MODELING OF INFILTRATION CHARACTERISTICS THROUGH HEXAGONAL MODULAR PERMEABLE PAVEMENTS DESIGN USING FLOW-3D

by

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PEMODELAN CIRI PENYUSUPAN MELALUI HEKSAGON MODULAR TURAPAN TELAP REKABENTUK MENGGUNAKAN FLOW-3D

ABSTRAK

Modular telap turapan telah dianggap sebagai alat yang berkesan dalam membantu dengan kawalan air ribut. Turapan telap kini dianggap sebagai BMP berkesan untuk mengurangkan jumlah air ribut larian dan aliran puncak. Untuk terus menguji jawapan hidrologi dan hidraulik pelbagai reka bentuk turapan telap, pelantar penyusupan terdiri ciptaan baru Hexagon Modular Pavement System, (HMPS) telah dibina. Setiap bahagian turapan meliputi kawasan seluas 0.313m^2 dan kedalaman 0.6m. Seksyen HMPS terdiri daripada modular heksagon dengan diisi oleh kelikir dan lapisan lapisan asas kelikir. Aliran keluar dari turapan telap bersaliran melalui saluran keluar dibawah lapisan asas batu. Perbezaan hidrologi antara turapan telah dinilai untuk isipadu air larian permukaan dan jumlah isipadu aliran keluar. Kesan kedalaman hujan dan intensiti hujan telah dinilai untuk semua tindak balas hidrologi. HMPS mengurangkan jumlah air larian permukaan dan kadar aliran puncak daripada jenis asfalt. Kajian ini akan terus memberi tumpuan kepada pemodelan dan menggambarkan perubahan dalam turapan telap menggunakan FLOW-3D dalam bekerjasama dengan eksperimen makmal. Perisian telah ditentukur dengan data dari kedua-dua makmal dan eksperimen tapak. Bidang magnitud bidang halaju dan tekanan diperhatikan berbanding dengan ciri-ciri penyusupan dalam HMPS ketebalan lapisan yang berbeza. Keputusan ketinggian air dari FLOW-3D adalah sama dengan data cerapan makmal. Berdasarkan kajian ini, HMPS berkeliangan 35% dicadangkan. Setiap unit HMPS berketebalan 10cm; oleh itu enam unit yang disusun diatas satu sama lain diperlukan bagi menghasilkan ketebalan sistem, yang dapat menampung hujan 0.3cm dalam masa sejam.

MODELING THE EFFECTS OF INFILTRATION WITHIN HEXAGONAL MODULAR PERMEABLE PAVEMENT USING FLOW-3D

ABSTRACT

Modular permeable pavements have been regarded as an effective tool in helping with stormwater control. Permeable pavements are now considered an effective BMP for reducing stormwater runoff volume and peak flow. To further test the hydrologic and hydraulic responses of various permeable pavement designs, an infiltration rig consisting of newly invention Hexagonal Modular Permeable Pavement System, (HMPS) was constructed. Each pavement section covered an area of 0.313 m^2 and 0.6m depth. The HMPS sections consisted of hexagonal modular with gravel fill and were underlain by gravel base layer. Exfiltrate from the permeable pavements drained via underdrains in the gravel base layer. Hydrologic differences among pavements were evaluated for surface runoff volume and total outflow volume. The effects of rainfall depth and rainfall intensity were evaluated for all hydrologic responses. HMPS significantly reduced surface runoff volumes and peak flow rates from those of asphalt. This study further focused on modelling and visualizing the changes in the permeable pavements using FLOW-3D in cooperating with laboratory experiment. The software was calibrated with the data from both laboratory and on site experiment. Velocity magnitude fields and pressure fields were observed against to infiltration characteristics in different HMPS layer thickness. Results from FLOW-3D showed that height of water were agreeable to laboratory observed data. Based upon this study, HMPS with porosity of 35% was recommended. Each unit of HMPS would consist of 10cm thick of hexagonal module; thus six vertical units would be required to make up the total thickness of the system, which would cater for 0.3cm/hour rainfall intensity.

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LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
CGP	Concrete Grid Pavers
HMPS	Hexagonal Modular Pavement Systems
PA	Permeable Asphalt
PC	Permeable concrete
PICP	Permeable interlocking concrete pavers

LIST OF PUBLICATIONS

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The need to manage stormwater runoff urban areas was recognised by some of the earliest human civilisations (Webster, 1962). Whilst the introduction of impervious surfaces was known to be one of the primary causes of urban stormwater problems, widespread investigation and use of pervious paved surfaces is not reported until the last few decades of the twentieth century (Shackel and Pearson, 2004). Since that time, the scientific and engineering literature on porous pavement has reported numerous advances in knowledge as well as a wide range of practical expenses. A confrontation appears to exist between the widely recognised potential of porous pavements. The precipitation of unsatisfactory performance derived from numerous negative experiences in field installations. As a result, a mild polarisation is evident between those who would excuse poor performance as the result of identifiable problems that may be rectified, and those who would claim that since such problems are an inescapable fact of life, their absence should not be relied upon for satisfactory performance. However, as the pressure for urban land and for improved environmental outcomes increases, the pressure to extract the full potential from every management practice does too.

The principle of urban stormwater management is to minimise the downstream impacts of urban development. Perhaps the most noticeable of these impervious impacts is to observed increase in peak discharges. This increase is a result to a greater runoff volume generated by impervious surfaces and the increased efficiency of the urban drainage network. Due to the potentially significant increase in downstream flood damage, the control of flooding has been the primary focus of urban stormwater management for many decades (Sonneman et al., 2001). More recently, the consequences of uncontrolled non-point source pollution on our receiving waters have become apparent. In response, urban stormwater management has evolved to include the removal of pollutants as a primary objective. Controlling the impacts of increased flow duration on urban morphology, whilst acknowledged as a significant issue for some time, is now also becoming recognised as an important goal of effective urban stormwater management.

Given that the impacts of urbanisation on stormwater are linked to the introduction of impervious areas, the adoption of pervious paved surfaces is an intuitive response to the challenge of managing urban stormwater. It is unsurprising then since that the potential of porous pavements to control urbanisation impacts has been recognised. Compared to many other control structural management practices, porous pavement has a particular advantage for not requiring additional land area. In addition, porous pavement is capable of controlling stormwater quantity as well as quality, making it potentially effective in meeting the key stormwater management objectives of peak discharge control, pollutant removal and runoff volume reduction.

Whilst the potential of porous pavement is widely acknowledged, reported experience in field applications is variable. Commonly cited deficiencies in porous pavement serviceability include clogging due to pollutant accumulation and structural inferiority. Sonneman et al., 2001 suggests that both of these problems may be mitigated by alternative approaches to pavement design. For example, the combined use of porous and impervious pavements presents the opportunity to combine the attractive hydrologic and water quality improvement performance of porous pavement with the high structural and durability of impervious pavement. In addition, the design of porous pavement to trap particles deeper within the pavement structure may hinder the development of a distinct layer of particulate accumulation, which results in rapid clogging.

The design and engineering assessment of permeable pavements involves developing an understanding of the very complex behaviour of moving water through a complex soil strata. To accomplish this, the engineer must develop a thorough understanding of the complexities of fluid flow phenomena - complexities that are often highly two and three dimensional in nature. In early years, physical model studies would have been the only practical medium available to gain insight into the three dimensional and time-dependent nature of fluid flow. However, physical modelling is typically only undertaken during the final stages of design, and can be costly to execute. With the advancements in computing power made since the 1980's, computational fluid dynamics, CFD analysis has emerged as a powerful alternative design tool, and can be used to provide insight into hydraulic design at all levels of study. A sophisticated computer model, FLOW-3D, was carefully reviewed and tested prior to ensure its use as a design tool would be appropriate. Following this confirmation, the three dimensional model was used to evaluate a number of complex hydraulic design issues associated with these permeable pavements.

1.2 Problem Statement

Runoff from impervious surface areas carries pollutants, such as sediments, nutrients, and heavy metals, into surface waters. Consistent water quality performance standards have been observed from pervious pavements, with reductions in TSS, TP and TN of around 70% to 100%, 40% to 80% and 60% to 80% respectively (Bond et al., 1999; Pratt, 1999; Pagotto et al., 2000; Fletcher et al., 2003). Hydrocarbon and metal reductions are normally around 85% and 75% correspondingly. These results reveal that pervious pavement itself has an ability to meet the water quality standards recommended by EPA (1999). If the infiltrated water could be harvested, it could be productively reused with the appropriate level of treatment.

Most of the urban floods occur because of existing drainage systems are unable to handle peak flows during rainfall events. The most apparent effect of urbanisation on catchment hydrology is the increase in the magnitude of stormwater flow into natural waterways which causes flooding, river degradation and soil erosion and affects public safety. The precipitated water flows over impervious surfaces polluting receiving waters and exacerbating floods. Impervious surfaces directly reduce the water-retaining function of the soil in the urban landscape. This loss may be absolute, because water that previously recharged groundwater, now flows rapidly across the land surface and arrives at the stream, possibly causing floods. Water is also lost by evaporation from impervious surfaces.

The process of urbanization not only destroys the vegetation cover but also changes the natural course of water flow. The increase in urbanization leads to the construction of more roads, parking lots, sidewalks, and buildings; in so doing result in reducing landscapes that absorb water. These less permeable landscapes create flooding and more stormwater runoff. The runoff carries pollutants picked up from roofs, yards, parking lots, roads, and other sources. The water flow from the impervious surfaces degrades the water quality in streams (Thurston, 2001).

Increased urbanization causes pervious green fields to be converted to impervious areas therefore increasing stormwater runoff.

In the earlier stormwater management practices emphasis was to remove the water as quickly as possible with little regard on how it was done or evaluating the adverse impact of receiving water. In this study, new product called Hexagonal Modular Pavement System, (HMPS) which could mitigate both quantity and quality was investigated its infiltration capability using experimental and software simulation, FLOW-3D.

1.3 Scope of Research

A wide variety of porous pavement option is available, each with advantages and disadvantages for various applications. However, the common features of all porous pavements include a permeable surface layer overlying a reservoir storage layer. The characteristics of the reservoir storage layer are similar for most types of porous pavement, typically consisting of a layer of crushed stone. This layer is used to store water before it is discharge to the underlying soil or laterally towards a piped drainage system. The surface layer of porous pavement may be monolithic.

Given the wide range of porous pavement configurations it is not possible to develop a completely generic description of porous pavement behaviour. Hence, the scope of any study of porous pavement is tied to a particular form of implementation, although aspects of the results will have wider application. In this study, a modular pavement surface layer constructed on an impervious membrane is selected for investigation. Modular pavements without infiltration are identified by Shackel and Person, 2004 as having some advantages over alternate configurations, although the application is generally restricted to areas with low traffic speeds, such as car-parking. Such pavements are readily available and represented in a range of proprietary products. These pavements were selected on the basis of their attractive hydrologic characteristics in permitting significant evaporative water loss.

The rate of infiltration in the porous pavement is affected by the structure of the different types of layers in the system. Since this study is primarily concerned with estimating total infiltration, rather than understanding the dynamics of evaporation, infiltrative processes are investigated at the macro scale. This approach focuses on estimating the rate of infiltration based on an empirically-derived relationship between infiltrative water losses without modelling outer heat in detail.

Given that stormwater practice requires consideration of a wide range of issues across multiple disciplines, it is impossible for any single study to address all of the relevant concepts and processes. Conclusions on the effectiveness of porous pavement for stormwater practice derived from this study are based on hydrologic considerations. Other important issues relating to stormwater management effectiveness, such as the structural adequacy of the selected pavement configuration and economic consideration have not been addressed.

1.4 Objectives

This thesis has three primary objectives in which are relate to prediction of the stormwater management effectiveness of modular permeable pavement systems:

i. To design the most suitable modular permeable pavement arrangement for stormwater management scale.

This objective was achieved by analysing the results of plot-scale, experiment featuring boxes of various pavement types. The relative importance of the modular permeable pavement of the infiltrate processes was examined, as was the effect of extended detention within the pavement structure.

ii. To compare the experimental and model results under the same operating conditions.

To achieve this objective, the experimental permeable pavement was subjected to a simulated rainfall. The measured hydraulic parameters was used a simple and predictive model for stormwater quality improvement by permeable pavement.

iii. To predict the hydraulic performance of the designed pavement using the computational model, FLOW-3D.

This was achieved through observation and modelling of flow through the experimental permeable pavement constructed. The hydraulic behaviour inside the experimental pavement has given a physical understanding of the results of the modelling. Finally by calibrating and validating FLOW-3D model, the final design was achieve.

CHAPTER 2

LITERATURE REVIEW

2.1 Review of Stormwater Management Approaches

The principal objective of urban stormwater management is to minimise the downstream impacts of urban development through the implementation of appropriate policy, landuse planning and engineering measures. In the past, stormwater management focused on controlling the increase in peak flood discharges, primarily via retention/detention facilities (Henshaw and Booth, 2000; Newton, 2001; DID, 2011). More recently, water quality targets have been formally incorporated in design objectives for urban stormwater management. The need to control runoff duration, as well as peak discharges, has been recognised for some time, but is now regarded as a critical and often neglected criterion for effective urban stormwater management. On the basis, design objectives for effective urban stormwater management measures as in DID, 2010 should include:

a) control of peak flood discharges to protect against flooding and promote stable stream morphology,

b) control of water quality to protect receiving waters and urban waterways from both the acute and chronic effects of pollution, and

c) control of runoff volume and flow duration for smaller events so that to protect stream morphology and hence riparian habitat.

Hence, porous pavement is one of the best management practices (BMP) with the capacity to meet all three of these objectives

2.2 Structural and Non-Structural Management Measures

Urban stormwater management measures may be divided into structural and non-structural measures. Structural measures, sometimes referred to as The Best Management Practice (BMPs), are engineered facilities or design practices that modify the hydrologic and or water quality response of an urbanised catchment. Such measures may be further divided into those that treat stormwater near its source and those located further downstream along the drainage system. Examples of source controls include rainwaters tanks, porous pavements, on-site detention basins, constructed wetlands and etc. Improved stormwater management is obtained by adopting a range of structural measures, each with different pollutant removal mechanisms and effectiveness, in series to provide a treatment "train" (Urbonas, 1997; Shackel and Person, 2004; DID, 2011).

Non structural measures are those which aim to influence design practice and community behaviour and attitudes. Examples of non structural measures include landuse planning, policy, education and enforcement. It is noted that the term "source controls" is sometimes used to refer to non-structural measures (Deltic and Fletcher, 2007) such as community education, which aims to lower rates of pollutant generation due to modified community behaviour, thereby reducing the "source" of pollution.

Any effective urban stormwater management system will include a range of structural and non structural measures. However, it has been suggested that the best approach to urban stromwater management is to reduce or eliminate the problem at the source by preventive measures (Heaney et. al., 1999). Source control techniques, once regarded as a last resort, are gaining favour as an effective component of urban stormwater management (Pratt 1995; Ferguson, 2005). Source control is particularly appropriate in regions with a combined sewer system which carries both wastewater and stormwater flows (Pratt 1995; Fletcher et al., 2003).

2.3 The Imperviousness and Urbanisation Impacts

Observable impacts of urbanisation on waterways include physical degradation due to erosion or deposition (Zhang et al., 2006), reduction in biodiversity of aquatic flora and fauna (Walsh, 2000), and the reduction in water quality (Hatt et al., 2004). A number of investigations have shown a relationship between these impervious expect and stream degradation.

Schueler (1994) revised relating imperviousness to specific changes in hydrology, habitat structure, water quality and biodiversity of aquatic systems. The results of this review indicated that significant stream degradation was consistently found to occur at relatively low levels of imperviousness to be a powerful and important indicator of stream quality.

Booth and Jackson (1997) investigated the relationship between imperviousness and channel stability in Washington State, USA and they found that instability was almost ubiquitous where the contributing effective impervious areas exceed about 10%. However, they note that these results do not necessarily imply a threshold and that degradation begins at very low levels of urban development. Henshaw and Booth (2000) noted the additional importance of the responsiveness of the channel and catchment to land use change. Booth (1990) reached a similar conclusion, finding that channel slope and geologic material are particularly critical in determining the susceptibility of a given channel to erosion following urbanisation.

Walsh et al., (2001) investigated macroinverterbrate community composition in small streams of the Melbourne region with varying degrees of urbanisation and stormwater drainage intensity. They found that macroinverterbrate communities in metropolitan areas (1 % to 51% imperviousness) were all severely degraded, with high abundances of a few tolerant taxa. The results of this and a concurrent study of benthic diatom communities by Sonneman et al., (2001) found that both diatom and macroinverterbrate communities were sensitive indicators of urban derived impacts. However, diatoms were found to be better indicators of nutrient enrichment, while macroinverterbrates were better integrative indicators of catchment disturbance. These studies also showed among the sites of comparable imperviousness, hinterland communities were less degraded than those of intensively drained metropolitan sites. On the basis they hypothesize that the intensity of the urban drainage is a more important indicator of community health than imperviousness alone. Hatt et al (2004) have also proposed drainage connectivity as an important explanatory variable for pollutant concentrations in urban streams.

The observed correlation between imperviousness and physical and ecological degradation of urban waterways supports the potential effectiveness of management measures such as porous pavement which reduce both the total impervious area and the hydraulic connectivity of the drainage system.

2.4 Modelling of Flows from Pervious Pavements

James et al. (2003) developed the Storm Water Management Model for Permeable Pavements (PCSWMMPP), a computational model to predict the hydraulic performance and assist the design of the drainage system for pervious pavements especially permeable pavements. The model uses Manning's equation to calculate the surface runoff volume, the Green and Ampt infiltration equation (Mein, 1980) to calculate the infiltration rate through the bedding layer, and Darcy's Law (James et al., 2003) to calculate the percolation rate through the sub-base layer.

Jayasuriya et al. (2006b) reported that algorithms in the PCSWMMPP model can be successfully used in hydraulics calculations when designing permeable pavements. Zhang et al. (2006) successfully estimated all parameters of the Green and Ampt infiltration algorithm and Darcy's equation in the laboratory from physical properties of the aggregates. Shackel et al. (2003) used PCSWMMPP to design the drainage of the permeable pavement and Lockpave-Pro2001 to design the pavement structure at Smith Street, Australia. According to the Lockpave-Pro2001 and PCSWMMPP models the thickness of the sub-base layer was 200mm for the maximum design rainfall. The researchers were satisfied with the performance of the constructed permeable pavement with the results obtained from LOCKPAVE-Pro2001 and PCSWMMPP models.

2.5 Hydraulic Performance of Pervious Pavements

2.5.1 Stormwater Quantity Control Using Permeable Pavement

A permeable pavement consists of a surface layer, overlying a sub base layer which rests on the existing soil. One or more intermediate layers, such as a filter course of fine sand, may also be included between the surface layer and the sub base. The functions of the pavement surface are to support load without undue deformation and to allow stormwater infiltration to the sub base. The sub base has a structural role in distributing the pavement load to the underlying soil, but also acts as a water storage layer and hence is sometimes referred to as a reservoir course. Water may be removed from the pavement structure either by infiltration to the underlying soil or by collection in a conventional drainage system beneath the pavement surface.

The surface layer of permeable pavement may be either monolithic or modular. Monolithic permeable pavement consists of bound granular material, such as asphalt or concrete without the finer aggregate grain sizes. Modular permeable pavement is constructed from individual concrete, clay, or plastic paving blocks which may act as a structural matrix for unbound gravel or soil which is exposed at the surface. The use of gravel is preferred to soil for the interstitial material, since soil is commonly subject to compaction by vehicular traffic, reducing the pavement's infiltration capacity (Siriwardene et. al., 1997).

The principal mechanism for stormwater quality and quantity control by permeable pavement includes:

a) attenuation of peak flow rates by temporary storage within the granular media

b) capture of water within the pavement structure for subsequent disposal by evaporation or infiltration to the underlying soil

c) sedimentation, filtration and adsorption of pollutants and

d) biological assimilation of pollutants by microbial activity within the permeable media

2.5.2 Permeable Pavements

Permeable pavements are alternatives to traditional impervious asphalt and concrete pavements. Interconnected void spaces in the pavement allow for water to infiltrate into a subsurface storage zone during rainfall events. In areas underlain with highly permeable soils, the captured water infiltrates into the sub-soil. In areas containing soils of lower permeability, water can leave the pavement though an underdrain system. The water that passes through and leaves the pavement is referred to as exfiltration. Figure 2.1 shows an example of a standard permeable pavement cross-section.

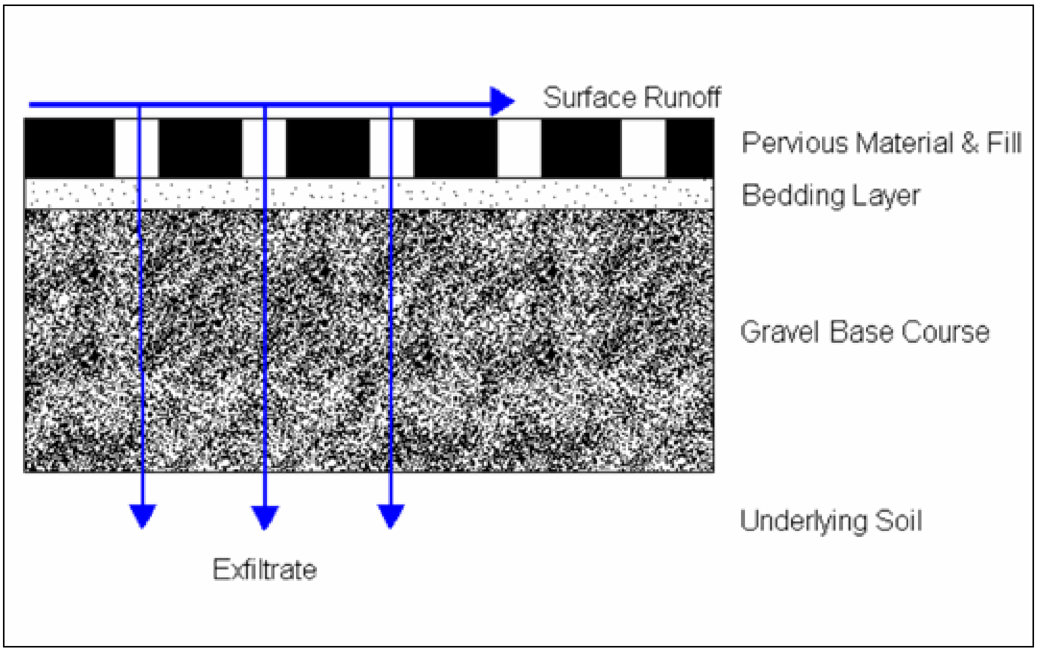
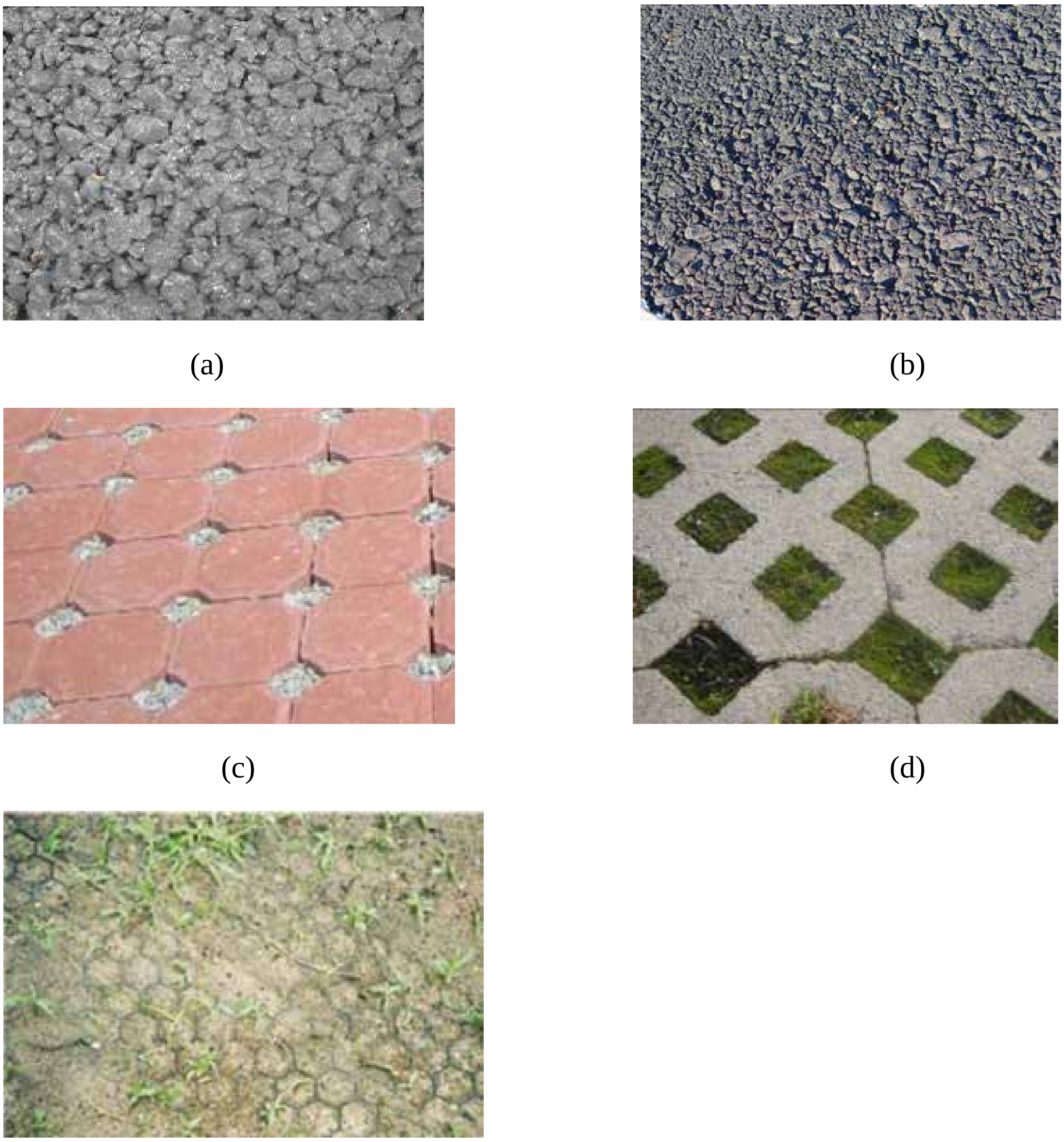


Figure 2.1: Cross-section of a typical block paver permeable pavement installation without under drains (www.ciria.org)

These are several different types of permeable pavements. The main differences among each pavement type are in the total pore space, spatial arrangement of the underlying pervious layers, and structural strength. The most common types include permeable concrete (PC), permeable asphalt (PA), permeable interlocking concrete pavers (PICP), concrete grid pavers (CGP), and plastic grid pavers. Figure 2.2 depicts several of these pavement types, which are further discussed.



(a) (b) (c) (d) (e)

Figure 2.2: (a) Permeable Concrete. (b) Porous Asphalt. (c) Permeable interlocking concrete pavers with pea gravel fill. (d) Concrete grid pavers with topsoil and grass fill. (e) Plastic reinforcement grid pavers with earth and grass fill

Permeable concrete is a mixture of Ordinary Portland Cement (OPC), fly ash, washed gravel, and water. The water to cementations material ratio is typically 0.35-0.45 as suggested by National Ready Mixed Concrete Association, NRMCA, (2004).

Unlike traditional installations of concrete, permeable concrete usually contains a void content of 15-25 percent which allows water to infiltrate directly through the pavement surface to the subsurface. A fine, washed gravel, less than 13 mm in size (No. 8 or 89 stone), is added to the concrete mixture to increase the void space (GCPA, 2006). The additional in admixture improves the bonding and strength of the pavements. These pavements are typically laid with a 10-20 cm thickness and may contain a gravel base course for additional storage or infiltration. Compressive strength can range from 2.8 to 28 MPa, (NRMCA, 2004).

Permeable asphalt consists of fine and course aggregate stone bound by a bituminous based binder. The amount of fine aggregate is reduced to allow for a larger void space of typically 15-20 percent. Thickness of the asphalt depends on the traffic load, but usually ranges from 7.5 to 18 cm. A required underlying base course increases storage and adds strength (Ferguson, 2005).

Permeable interlocking concrete pavements (PICP) are available in many different shapes and sizes. When lain, the blocks forms patterns that create openings through which rainfall can infiltrate. These openings, generally 8-20% of the surface area, are typically filled with pea gravel aggregate, but can also contain top soil and grass. ASTM C936, (2001a) specifications state that the pavers must be at least 60mm thick with a compressive strength of 55 MPa or greater. Typical installations consist of the pavers and gravel fill, a 38 to 76mm fine gravel bedding layer, and a gravel base course storage layer (ICPI, 2004).

ASTM C 1319, Standard Specification for Concrete Grid Paving Units, CGP (2001b) describes properties and specifications for concrete grid pavers (CGP). CGP are typically thick with a maximum 60 x 60 cm dimension. The percent open area ranges from 20% to 50% and can contain topsoil and grass, sand, or aggregate in the void space. The minimum average compressive strength of CGP can be no less than 35 MPa. A typical installation consists of grid pavers with fill media, 25 to 38 mm of bedding sand, gravel base course, and a compacted soil subgrade (ICPI, 2004).

Modular pavement or plastic reinforcement grid pavers (PRGP), also called geocells, consist of flexible plastic interlocking units that allow for infiltration through large gaps filled with gravel or topsoil planted with turf grass. A sand bedding layer and gravel base course are often added to increase infiltration and storage. The empty grids are typically 90-98% open space, so void space is dependent on the fill media (Ferguson, 2005). To date, no uniform standards exist; however, one product specification defines the typical load-bearing capacity of empty grids at approximately 13.8 MPa. This value increases up to 38 MPa when filled with various materials (Invisible Structures, 2001).

2.5.3 Reduction in Surface Water Quantity

Urbanisation drastically reduces pervious areas. The ultimate result of an increase in impervious areas is the null capability of absorbing water into the soil surface. This will totally ended the natural filtration of pervious areas. The aftermath of the increase in impervious areas could result in sudden floods or flash floods, even for small rain events.

A number of researchers (Smith, 1984; Pratt et al., 1995; Abbott et al., 2000; Shackel et al., 2003; Shackel and Pearson, 2004; Zhang et al., 2006) have carried out laboratory and field experiments to investigate the reduction of flows such as peak discharge and runoff volume due to the introduction of pervious pavements in form of impermeable concrete or asphalt surfaces in urban areas. All noted a significant reduction in flows and improvements to water quality by using pervious pavements instead of conventional pavements.

Hogland et al. (1987, 1990) and Larson (1990) reported the use of pervious pavements (Porous Concrete Asphalt) as early as the 1980s for car parking areas and for roads and driveways in residential developments in Sweden. The infiltrated water was drained from the sub base into the stormwater drainage system. These pavements were also designed to increase the groundwater recharge and to reduce the pressure on the drainage infrastructure. The construction of these pervious pavements successfully reduced the volume of stormwater discharged by about 40% compared to the total discharge from an impervious surface.

Meanwhile, in Nottingham a permeable concrete block car park was monitored for stormwater discharges (Mantle, 1993; Pratt et al., 2003). Being completely enclosed within an impermeable membrane, outflow was limited to flows from the sub-base drains and to evaporation from the surface. On average there was a 40% reduction of the volume of stormwater discharged as compared with the performance of traditional impermeable surfaces, which discharge close to 100% runoff to the drainage system within the storm duration. The amount of water discharged depends on the sub-base material. They also observed that the reduction in runoff varied by 34% and 47% when sub-bases were blast furnace slag and granite respectively. This is due to the water storage capacity in the pavement structure due to surface wetting and absorption. According to them, during some storms, the start of discharge from the sub-base drain was several hours after the commencement of the rainfall event. As a result they observed that the outflow hydrograph of the pervious pavement car park was markedly different from that of a traditional, impermeable one.

Smith (1984) carried out a study on comparison of runoff reductions from two different surfaces in the City of Dayton, Ohio. One car park was surfaced with grass-concrete and the second was surfaced with impermeable asphalt. The observations showed that runoff volume from the grass-concrete pervious car park into the drain ranged from 0% to 35% of the runoff from the asphalt surface. The storm for which the highest percentage of runoff was monitored from the previous surface was not the largest storm, but one which followed immediately wet day, from which there had been no runoff. This is an indication that antecedent moisture conditions are important, and the number of dry days between storms determines the effectiveness of the pavement to absorb stormwater.

Abbott et al. (2000) provided similar observations at the Wheatley Motorway Service Area, Oxford shire in England from a porous concrete block-surfaced car park. The car park area monitored was 6250m^2 and surfaced with porous concrete blocks. The amount of water drained from the sub-base during events varied from 4% to 47% of the rainfall volume, with an average value of 22.5%. Some events took as long as 2 to 3 days for flow to cease. The peak outflow was markedly reduced (at Wheatley, a peak rainfall intensity of 12mm/h was reduced to 0.4mm/h at the outflow); the duration of discharge was extended, (sometimes considerably); and there was a significant lag between start of rainfall and start of outflow. For an example, at the Bank of Scotland car park this varied from some 40 to140 minutes. If a subsequent event occurred before runoff had eased, the flow was superimposed on the previous event discharge. This introduced the phenomenon of a ‘base flow’ release from the sub-base.

According to Day et al. (1981), the mean percentage surface runoff from two large elemental permeable block surfaces was almost zero compared to 78% from a concrete paved surface. Their results showed that pervious pavements could absorb almost all the runoff generated through voids in them. Table 2.1 summarises the reduction in runoff volume from different types of pervious surfaces based on earlier research.

Based on case studies, all types of surfaces for examples porous and permeable have reduced runoff volume up to 47% compared to runoff from an impermeable surface as shown in Table 2.1. The utilization of modular pavement delay hydrograph peak flow and delay the base flow. These are in line with the concept of sustainable drainage system (DID, 2010).

Table 2.1 Summary results: the reduction of runoff volume from different pervious surfaces based on literature

Pavement type	Average Reduction in volume (%)	Study reference
Porous concrete asphalt Permeable concrete block surface (Blast furnace slag sub-base) Permeable concrete block surface (Granite sub-base)	40 34 47	Hogland et al. (1987; 1990), Larson (1990), Mantle (1993); Pratt et al., (1989; 1990; 1995)
Permeable grass concrete	0 to 35	Smith (1984)
Porous concrete block surface	4 to 47 (Average 22.5)	Abbott et al. (2000)

2.5.4 Reduction in the Infiltration Rate

The surface infiltration rate depends on the pervious surface, bedding and sub-base materials. Infiltration rates for porous concrete asphalt surfaces have been measured as high as 40,000- 60,000mm/h, but values are typically far lower and change with time as debris accumulates in pores in the surface or in inlets (Pratt et al., 2003).

Borgwardt (1994) from the Institute for Planning Green Spaces and Landscape Architecture, United Kingdom has conducted a study on UNI ECO-STONE® permeable paving. It was said that high permeability when it is constructed with gravel 2-5 mm chips in the drainage openings. The permeability was 2 m/sec (720000 mm/hr) to 10 m/sec (36000000 mm/hr) ‘as laid on site’; this number decreased over time. After 5 years, permeability was 3 m/s (10800000 mm/hr) to 5 m/sec (18000000 mm/hr). Borgwardt’s study showed that the permeability of the pavement was reduced with usage.

Abbott et al. (2000) reported results from tests conducted at a new car park, surfaced with small element concrete blocks. The infiltrations through the block surface itself and through the gaps between blocks were 550 mm/h and 27,000 mm/h respectively. At a similar car park, after three years of used, it was noted that the presence of dirt and oil spillage on the pavement significantly reduced the infiltration rates from both the blocks and the gaps between them. The surface infiltration rate of the porous blocks was assessed, both through the blocks themselves and via the gaps between blocks. There was a large variation in the block infiltration rate (250 mm/h to 14,000 mm/h), as same as the tests on the gaps, but here the infiltration rates were 50 times higher (11,000 mm/h to 229,000 mm/h). The infiltration tests were repeated after a

10 months interval, and revealed that the blocks in some cases had become largely impermeable due to clogging, although the gaps still performed well.

The permeable concrete blocks as used at Nottingham (Pratt et al., 1989) were used at Shire Hall in England as similar system as at Nottingham for the surfacing of infiltration trenches along one side of a 6500m^2 block-paved car park. The car park, constructed in 1986, was graded to fall to one side, where a one meter wide infiltration surface intercepted the runoff. During installation, the infiltration rate of the concrete block surface, which contained a regular pattern of 50mm diameter, gravel filled holes for inflow was 4,500 mm/h. After six years use, the infiltration rate of the surface was 2,600 mm/h, which was still sufficient to ensure full interception of runoff, equivalent to rainfall intensity on the whole car park of 60mm/h (Pratt et al., 1989).

Australian researchers, Suarman et al. (1999) carried out a laboratory study applied to four potential permeable substructures or permeable surfaces conducted over a period of 24 simulated years. The simulation study used a sediment concentration inflow (80 mg/L), comparable to those which could be expected in the substructures beneath permeable car parks in stable and fully established Adelaide suburbs. Failure of the construction was said to be when hydraulic conductivity of the primary filter systems (upper 50 mm of substructure) falls to 1/3 of the ‘as constructed’ value.

Valkman (1999) performed a laboratory study on the substructure of permeable paving’s. 30 years of sediment loading was simulated by utilizes accelerated loading techniques. A total sediment load of 200 mg/L was applied. Four different substructures were tested, two substructures for “Grasspave” and two substructures for “Formpave” (type of concrete block pavement). It was found that after simulating

5 years of sediment loading, the hydraulic conductivity dropped to 10% of its initial value. The hydraulic conductivity decreased until it reached equilibrium after 20 years in 3 laboratory pavements. The hydraulic conductivity 20 years after construction was approximately two percentage of its “as constructed” conductivity value. For the substructure with 5 mm and 20 mm crushed rock the reduction in conductivity reached equilibrium after 40 years at approximately 8% of its “as constructed” conductivity value.

The Urban Water Resources Centre (2002a), at the University of South Australia has tested a laboratory model which consists of four test beds, two test beds from BORAL Formpave, ROCLA Ecoloc and Grasspave. Two test beds containing BORAL Formpave blocks were installed in the rig, one of which was subjected to daily (equivalent to yearly) surface cleaning with stiff brush and vacuum to simulate a field street sweeping device. The second test using the BORAL Formpave blocks bed was not cleaned. The results revealed that the hydraulic conductivity through the BORAL Formpave test beds was predictably high at the commencement of the test. Hydraulic conductivity declined throughout the 35 years from 4.8×10^{-2}m/s to 1.9×10^{-2}m/s (average of both test beds), an average reduction of 59%. Hydraulic conductivity of the ROCLA Ecoloc was similar to the BORAL Formpave test beds, though slightly lower throughout. Grasspave exhibited a hydraulic conductivity an order of magnitude lower again than the other three pavements under test. This was due to the propagating sand content in the base material and within the Grasspave mat. Sediment input equivalent to 35 years was simulated and sprayed over permeable surfaces over a period of 420 months. Over the 35 year simulation test ROCLA Ecoloc and Grasspave experienced declines in hydraulic conductivity of 68% and 75% respectively.

The other study used four existing permeable pavement sites in Adelaide to carry out their research on field studies at Kirkaldy Avenue (BORAL Formpave), Victoria Road car park (BORAL Formpave), Fletcher Lane (ROCLA Ecoloc) and St. Elizabeth's Anglican Church (Grasspave). At all four sites hydraulic conductivity tests were carried out and the results showed that clogging occurred at a rapid rate at locations where runoff flowing onto the pavement was concentrated. It also revealed that the hydraulic conductivity was very high in locations where permeable pavements are subjected to rainfall only. Based on the studies reported, Table 2.2 summarises the reduction in infiltration rates or hydraulic conductivity with time due to clogging in different types of pervious surfaces. In some of the reported studies the infiltration and the hydraulic conductivity reduced considerably (as high as 75% - 90%). Furthermore, in the results reported by Borgwardt (1994) the permeability dropped by 90% within 5 years. Valkman (1999) has observed that the hydraulic conductivity varied with the size of the sub base aggregates.

In summary, the overall performance of the reduction of infiltration base is summarized in Table .2. It is important to maintain the surfaces with regular cleaning programs in order to retain a high infiltration rate. It is also important to minimise the pollutants coming from the surrounding area on to the surface. This could be achieved by integrating other water sensitive urban drainage, WSUD features before the pervious pavement. For example the construction of a swale around the pervious pavement car park before the stormwater is washed off on to the surface would greatly assist the longevity of the pavement.