastructure. The actual products are fabricated in 2015, which are then tested and investigated for various structural, roadworks, hydraulics and hydrological assessments. StormPav is a full precast product made using Grade 50 concrete. It’s crushing load is 100kN/unit which is higher than 40kN/single wheel of 80kN Standard axle load. The StormPav can provide uniform settlement with interlocking and monolithic characters. With more manufactured and fabricated moulds to produce StormPav in 2016, the StormPav started it mass production to achieve more research accomplishment of the product.

| Researcher | Research |
|------------|----------|
| [111-116]  | Planning and Pre-liminary Design (2013-2018) |
|            | • Prototype design and development of accessories and fabrication of testing accessories and devices (construction of rainfall simulator, formation of interlocking mould set, shear key for precast casting) |
|            | • Preliminary studies on the structural and hydrological design properties, performances and characteristics. |
|            | • Determination on effectiveness in stormwater management. |
| [117-128]  | Implementation and Application (2018-2020) |
|            | • Field and laboratory studies on the hydrological performance, hydraulics and flow regime, and structural requirements. (e.g determination on optimal structure materials and thickness, selection of parameters for model verification, stormwater quantity and quality, stormwater infiltration capacities and rate and pollutant removal efficiency) |
|            | • Investigation of parameters establishment (structural and hydrological) with modelling tools to aid in assessment. (e.g case study application in various aspects and scenarios such as at different design lifespan, topographical features and identification of appropriate drainage areas. |

StormPav is an innovative integrated building system, IBS green pavement with structural, environmental and economic advantages. For instance, the hydrological benefit provided by StormPav is capable of providing stormwater detention of 3 hours continuous rainfall intensity of 80mm/hr of 10-year ARI and met the hydrological design requirements for the events up to 10-yr ARI [124]. The system collect first flush of rainfall about 25mm and trap the pollutant as coating on large surface area inside StormPav and also at location of geotextile fabric placed onto subgrade. Case study application on StormPav resulted with runoff reduction to almost 60 to 70% with loss to infiltration of almost 90% [126]. Therefore, it is able to meet Environmental Protection Agency (EPA), USA stormwater regulations to reduce overall runoff and attenuate peak flow, whereby converting
stormwater runoff through infiltration. Besides, StormPav, applying as road pavement, can utilise subgrade soil of hydrologic soil groups (HSG) A and B to control the flood for the rainfall events of 10-yr ARI by providing a detention period of 24 to 72 hr [126]. This also claims low risk of subsoil pollutant accumulation and also seasonal high water table should be at least 300 to 600 mm below of pavement formation level.

Furthermore, by comparing to the typical permeable pavement, StormPav appears as a more favourable choice in terms of cost-effectiveness. Due to its precast set with mini size, an easy and rapid installation can be expected. This is because it can be lifted manually or by using simple mechanical machines, and hence saving the installation time and manpower. In addition, the estimated production cost is around $30/ m² or $0.50/ ft², which is significantly lower if compared to the normal permeable pavement [124]. On the other hand, parking lot paved with this IBS acts as micro-detention pond thus it reduces the need for large detention basin. As the reducing runoff from parking lot paved with StormPav it allows the use of smaller drain. Thus, StormPav is able to reduce stormwater impact fee as imposed by authority on drainage system. In supporting local economy it is able to produce at temporary casting yard near construction site thus its use in low speed road especially parking lot, business centre and housing minimizes transport costs and related energy consumption. The light color of concrete pavement absorbs less heat from solar radiation and the large open space of 0.19m³/m² pavement area stores less heat, helping to lower heat island effects in urban areas. This pavement is suitable for protecting trees in a paved environment, sidewalks and landscaping, because it allows adjacent trees to receive more air and water. Therefore, the product shows a promising results as a new and innovative green pavement product.

Conclusion
StormPav is a green pavement with sustainability characteristics, which allow it to be incorporated into green infrastructure and stormwater management planning. In this paper, based on the recent studies, the proposed StormPav with current design can provide a promising result in terms of hydrological performance and assessments. Hence, it can be concluded that the StormPav appears as an alternative as a sustainable green pavement approach which can be served as a component in the road system and stormwater management.

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