MSc Environmental Sustainability

Title

Factors that influence clogging mechanics in permeable pavement systems and solution suggestion to increase effective life

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MSc Project Declaration

I declare that the work contained in this project has not been submitted for any other award and that it is all my own work. To the best of my knowledge, the work contains no material previously published or written by another person except where due reference is made in the text of the project.

Title of project:

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Abstract

Changing environmental conditions and increasing urbanisation present new challenges to urban drainage systems that require new solutions and implementations. Such changes along with increasing public awareness about environmental issues paved the way for more sustainable solutions for urban drainage. In the last decades, concept of sustainable urban drainage has been adapted to the requirements of various different environments. A number of different solutions such as infiltration trenches, swales and permeable surfaces were presented over the years. As part of sustainable urban drainage systems, permeable pavement systems play a crucial role in urban drainage. Adaptability, stormwater retention and pollution control capabilities of permeable pavement systems make them a strong replacement option for impervious surfaces in urban environments. However studies and experiences have shown that performance issues do hinder the capabilities of some applications. Clogging of system mainly caused by particle accumulation has shown to be the primary challenge that permeable pavement systems face. Such is that some applications with expected effective life of 20 to 30 years were performing with rates less than adequate after 5 years of use due to clogging.

Much is yet to be uncovered about the hydrological processes of permeable pavements. Clogging mechanics, how it occurs and factors that influence it are among topics that require more research. This study attempts to uncover more about clogging mechanics and suggest optional designs that would increase the effective life of permeable pavement systems. Using previous studies and data obtained by other researchers, a representative environment was created in this study. Different variables in play were analysed using hydrological models and formulas. Results obtained were used to provide detailed analysis and interpretations regarding hydrological processes. Findings of these tests include the role of urban sediment characteristics present in urban stormwater and performance comparisons of suggested design modifications. As a result, this study has revealed the significance of size and mass of pollutants on infiltration rate. To counter clogging, modified paver block designs were introduced. Both advantages and disadvantages of modified designs were presented, and to conclude, recommendations for further studies were presented.

Table of Contents

List of Tables

List of Figures

1. CHAPTER ONE: INTRODUCTION

1.1.Background

After the Industrial Revolution, increasing human population and urbanisation have led to large cities the world has never seen before (Mays, Brickley and Ives, 2008). Invention of better building materials paved the road for durable multi-storey buildings and increased population density in urban areas. Following, the desire to live in urban areas increased the value of the land, which inevitably led to the use of all available land for construction. Lands previously covered with soil and vegetation was almost entirely covered with structures. This situation created an unforeseen problem. Natural hydrological cycle of water required infiltration of precipitation yet coverage of large portions of land with impermeable surfaces have led to 90% of rainfall staying on surface (Sheng and Wilson, 2009). In 19th century, drainage systems still used today were devised to transport the surface runoff from desired locations to discharge zones (Scholz and Grabowiecki, 2007). This solution was feasible enough for time of invention considering urban populations were still low compared to today's urban populations, environmental awareness was not as developed as it is today, climate was not affected by severe human activity and although urban centres were larger than before, they were still much smaller than they are today.

Starting from the second half of the 20th century, human impact on Earth reached critical levels. By the year 1950, 30% of world population was living in urban areas; while more than half of world population is living in urban areas in 2018 (United Nations, 2018). Deforestation, destruction of natural habitats, depletion of natural sources and many other human impacts on the environment but especially carbon emissions, which follow an almost linear increase after the industrial revolution and start increasing exponentially after the Second World War caused a dramatic impact on the natural cycles of earth (Steffen et al., 2007). Such impacts triggered an undeniable change in the global climate patterns (Root et al., 2003; Dillion et al., 2010; Thompson and Kuo, 2012; VijayaVenkataRaman, Iniyan and Goic, 2012; Lee and Kim, 2017). One of the most notable effects of changing climate patterns is increased frequency and severity of extreme weather events (Cai et al., 2014; Angelil et al., 2014; Hansen et al., 2014). Frequency and intensity of heavy rainfall occurrences increased drastically in recent decades (Lau and Zhou, 2012; Iwasaki, 2014). A combination of using ancient methods to drain stormwater, increasing population and urbanisation, increasing severity of weather events and using floodplains for human settlements drastically increase the risk of disasters (Mailhot and Duchesne, 2010).

Most cities continue to rely on conventional drainage systems in modern times (Scholz and Grabowiecki, 2007). Maintenance issues are known to cause problems in conventional drainage systems such as pipe bursts and clogging (Fons, 1993). Results of these issues range from local nuisances to flooding of large areas, with possibility of causing much damage. Additionally, the purpose of conventional drainage systems is to transport the surface runoff from the drainage area to a designated discharge point, usually an existing natural water body. Having no pollution treatment mechanisms during transport, conventional drainage systems collect the pollutants from the entire drainage area and in most cases release it to a designated discharge point. Pollutants from large urban areas, concentrated into such small areas cause unprecedented environmental impact.

Increasing awareness in environmental issues and increasing need for an effective solution for urban stormwater management resulted in introduction of Sustainable Urban Drainage Systems (SUDS) (Marsalek and Chocat, 2002). Sustainable urban drainage systems were devised to provide an efficient drainage infrastructure while protecting natural hydrological cycle, as well as providing pollution control and comparably more natural environments (Woods-Ballard et al., 2015). In order to address needs of various locations and different circumstances, different types of sustainable urban drainage systems were introduced over time (Hoang and Fenner, 2016). Infiltration trenches, swales, dry and wet basins, permeable pavement systems, ponds are among varieties created for different requirements with producing lowest impact on the environment possible in mind (Fryd et al., 2012). Depending on availability and requirements of local environment, installed drainage systems may have one or more main objectives such as stormwater retention and control, pollution control and contribution to groundwater recharge (Tedoldi et al., 2016). However availability of options sometimes depend on land availability more than any other parameter, which requires adaptation to complex built environments (Backhaus and Fryd, 2012).

In order to replace impermeable surfaces used in urban environments and conventional drainage systems used with them, use of pervious asphalt, pervious concrete and permeable modular pavement systems were introduced (Woods-Ballard et al., 2015). These systems allow water to infiltrate through the structure and provide much needed pollution control and stormwater retention (Alsubih et al., 2016). Permeable pavement systems, a subtype of sustainable urban drainage systems, are the main focus of this study.

1.2.Purpose of the Study

Concept of using pavements for roads is very old, the most famous example being the Roman roads dating back to the year 300 BC (Capedri, Grandi and Venturelli, 2003), however, the concept of sustainability in urban development is fairly new, introduced roughly 30 years ago (Montagne-Villette, 2013). Studies about permeable pavement systems started to increase in number by the 1990s; yet there remain uncertainties regarding hydrological processes, compaction mechanics and interaction with their surroundings (Pantsi et al, 2017). Such uncertainties also have their reflections on the market. Some manufacturing companies claim that permeable pavement systems have an effective life of at least two decades, and on the other hand studies have shown that a sharp decrease in permeability is observed after 5 years of use (Pezzaniti, Beecham and Kandasamy, 2009). Such gaps and uncertainties in knowledge are considerable hindrances to the effective use and utilisation of permeable pavement systems.

Sustainable infrastructure systems must be able to address needs of both the environment and the people. In order to be a feasible alternative for conventional drainage systems, permeable pavement systems must have a long effective life with high efficiency. Purpose of this study is to propose a feasible solution for increasing the effective life of permeable pavement systems while trying to uncover more about hydrological processes involved.

1.3.Aim and Objectives

The aim of this study is to examine the current knowledge about performance of permeable pavement systems and to introduce new possible solutions for prolonged effectiveness. Any possible solutions must be economically, physically and environmentally feasible. Currently known challenges for permeable pavement systems must be examined and performance projections of suggested solutions must be critically analysed. Therefore achieving the aim requires addressing following objectives:

- Identifying factors that influence infiltration rate decrease of permeable pavement systems
- Proposing new and better solution for perceived challenges
- Testing the theoretical feasibility of suggested solution

These objectives are addressed in following chapters and the introduction of new possible solution is achieved.

1.4.Research Approach

In order to address the objectives presented above and to achieve the aim given, a qualitative research was undertaken. An extensive literature review was conducted to be able to identify known and possible factors that influence the effective life and performance of permeable pavement systems. Current solutions available for prolonging effectiveness and restoring performance of permeable pavement systems are critically reviewed. Findings from previous studies were used to derive hypotheses. These hypotheses were tested critically for feasibility in theory, using previous data and findings. Data and findings used from previous studies include clogging and accumulated particle analysis tests, load bearing and compaction analyses, performance comparisons under different climate conditions and infiltration tests. These findings were put together and tested in an environment represents challenges faced by permeable pavement systems. Results of tests were presented, critically analysed and interpretations were made.

1.5.Thesis Structure

Current chapter serves as an introduction and is followed by chapters given below.

Chapter 2: In this chapter a review of previous studies about different aspects of permeable pavement systems can be found. Purpose of permeable pavement systems, general structure, benefits to the environment, issues regarding performance and adaptation to different conditions are evaluated. Previously introduced solutions for prolonging effective life of permeable pavement systems was presented. Hypotheses are introduced throughout the Chapter 2, each after review of topics related.

Chapter 3: In this chapter methods of testing are introduced. Data sources are pointed out and detailed descriptions of variables were given. Drainage slot designs are presented. Calculations used are explained step by step and methods used for testing different aspects are outlined.

Chapter 4: Given in this chapter are the data and findings used for testing the hypotheses introduced in Chapter 2. Results of testing methods introduced in Chapter 3 are shown with brief explanations using tables and graphs.

Chapter 5: In this chapter detailed interpretations of results presented in Chapter 4 are given. Results are critically analysed using tables and graphs. Relationships between different characteristics and design changes are evaluated. Testing results of hypotheses are presented.

Chapter 6: Research outcome summarised. With summary of each chapter, addressing performance of aims and objectives is assessed. Research limitations are outlined and recommendations are presented.

1.6.Conclusion

This chapter introduced the suggested solutions for improving performance of permeable pavement systems. Need for an effective and sustainable urban drainage system is outlined, followed by the purpose of this study and clear identification of aims and objectives. Research approach is introduced and information about each chapter is given. A detailed introduction of hypotheses and the Literature Review can be found in the next chapter.

2. CHAPTER TWO: LITERATURE REVIEW

2.1.Introduction

In order to investigate the determinants surrounding the permeable pavement performance, it is necessary to examine and critically analyse previous studies. Several different areas of study should be reviewed during this process: Permeable pavemets, filtering properties of permeable pavements, clogging issues, compaction, local conditions and structural properties. New hypotheses are derived from the existing literature and introduced throughout the Chapter 2.

2.2.Permeable Pavements

Main purpose of permeable pavement systems is to replace conventional drainage systems by providing in-situ and environmentally friendly solutions to drainage (Kumar et al., 2016). Instead of transporting drained water and pollutants to a further location, permeable pavement systems allow water to infiltrate through the system (Novotny and Novotny, 2008). During infiltration, permeable pavement systems mimic nature by replicating infiltration, filtration, storage, evaporation, retention properties (Fryd et al., 2012). A typical structure of a permeable pavement system consists of a permeable surface paving, bedding aggregate which surface paving is placed on and beneath them base and/or sub-base aggregate (Dierkes, Lucke and Helmreich, 2015) (Figure 2-1).

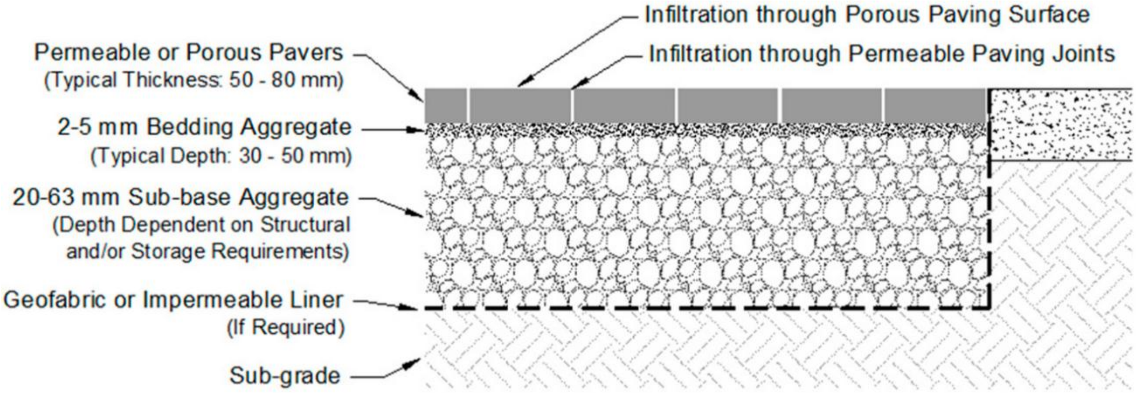

Figure 2-1 Typical structure of a permeable pavement system (Scholz and Grabowiecki, 2007)

Within this structure, bedding layer below the pavements also acts as a filtration medium and coarse aggregate beneath both layers functions as a reservoir (Sansalone et al., 2012). Depending on the design intentions, permeable pavement systems can offer considerable water retention rates, which significantly reduce flood risk during extreme weather events (Hu et al., 2018). However, similar to all civil engineering systems, design of a permeable pavement system is subject to change according to the needs of installation site (Drake, Bradford, Marsalek, 2013; Rodriguez-Rojas et al., 2018). Drake and colleagues state that these changes may range from different components that provide different filtration rates and perforated pipes to transport water collected in sub-base layer, to different layers with different thicknesses designed accordingly for the site requirements. Various reasons such as a risk of groundwater contamination or simply not desiring any infiltration make installation of an impermeable membrane and a discharge system a necessity (Wilson et al., 2003). It should be noted that design specifications of permeable pavements are dictated chiefly by design purpose of the pavement as well as the characteristics of the strata underneath (Ball and Rankin, 2008). Common uses for permeable pavement applications are as parking areas, for slow and/or low intensity vehicle use, pedestrian use, for slope stabilisation, land irrigation and erosion control (Scholz and Grabowiecki, 2007).

2.3.Permeability and Infiltration

Main feature of permeable pavement systems is their ability to let water infiltrate through the structure body (Alsubih et al., 2016). Porous structure of permeable pavement enables water passage through pores in the system (Pezzaniti, Beecham and Kandasamy, 2009). This ratio of pore volume to the overall volume is known as porosity of a medium (Delgado, 2009). Porosity of layers within permeable pavement systems share same principles regarding void fraction as natural sediments and the porosity of each is dependent on characteristics of particles that form the structure (Sansalone et al., 2012). Size distribution of particles is main determinant of porosity of a structure (Kuang et al., 2011). Although grains larger in size would form large voids between them when packed together, a well graded aggregate would contain particles with a variety of sizes including small particles, which would eventually fill the voids between large particles, resulting in a low porosity rate (Masch and Denny, 1966). Conversely, Masch and Denny (1966) also argue that even though relatively small particles would form smaller voids between them, absence of particles in smaller size would leave the forming voids empty, contributing to a higher porosity rate.

Permeability is known as the ability to let liquids pass through structure in fluid mechanics and earth sciences (Darcy 1856; cited in Brown 2002). Permeability is related to porosity as water transport happens through connected pores (Arya and Heitman, 2010). Flow of water occurs due to force applied by pressure difference of two locations and water flows from high pressure point to low pressure point along the gradient (Darcy 1856; cited in Brown 2002). Permeability of a soil layer is determined by various parameters such as particle size distribution, saturation and additional materials involved such as organic materials or dissolved materials within water (Fischer et al., 1990). Additionally, infiltration of water through soil involves three dimensional flows in which vertical movements of water is mainly controlled by gravity and horizontal movements of water is controlled by capillary forces and pressure differences (Warrick, and Zhang, 1987). These movements in combination allow more water to be let through the body of soil, defining the infiltration rate.

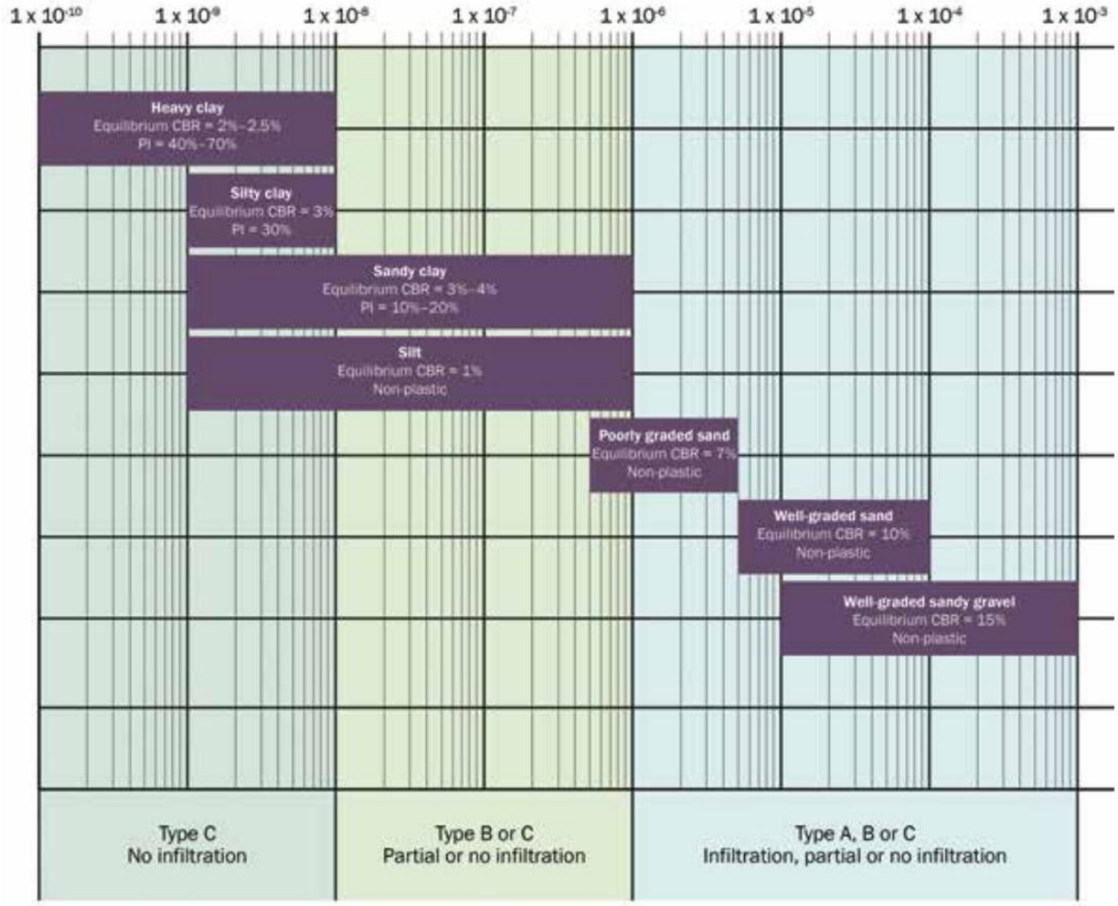

Figure 2-2 Typical ranges of permeability coefficient (m/s) (Woods-Ballard et al., 2015)

Unlike conventional drainage systems, permeable pavement systems mimic nature by replicating the infiltration properties of soils up to a certain extent (Fryd et al., 2012). Granular structure of layers within permeable pavement body creates conditions similar to those created by natural soils and aggregate choices determine the permeability and infiltration rate of the system using the same principles as soils (Valinski and Chandler, 2015). Different from natural occurrences, aggregates in permeable pavements are manually built and therefore it is possible to achieve desired infiltration rates by using aggregates with right characteristics (Cui and Bhattacharya, 2015) (Figure 2-2). Commonly known calculation method of infiltration rate using aggregate size characteristics were presented by Hazen (1911) and uses particle size distribution characteristics of medium as basis.

2.4.Pollutant removal and filtration

As a type of Sustainable Urban Drainage Systems (SUDS), permeable pavement systems offer a wide range of benefits for the environment. Depending on design, a permeable pavement system has potential to serve as a pollution control mechanism (Kachchu, Lucke and Boogaard, 2014). However, use of permeable pavements as a source control device to pollution is most feasible in developed urban areas where stormwater is expected to carry lesser amount of sediments (Beecham, Pezzaniti and Kandasamy, 2012). Majority of pollution in urban stormwater can be attributed to non-point sources, making it challenging to control and best addressed by use of permeable pavement systems (Pratt, Newman and Bond, 1999). Pollutants washing off from buildings, vehicles and other objects during precipitation events, combined with unavoidable pollution from vehicles and decomposing organic matter result in a distinct composition of pollutants in urban stormwater (Mullaney and Lucke, 2013). Within this composition, pollutants mainly from vehicles, such as hydrocarbons present a serious hazard for the environment (Hatt, Fletcher and Deletic, 2009). Additionally, heavy metal pollutants stick to fine sediments carried in urban stormwater and may result in hazardous deposits rich in heavy metals if not contained (Razo et al., 2004). During infiltration, permeable pavement systems filter the pollutants as water goes through the body and coarse aggregates (Scholz, 2013). Beneath the surface paving, bedding aggregate with smaller particles act as a filtering medium, removing particles from stormwater and improving quality (Cui and Bhattacharya, 2015). Studies have shown that permeable pavement systems are able to filter and retain almost any kind of pollutant present in stormwater, including heavy metals and hydrocarbons (Legret and Colandini, 1999, Aryal, Beecham and Lee, 2015). Naturally occurring bacteria in the top layers of structure proven to be able to degrade hydrocarbons, while using organic pollutants such as fallen leaves as supplement (Newman et al., 2002). Furthermore, heavy metal pollutants sticking to fine particles stay on top layers due to filtration (Dierkes, Holte and Geiger, 1999). Although aggregates within permeable pavement systems offer a significant pollutant removal, installation of geofabric layers would prove beneficial where pollutant removal is crucial end extensive filtration is required (Mandal, 1987). Overall, top layers of aggregate in the permeable pavement systems are proven to be very effective in filtration of particle pollutants and sediments in urban stormwater (Legret, Colandini and Le Marc, 1996).

2.5.Clogging

As a result of filtration, accumulation of materials is known to cause clogging in permeable pavements by blocking pores and reducing permeability (Razzagmanesh and Beecham, 2018). Modular structure of permeable pavement systems allows stormwater to pass between individual pavers, gathering pollutants to small areas (Ferguson, 2005). This continuing process, which eventually results in the drop of infiltration rates to unacceptable levels, determines the effective lifespan of a permeable pavement system (Suarman, Argue and Pezzaniti, 1999; Wong, 2006). Characteristics of surrounding environment and composition of materials present in surface runoff affect directly the effective life of a permeable pavement, as well as the structure of permeable pavement itself (Deo, Sumanasooriya and Neithalath, 2009). Installation of a geofabric layer may have beneficial results such as increased efficiency in filtration of materials and better hydrocarbon degradation rates, yet it is also argued that such layers with lower permeability and higher particle retention capabilities shorten the effective life of the system and overall permeability (Pratt, 1997). On the other hand, studies have shown that only a small portion of sediments are retained in the geofabric layers, while majority of sediments are accumulated in the bedding layer before reaching geofabric (Lucke and Beecham, 2011).

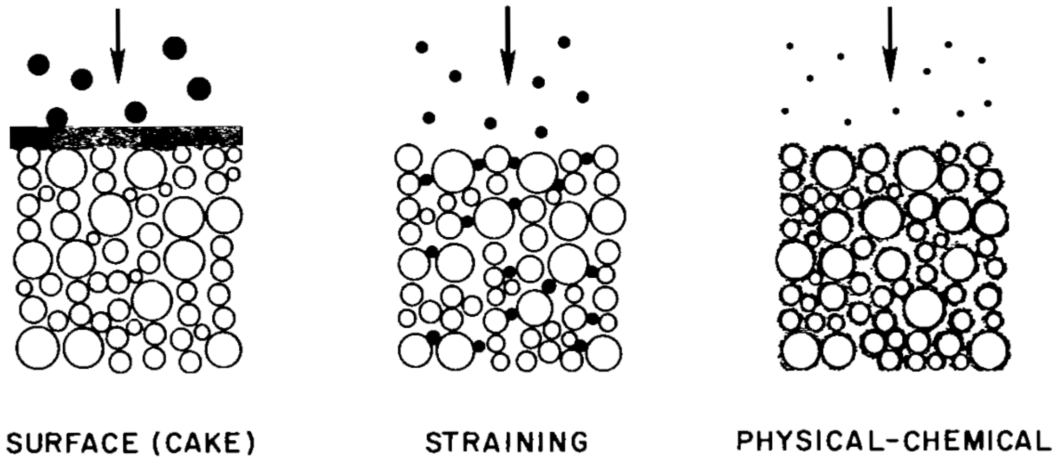

Figure 2-3 Visualisation of different types of filtration (McDowell-Boyer, Hunt and Sitar, 1986)

Although clogging is a major factor in defining the effective life of permeable pavement systems, mechanics and processes surrounding it are still not clearly identified (Yong, McCarthy and Delectic, 2013). Clogging occurs when particles accumulate in and block voids within the structure, blocking paths (Pratt, Mantle and Schofield, 1995). Large particles carried by stormwater may be filtered on surface of aggregate, while particles small enough to enter medium are strained within structure, and smaller particles relative to structure grain size may be held by physical and chemical forces (McDowell-Boyer, Hunt and Sitar, 1986)(Figure 2-3). Low permeability of bedding aggregate and optional installation of a geotextile filter beneath the bedding aggregate for pollution retention, results in top layers of the system acting as a filtering medium with significant particle retention yet considerably low permeability (Collins et al., 2010) Mainly straining of particles and adhesion of smaller particles to permeable pavement structure are responsible for clogging, as they block paths within structure, blocking way for even more particles (Balades, Legret and Madiec, 1995; Liu et al., 2015). Although smaller particles are expected to go deep into the aggregate due to their size, rather than blocking the path in the entirety of the structure, occurrence of clogging near surface shows that small particles pose threat of clogging near surface (Bean, Hunt and Bidelspach, 2007). Studies about infiltration rate and maintenance measures also have proven that cleaning top layers by vacuum cleaning and heavy rain restores the surface infiltration rates significantly, yet only removing sediments accumulated between pavers had little effect, meaning clogging of pores within the aggregate has more impact than accumulation above the aggregate (Drake and Bradford, 2013; Winston et al., 2016). Based on this, it is proposed that size distribution of particles around installation area has a direct influence on effective life of a permeable pavement system.

Hypothesis 1: *Accumulating particle sizes directly influence effectiveness and effective life of a permeable pavement system.*

Penetration range of suspended particles into the permeable formation is determined by the particle size in natural occurrences, and particle size is proven to be in a negative correlation with the penetration depth due to clogging mechanics (Jeong et al., 2018). In case of permeable pavements, clogging mechanics are effective on upper layers with relatively low permeability (Coleri et al., 2013), while on the other hand, any particles remaining in lower layers which act as a reservoir are only subject to adhesive forces (Ranade, 1987). Taking into account that in some cases more than 90% of materials entering the system stays within the top layers (Fach and Geiger, 2005), it is safe to argue that no decisive particle transportation or clogging process takes place within the reservoir layer.

Importance of top layers with low permeability remains crucial and as the infiltration and clogging processes are understood further, more and more studies about improving the effective life and performance are being conducted. A concept study has shown that cutting drainage slots below the paving blocks to provide more space for sediments is a very effective solution for improving effective life and delay clogging (Lucke, 2014). Accumulation of small particles between pavers impact the infiltration rates further, particles with size of 250-550 μm having the largest impact (Nichols and Lucke, 2017). Smaller particles would be carried further and longer on surface by slow moving liquid flows due to requiring comparably less energy to be carried (Farenhorst and Bryan, 1995). Considering the facts that accumulation of material with low permeability directly impacts the infiltration performance (Civan, Knapp and Ohen, 1995) and dispersion density of such materials into aggregate governs the severity of impact on permeability (Darcy 1856; cited in Brown 2002), spreading sediments and therefore the effects of clogging to a wider area beneath paving blocks would significantly increase the effective life and performance of a permeable pavement system.

Hypothesis 2: *Creating wide drainage slots beneath paver blocks would significantly increase the effectiveness and effective life of a permeable pavement.*

2.6.Compaction

Compaction occurs in structures where particles are able to move to open pores under external forces (Fowler and Yang, 1998; Nimmo, 2004). In case of permeable pavements, external factor responsible for compaction is traffic load the system endures (Cipolla, Maglionico and Stojkov, 2015). Frequency of load bearings, as well as the amount and of load has direct impact on structure integrity and performance (Ahmed and Erlingsson, 2013). Although using materials with sufficient properties such as suitable particle crushing strength does prolong the effectiveness by delaying the effects of clogging, as long as a permeable system is subjected to loads, compaction will eventually occur (Cui and Bhattacharya, 2015). Additionally, Cui and Bhattacharya (2015) argue that having a wide particle size range would reduce the impact of compacting by distributing the load more evenly throughout the structure, reducing particle damage. Therefore it can be argued that leaving spaces below paving blocks for sediments would increase pressure on aggregate contacting the block and cause particle breaking where heavy loads are endured by pavement system.

Hypothesis 3: *Drainage slots beneath paver blocks would amplify the effects of compaction.*

2.7.Local Climate Conditions

Permeable pavement systems are suitable for different conditions; however, hydrological characteristics of a permeable pavement system must be adapted to the local climate, as the amount of precipitation is dependent on local climate (Dawson, 2009). In the United Kingdom, precipitation is known to occur throughout all seasons with small differences every year (Hall and Hanna, 2018). On the other hand, in some Mediterranean cities the total yearly precipitation is roughly the same, if not more, yet this precipitation happens in a span of a few weeks to a few months, instead of an entire year (Martinez et al., 2008). Studies have shown that permeable pavement systems are able to withstand heavy rains with high intensity and long duration as long as a sufficient reservoir is present (Pratt, 1999). However, sediments and particles present in different urban environments are also characteristically different depending on the area (Lee et al., 2018). Amount of dust and fine grains in urban areas is significantly greater in areas where hot and dry seasons are followed by heavy seasonal rains, compared to places where precipitation events are more frequent (Garcia-Ruiz et al., 2002).

Similar to hot climates, areas with cold climates present new challenges such as frost heave, where freezing liquids in the ground cause serious deformations on the surface (Rempel, 2010). Use of conventional drainage systems is known to cause damage during cold seasons by transporting cold air below surface, freezing drinking water pipes and freezing the ground (Bäckström and Viklander, 2008). Various types of Urban Sustainable Drainage Systems were tested in challengingly cold situations such as retention basins, ponds, swales (Bäckström, 1998); however, studies about use of permeable pavement systems seem to be limited. It is possible to argue that systems which allow water to infiltrate through their body may be clogged with ice in cold periods (Lindwall and Hogland, 1981; cited in Bäckström and Viklander, 2008), yet on the other hand high evaporation rates of permeable pavement systems allow fast drying process, reducing the risk of clogging with ice (Strake, Göbel and Coldewey, 2010). The feasibility of clogging delaying spaces below pavers in cold climates is debatable as with the feasibility of permeable pavements themselves, but on the other hand, creating spaces under pavers for sediments would prove beneficial in applications in different climactic conditions.

Hypothesis 4: *Clogging delaying system would be useful in temperatures above freezing point.*

2.8.Load Bearing

Permeable pavements are used in areas where surface paving is subject to medium-low loads such as parking lots, low traffic zones and pedestrian use areas (Scholz and Grabowiecki, 2007). Although the burden carried by the pavers is considerably low where the area is used only by pedestrians, parking lots and exposition to traffic load require adequate load bearing capacity (Elshaer, Ghayoomi and Daniel, 2017). This load bearing capacity and occurrence risk of structural failures mainly in relationship with sub-base thickness (Knapton and Barber, 1979). Studies have shown that bedding aggregate layer transmits the pressure applied mainly on a vertical axis and layers below bedding aggregate distribute the force throughout the structure (Cui and Bhattacharya, 2017)(Figure 2-4). Although the effect of pavement block thickness is relatively smaller, thickness of paver blocks has shown to have influence on load bearing capacity (Ling, 2007). Additionally, paver block thickness restrictions were stated in installation guide publications for each traffic load criteria (Woods-Ballard et al., 2015)(See Appendix 1 & 2). Therefore cutting slots for drainage below pavers would be beneficial for infiltration; however, disruption of structural integrity of brick with large gaps would seriously reduce the carry capacity (Donduren, 2016). Additionally, reducing the cross sectional area of load bearing pavers would increase the pressure proportionately (Miller, 1939). Load carried by the system may cause damage to the structure after several years of service; yet increasing the pressure on pavers by reducing the load bearing surface area would only increase the frequency of such occurrences (Hein, 2015). Therefore it is possible to argue that even though cutting slots beneath pavers would increase infiltration performance and delay clogging, it also reduces the carry capacity and structural integrity of the system.

Hypothesis 5: *Drainage slots would decrease load bearing capacity.*

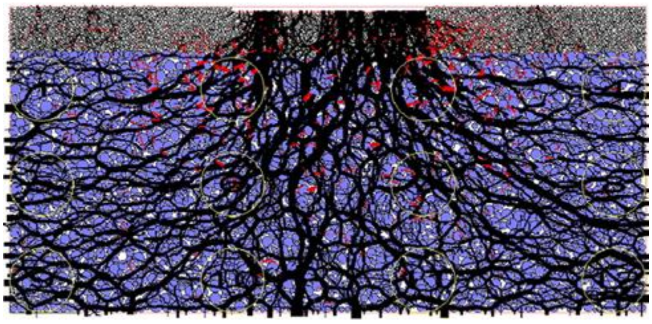

Figure 2-4 Visualisation of force distribution within permeable pavement body (Cui and Bhattacharya, 2017)

2.9.Research Gap

Although their popularity is on the rise, the concept of sustainable urban drainage systems and use of permeable pavement systems are new, compared to other infrastructure systems (Duffy, Berwick and Dello Sterpaio, 2015) Installation of new sustainable urban drainage systems require either creation of new urban areas (Butler and Parkinson, 1997) or replacement of older systems by retrofitting (Stovin and Swan, 2007). Furthermore, challenges in implementation of sustainable urban drainage systems to existing frameworks further hinder the development (Ellis and Lundy, 2016). Scarcity of case studies and installations, collectively with practical reasons require most experiments to be conducted in laboratories where replicating some crucial parameters is challenging (Sanudo-Fontaneda et al., 2013), while effectiveness of available monitoring systems and restrictions constrict the precision and amount of data gathered from field studies (Li, Kayhanian and Harvey, 2013). Lack of resources about essential topics such as compaction deems an extensive inter-disciplinary research necessary in order to define active parameters in this study.

Majority of studies on permeable pavement systems aim to address the issue of clogging by simulating sediment accumulation under laboratory conditions or conducting infiltration tests on field (Pezzaniti, Beecham and Kandasamy, 2009). Through various experiments, studies have shown that clogging is one of the main factors that determine the effective life of permeable pavement systems (Suarman, Argue and Pezzaniti, 1999; Wong, 2006). A concept study was conducted by Lucke (2014) in order to find solutions for improving the effective life of permeable pavements and has shown that cutting slots below pavers would increase the effective life of the system. Although this study shows that slots allow sediment accumulation and infiltration, experiments focusing on isolated variables such as different width values with fixed height value for slots would have revealed significantly more information about clogging mechanics.

2.10. Conclusion

Permeable pavement systems offer sustainable solutions for urban drainage (Kumar et al., 2016). Different designs and adaptations emerge for requirement of local conditions (Mandal, 1987; Dierkes, Lucke and Helmreich, 2015). Addition of components such as filtering material, impermeable layer underneath the system and perforated pipes has the ability to address any challenge a location might offer (Wilson et al., 2003; Ball and Rankin, 2008). Aside from flexible design, most notable benefits permeable pavements offer is stormwater control and pollution retention (Kachchu, Lucke and Boogaard, 2014). However, pollution retention also determines the effective life of the permeable pavement system, as material accumulation cause clogging and significantly reducing infiltration levels, rendering the system ineffective (Razzagmanesh and Beecham, 2018). Another variable that influences infiltration rates is compaction, where the weight above the pavement compresses the aggregate, forcing materials to fill the voids and reducing the permeability (Fowler and Yang, 1998; Cipolla, Maglionico and Stojkov, 2015). Although permeable pavement systems are best utilised in areas where the amount of weight is lower than the weight endured by asphalt driveways, weight carried is still enough to cause compaction (Cui and Bhattacharya, 2015). Considering maintenance issues on the surface of the permeable pavement systems can occur due to broken pavers, it should be mentioned that one of the main determinants of load bearing capacity of a permeable pavement system is the amount of load the pavement on the surface can carry (Hein, 2015; Donduren, 2016; Elshaer, Ghayoomi and Daniel, 2017).

Although the utilisation potential of permeable pavement systems is very high, certain setbacks, both legal and practical, keep the utilisation to a limited amount (Butler and Parkinson, 1997; Stovin and Swan, 2007; Ellis and Lundy, 2016). Limitations, combined with the practical challenges which make it difficult to monitor processes within permeable pavement systems, result in crucial gaps in the literature such as many uncertainties revolving around clogging processes and compaction (Suarman, Argue and Pezzaniti, 1999; Wong, 2006; Li, Kayhanian and Harvey, 2013).

In the light of available studies and interdisciplinary research, following hypotheses are derived to be tested in the following chapter.

Hypothesis 1: Accumulating particle sizes directly influence effectiveness and effective life of a permeable pavement system.

Hypothesis 2: Creating wide drainage slots beneath paver blocks would significantly increase the effectiveness and effective life of a permeable pavement.

Hypothesis 3: Drainage slots beneath paver blocks would amplify the effects of compaction.

Hypothesis 4: Clogging delaying system would be useful in temperatures above freezing point.

Hypothesis 5: Drainage slots would decrease load bearing capacity.

3. CHAPTER THREE: RESEARCH METHODOLOGY

3.1.Introduction

In this chapter, research methods and data used are introduced. Variables are defined and detailed descriptions are given. Aside from availability, reasons for choosing the used data were explained. Data analyses were conducted using the data available and a representative environment with specific amounts of precipitation and suspended urban sediments in urban stormwater is created. Within this environment a number of test combinations were created in order to be able to isolate focused variables and test effects without inclusion of others. Calculation steps used for tests were explained. Reader is informed about assumptions, values and reasons of choosing calculations throughout the chapter.

3.2.Research Method

In order to be able to conduct a reliable and scientific research, it is crucial to obtain a focused and step by step approach that clarifies every detail (Sekaran and Bougie, 2013). Obtaining data required to conduct such studies may be both economically and technically challenging; however, developing technology in recent years significantly made it easier to share and access existing data (Doolan, Winters and Nouredini, 2007). Therefore it was decided to use existing data available in this study and follow a secondary data analysis. To test the hypotheses, creation of synthetic environments similar to those used in previous studies (Lucke, 2014) was decided. Data available were also used to define environment elements such as precipitation. Variables were isolated within created environments for appropriate testing.

3.3.Pavement Structure and Aggregate

Permeable pavement design for the simulation model is prepared using guidelines defined by publications The SuDS Manual (Woods-Ballard et al., 2015) and Permeable Pavements (Interpave, 2010). Considering that clogging occurs on the surface layers and material properties chosen for reaching adequate permeability and load bearing values for layers beneath the bedding aggregate would not affect the outcome of this simulation model, including only top layers in simulation model is decided. Therefore permeable pavement in the simulation model consists of surface blocks and a bedding layer. Thickness of surface paving in model is 80 millimetres and thickness of bedding aggregate is 50 millimetres. Woods-Ballard et al (2015) stated in their publication that permeability of bedding aggregate should not be less than $6x10^{-2}$ m/s and overall permeability of pavement surface should be at least 2500 mm/h when tested in newly built state. In order to create similar conditions with the work of Lucke (2014), a layer of 50 millimetres thick bedding aggregate with grain size between 2 and 5 millimetres was used. Aggregate d_{10} value was assumed 2.18 mm in order to provide aggregate porosity mentioned in Woods–Ballard et al. (2015). Aggregate density was assumed as 1620 kg/m^3 using average density for sediments with given size range (StructX, 2018).

3.4.Sediment Characteristics

In order to be able to analyse clogging mechanics, accumulating materials and their characteristics must be defined properly. Previous studies about urban sediment size and distribution are used as primary source. Data obtained from various studies are used to determine average sediment sizes for urban environment modelling. Particle size distribution analysis is used for determining the characteristics of particles present in taken samples (Charters, Cochrane and O'Sullivan, 2015). Results of analysis show the size distribution percentages of sample. Sizes which 10%, 50% and 90% of particle mass is smaller than are referred to as d_{10}, d_{50}, and d_{90} respectively. For this study, 3 different urban sediment characteristics are defined using data obtained from previous studies (Table 3-1).

Table 3-1 Size distributions, locations, obtaining methods and sources of sediment samples (Author)

Origin	d10 (µm)	d50 (µm)	d90 (µm)	Method	Source
BRA	19.725	84.1	228.1	Vacuum cleaner	Poleto et al (2009)
NZL	23.2	71.6	177.2	Grab and Automatic sampling	Charters, Cochrane and O'Sullivan (2015)
CHI	60	110	420	Vacuum cleaner	Zhao et al (2010)

Sample collections in studies were conducted by using various methods chosen by authors, which are sampling by grabbing and automatic sampling (Charters, Cochrane and O'Sullivan, 2015) and using vacuum cleaners to take samples from streets near city centre (Poleto et al., 2009; Zhao et al., 2010). For studies with more than one sediment size value, average particle sizes are calculated by using mean value calculation. Disparities among the number of samples taken in studies were the underlying reason for average value calculation. Percentage of sediments with particles larger than bedding aggregate d_{10} were considered as 100% for NZL, 80% for BRA and 65% for CHI, judging by particle size distribution data. Concentration of urban sediments in urban stormwater was acquired from Lucke (2014) and a concentration of 150 grams of sediments in a cubic meter of stormwater is assumed. Density of sediment samples was acquired from Minnesota Pollution Control Agency (2015) and a density of 1.1 g/cm^3 was assumed for all samples due to insignificant density differences between sediments.

Size distribution analysis results taken from available studies can be found in Appendix 3.

3.5.Precipitation Characteristics

Adapting an urban infrastructure system to a simulation model requires accurate assumptions (Einfalt, Krejci and Schilling, 1998). Two different types of precipitation data were required for this study. Annual average precipitation data was required for calculating yearly sediment discharge and high intensity short duration amounts available for testing were required for infiltration tests. 800 millimetres, the annual average precipitation for Eastern Scotland was obtained from available datasets published by Met Office (2018) to be used in calculations.

In order to represent challenges faced by permeable pavement systems, high intensity rainfall with short duration was included in performance simulation model. Inclusion of ice and snow melt was considered, however, excluded due to the involvement of high number of variables in process (Skyllingstad et al., 2015) and effects of such events were assumed similar to of rainfall events. Low intensity rainfall events with long durations were also excluded from the simulation model, considering large volumes of intake with low intensity is not a challenge regarding infiltration rates of upper layers, but instead is a challenge regarding the retention characteristics of lower layers (Sansalone et al., 2012). As a result, three high intensity rainfall events, 50, 100 and 150 mm/h, were tested in the performance simulation model and were adopted from Brugin et al. (2017).

3.6.Paver Block Characteristics

The SuDS Manual (Woods-Ballard et al., 2015) was used to determine the thickness of paving blocks and using blocks with thickness of 80 millimetres was decided. Required minimum thickness of pavement blocks for areas with less than 2000 kg anticipated axle load is defined as 50 mm (See Appendix 2) (Woods-Ballard et al., 2015). Although overall thickness of chosen paving blocks was 80 mm, minimum required thickness of 50 mm was left intact on the top, while bottom 30 mm was enabled for working on. In order to retain the load bearing capabilities and structural integrity of paving blocks, maximum load bearing surface area reduction was limited to the 25% of block surface. For testing, cutting square and rectangular slot patterns were chosen for ease of calculation and real-life feasibility. For availability, dimensions of paving block are taken from an existing product available on market. For performance simulation testing, a paving block with dimensions of 240x120x80 mm was used (Tobermore, 2018). For ease of calculation and structural integrity, three-slot design was borrowed from Lucke (2014).

In order to analyse the role of both width and height of the slots, both parameters were tested in isolation. To test the impact of change in width, 3 different width values with different fixed height values were tested. To test the impact of change height, 3 different height values with different fixed width values werse tested. For comparison, one design with no modifications is also tested. Overall, 10 different brick designs were tested. Dimensions of slots can be seen in Table 3-2.

Table 3-2 Width and height dimensions of drainage slot designs (Author)

	Width x Height of Slots		
	a	b	c
x	10mm x 10mm	15mm x 10mm	20mm x 10mm
y	10mm x 15mm	15mm x 15mm	20mm x 15mm
z	10mm x 20mm	15mm x 20mm	20mm x 20mm

Dimensions ax, ay and az were used to examine the effect of increasing height of slots with a fixed width of 10 mm, bx, by and bz were used to examine the same effect with a fixed width of 15 mm and cx, cy and cz were used to examine the same effect with a fixed width of 20mm. Similarly, dimensions ax, bx and cx were used to examine the effect of increasing width with a fixed height of 10 mm, ay, by, cy with a fixed height of 15 mm and dimensions az, bz, cz were used to examine the effects of increasing width with a fixed height of 20 mm. Joint space width of 6 mm between paver blocks is adapted from Hassani and Mohammad (2008) and instead of calculating sediment accumulation for more than one block, each block is given a 3 mm joint gap surrounding them for sediment accumulation calculations. View of blocks from different angles can be seen in Figure 3-1.

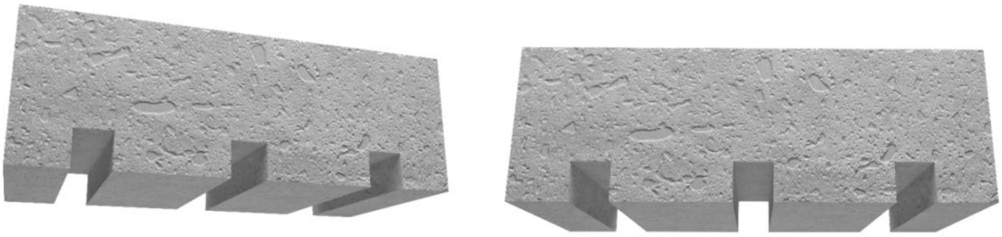

Figure 3-1 View of paver block with 20mm x 20mm drainage slot design (Author)

3.7. Performance Analysis

3.7.1. Hydrological significance of slot width

Hydraulic conductivity (K) of pavement system was analysed using precipitation (P) data, aggregate characteristics and accumulating suspended sediments (Δm). Migration of stormwater from surrounding areas was not taken into account. To be able to analyse the hydrological processes within the system, sediment deposition and change in hydraulic conductivity were calculated for different scenarios. Purpose of this analysis is to define processes using percentages and ratios.

Table 3-3 Area calculations used (Author)

Area Calculations	
$A = l \times w$	**(3.1)**
$A_P = [l + (2l_j)] \text{ x } [w + (2l_j)]$	**(3.2)**
$A_j = A_P - A$	**(3.3)**
$A_i = A_j + 3(w \times w_s)$	**(3.4)**

Block dimensions are represented with l for length, w for width and h for height. Horizontal area of block represented with A, and calculated using **(3.1)**. With the inclusion of 3 mm joint gap (l_j), total block precipitation area (A_P) can be found using the calculation **(3.2)**. To find the total infiltration area (A_i), calculation **(3.4)** was used where slot width is represented with w_s.

Table 3-4 Precipitation and sediment calculations used (Author)

Precipitation and Sediment Calculations	
$V_P = P \times A_P$	**(3.5)**
$\Delta m = \rho_s \times V_P$	**(3.6)**
$\Delta m' = \Delta m \,/\, A_i$	**(3.7)**

Using the annual average precipitation and precipitation area, annual average precipitation volume V_P was calculated **(3.5)**. Due to limitations, migration of stormwater from surrounding areas was not taken into account and only the precipitation falling on A_P was calculated. Therefore urban sediments present in surroundings were also excluded and only the average sediment amount in infiltrating stormwater was calculated. One year worth of sediment mass (Δm) was calculated using suspended sediment concentration in stormwater (ρ_i) **(3.6).** For comparison purposes, yearly sediment deposition per infiltration area ($\Delta m'$) can be found using calculation **(3.7).**

Table 3-5 Aggregate calculations used (Author)

Aggregate Calculations	
$V_a = h_a \times A_P$	**(3.8)**
$m_a = \rho_a \times V_a$	**(3.9)**
$m_c = m_a \times (A_i / A_P)$	**(3.10)**
$m_T = m_c + \Delta m$	**(3.11)**

Real life situations make it possible to measure the mass of the aggregate manually and therefore, more accurately. However, situations where such options are not available require obtaining values using calculations. In order to find aggregate mass (m_a) on precipitation area, aggregate volume (V_a) was calculated using aggregate thickness (h_a) and precipitation area **(3.8)**. Following, mass of aggregate is calculated with density (ρ_a) and volume of aggregate **(3.9)**. Transportation of sediments through bedding aggregate was assumed to be following a straight vertical line in this study due to limitations. Therefore, clogging and accumulation of materials were assumed to occur within the infiltration area. Calculation **(3.10)** was used to find the amount of aggregate affected by sediment accumulation (m_c), using mass of aggregate, precipitation area and infiltration area. Total material mass after one year of accumulation (m_T) was found by adding accumulating suspended sediment mass (Δm) to affected aggregate mass **(3.11)**.

Table 3-6 Size distribution calculations used (Author)

D_{10} Calculations	
$m_{ad10} = m_c \times 10\%$	**(3.12)**
$R = (m_{ad10} + m'_{ad10}) / m_T$	**(3.13)**
$R_R = R / 10\%$	**(3.14)**
$d'_{10} = d_{10} / R_R$	**(3.15)**

Addition of fine particles that are smaller than the d_{10} size of bedding aggregate would decrease the d_{10} value of layer. Although the best possible option is to make a real life experiment involving a particle size distribution analysis, lack of resources require calculation of such values. In order to make such calculation, uniformity of bedding layer in infiltration area (A_i) was assumed. To be able to find the new d_{10} value after a year of accumulation (d'_{10}), mass of aggregate d_{10} (m_{ad10}) was obtained using calculation **(3.12)**. Ratio of particles with different masses after introduction of sediments (R) was found by adding the mass of sediments smaller than d_{10} size (m'_{ad10}) to aggregate d_{10} and dividing the result by total mass of sediments and aggregate (m_T) **(3.13)**. The change in ratio (R_R) was found by using calculation **(3.14)** and the d_{10} size of aggregate sediment mixture (d'_{10}) was found by using calculation **(3.15)**.

Table 3-7 Permeability calculations used (Author)

Permeability Calculations	
$K = C\ (d_{10})^2$	**(3.16)**
$RK = 1 - (K_2\ /\ K_1) = 1 - [(d'_{10})^2\ \ /\ (d_{10})^2\ ]$	**(3.17)**

Values of d_{10} and d'_{10} were used to investigate the change in hydraulic conductivity using formula proposed by Hazen (1911) **(3.16)**, where C is constant with different values depending on the source (Hussain and Gabi, 2016) and d_{10} is the grain size which 10% of particles are smaller. Considering the only variables in given formula are hydraulic conductivity and d_{10}, change in hydraulic conductivity was found using the calculation **(3.17)** and was expressed in percentages.

3.7.2. Hydrological significance of slot height

In hydrological sense, slot height mainly affects the effective life by allowing more sediment accumulation in slot area. In this study, accumulated sediment height was calculated using sediment mass and density. For this calculation, accumulating sediments and bedding aggregate were considered as two separate units. Sediment accumulation was assumed to occur on top of the bedding aggregate and volume of accumulating material was calculated using mass and density of sediments. Therefore, calculation **(3.18)** was used to find one year worth of sediment volume (Δv) with sediment density (ρ_s) and sediment mass (Δm). Volume of accumulating sediments and infiltration area was used to determine yearly accumulation height (h_y) of sediments **(3.19)**. Using slot height (h_s) and yearly accumulation height, filling time of slots (t_s) was calculated **(3.20)**.

Table 3-8 Sediment accumulation calculations used (Author)

Sediment Accumulation Calculations	
$\Delta v\ = \rho_s\ /\ \Delta m$	**(3.18)**
$h_y\ = \Delta v\ /\ A_i$	**(3.19)**
$t_s = h_s\ /\ h_y$	**(3.20)**

3.7.3. Structural significance of slots

Changes in load bearing capacity of paving blocks were estimated using the change in the structural integrity. Load bearing capacity of permeable pavement blocks was taken from The SuDS Manual (Woods-Ballard et al., 2015) and maximum anticipated axle loads for paver blocks with 80mm thickness and 50mm thickness were adapted. Additionally, considering the pressure applied from paver block to bedding aggregate is dependent on the surface area the force is applied with, change in surface area was used to determine the increase in pressure applied **(3.21)**.

Table 3-9 Pressure calculation used (Author)

Pressure Calculation
$p = F / [A \times (l - 3w_s) / l]$ **(3.21)**

3.7.4. Runoff prediction

Surface runoff occurs when precipitation rate is greater than infiltration rate (Czyzyk and Swierkot, 2017). Minimum appropriate infiltration rate of 2500 mm/h given in SuDS Manual (Woods-Ballard et al., 2015) was used as starting point. Calculated hydraulic conductivity decrease rates were used to determine the infiltration rate for each year. Three different precipitation rates, 50, 100 and 150 mm/h adapted from Brugin et al. (2017) were used to evaluate system condition and performance. Runoff predictions are presented in the Chapter 5, as part of Analysis and Interpretations.

3.8.Conclusion

In this chapter, data required to test the hypotheses and means of obtaining were explained. Variables used in testing were introduced. Calculations and test methods were explained. Results obtained using given methods is presented in Chapter 4.

4. CHAPTER FOUR: RESULTS

4.1.Introduction

In this chapter presented are the results obtained using the data and methods presented in previous chapter. Each set of result required for hypotheses evaluation are presented with brief explanations using tables and graphs.

4.2.Infiltration Area

Infiltration area calculations were conducted using Hydropave 240 (Tobermore, 2018) paver block dimensions and 3 mm joint space adapted from Hassani and Mohammad (2008). Infiltration areas for control design and slot designs with three different width values were calculated. Cutting drainage slots beneath paving blocks has shown to be significantly effective in increasing infiltration area. Graph 4-1 shows the infiltration areas for each design.

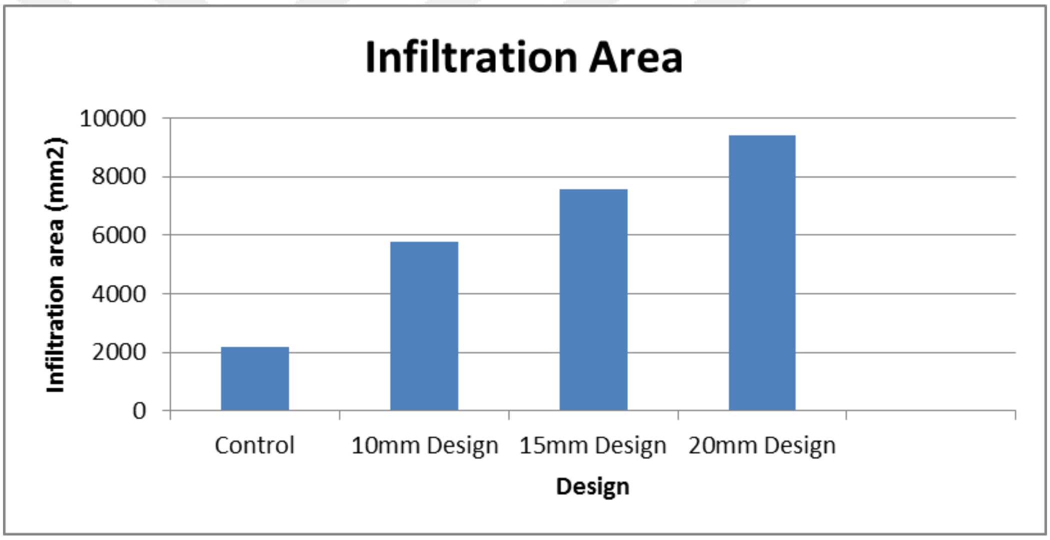

Figure 4-1 Infiltration areas (Author)

As can be seen in the graph, original design with no slots has the least infiltration area. Among three different slot designs, 20 mm wide slot design offer the largest infiltration area. Using the infiltration areas, yearly sediment accumulation per area was calculated for each different design. Figure 4-2 shows the result of infiltration area difference. Low infiltration area result in high sediment accumulation density per infiltration area in control design. Conversely, significantly low accumulation density is seen in designs with slots.

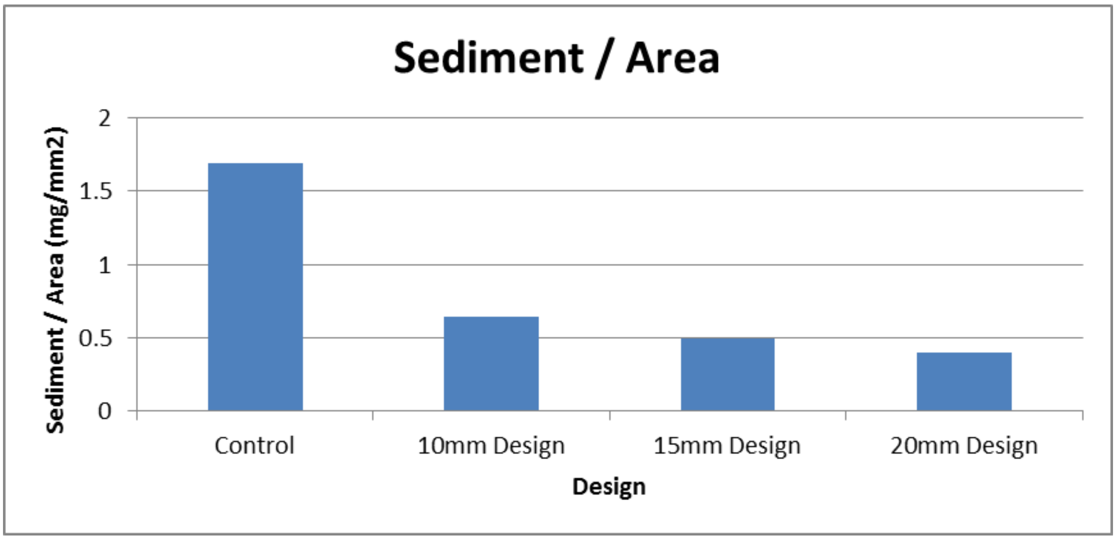

Figure 4-2 Sediment / Area ratio (mg/mm2) (Author)

4.3.Permeability Change

Sample sediment data obtained from Charters, Cochrane and O'Sullivan (2015), Poleto et al. (2009) and Zhao et al. (2010) were put into analysis. Using 800 mm annual average precipitation amount (Met Office, 2018) and 150 mg/l average yearly total sediment amount in stormwater (Lucke. 2014), amount of yearly sediment accumulation was calculated. Accumulated sediments and aggregate beneath them considered as one single unit and change in the particle size distribution of aggregate after introduction of particles was analysed. Introduction of sediments (NZL, BRA and CHI) resulted in different reaction from the system due to their different particle size distribution characteristics. Infiltration rate change for each year was calculated for different designs and different sediment types.

Table 4-1 Infiltration rates for three sediment samples with control design, 10 years (Author)

	0	1	2	3	4	5	6	7	8	9	10
NZL	2500	1782.32	1278.643	922.8513	669.9454	489.084272	358.9885	264.8806	196.434	146.3889	109.6115
BRA	2500	1912.322	1470.181	1135.766	881.5323	687.30044	538.2022	423.2234	334.1623	264.8806	210.7618
CHI	2500	2019.39	1637.824	1333.568	1089.937	894.059901	735.9616	607.8744	503.7238	418.7387	349.1568

Table 4-1 shows the infiltration rates for standard brick design with application of three different sediment types. Adequate infiltration value of 2500 mm/h determined by Woods-Ballard et al., (2015) was taken as newly built infiltration rate. Aggregate d_{10} value and change in infiltration rate was calculated for each year using values of previous year as base value. Results obtained from calculations were similar to observations in previous studies. Significant decrease of infiltration rate over the years was observed. Different sediment characteristics have shown to have different impacts and the impact of fine sediments (NZL) on infiltration rate was proven to be expectedly higher compared to urban sediments with larger particles (BRA and CHI). To test the effects of slots designs, permeability change model was used on pavement block design with 10mm slot width first. Three sample sediment sizes were applied in the model and same calculations were made.

Table 4-2 Infiltration rates for three sediment samples with 10 mm width slot design, 10 years (Author)

	0	1	2	3	4	5	6	7	8	9	10
NZL	2500	2180.564	1903.905	1664.036	1455.844	1274.95439	1117.626	980.6491	861.2725	757.1314	666.1928
BRA	2500	2246.033	2019.508	1817.286	1636.604	1475.03296	1330.432	1200.913	1084.809	980.6491	887.1313
CHI	2500	2297.089	2112.013	1943.085	1788.79	1647.76456	1518.782	1400.735	1292.627	1193.557	1102.713

In Table 4-2, infiltration rate of pavement block design with 10mm drainage slots is shown. Sample sediment with highest particle size, CHI, was shown to cause least amount of infiltration rate decrease, followed by BRA sediment sample with smaller particles. Similar to the standard design, NZL sediment sample has the greatest impact on the infiltration rate of paver block with 10 mm drainage slot, yet, in a smaller scale compared to standard design.

Table 4-3 Infiltration rates for three sediment samples with 15 mm width slot design, 10 years (Author)

	0	1	2	3	4	5	6	7	8	9	10
NZL	2500	2250.051	2026.333	1825.965	1646.396	1485.36534	1340.869	1211.13	1094.571	989.789	895.5387
BRA	2500	2302.249	2121.163	1955.252	1803.167	1663.68714	1535.703	1418.21	1310.295	1211.13	1119.964
CHI	2500	2342.599	2195.947	2059.253	1931.79	1812.88521	1701.92	1598.323	1501.568	1411.167	1326.67

Table 4-4 Infiltration rates for three sediment samples with 20 mm width slot design, 10 years (Author)

	0	1	2	3	4	5	6	7	8	9	10
NZL	2500	2294.72	2107.152	1935.693	1778.895	1635.44263	1504.147	1383.927	1273.805	1172.892	1080.38
BRA	2500	2338.094	2187.371	2047.01	1916.255	1794.4083	1680.825	1574.91	1476.113	1383.927	1297.883
CHI	2500	2371.437	2250.053	2135.415	2027.12	1924.78799	1828.066	1736.622	1650.145	1568.345	1490.949

Results of same performance tests for 15mm slot design and 20mm slot design can be seen above. Infiltration rates for 15mm slot design can be seen in Table 4-3 and results for 20mm slot design can be seen in Table 4-4. In both designs, similar characteristics to 10mm slot design were observed.

4.4.Effects of Slot Height and Structural Changes

Effects of different slot height designs were analysed. One average density value, 1.1 g/cm^3 was used to represent three sediment samples. Yearly accumulation volume was calculated using yearly accumulating sediment mass and sediment density. Accumulation thickness is in relation with infiltration area, therefore yearly accumulation thickness and time required to fill the slots with sediments were calculated for each slot width design.

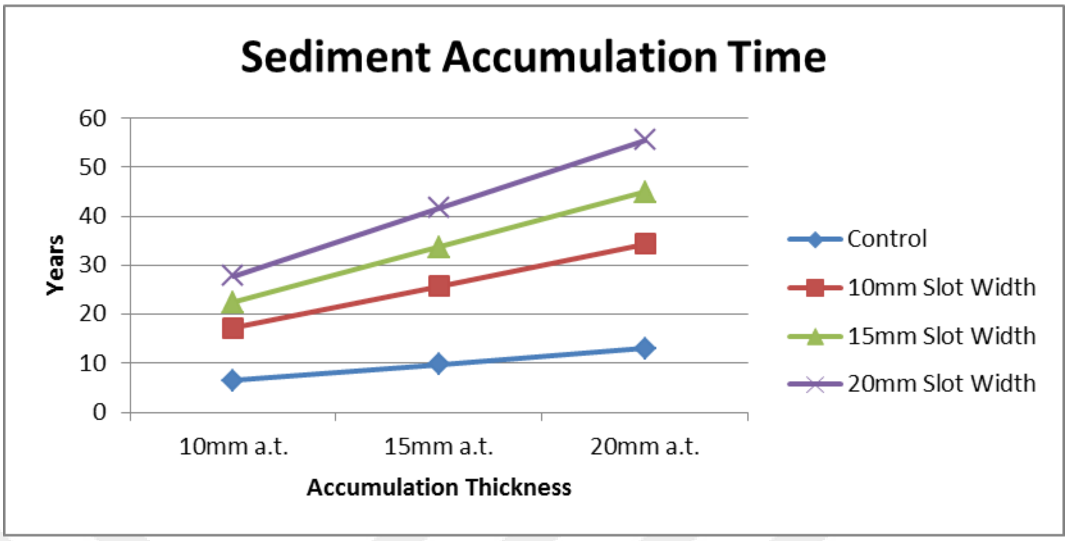

Figure 4-3 Sediment accumulation times (Author)

Figure 4-3 shows the expected accumulation times for different designs. 800 mm annual average precipitation and 150 g/m^3 sediment density in stormwater were taken as base variables for this simulation model. Results of accumulation thickness and time for control design were similar to those of previous studies; however, required time for sediment accumulation estimations for pavement designs with slots were beyond most expectations, if not all.

On the other hand, structural changes resulted by slot heights were calculated using percentage of intact thickness decrease of paver block. However detailed analyses regarding the impact of slot heights on paver block load bearing capacity and structural performance will be presented in the following chapter, as regulated requirements may change the impact of slot heights on the system. Conversely, changing load bearing surface area of pavement block also has a distinct impact on the system. Changes in surface areas of block surface for different designs were calculated and can be seen in Table 4-5. Changes in applied pressure to the bedding aggregate due to the changing load bearing surface area are addressed in the next chapter.

Table 4-5 Block surface areas for each design (Author)

	Control	10mm Slot	15mm Slot	20mm Slot
Slot Area	0	3600	5400	7200
Block Surface Area	28800	25200	23400	21600
Surface Area %	100.00%	87.50%	81.25%	75.00%

4.5.Conclusion

In this section, results of tests conducted were presented using graphs and tables. Brief explanations were made about every result and basic relationships between different designs and results were outlined. Detailed results regarding the calculations and tests can be found in Appendix 4. Detailed analysis and interpretations of results are presented in the following chapter.

5. CHAPTER FIVE: ANALYSIS AND INTERPRETATIONS

5.1.Introduction

In this chapter results shown in Chapter 4 are analysed. First, sediment characteristics are analysed and the impact of different sediment samples are evaluated. Differences between samples are linked with differences between results and properties with most significance are presented. Defined sediment characteristics and impact differences were used in combination with results from previous chapter to analyse the hydrological performance of suggested drainage slot designs. Advantages and disadvantages provided by different designs are outlined and both positive and negative impacts of suggested designs are presented. Following, structural performance analysis and interpretations are made. Finally, findings, analyses and interpretations are put together to determine the feasible and effective designs and rule out the impractical designs, followed by evaluation of hypotheses presented in Chapter 2.

5.2.Performance Analysis

5.2.1. Sediment Characteristics

Hydrological performance tests in this study mainly consisted of infiltration rate comparisons. To be able to check the accuracy of testing methods and data explained in Chapter 3, standard pavement block design tests were compared to previous studies. Pezzaniti, Beecham and Kandasamy (2009) state that in the study conducted by Borgwardt (1997), a decrease of 50% in infiltration rate in 5 years, which was followed

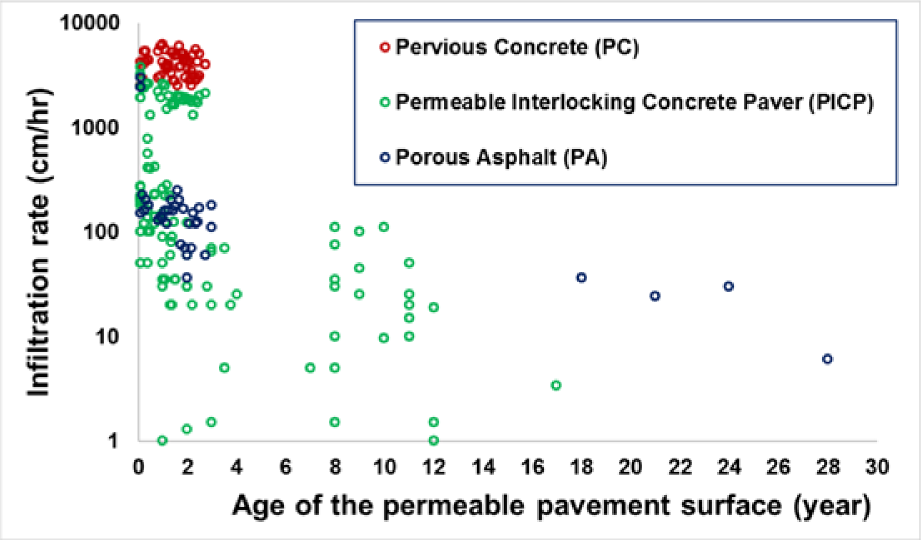

Figure 5-1 Age of pervious drainage infrastructure age - Infiltration rate graph (Razzaghmanesh and Beecham, 2018)

by a decrease to an infiltration rate of 1 mm/h in the sixth year, was observed. It is possible to observe these conditions in the simulation model used in this study, with using appropriate set of data. Additionally, age-infiltration rate graph obtained from Razzaghmanesh and Beecham (2018) (Figure 5-1) displays a range of observations some of which are very similar to observations in this study.

Table 5-1 Sediment size distributions and performance losses after 5 years of use (Author)

Sample	d10 (µm)	d50 (µm)	d90 (µm)	% Decrease
NZL	23.2	71.6	177.2	80.44%
BRA	19.725	84.1	228.1	72.51%
CHI	60	110	420	64.24%

Results obtained from performance tests of control design shows the significant difference the accumulating sediment size makes. Table 5-1 shows the d_{10} d_{50} and d_{90} particle sizes of sediment samples along with infiltration rate decrease after 5 years of use. Hazen (1911) equation was used to compare infiltration rates and determine infiltration rate reductions. Constant value in the equation was ignored in comparisons, leaving the d_{10} value the only determining variable. Reduction of infiltration rate following the introduction of fine sediments to the bedding aggregate is an expected result; however, different change rates of d_{10} value and infiltration rate reaction to such changes have shown the significance of sediment amount, as well as size. NZL sample has the greatest impact on infiltration rate. Among three samples, BRA sample taken from Poleto et al. (2009) has the smallest d_{10} value. However, BRA sample also contains large particles, which are larger than d_{10} value of bedding aggregate and consists of 20% of the sample mass. On the other hand, NZL sample has a greater d_{10} value than of BRA sample, yet almost 100% of particles in NZL sample are smaller than d_{10} value of bedding aggregate. This difference shows that the amount of introduced sediments smaller than aggregate d_{10} value has greater significance than size difference of particles. Impact of CHI sample has further proven this observation. CHI sample consists of fairly large particles, grain size of 35% of sample mass is larger than d_{10} value of bedding aggregate, however, after 5 years of use has caused almost 65% decrease in infiltration rate. This impact was caused by the amount of sediments with grain size smaller than bedding aggregate d_{10} value.

However, research methods used in this study require making of necessary assumptions. Accumulating sediment amount (Δm) was calculated without taking the sediment retention rate into account. 100% of suspended sediments in stormwater were assumed to be accumulating within the system. Such assumption was made in order to be able to analyse the crucial impacts of sediment accumulation. If adapted to different situations, particle retention rate and suspended sediments remaining in filtered stormwater would play an essential role. Reduction of infiltration rate was calculated using the mass of retained materials with smaller size than aggregate d_{10} value. In different cases, particles with 50-100 μm would have very little significance in the beginning and remain unfiltered in stormwater while larger particles having an impact. In such cases Δm amount should not include the mass of unfiltered sediments for accurate results. Retention of smaller particles would eventually result in clogging of pores, which as a result would make it possible for smaller particles to have an impact on infiltration rate. Therefore it is crucial to determine the sediment retention rate and amount precisely in order to obtain accurate results using the performance simulation model used in this study.

5.2.2. Drainage Slots

Material accumulation in the bedding aggregate was calculated using the infiltration area of systems. In standard design of paver blocks, impermeable structure of blocks only allows water to infiltrate through the joint gaps between blocks. Accumulating sediment mass per unit area was calculated using the joint gap area surrounding paving block. As a method of increasing infiltration area, drainage slots beneath paver blocks with different dimensions were tested. It was expected that largest slot design would be the most successful. Three different width designs, 10mm, 15mm and 20mm were tested. Introduction of drainage slots provided a significant increase in available infiltration area, which would spread the effects of clogging to a wider area.

Introduction of drainage slots provided a significant increase in infiltration area for stormwater. However infiltration on the surface of pavement blocks still happens through the joint gaps between paver blocks. It is known that large materials and pollutants such as fallen leaves or plastic packaging may block these joint gaps and prevent water drainage. If aligned correctly, drainage slots beneath pavers would form a continuous path for water to bypass such blockages. Such advantage further reduces the risk of clogging, as large material accumulation on the surface of permeable pavement is one of the performance hindering factors (Winston et al., 2016). Most importantly, increased area of infiltration would spread the effects of clogging with less impact. Transportation of surface runoff from adjacent impermeable surfaces places an increased sediment load on the edges of permeable pavement and results in clogging to occur sooner than expected (Sanudo-Fontaneda et al., 2012). Drainage slots beneath paver blocks not only provide more infiltration area for surface runoff from adjacent areas, but also paths created allow infiltration to occur more spread out and evenly over a larger area.

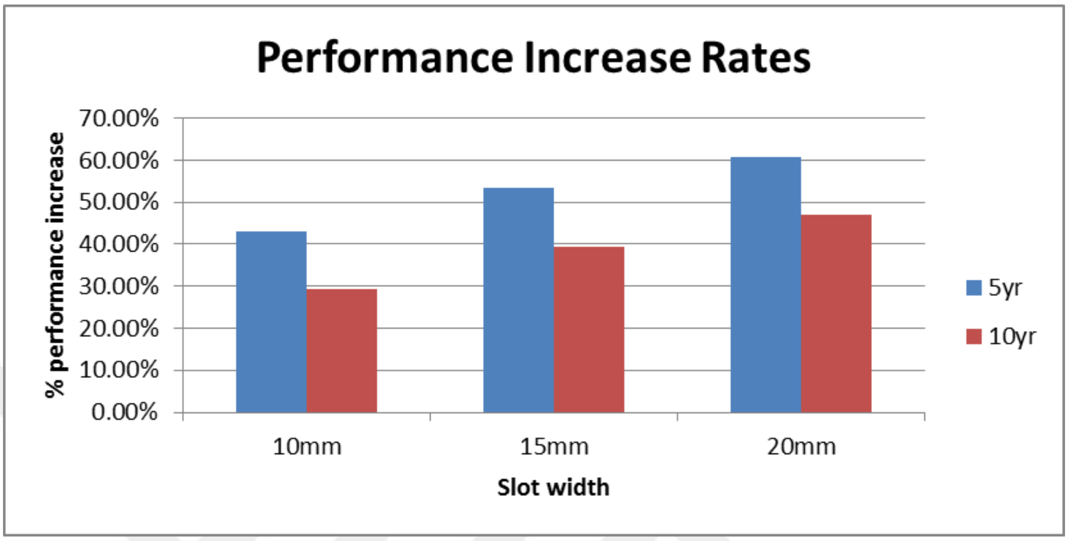

Figure 5-2 Performance increase rates of designs (Author)

Figure 5-2 shows the average performance increase rates each design provides. Comparison of infiltration rate losses after 5 and 10 years of use shows that more performance increase can be observed with more infiltration area. After 5 years of use even the smallest slot design is expected to perform more than 40% better than the standard design, while largest slot design performs 60% better. After 10 years of use increase of performance drops in all designs. Occurrence of clogging slows down the decrease of infiltration rate over time, which results in relatively less increased performance rates. Comparison of infiltration rates of different designs over 10 years is able to show the performance difference in a separate way.

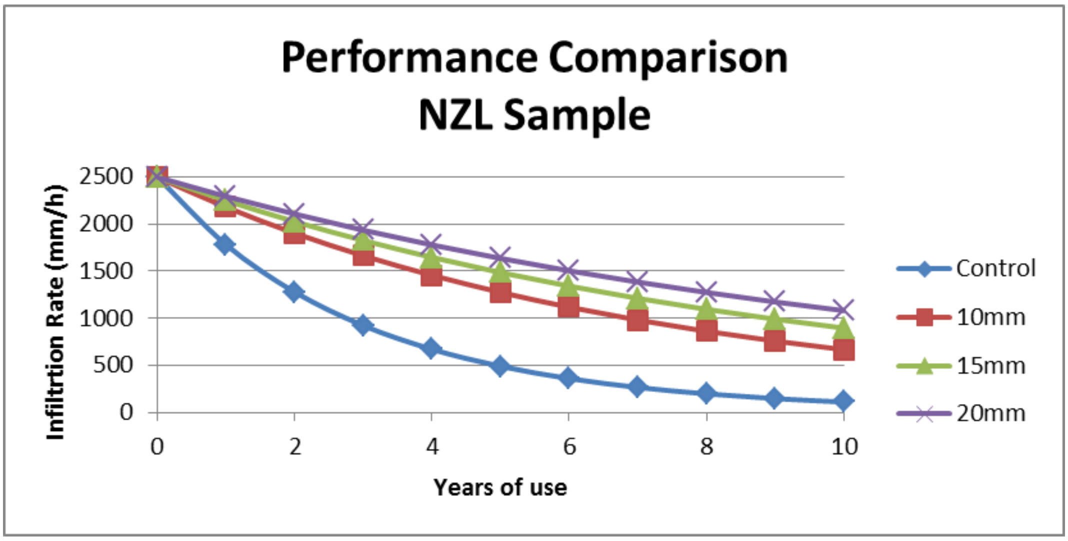

Figure 5-3 Performance comparison of designs with NZL sediment sample, 10 years (Author)

Performance comparison of three different drainage slot width designs and control design can be seen in Figure 5-3. Infiltration rate of control design drops rapidly after installation and after 9 years, drops below 150 mm/h. Paver blocks designs with infiltration slots show better performance over 10 years and show little sign of clogging. After 10 years of use infiltration rates are still above 500 mm/h and infiltration rate of 20mm slot design is even above 1000 mm/h. Such results deemed use of previously determined limits of heavy rains, 50 mm/h and 100 mm/h unnecessary as lowest infiltration rate ever achieved in this study is above 100 mm/h. Average results obtained by averaging infiltration rates of three different sediment samples show identical conclusions. As seen in Figure 5-4, paver block design with drainage slots show high rates of infiltration, while infiltration rate of standard design drops drastically. Infiltration rate comparison results obtained by averaging different sediment results show that overall performance increase achieved by drainage slot designs are 396% performance increase for 10 mm wide slot design, 499% performance increase for 15 mm wide slot design and 577% performance increase for 20 mm wide slot design after 10 years of use.

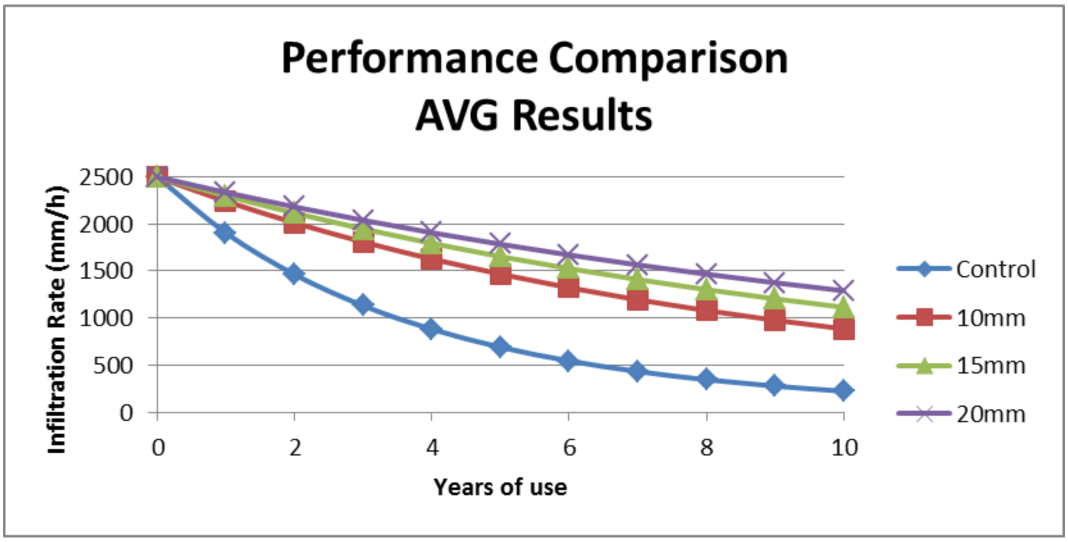

Figure 5-4 Average of results with three sediment samples - 10 years (Author)

Creating drainage slots beneath pavers would be beneficial as long as water is allowed to move through the slots. Water seeping through joint gaps and moving freely beneath paver blocks is the main requirement for this system. In order to provide room for water, slot has to be high enough so that accumulation of materials would not hinder the flow of water. In his study, Lucke (2014) has conducted experiments using slots with height of 3mm, 6mm and 9mm and increase of slot height resulted in accumulation of more sediments. In this study, higher slot height values were tested. Aside from structural limitations, it was expected to find a height limit that beyond which increasing the slot height would not grant any benefit. 10mm, 15mm and 20mm slot height designs were tested in this study in order to determine such height limit.

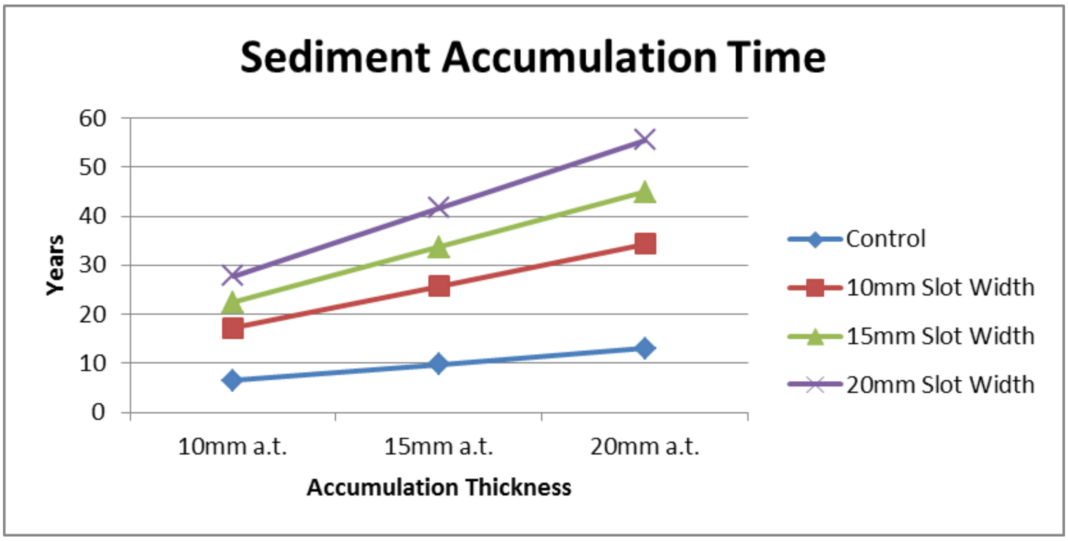

Figure 5-5 Sediment accumulation times for designs (Author)

Figure 5-5 shows the required time for different sediment accumulation heights with different designs. Accumulation of sediments was calculated without taking sediment infiltration into aggregate body. Achieving a safer result was aimed with that decision and sediment accumulation on bedding aggregate was calculated by using sediment density and yearly accumulation. Results suggest that using standard design would result in 20mm accumulation in 12 years. However increased infiltration area provided by drainage slot designs increase the time required for significant accumulation to levels beyond any expected service life. Using 20 mm slot width design, almost 30 years of use is required to achieve 10 mm of sediment accumulation. Judging by the results, 10 mm accumulation height, therefore 10 mm slot height can be regarded as benefit limit for the height design. Drainage slots with height greater than 10 mm would not grant any additional benefit as permeable pavement system would reach the end of expected service life by the time slots fill with sediments.

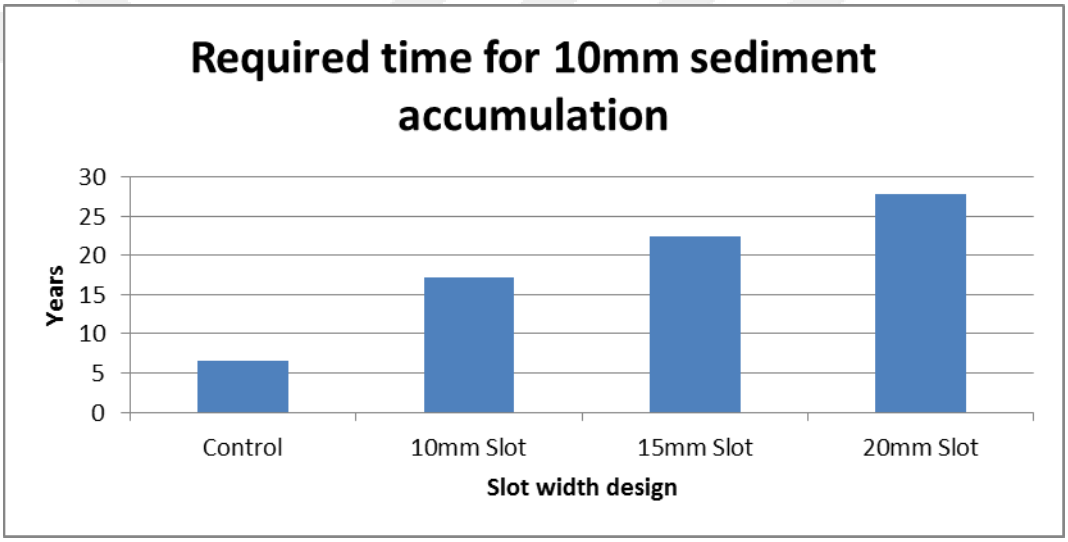

Figure 5-6 Required time for 10mm sediment accumulation (Author)

Figure 5-6 shows the time required for sediment accumulation to reach 10 mm thickness with different designs. Time required for 10 mm sediment accumulation with standard paver block design has shown to be probable in real life applications (Razzagmanesh and Beecham, 2018). It should be noted that sediment accumulation thickness does not take maintenance efforts into account. Previous studies have shown that maintenance techniques such as vacuum cleaning, and pressure washing would restore infiltration rate of permeable pavement systems (Drake and Bradford, 2013; Winston et al., 2016). In case of pavement blocks with drainage slots beneath, most effective sediment removal method would be vacuum cleaning. A cleaning effort carried out at least once in 15 years of service would completely clean the slots, restoring the system to its full performance in regards of sediment accumulation. Therefore it is safe to argue that 10 mm slot height design is the most effective among suggested designs, regardless of slot width.

5.2.3. Structural Performance

Disruption of structural integrity of paver block, reduction of load bearing capacity or similar negative effects were the main concerns of this study. Creating drainage slots beneath paver blocks inevitably affects the capabilities of an intact paver block; however, suggested solution would be effective if the benefits are high enough and disadvantages are negligible enough. Reduction of effective paver block thickness is a direct result of creation of drainage slots. At the same time load bearing capacity of a paver block not only depends on the geometric properties, but also material properties. Considering indicating any definite capacity without proper product data input would prove inefficient, it was decided to use the legal obligations as basis for load bearing analysis.

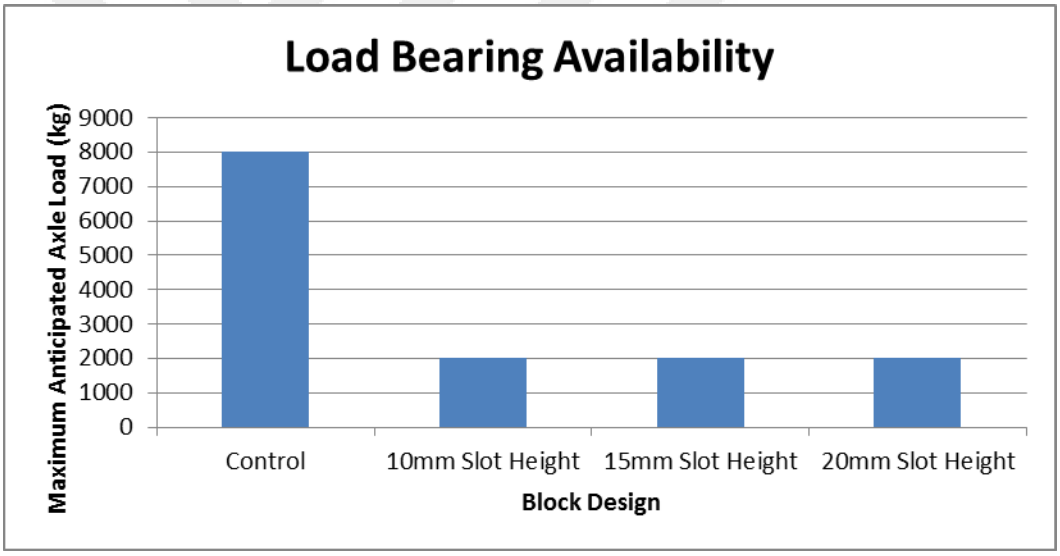

Figure 5-7 Load bearing availability of designs (Author)

The SuDS Manual (Woods-Ballard et al., 2015) clearly outlines the design requirements of permeable pavements for different design purposes. Permeable pavements in areas where maximum anticipated axle load is 8000 kg must have paver blocks with a minimum of 80 mm thickness, while pavements in areas with maximum anticipated axle load of 2000 kg must have at least 50 mm thick paver blocks (Woods-Ballard et al., 2015). Considering such requirements are in place, slot height impact on load bearing capacity was identified using given requirements. Therefore load bearing capacity for paver block designs can be described as 80 mm thickness capability for control design and 50 mm thickness capability for any design with less than 80 mm intact block thickness. Boundary values of 8000 kg and 2000 kg were suggested by Knapton, Morell and Simeunovich (2012) and were based on vehicular loads and performance limitations of paver blocks. These values bring results shown in Figure 5-7. Regardless actual load bearing capabilities, required load bearing limit for control design can be decided as a maximum of 8000 kg of axial load, and for drainage slot designs, 2000 kg of axial load.

Changes in drainage have their main impact on pressure applied to bedding aggregate by paver blocks as mentioned in previous chapter. Pressure applied to bedding aggregate is known to cause compaction over time (Cipolla, Maglionico and Stojkov, 2015) and increase of such pressure would result in higher intensity of clogging. However introduction of drainage slots does increase the pressure applied only on surfaces touching the bedding aggregate. Pressure increase rates as a result of surface area reduction can be seen in 5-8. As shown in the graph, creation of drainage slots result in up to 33.3% increase in pressure applied to bedding aggregate by load bearing paver block surfaces. Such difference is the result of slot areas beneath blocks not being able to transfer the force applied. Remaining surface of block would transfer the force applied, but with 14.29%, 23.8% and 33.3% increases for 10 mm, 15 mm and 20 mm slot width designs respectively. Although compaction mechanics of permeable pavement systems not entirely known and therefore achieving definitive results is not possible, it is safe to argue that such increases in pressure applied to bedding aggregate would increase the effects of compaction where pavement block touches the aggregate.

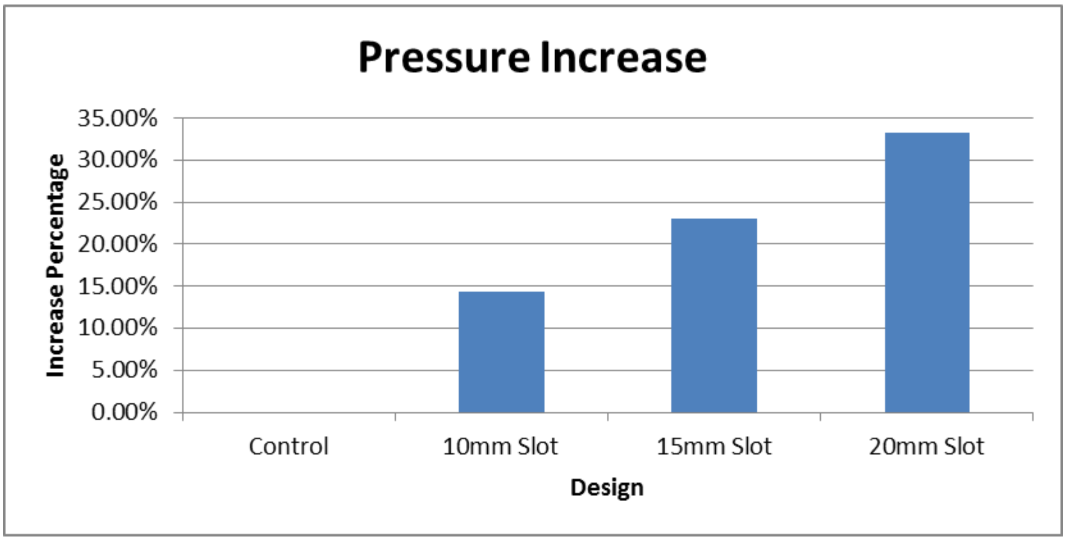

Figure 5-8 Pressure increase with different designs (Author)

Furthermore, pressure being applied to bedding aggregate from small separate areas instead of whole block surface would cause additional problems. Forces that cause compaction would force bedding aggregate to fill the drainage slots up to some extent. Such concern may not be necessary for a design with smaller slot width, yet a slot width greater than 20 mm would disrupt the force distribution that keeps the system intact. Previous studies also have shown that bedding aggregate plays a crucial role in transferring and distribution of load through pavement body and change in aggregate characteristics may create significant changes in structural performance (Cui and Bhattacharya, 2015). Therefore it can be suggested that large drainage slot designs may cause structural failures and compaction, with severity depending on the bedding aggregate characteristics.

5.3.Challenges and adaptations

Results of this study show that creating drainage slots beneath paver blocks would be an effective method for extending effective life of a permeable pavement system. However, different challenges presented by various locations may or may not make use of paver blocks with drainage slots feasible.

Environmental conditions of the location play a crucial role on effectiveness of permeable pavement systems. Local climate conditions not only determine the effectiveness and effective life of the system, but also determine the structural characteristics (Dawson, 2009). Areas that are subject to high intensity rains require much higher infiltration rates in order to avoid surface runoff. Suggested drainage slot design offers additional infiltration area, which significantly increases the capability of pavement system. Heavy rains are also known for bringing pollutants larger both in size and in quantity. Such pollutants may cause clogging both on the surface of the permeable pavement and the surface of the bedding aggregate. Effects of surface clogging would be negated by paths beneath pavers formed by drainage slots and aggregate clogging would be delayed due to increased area and spread out pollutants. Infiltration rate decrease projections show that slot designs would perform sufficiently after 10 years of service and keep performing with very high efficiency.

Occurrence of precipitation may also be in form of snowing or other means which may stay on the surface before infiltration. Such areas with colder climates may also be subject to frost heave, which significantly deforms the surface (Rempel, 2010). These challenges presented by cold climates may be well addressed by suggested drainage slot designs. Increased drainage area and breathability would result in higher evaporation rate through the system and drier structure. Such features not only prevent clogging of system by freezing, but also by keeping the structure dry, may act as an effective preventive measure against frost heave (Strake, Göbel and Coldewey, 2010). However it should be noted that sudden temperature changes may be detrimental for the permeable pavement structure. Standard design of permeable pavement systems does allow water to infiltrate through joint gaps, which cover a small area compared to the overall area of pavement system. During a sudden temperature drop below freezing point moist aggregate and accumulated sediments in joint gaps may be subject to freezing yet would not damage the structure. Increased infiltration area provided by drainage slots may cause damage to the structure if the moist aggregate freezes. Frozen aggregate and sediments accumulated on top would cover a greater area compared to standard design, which may damage the structure with increasing volume of water, similar to the frost heave (Rempel, 2010).

Conversely, as pointed out by Garcia-Ruiz et al., (2002), areas with hot climates, infrequent rains and with high daily highest-lowest temperature differences are known to have higher amount of fine particles in urban sediment composition. Such conditions may have reflected themselves into this study with NZL sediment samples, taken from Christchurch New Zealand (Charters, Cochrane and O'Sullivan, 2015). During testing using Eastern Scotland precipitation data, it was observed that NZL sediment sample caused greatest impact on infiltration rate, a challenge predicted by Garcia-Ruiz et al. (2002). It should be noted that use of Eastern Scotland precipitation data prevents these results to fully represent the region, yet likeness of annual average precipitation amount of locations must also be taken into account. Nevertheless, suggested drainage slot designs increased performance significantly in projections. Infiltration rate projections for 10 years show that a permeable pavement system subject to NZL sample in urban stormwater is expected to perform 607.78% better with 10 mm wide slot design, 817.01% better with 15 mm wide slot design and 985.64% better with 20 mm wide slot design.

On the other hand, major setbacks of drainage slot designs are about structural properties of the system. Creation of drainage slots beneath paver blocks decrease the load bearing capability of the block. As outlined by the suds manual, decreasing thickness of intact paver block below 80 mm would inevitably degrade its capability to a lower grade, which in this case lowers the axle load bearing availability of block from 8000 kg to 2000 kg (Woods-Ballard et al., 2015). Such hindrance may be avoided by using a block with greater thickness such as 100 mm, and creating drainage slots beneath. This solution would allow paver blocks to bear higher loads in theory; however, practicality of such solution is questionable. Increasing thickness of paver blocks would result in achieving 80 mm intact block thickness with axle load bearing limit of 8000 kg, yet increased load on paver blocks and up to 25% smaller pressure transfer area beneath pavers compared to standard design may result in paver block sinking into bedding aggregate. This would negate all benefits of suggested designs, would cause structural failures in paver block and would prevent proper load distribution within structure body. Effects of compaction would still be an issue for paver block under axle load of 2000 kg but compared to load of 8000 kg, effects would be negligible. Nonetheless, in order to understand the structural performance of suggested drainage slot designs, laboratory tests and focused studies may be necessary.

5.4.Summary of Findings

Earlier sections of this chapter provided analysis and interpretations of results shown in the Chapter 4. Obtained results provided information regarding infiltration and clogging processes. By using Hazen (1911) equation to determine the projected infiltration rate, impact of smaller particles on infiltration rate was shown. It was observed that amount of particles smaller in size than the d_{10} size of bedding aggregate has the greatest significance in infiltration rate reduction.

Challenges faced by permeable pavement systems were identified and those in relation with bedding aggregate performance were outlined. In response to such challenges, suggested solution by Lucke (2014) was taken as basis and further studies were conducted. Creation of drainage slots beneath paver blocks was analysed and design performance reliance on width and height of slots were investigated. It was found that hydrological performance of drainage slot designs mainly depended on slot width and more than 10 mm slot height would provide no estimated hydrological benefit.

Probable performance of suggested slot designs were forecasted when subjected to previously observed extremities and challenges faced by permeable pavement systems such as extreme cold. Through interpretation of design differences, it was suggested that permeable pavement systems involves paver blocks with drainage slots may have both advantages and disadvantages depending on the situation. It was concluded that further studies regarding the topic is necessary in order to fully understand the process.

Structural analysis for slot designs were conducted and it was determined that use of paver blocks with drainage slots would be best suitable in areas where pavement system is used by pedestrians, cyclists or car parks used by light vehicles. It was noted that with modifications it may be possible to use slot designs with paver blocks for heavier duty uses, yet further studies would be required for performance prediction. It was also pointed out that creation of large drainage slots may disrupt the force distribution within the permeable pavement body and may cause structural failures.

Analysing 10 year performance projections have shown that suggested drainage slot designs beneath paver blocks would significantly increase the hydrological performance of permeable pavement systems. Result have shown that after 10 years of service block drainage slot designs with widths of 10 mm, 15 mm and 20 mm would perform an average of 396%, 499% and 577% respectively. Drainage slot designs were also observed to provide significantly higher performance increase where urban sediment composition consists of mostly fine sediments. In one such example, a suggested drainage slot solution provided a performance increase of 985% in 10 years of use projection, with 20 mm wide slot design.

Data collected from studies of various sources formed the basis of this study. Effectiveness of suggested designs was tested and significance of sediment size was underlined. In conclusion, 10 mm height design and all width designs were found to be very effective. Sediment characteristics were shown to be decisive. Results obtained were parallel to earlier studies and analyses were used to evaluate hypotheses of this study. Evaluation of hypotheses can be found in Table 5-2.

Table 5-2 Evaluation of hypotheses (Author)

Hypothesis 1: Accumulating particle sizes directly influence effectiveness and effective life of a permeable pavement system.	Accepted
Hypothesis 2: Creating wide drainage slots beneath paver blocks would significantly increase the effectiveness and effective life of a permeable pavement.	Accepted
Hypothesis 3: Drainage slots beneath paver blocks would amplify the effects of compaction.	Partially Accepted
Hypothesis 4: Clogging delaying system would be useful in temperatures above freezing point.	Accepted
Hypothesis 5: Drainage slots would decrease load bearing capacity.	Accepted

5.5.Conclusion

In this section analyses regarding the study were presented. Using the results shown in Chapter 4, interpretations regarding urban sediment impact on permeable pavements were made. These interpretations were then combined with remaining results and were used to evaluate different performance aspects of suggested drainage slot designs. Among drainage slot designs, any slot height more than 10 mm was found to be providing no additional hydrological performance benefit. Furthermore, structural performance analysis shown that drainage slots with great width values may be detrimental for structural integrity and force distribution. Finally, overall interpretations of results were presented, followed by evaluation of hypotheses.

6. CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1.Introduction

This chapter summarises this study and underlines the significance of research outcomes in flood mitigation and sustainable urban drainage systems. To begin, each chapter is summarised and significant details is pointed out. Following, aims and objectives introduced in first chapter and how they were addressed is explained. Research limitations are outlined and recommendations are presented, followed by conclusions.

6.2.Research Summary

In the first chapter, topic introduction was done with underlying the significance of sustainable urban drainage systems. Different sustainable drainage systems were defined and among them the topic of this study, permeable pavement systems were presented. Research approach and thesis structure were defined. Aim and objectives of research were identified.

Second chapter involved branching of main topic and surveying of literature. To begin, permeable pavements, their purpose were explained along with structural and hydrological properties. Main features that differentiate permeable pavement systems from conventional drainage systems were presented. Challenges and crucial impact points on permeable pavement system performance such as clogging and compaction were explained. Previous research and studies were used as a base and throughout the chapter new hypotheses to fulfil the aim and objectives were derived. Hypotheses were chosen to cover various aspects of a suggested solution that serves the aim of this study.

Third chapter comprised of introduction of data and methodology of research. In order to identify the variables in the beginning, data involved in study were introduced first. Three different urban sediment samples were obtained from studies. Additionally, using study conducted by Lucke (2014) as basis, drainage slot designs beneath paver blocks were introduced. In order to reach applicable results, a synthetic exemplary environment was created using data obtained from previous studies. Reliability of this environment and infiltration rate testing methods was approved by comparing obtained results to findings of case studies. Following, drainage slot designs were tested with three different urban sediment samples and performance projections for 10 years of service time were prepared and depending on circumstances, up to 985% performance increase at the end of 10 years was delivered. Structural property changes of paver block by introduction of drainage slots were also analysed to determine the limitations of proposed solution. Findings and results were presented in the following chapter using tables and charts. Brief explanations were given with each set of results.

Analysis and interpretations of results were presented in the fifth chapter. Critical analyses of results have shown that growing scale of drainage slots would prove inefficient after certain point. Height design for drainage slots consisted of three options, 10 mm, 15 mm and 20 mm; however it was found out that heights beyond 10 mm would present no hydrological benefit and therefore designs were discarded. Additionally, structural integrity analysis has shown that creation of wide slots beneath paver blocks would endanger the structural integrity of system by disrupting force distribution. Furthermore both reduced intact pavement thickness and increased pressure beneath paver blocks were found to be hindering load bearing capacity of system from 8000 kg of axle load to 2000 kg of axle load. It was concluded that introduction of drainage slots would increase hydrological performance and delay clogging effects with the cost of structural performance. Overall, sediment characteristics were demonstrated to be decisive and 10 mm, 15 mm and 20 mm width designs with 10 mm height design were found to be successful in increasing performance of permeable pavement system over the course of 10 years.

In this chapter summarisation of research has taken place. Research output was outlined, aim and objectives were addressed and study was finalised by presenting limitations and recommendations.

6.3.Addressing Aim and Objectives

As presented in the first chapter, aim of this study was examining current knowledge about permeable pavement system performance and suggesting a solution for prolonging effective life. Following this aim was achieved by completing objectives.

- Identifying factors that influence infiltration rate decrease of permeable pavement systems.

Influencing factors were introduced mainly in Chapter 2. Clogging and compaction were found to be main determinants of performance over time. Significance of urban sediment size was proven through conducted analysis and responses of permeable pavement aggregate to introduction of a variety of sediment sizes were evaluated.

- Proposing new and better solution for perceived challenges.

Using work of Lucke (2014) as a basis, modified designs for drainage slots beneath paver blocks were introduced. Modifications were made to amplify performance increase output by enlarging drainage slots.

- Testing the theoretical feasibility of suggested solution.

Using methods defined in Chapter 3, structural and hydrological performance of slot designs were tested. Infiltration rate calculations were made using obtained data and results were compared to determine the effectiveness of suggested designs. Two height designs were found to be unfeasible and therefore discarded. Remaining designs were shown to be effective with certain limitations.

6.4.Research Limitations

Aim and objectives presented above were met using data obtained from previously conducted studies and various sources. Calculations and tests were conducted using derivative methods instead of direct measuring. Relying solely on calculations without any laboratory or field testing hindered the capability of this study. Additionally, obtaining results that represent conditions belonging to a certain location was not possible due to the high variety of data sources. Therefore output of this research only proves theoretical feasibility of suggested drainage slot designs. In order to be able to fully prove the effectiveness and feasibility of suggested solutions, real life experiments and observations are necessary.

6.5.Recommendations

Permeable pavement systems offer many research areas for further studies. Investigation of clogging mechanics and material infiltration through aggregate body would provide significant knowledge which can be used to increase performance of permeable pavements. Additionally, providing more insight on compaction and its relation with infiltration rates would be beneficial. Providing higher amounts of research output about permeable pavements is crucial for building trust and more knowledge towards permeable pavement systems, which would eventually result in wider use and more sustainable urban environment (Ellis and Lundy, 2016).

Regarding this study, replication of research output in laboratory or field conditions would be significantly beneficial. Infiltration rate tests using precipitation simulation and introduction of yearly accumulated sediments would be crucial to prove the efficiency of suggested calculation methods and sediment size significance.

Furthermore, suggested infiltration slot designs beneath paver blocks should be put through tests and analyses in order to fully determine the design capabilities. In current state it remains unclear that beyond which slot width structural integrity is crucially disrupted and this information would prove to be pivotal. Additionally, impact of slot height should be investigated further for determination of more accurate load bearing limitations. In its current state proposed improvement designs seem to be primitive and require further improvements and studies.

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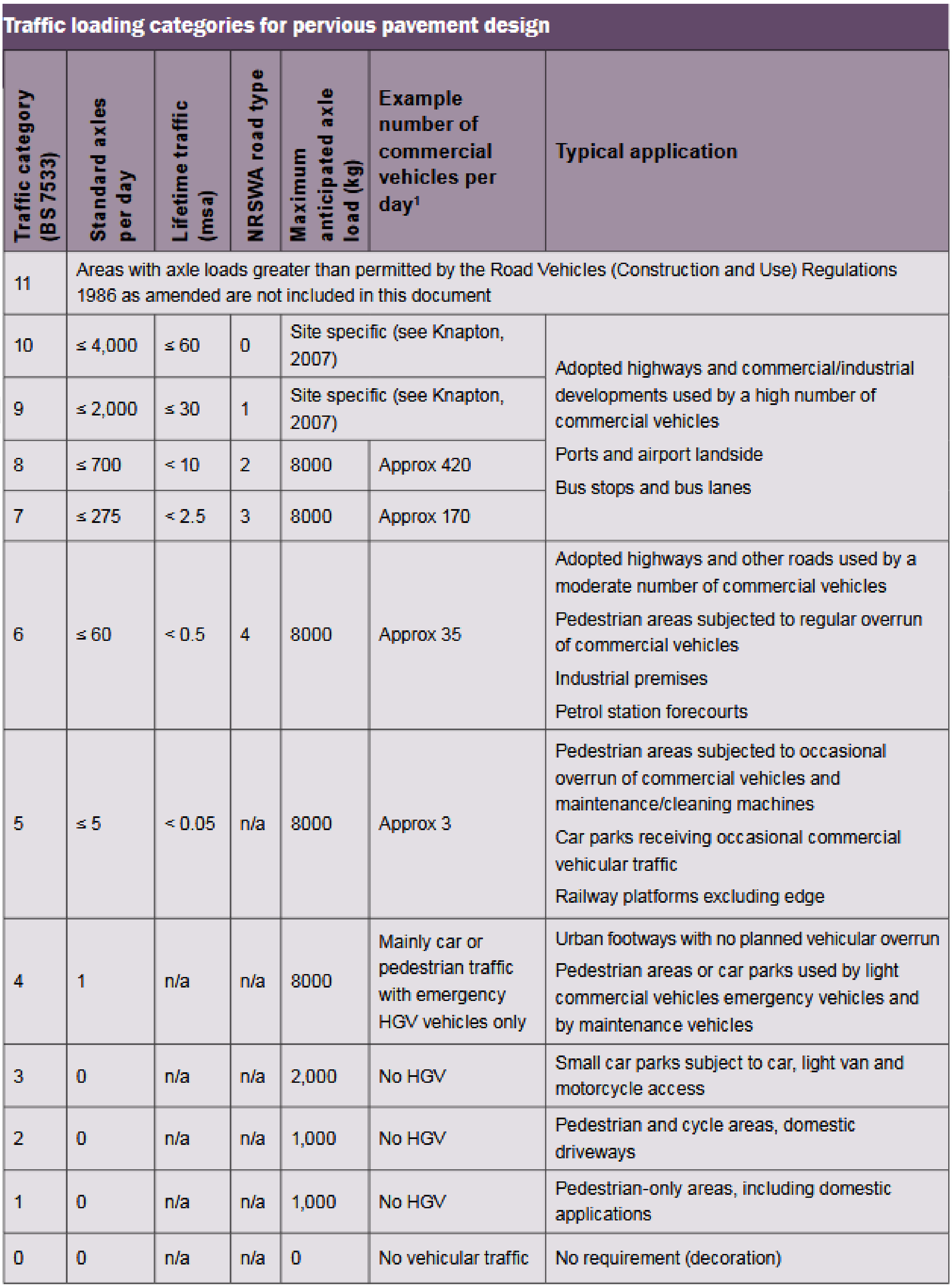
APPENDIX

Appendix 1

Traffic loading categories for pervious pavement design (Woods-Ballard et al., 2015)

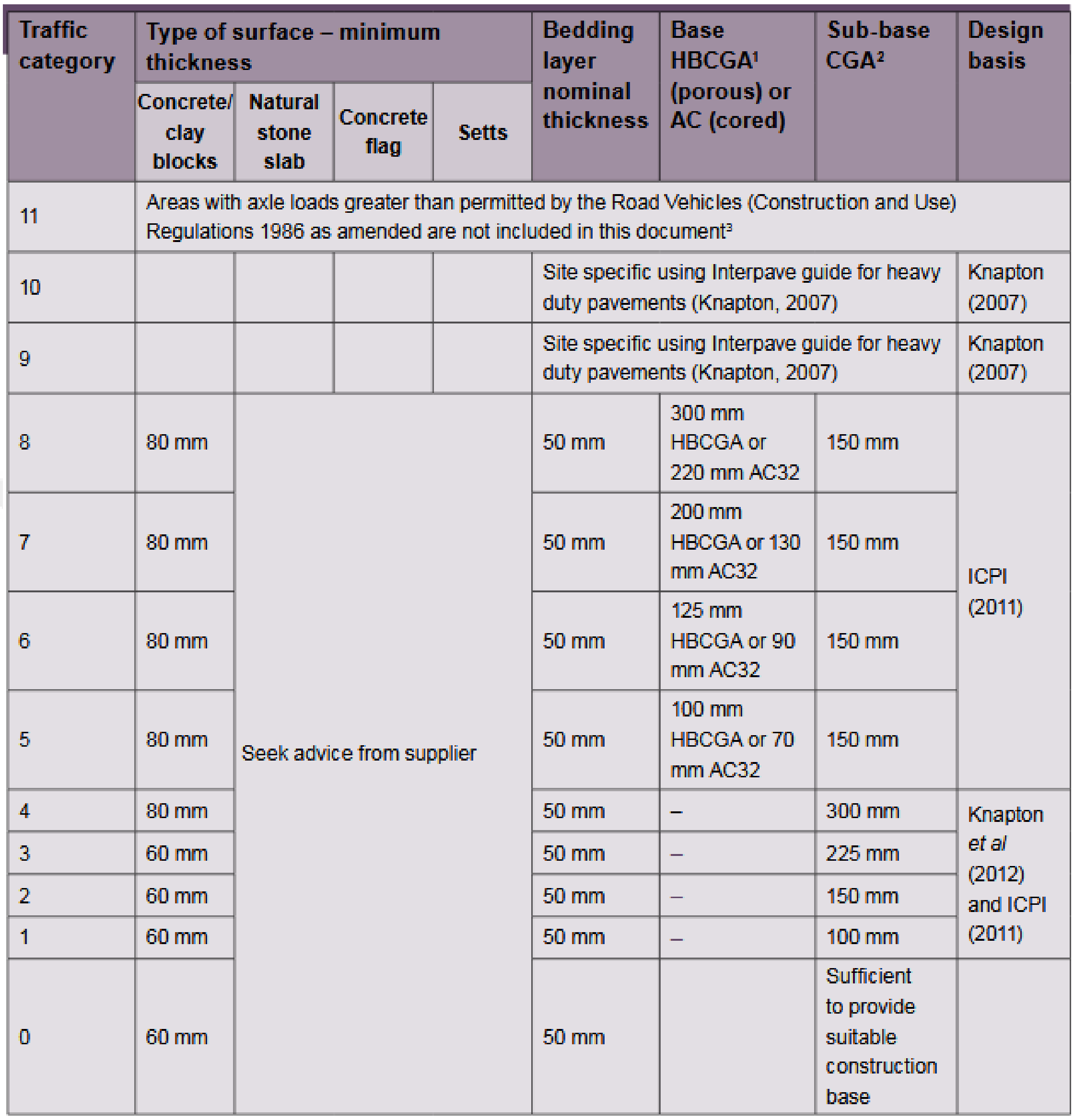


Traffic loading categories for pervious pavement design

Traffic category (BS 7533)	Standard axles per day	Lifetime traffic (msa)	NRSWA road type	Maximum anticipated axle load (kg)	Example number of commercial vehicles per day[1]	Typical application
11	Areas with axle loads greater than permitted by the Road Vehicles (Construction and Use) Regulations 1986 as amended are not included in this document					
10	≤ 4,000	≤ 60	0	Site specific (see Knapton, 2007)		Adopted highways and commercial/industrial developments used by a high number of commercial vehicles Ports and airport landside Bus stops and bus lanes
9	≤ 2,000	≤ 30	1	Site specific (see Knapton, 2007)		
8	≤ 700	< 10	2	8000	Approx 420	
7	≤ 275	< 2.5	3	8000	Approx 170	
6	≤ 60	< 0.5	4	8000	Approx 35	Adopted highways and other roads used by a moderate number of commercial vehicles Pedestrian areas subjected to regular overrun of commercial vehicles Industrial premises Petrol station forecourts
5	≤ 5	< 0.05	n/a	8000	Approx 3	Pedestrian areas subjected to occasional overrun of commercial vehicles and maintenance/cleaning machines Car parks receiving occasional commercial vehicular traffic Railway platforms excluding edge
4	1	n/a	n/a	8000	Mainly car or pedestrian traffic with emergency HGV vehicles only	Urban footways with no planned vehicular overrun Pedestrian areas or car parks used by light commercial vehicles emergency vehicles and by maintenance vehicles
3	0	n/a	n/a	2,000	No HGV	Small car parks subject to car, light van and motorcycle access
2	0	n/a	n/a	1,000	No HGV	Pedestrian and cycle areas, domestic driveways
1	0	n/a	n/a	1,000	No HGV	Pedestrian-only areas, including domestic applications
0	0	n/a	n/a	0	No vehicular traffic	No requirement (decoration)

Appendix 2

Typical construction thickness for modular paving over subgrade (Woods-Ballard et al., 2015)



Traffic category	Type of surface – minimum thickness				Bedding layer nominal thickness	Base HBCGA^1 (porous) or AC (cored)	Sub-base CGA^2	Design basis
	Concrete/ clay blocks	Natural stone slab	Concrete flag	Setts				
11	Areas with axle loads greater than permitted by the Road Vehicles (Construction and Use) Regulations 1986 as amended are not included in this document^3							
10					Site specific using Interpave guide for heavy duty pavements (Knapton, 2007)			Knapton (2007)
9					Site specific using Interpave guide for heavy duty pavements (Knapton, 2007)			Knapton (2007)
8	80 mm	Seek advice from supplier			50 mm	300 mm HBCGA or 220 mm AC32	150 mm	ICPI (2011)
7	80 mm				50 mm	200 mm HBCGA or 130 mm AC32	150 mm	
6	80 mm				50 mm	125 mm HBCGA or 90 mm AC32	150 mm	
5	80 mm				50 mm	100 mm HBCGA or 70 mm AC32	150 mm	
4	80 mm				50 mm	–	300 mm	Knapton *et al* (2012) and ICPI (2011)
3	60 mm				50 mm	–	225 mm	
2	60 mm				50 mm	–	150 mm	
1	60 mm				50 mm	–	100 mm	
0	60 mm				50 mm		Sufficient to provide suitable construction base	

Appendix 3

Particle size distribution analysis results (Poleto et al, 2009: Zhao et al., 2010; Charters, Cochrane and O’Sullivan, 2015)

Sample Location	d10 (µm)	d50 (µm)	d90 (µm)	Method	Source
(BRA) Venancio Aires	37	95	232	Vacuum Cleaner	Poleto et al (2009)
(BRA) Taquari	13	117	249		
(BRA) Lajeado	19	100	247		
(BRA) Bom Retiro do Sul	25	87	243		
(BRA) Estrela	46	97	200		
(BRA) Montenegro	31	96	247		
(BRA) Mato Leitao	6.5	55	202		
(BRA) Novo Hamburgo	32	82	180		
(BRA) Ivoti	14	115	246		
(BRA) Dois Irmaos	7	57	459		
(BRA) Picada Café	19	85	205		
(BRA) Morro Reuter	30	122	248		
(BRA) Nova Petropolis	8.5	71	190		
(BRA) Portao	14	77	225		
(BRA) Estancia Velha	6.5	28	188		
(BRA) Viamao	3	26	76		
(BRA) Porto Alegre	14	77	225		
(BRA) Capela de Santana	27	92	243		
(BRA) Guaiba	17	112	247		
(BRA) Eldorado do Sul	25	91	210		
(NZL) Christchurch	23.2	71.6	177.2	Grab and Automatic sampling	Charters, Cochrane, O'Sullivan (2015)
(CHI) Beijing	60	110	420	Vacuum Cleaner	Zhao et al (2010)

Appendix 4

Infiltration rate calculations

	y1	y2	y3	y4	y5	y6	y7	y8	y9	y10
BLOCK	Control									
Length	240	240	240	240	240	240	240	240	240	240
Width	120	120	120	120	120	120	120	120	120	120
Heigth	80	80	80	80	80	80	80	80	80	80
SLOT										
Width	0	0	0	0	0	0	0	0	0	0
PRECIPITATION										
Ann Avg	800	800	800	800	800	800	800	800	800	800
Sediment dens	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015
AGGREGATE										
Thickness	50	50	50	50	50	50	50	50	50	50
Density	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62
d10	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18
m'ad10	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52
3.01	28800	28800	28800	28800	28800	28800	28800	28800	28800	28800
3.02	30996	30996	30996	30996	30996	30996	30996	30996	30996	30996
3.03	2196	2196	2196	2196	2196	2196	2196	2196	2196	2196
3.04	2196	2196	2196	2196	2196	2196	2196	2196	2196	2196
3.05	24796800	24796800	24796800	24796800	24796800	24796800	24796800	24796800	24796800	24796800
3.06	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52
3.07	1.693770492	1.693770492	1.693770492	1.693770492	1.693770492	1.693770492	1.693770492	1.693770492	1.693770492	1.693770492
3.08	1549800									
3.09	2510676									
3.10	177876.00	181595.52	185315.04	189034.56	192754.08	196473.60	200193.12	203912.64	207632.16	211351.68
3.11	181595.52	185315.04	189034.56	192754.08	196473.60	200193.12	203912.64	207632.16	211351.68	215071.20
3.12	17787.6	18159.552	18531.504	18903.456	19275.408	19647.36	20019.312	20391.264	20763.216	21135.168
3.13	0.118434199	0.1180642	0.117708762	0.117367041	0.117038259	0.116721694	0.116416677	0.116122589	0.115838852	0.115564929
3.14	1.184341993	1.180642003	1.177087618	1.173670409	1.170382586	1.167216935	1.164166773	1.161225891	1.158388521	1.155649292
3.15	1.840684544	1.846453027	1.852028656	1.857420944	1.862638787	1.867690516	1.872583938	1.877326381	1.881924726	1.886385442
3.16	0.287071882	0.282596419	0.278257271	0.274048362	0.269963965	0.265998682	0.262147419	0.258405365	0.254767975	0.25123095

	y1	y2	y3	y4	y5	y6	y7	y8	y9	y10
BLOCK	10									
Length	240	240	240	240	240	240	240	240	240	240
Width	120	120	120	120	120	120	120	120	120	120
Heigth	80	80	80	80	80	80	80	80	80	80
SLOT										
Width	10	10	10	10	10	10	10	10	10	10
PRECIPITATION										
Ann Avg	800	800	800	800	800	800	800	800	800	800
Sediment dens	0	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015
AGGREGATE										
Thickness	50	50	50	50	50	50	50	50	50	50
Density	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62
d10	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18
m'ad10	0	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52
3.01	28800	28800	28800	28800	28800	28800	28800	28800	28800	28800
3.02	30996	30996	30996	30996	30996	30996	30996	30996	30996	30996
3.03	2196	2196	2196	2196	2196	2196	2196	2196	2196	2196
3.04	5796	5796	5796	5796	5796	5796	5796	5796	5796	5796
3.05	24796800	24796800	24796800	24796800	24796800	24796800	24796800	24796800	24796800	24796800
3.06	0	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52
3.07	0	0.64173913	0.64173913	0.64173913	0.64173913	0.64173913	0.64173913	0.64173913	0.64173913	0.64173913
3.08	1549800									
3.09	2510676									
3.10	469476.00	469476.00	473195.52	476915.04	480634.56	484354.08	488073.60	491793.12	495512.64	499232.16
3.11	469476.00	473195.52	476915.04	480634.56	484354.08	488073.60	491793.12	495512.64	499232.16	502951.68
3.12	46947.6	46947.6	47319.552	47691.504	48063.456	48435.408	48807.36	49179.312	49551.264	49923.216
3.13	0.1	0.107074387	0.107019212	0.106964892	0.106911407	0.106858736	0.106806862	0.106755767	0.106705433	0.106655844
3.14	1	1.070743865	1.070192125	1.069648924	1.069114066	1.068587361	1.068068622	1.067557671	1.067054334	1.066558442
3.15	2.18	2.035967771	2.037017419	2.038051879	2.039071479	2.040076535	2.041067358	2.042044246	2.043007493	2.043957382
3.16	0	0.127774437	0.126874849	0.125987825	0.125113102	0.124250427	0.123399554	0.122560242	0.121732258	0.120915373

	y1	y2	y3	y4	y5	y6	y7	y8	y9	y10
BLOCK	15									
Length	240	240	240	240	240	240	240	240	240	240
Width	120	120	120	120	120	120	120	120	120	120
Heigth	80	80	80	80	80	80	80	80	80	80
SLOT										
Width	15	15	15	15	15	15	15	15	15	15
PRECIPITATION										
Ann Avg	800	800	800	800	800	800	800	800	800	800
Sediment dens	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015
AGGREGATE										
Thickness	50	50	50	50	50	50	50	50	50	50
Density	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62
d10	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18
m'ad10	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52
3.01	28800	28800	28800	28800	28800	28800	28800	28800	28800	28800
3.02	30996	30996	30996	30996	30996	30996	30996	30996	30996	30996
3.03	2196	2196	2196	2196	2196	2196	2196	2196	2196	2196
3.04	7596	7596	7596	7596	7596	7596	7596	7596	7596	7596
3.05	24796800	24796800	24796800	24796800	24796800	24796800	24796800	24796800	24796800	24796800
3.06	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52
3.07	0.489668246	0.489668246	0.489668246	0.489668246	0.489668246	0.489668246	0.489668246	0.489668246	0.489668246	0.489668246
3.08	1549800									
3.09	2510676									
3.10	615276.00	618995.52	622715.04	626434.56	630154.08	633873.60	637593.12	641312.64	645032.16	648751.68
3.11	618995.52	622715.04	626434.56	630154.08	633873.60	637593.12	641312.64	645032.16	648751.68	652471.20
3.12	61527.6	61899.552	62271.504	62643.456	63015.408	63387.36	63759.312	64131.264	64503.216	64875.168
3.13	0.105408065	0.105375762	0.105343843	0.105312301	0.105281129	0.10525032	0.105219869	0.105189769	0.105160014	0.105130599
3.14	1.05408065	1.053757622	1.053438431	1.053123008	1.052811286	1.052503201	1.05219869	1.051897691	1.051600144	1.051305989
3.15	2.068152945	2.068786933	2.069413775	2.07003359	2.070646496	2.071252607	2.071852037	2.072444894	2.073031287	2.073611321
3.16	0.099979673	0.099427789	0.09888196	0.098342088	0.097808074	0.097279824	0.096757246	0.096240249	0.095728744	0.095222643

	y1	y2	y3	y4	y5	y6	y7	y8	y9	y10
BLOCK	20									
Length	240	240	240	240	240	240	240	240	240	240
Width	120	120	120	120	120	120	120	120	120	120
Heigth	80	80	80	80	80	80	80	80	80	80
SLOT										
Width	20	20	20	20	20	20	20	20	20	20
PRECIPITATION										
Ann Avg	800	800	800	800	800	800	800	800	800	800
Sediment dens	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015
AGGREGATE										
Thickness	50	50	50	50	50	50	50	50	50	50
Density	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62
d10	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18
m'ad10	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52
3.01	28800	28800	28800	28800	28800	28800	28800	28800	28800	28800
3.02	30996	30996	30996	30996	30996	30996	30996	30996	30996	30996
3.03	2196	2196	2196	2196	2196	2196	2196	2196	2196	2196
3.04	9396	9396	9396	9396	9396	9396	9396	9396	9396	9396
3.05	24796800	24796800	24796800	24796800	24796800	24796800	24796800	24796800	24796800	24796800
3.06	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52	3719.52
3.07	0.395862069	0.395862069	0.395862069	0.395862069	0.395862069	0.395862069	0.395862069	0.395862069	0.395862069	0.395862069
3.08	1549800									
3.09	2510676									
3.10	761076.00	764795.52	768515.04	772234.56	775954.08	779673.60	783393.12	787112.64	790832.16	794551.68
3.11	764795.52	768515.04	772234.56	775954.08	779673.60	783393.12	787112.64	790832.16	794551.68	798271.20
3.12	76107.6	76479.552	76851.504	77223.456	77595.408	77967.36	78339.312	78711.264	79083.216	79455.168
3.13	0.104377076	0.104355891	0.104334911	0.104314132	0.104293551	0.104273165	0.104252972	0.104232969	0.104213153	0.104193522
3.14	1.043770758	1.043558913	1.043349109	1.043141316	1.042935505	1.042731649	1.04252972	1.04232969	1.042131533	1.041935222
3.15	2.088581216	2.089005203	2.089425276	2.089841488	2.090253893	2.090662542	2.091067486	2.091468776	2.09186646	2.092260588
3.16	0.082111881	0.081739176	0.081369837	0.08100382	0.080641079	0.080281571	0.079925252	0.079572082	0.079222017	0.078875017