University of Southern Queensland

Faculty of Engineering and Built Environment

Water Sensitive Urban Design for Sustainable Road Development

A dissertation submitted by

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Abstract

This article compares the performance of three permeable pavement materials: porous asphalt, pervious concrete and permeable interlocking concrete pavers that have been implemented on low volume residential road applications via a thorough literature review and an analysis of four case studies in the United States. The research was undertaken due to the common belief that permeable road surfaces are deficient in structural integrity due to their porous nature and therefore limiting their use to footpaths, driveways and car parks. Their reduced structural integrity is said to cause a reduction in their design life when compared to traditional surface options. Recent advancements in technology and mix designs have produced successful applications of all three pavement types to low volume road applications therefore dispelling these common beliefs.

This study is important as urbanisation is creating more runoff which needs to be sustainably handled and the current infrastructure and land space is already strained. Although the case studies analysed in this study are in their infancies, all three pavement types are wearing as designed. Porous asphalt, pervious concrete and permeable interlocking concrete pavers have each been successfully implemented on various projects and the current results show that each are feasible for low volume residential road applications. However it is difficult to nominate which pavement type is best for low volume residential road applications as each application and intended use will be unique. Early indications show that pervious concrete may be the most well rounded surface type in terms of costs, maintenance factors, availability of materials, water infiltration effectiveness and desired secondary benefits. This study also discovered that there are no common practices in terms of maintenance techniques and frequencies and recommends this as a further research area.

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ENG4111/ENG4112 Research Project

Limitations of Use

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

H. Spurling

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1 Introduction

The growing population is having a profound effect on urbanisation, causing an increase in pressure on the sustainability of existing stormwater infrastructure. Urbanisation develops the natural landscape into a network of impermeable surfaces that create large amounts of runoff that for the most part would otherwise not naturally occur. Rather than the rainfall percolate naturally through the soil and recharge underground water stores, it must now be collected through stormwater drainage systems in which it will travel through to ultimately be treated. The current stormwater networks already deal with large amounts of runoff therefore further land development in the future is only increasing this strain. In addition, stormwater can become substantially polluted between its starting location – for example a road, and its end location – a water treatment facility. To alleviate these issues, Water Sensitive Urban Design (WSUD) techniques should be employed when designing roads so that they are sustainable for the future and have as little impact on the environment as possible.

This research was designed to explore the current advancements in permeable surfaces. The focus of this study is on the various road pavement options that are currently available and the feasibility of their use on low volume residential roads. Permeable road surfaces allow water infiltration into underground water stores while naturally filtering contaminants. An extensive literature review has been performed in order to fully appreciate this increasingly necessary aspect of construction. This has been followed by a review of four case studies.

1.1 Research Objectives

This project has been conducted to review and analyse the current pavement options that can be utilised in water sensitive urban design, as well as determine the feasibility of their use on low volume residential roads. This study is also concerned with current maintenance practices employed on these pavement options.

1.2 Definitions

sq. yd. – square yards

cu yd. – cubic yards

sq. ft. – square feet

dB – decibels

in – inches

m - metres

mm – millimetres

cm – centimeters

s – second

1.3 Project Scope

The chosen focus of this study is the ability of a pavement surface to withstand low volume traffic only while sustainably handling the runoff from substantial storm events. Keller and Sherar (2003) define a low volume road as one that has an Average Daily Traffic volume of less than 400. This study also considers maintenance techniques and their ability to influence the performance of the pavement.

This study does not focus on water quality, or a pavement's effectiveness to filter contaminants from runoff. The interested reader is directed to the vast amount of literature that has already been undertaken with these aims in mind.

2 Methodology

This research project has been performed as a desk study. It has involved a thorough literature review performed via electronic means. Research of past and current literature has been conducted on journal articles, reports and any other relevant sources. The findings have been compiled into a literature review as a basis for this study.

Research has not been limited to any particular geographic area of the world. This has enabled a vast amount of literature to be relevant to this particular topic and a well-rounded literature review to be prepared. Many countries around the world have adopted WSUD practices at varying levels, so experiences, differences and lessons learned from each have proven to be important in this analysis.

Information has been obtained from multiple sources. Access to reputable online journal databases has been provided by the University of Southern Queensland. Other reports, journals and articles have been discovered through citing in literature.

A number of case studies have been analysed in order to extract valuable information and recommendations related to this research. The feasibility of the application of various permeable pavement types to low volume residential roads has been analysed. Information on the case studies has been obtained through online sources as well as direct contact with the engineers of the respective projects. Information and data on infiltration rates, construction methods, maintenance techniques and performance over time have been outlined. The successes, limitations and lessons learned regarding each of the permeable surfaces have then been determined. Recommendations were then made for pavement suitability on low volume residential roads.

3 Literature Review

3.1 Water Sensitive Urban Design

Water is a very important commodity in Australia and should therefore be used and disposed of in a sustainable manner. One process used to sustainably deal with water is called Water Sensitive Urban Design (WSUD). According to the consultancy firm BMT-WBM (2009), WSUD is defined as:

> "the integrated design of the urban water cycle, incorporating water supply, wastewater, stormwater and groundwater management, urban design and environmental protection."

WSUD is implemented in the design of many features in the civil world in order to minimise any adverse effects on the environment. That is, when designing and constructing, the aforementioned components of the urban world should be taken into consideration. WSUD is also known as Low Impact Development in the United States and Sustainable Urban Drainage Systems in the United Kingdom. The following is a summary of some of benefits and aims in implementing WSUD.

Protecting Water and Environmental Quality

Reducing the contaminants in water introduced from human activity is a major goal when implementing WSUD. Hence, the spread of pollutants through water ways and ultimately into the environment can be minimised.

Minimising Water Quantity

Recycling water as well as reintroducing it back into the environment helps to reduce the amount of water that is needed to be handled and treated. The benefits of this are:

- Reduced costs of stormwater infrastructure.
- Reduced space for stormwater infrastructure.
- Flood minimisation.
- Flood attenuation.
- Reduced erosion of water ways.

Improve Visual Aesthetics of the landscape

Reducing the quantity of water to be handled and treated will result in minimising the bulky and intrusive infrastructure required to handle it. Therefore this will save land space, leading to improved aesthetics in urban areas.

Groundwater Recharge

Australia is typically a drought prone country, so any reasonable necessary steps should be taken in order to preserve water stocks. Some aspects of WSUD including the use of permeable pavements can enhance infiltration of stormwater into underground aquifers which can then go on to be reused. This is the best case scenario as this is one of the processes that occurs naturally with a large portion of the stormwater, prior to developing an area with impervious surfaces.

Cost Savings

Initial installation costs of WSUD techniques can be more expensive than conventional methods. However taking into account the ongoing costs of traditional stormwater removal and treatment, the total costs over the lifecycle of a WSUD project can potentially be lower than conventional stormwater systems.

The following table is a site suitability evaluation which should be used to determine if a site is suitable to implement WSUD best management practices.

Table 3.1 - Site suitability review (BMT-WBM 2009, pp. 4-9)

Characteristic	Potential Implementation Constraint			Score
	Low	Moderate	High	
% Imperviousness (post implementation)	1 = 0-10%	2 = 10-50%	3 = 50-100%	
Average Slope	1 = 2-5%	2 = 0-1%	3 = >5%	
Developed Area	1 = <1ha	2 = 1-10ha	3 = >10ha	
Mean Annual Rainfall	1 = <600mm/yr	2 = 600-1200mm/yr	3 = >1200mm/yr	
Soil permeability	1 = 3.6-3600mm/hr	2 = >3600mm/hr	3 = <3.6mm/hr	
Groundwater Elevation	1 = >2m below surface	2 = 1-2m below surface	3 = <1m below surface	
Salinity or Acid Sulfate Hazard	1 = Not in defined hazard area	2 = low to moderate hazard	3 = high hazard area	
			Total Score	

For clarity, the information requirements for a WSUD suitability evaluation are included in Appendix A.

3.1.1 Methods of implementation

There are many ways that WSUD can be incorporated into construction. The following are some of these methods:

- Sedimentation basins
- Bioretention swales and basins
- Rain gardens
- Infiltration trenches
- Rainwater tanks for collecting and reusing water
- Aquifer storage and recovery
- Permeable pavements

This study has been undertaken to investigate the use of permeable surfaces on low volume residential roads, therefore the remaining sections of this report will be concentrated on this area of WSUD.

3.2 Permeable Pavements

Permeable pavements are a category of sustainable surfaces that allow water to percolate through them. Traditional pavements are typically impervious and repel water creating runoff. Runoff collects pollutants from human activity during its conveyance which can then contaminate the environment. In order to minimise this risk, the costly process of stormwater treatment must be performed before its released back into the environment. Permeable pavements however provide an alternative means of water treatment, conveyance and release. They can be used for surfaces of footpaths, driveways, car parks and roads. Natural treatment of runoff occurs as the water percolates through the porous surface, the sub-base and the underlying soil. Suspended solids are filtered from the water as it percolates through the porous medium. A similar process occurs to remove heavy metals and potentially harmful ions. Motor oil from vehicles is also naturally broken down by "aerobic bacteria and fungi that convert the oil into sugars such as glucose for growth and reproduction (Newman et al. 2006)." The type of soil in the sub grade will have a direct effect on the infiltration rate and treatment capabilities of the permeable pavement system. For example sandy soil will tend to allow excellent infiltration of the water, whereas clays will have lower infiltration rates. However clays tend to capture more pollutants due to their high cation exchange capacity (US EPA 2009b). The following are some secondary benefits of permeable road surfaces:

- Allows natural groundwater recharge
- Reduction in splash and spray, reduced aquaplaning
- Reduction in light reflection and headlight glare
- Increase skid resistance as it reduces hydroplaning by draining surface water
- Reduces urban heat island effect

Permeable surfaces are limited to installation on slopes of less than 2% US EPA (2009b) without the need to incorporate terracing, baffles or berms into the subgrade. New Jersey Department of Environmental Protection (2004) recommends a maximum slope of 5%. This is to prevent pooling of runoff underneath the road surface and promote even infiltration into the subgrade.

The use of permeable surfaces will often reduce the overall lifecycle cost of a project with the potential to lower initial construction costs, due to its ability to mitigate the need for swales, detention ponds and other conventional stormwater infrastructure (National Ready Mix Concrete Association 2011). However with these desirable benefits are some perceived disadvantages of adopting these types of surfaces. Concerns of the long-term performance due to clogging and reduced compressive strength have been the primary reason preventing the widespread uptake of this WSUD best management practice. However the ongoing research through pilot projects and improving technology is beginning to build a strong argument against some of the long-held myths about porous surfaces. Some of the more recent research is showing that with good mix designs and experienced contractors, these surfaces can perform just as well long-term as the conventional equivalents.

Three types of permeable surfaces have been investigated and will now be reviewed. They are porous asphalt, pervious concrete and permeable pavers. It should be noted that there is a lot of confusion around the three words ‘porous,’ ‘pervious’ and ‘permeable’ in industry and they are all often used interchangeably. However the following definitions are outlined below (American Public Works Association 2008):

- **Permeable** – Fluids can flow between the material, for example between adjacent paving blocks.
- **Porous** – Allows fluid flow through the material. Voids are not necessarily connected.
- **Pervious** – Allows fluid flow through the material. Voids are interconnected.

By the definitions above, ‘permeable’ is different to the other two as it states that liquid passes between and around the medium, whereas ‘pervious’ and ‘porous’ allow water to pass through the material. However it is surprising that throughout most literature, ‘porous’ and ‘pervious’ are essentially used interchangeably and there does not seem to be any clarity or general consensus regarding when each should be used. Consequently, this report may use ‘porous’ and ‘pervious’ in an interchangeable manner.

3.2.1 Porous Asphalt

The make-up of porous asphalt (PA) is very similar to conventional asphaltic surfaces. There are no essential additives or different ingredients required for the mix. The difference between the two is in the grading of the aggregate, whereby a PA mix is considered to be open-graded. An open-graded aggregate mix is that which has little to no fines. This creates gaps in between the larger sized aggregate to allow stormwater to permeate through. A study undertaken by Qingquan and Dongwei (2009) shows that the material passing the no.8 sieve (2.36 mm) has the most influence on the void percentage of an asphalt mix. It is this portion of the mix which would usually fill the large air voids left in between bigger particles. Therefore by minimising this fraction, an optimal open-graded design mix can be achieved.

PA has been used extensively since the 1950s as a wearing course on the surface of roads. It’s rough surface made it desirable due to its enhanced frictional properties, reduced headlight glare, noise pollution and splash and spray of surface water (Younger, Hicks & Gower 1994). However, the porous nature of PA can lead to lower compressive strengths when compared to conventional asphalt, so its use as the primary road surface layer has had a low adoption rate. There has however been a great deal of research in recent times and further development in technology which has enabled it to be used innovatively as the primary surface layer for driveways, car parks and some road applications. For example, Qingquan and Dongwei (2009, p. 138) claim that any reduction in strength in a PA mix due to the omission of fines and its porous nature can be alleviated by using a high performance binder, such as high-viscosity bitumen as it has been shown to provide strength and durability where the mix may otherwise be deficient.

Figure 3.1 clearly shows surface water on the conventional asphalt compared to the "dry" look of the PA. PA can be distinguished by eye as it has a coarser appearance.

Figure 3.1 - Comparison of appearance of conventional asphalt (left) & porous asphalt (right) (National Asphalt Pavement Association n.d.)

3.2.1(a) Design of porous asphalt

A typical cross section of a PA road is shown in Figure 3.2. The main components of a PA road are outlined as follows.

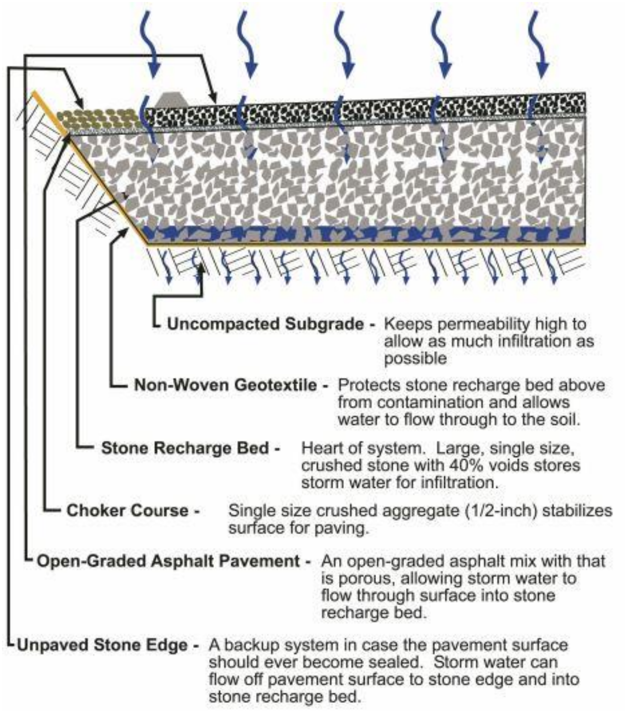

Figure 3.2 - Typical Porous Asphalt cross section (National Asphalt Pavement Association n.d.)

Open-Graded Asphalt

The surface layer contains the open –graded asphalt that will allow stormwater to penetrate the road. The thickness of this layer is dependent on the load bearing requirements. There does not seem to be any set guidelines for the exact air void percentage in any literature, however Qingquan and Dongwei (2009) reported that PA usually has a design air void percentage of 18-25%. The US EPA (2009b) states that PA should have a minimum of 16% air voids. European countries such as Switzerland use an air void percentage of roughly 20% (Poulikakos et al. 2006).

Choker Course

A single-sized aggregate is used for the choker course which is designed to fill the voids on the surface of the large aggregate of the sub-base to produce a smoother layer for the PA to be paved on.

Sub-base

The sub-base is made up of a uniformly graded crushed rock with approximately 40% void space (Goh & You 2012, p. 90). This layer is very important as it has a dual purpose. It provides much of the structural strength for the road as well as acting as a reservoir to temporarily store water until it infiltrates the subgrade. A perforated pipe can be included in this layer which will remove excess water should the sub-base overflow. The thickness of this layer is dependent on the storage requirement for runoff, the permeability of the in-situ soil and the structural strength requirements of the road.

Geotextile

A permeable geotextile liner is included between the sub-base and subgrade. The purpose of the geotextile is to prevent soil particles from the subgrade rising through the sub-base and having the potential to clog the system. It is also a final filter of the water before it enters the subgrade (Goh & You 2012).

Subgrade

The subgrade of a PA road is often left uncompacted so that the porosity of the soil stays as high as possible. This will ensure that infiltration rates are kept at their potential maximum (New Jersey Department of Environmental Protection 2004). The type of soil in the subgrade will have a direct effect on the design of the road cross section. For example a clay subgrade will have lower strength and lower infiltration rates compared to a sandy-type soil, therefore a thicker sub-base will be required for both strength and water storage (US EPA 2009b).

Unpaved stone edge

As seen in Figure 3.2, an unpaved stone section can be included on the side of the road which will act as a backup permeable surface should the PA surface fail due to clogging or if the rainfall rate exceeds that of the infiltration rate through the PA surface.

3.2.1(b) Construction methods

There are some important things to note on the construction of a PA road. As mentioned in section 3.2.1(a), the subgrade is often left uncompacted in order to preserve its ability to allow infiltration of water. This is in contrast to a conventional asphalt surface where the subgrade is compacted with a certain number of passes to achieve the density required for the project.

Also, the construction methods used to lay the actual PA surface is identical to any other asphalt surface, however care must be taken to execute these methods properly to ensure a strong permeable surface (North Carolina Department of Environment and Natural Resources 2012).

Some other differences are in relation to the site best management practices. Silt fences should be installed around the road construction to prevent sediment from runoff entering the PA surface during construction of the development. Care should be taken wherever possible to leave the construction of the PA surfaces until most if not all other construction has taken place on a project in order to prevent contamination and clogging from soils around the construction area (New Jersey Department of Environmental Protection 2004).

PA roads can either be designed to be curb-to-curb (the full width of the road), or to have an impermeable surface in the main travel lanes with permeable shoulders.

3.2.1(c) Advantages

- The PA surface is laid using the same techniques as conventional asphalt surfaces. Porous concrete however requires a different construction method which will be outlined in section 3.2.2.
- Studies have shown that PA performs better than conventional asphalt in regards to freeze-thaw cycles. This is due to higher latent heat in the ground caused by the higher moisture content of the soil (Goh & You 2012, p. 91).
- The noise of tyres on the road is reduced on a PA surface due to the sound waves propagating into the pores of the asphalt (Poulikakos et al. 2006, p. 32). Poulikakos et al. (2006) reports that PA surfaces can reduce road noise by 2-6 dB compared to a normal asphalt surface, and by up to 6 dB when compared to a concrete surface. Other research has shown noise reductions in the order of 3-5dB (Association of Japan Highway 1996 in Qingquan & Dongwei 2009, p. 135).
- More stable in-situ when compared to pavers as the PA layer one large connected mass.
- Some trial sections have shown that PA surfaces can produce acceptable rut resistance when compared to other mixes (Poulikakos et al. 2006, p. 26). Huddleston et al. (cited in Younger, Hicks and Gower (1994, p. 20)) reported that this is attributable to “the interlocking of the large quantity of course materials in the mix.

- Downtime for construction is not extensive when comparing to concrete.

3.2.1(d) Disadvantages

- Potential for accelerated ageing and stripping
- Reduction in porosity – high-speed lanes are self-cleaning, however slow-speed lanes or low volume roads are more prone to clogging, therefore reducing the permeability of the surface (Poulikakos et al. 2006, p. 26).
- Expected shorter service life than conventional asphalt surfaces

3.2.2 Pervious concrete

Pervious concrete (PC) is a material that can also be used for otherwise impermeable surfaces. This type of concrete is also often referred to as 'gap-graded,' 'porous,' 'no-fines' or 'low-density concrete.' It differs from conventional concrete surfaces due to having an open-graded aggregate mix. Much like the PA surfaces outlined in section 3.2.1, the open-graded aggregate mix contains little to no fines. This omission of fines enables the mix to have a rigid but porous skeleton which allows water infiltration. A pervious concrete mix contains the open-graded aggregate, Portland cement, water and any additives required to improve certain properties of the concrete.

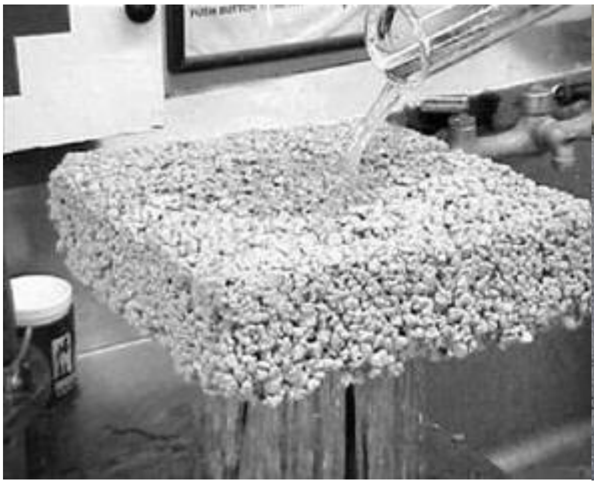

Figure 3.3 - Demonstration of water passing through porous concrete (National Ready Mix Concrete Association 2004)

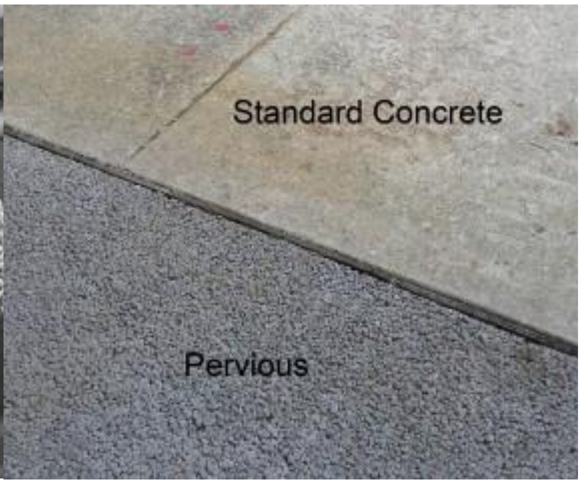

Figure 3.4 - Comparison of standard and porous concrete surfaces (PETRO Design/Build 2013)

PC typically develops lower compressive strengths than conventional concrete and this is the main reason for its limited adoption. Research has investigated factors which can enhance the potential compressive strength achievable by optimising the concrete mix. For example, studies show that the best aggregate to use for optimal compressive strength are crushed igneous rocks, due to their high strength. However when construction takes place in areas where access to this type of rock is limited, crushed dolomitic rock is recommended (Lian & Zhuge 2010, p. 2666). The size of the aggregate used in the mix has also been shown to have an effect on the compressive strength obtained, with the inclusion of a slight amount of smaller-sized aggregate producing higher strengths at the expense of permeability (Lian & Zhuge 2010).

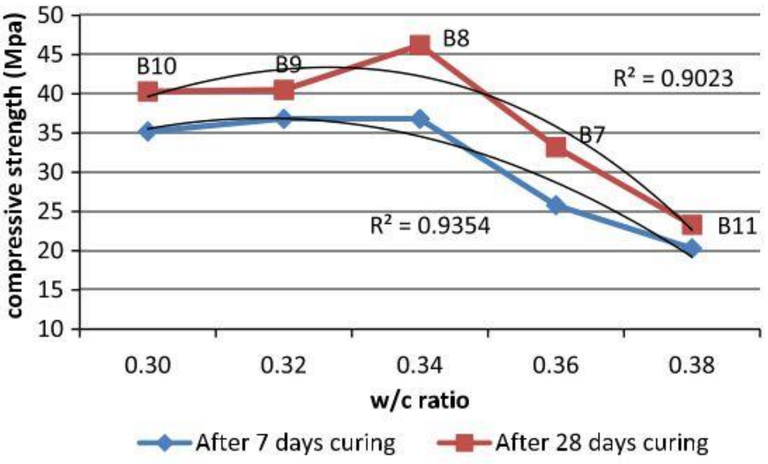

Figure 3.5 - Relationship between w/c ratio and compressive strength (Lian & Zhuge 2010, p. 2668)

Optimising the water content of the concrete mix can also aid in achieving higher compressive strengths. The water content of a PC mix is typically lower than conventional concrete mixes (de Solminihac et al. 2007). Studies have shown that the optimal water-to-cement (w/c) ratio is 0.32, which can produce 28 day compressive strengths of 40MPa with a hydraulic conductivity of 2.42 mm/s. In addition, w/c ratios of less than 0.30 are not recommended (Lian & Zhuge 2010). Mixes were investigated that produced higher hydraulic conductivities at the expense of strength and this is evident from Figure 3.5 and Figure 3.6. It is worth noting that the recommendation by Lian and Zhuge (2010) of a minimum w/c ratio of 0.30 is slightly contrary to that recommended by Colorado Ready Mix Concrete Association (2009, p. 12), which is a w/c ratio of between 0.26 and 0.35. A slight difference again in a study performed by de Solminihac et al. (2007) which recommends ratios between 0.35 and 0.38.

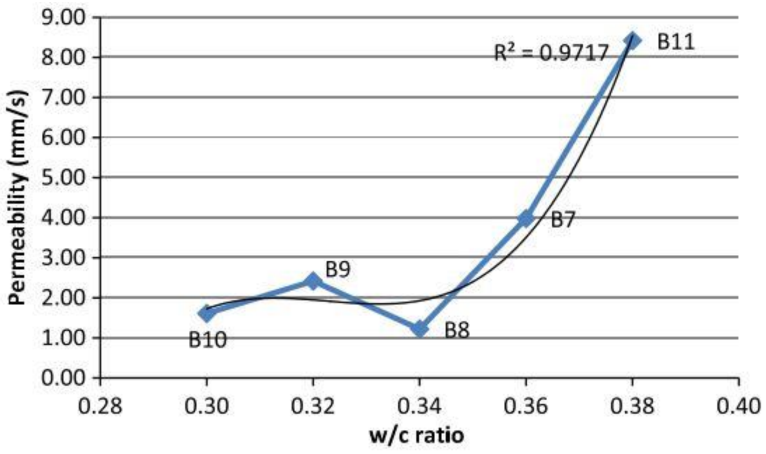

Figure 3.6 - Relationship between w/c ratio and permeability coefficient (Lian & Zhuge 2010, p. 2668)

It can be shown that the governing factor of compressive strength in PC is the ability of the cement to bind to the aggregate. In order to enhance the cement aggregate bond and therefore increase the compressive strength, a superplasticizer or silica fume can be added to the mix. This tends to change the failure mechanism to either failure of the aggregate or of the cement paste itself (Lian & Zhuge 2010).

PC has been used extensively for driveways and car parks as well as various road applications, especially as a friction or wearing course (US EPA 2009c). PC not only provides the benefits of WSUD, but also provides similar benefits to that of PA, such as reduced road noise and splash and spray among others. These benefits are outlined further in section.

3.2.2(a) Design of pervious concrete

A typical cross-section of a pervious concrete road is shown in Figure 3.7. The main components of a PC road are outlined as follows.

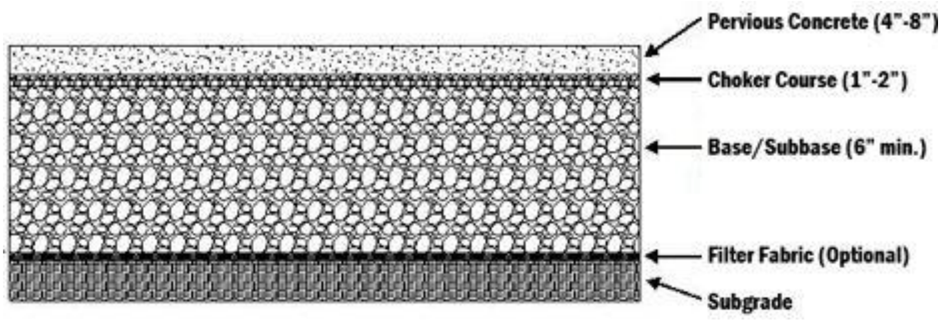

Figure 3.7 - Typical pervious concrete cross-section (US EPA 2009c)

Open-graded concrete mix

The surface layer contains the open –graded concrete mix that enables stormwater to penetrate the road. The thickness of this layer is dependent on the load bearing requirements of the road but it is generally 10-20 cm and the air void percentage typically ranges between 15-35% with an average of roughly 20% (US EPA 2009c). This information is in line with the recommendations made by Colorado Ready Mix Concrete Association (2009, p. 12) of 15-25%. The size of the aggregate is typically 10-15 mm (US EPA 2009c). A smaller aggregate will enhance the compressive strength but decrease the void space.

Choker Course

A single-sized aggregate is used for the choker course which is designed to fill the voids on the surface of the large aggregate of the sub-base to produce a smoother layer for the PC to be poured on.

Sub-base

The sub-base is made up of a uniformly graded crushed rock with approximately 40% void space (Goh & You 2012, p. 90). This layer is very important as it has a dual purpose. It provides much of the structural strength for the road, as well as acting as a reservoir to temporarily store water while it infiltrates the subgrade. A perforated pipe can be included in this layer which will remove excess water should the sub-base overflow. The thickness of this layer is dependent on the storage requirement for runoff, the permeability of the in-situ soil and the structural strength requirements of the road.

Geotextile

A permeable geotextile liner is included between the sub-base and subgrade. The purpose of the geotextile is to prevent soil particles from the subgrade rising through the sub-base and having the potential to clog the system. It is also a final filter of the water before it enters the subgrade (Goh & You 2012).

Subgrade

As with PA roads, the subgrade of a PC road is often left uncompacted so that the porosity of the soil stays as high as possible to ensure that infiltration rates are preserved at their potential maximum (New Jersey Department of Environmental Protection 2004). The type of soil in the subgrade will have a direct effect on the design of the road cross section.

3.2.2(b) Construction methods

A test pour should be performed 30 days before the PC is to be poured for the project. This is to ensure that the resulting mix develops the properties required. It should be noted that a PC mix is much drier than normal concrete and is therefore less workable. Slump tests are generally not performed on PC. Therefore standard testing methods such as those that determine void content, compressive strength and density are used to ensure quality control.

It is recommended that the delivery time from source to project should be no more than 60 mins without the addition of any retarding admixtures (US EPA 2009c).

Formwork must be set up just like any other concrete pour. A road is usually poured in strips or sections. Care must be taken during finishing, as vibration should be used very minimally so as to not consolidate the concrete and hence reduce its porosity. The PC is required to cure for at least 7 days before being opened to vehicular traffic (Charger Enterprises Inc. 2010).

3.2.2(c) Advantages

- The lighter colour of concrete compared to asphalt results in reduced urban air temperatures and can reduce street light requirements (US EPA 2009c).
- Pervious concrete can be advantageous over conventional concrete in areas exposed to freeze-thaw cycles. One improvement to conventional concrete was encouraging air entrainment in freeze-thaw areas which reduces spalling. Therefore the air voids in PC work in the same manner (American Public Works Association 2008).
- More stable in-situ when compared to pavers as the PC layer one large connected mass.

3.2.2(d) Disadvantages

- Requires the installation of formwork
- The minimum curing time of 7 days can be an inconvenience to residents
- Mix designs are very sensitive, requiring highly skilled and certified contractors with great attention to detail

3.2.3 Permeable Pavers

Permeable pavers (PPs) are designed such that there is significant joint space in between each paver which is filled with aggregate. Surface water percolates through the joints and into the underlying bed where it is temporarily detained until it infiltrates the subgrade. There are several variations of permeable paving blocks and they come in different shapes and sizes. These differ both in the material of the paver and their basic design. A study by Collins, Hunt and Hathaway (2008) shows that there is very little difference in runoff reduction between various pavement types. Pavers can be made from concrete, clay or synthetic materials. The two most widely used types of concrete pavers are concrete grid pavers (CGPs) and permeable interlocking concrete pavers (PICPs). This study focuses on PICPs.

PICPs are designed such that water can permeate through their roughly 10-15% by area of void space across a given pavement (US EPA 2009a). They usually come pre-manufactured on strips which can be easily laid manually or mechanically.

Although the common belief is that PPs should only be used in low load bearing situations such as driveways and car parks, there have been applications in North America, Europe and Brazil in which PPs have been used in shipping, factory and truck loading yards (Knapton and Cook, 2000; anon 2002b, cited in Shackel et al. 2008).

Figure 3.8 - Concrete grid pavers (CGP) (100k House 2010)

Figure 3.9 - Permeable interlocking concrete pavers (PICP) (Landscape Online 2013)

3.2.3(a) Design of permeable pavers

A typical cross-section of a permeable paving system is shown in Figure 3.10 and the main components of this system are outlined as follows.

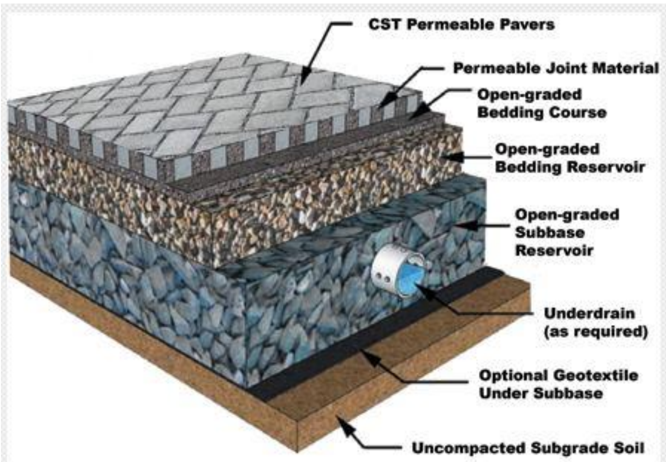

Figure 3.10 - Representation of a permeable paving system (Concrete Stone and Tile Corp 2013)

Pavers

Pavers come in various shapes such as squares, diamonds, and rectangles among others. The permeable area required is to be determined by the designer for the specific project. The shape, laying pattern and thickness influence the structural integrity of the pavement, with dentated shapes proving stronger than rectangular shapes. They should also be a minimum thickness of 80 mm for road use (Shackel 2010, p. 7). The recommended pattern for optimal structural performance is the herringbone pattern (Shackel 2010, p. 7).

Jointing aggregate

This aggregate is openly-graded to enable high infiltration rates and a recommended size of 2-5 mm (Shackel 2010, p. 1). Proper maintenance techniques should be performed to prevent clogging and weed growth. Maintenance is covered further in section 5 of this report.

Open-graded bedding course

The bedding is a layer of aggregate used to provide a smooth even surface for the PPs to be laid on. The optimal aggregate to be used for the bedding with respect to strength and infiltration rates is a clean 2-5 mm aggregate, which can be used for the bedding and jointing, therefore simplifying construction (Shackel et al. 2008).

Sub-base

The sub-base is usually made up of a uniformly graded crushed stone, but any unbound granular can be used. The void ratio is typically around 40% (Goh & You 2012; Shackel et al. 2008, p. 3). This layer is very important as it has a dual purpose. It provides much of the structural strength for the road, as well as acting as a reservoir to temporarily store water while it infiltrates the subgrade. A perforated pipe can be included in this layer which will remove excess water should the sub-base overflow. The thickness of this layer is dependent on the storage requirement for runoff, the permeability of the in-situ soil and the structural strength requirements of the road.

Geotextile

An optional permeable geotextile liner can be included between the sub-base and subgrade. The purpose of the geotextile is to prevent soil particles from the subgrade rising through the sub-base and having the potential to clog the system. It is also a final filter of the stormwater before it enters the subgrade (Goh & You 2012).

Subgrade

As with PA and PC roads, the subgrade of a PP road is often left uncompacted so that the porosity of the soil is at its maximum to ensure that infiltration rates are preserved (New Jersey Department of Environmental Protection 2004). However, Shackel (2010, p. 8) disagrees with this notion and recommends that

> "normal compaction standards for the base, sub-base and subgrade should be rigorously applied."

It should be noted that the type of soil in the subgrade will have a direct effect on the design of the road cross section.

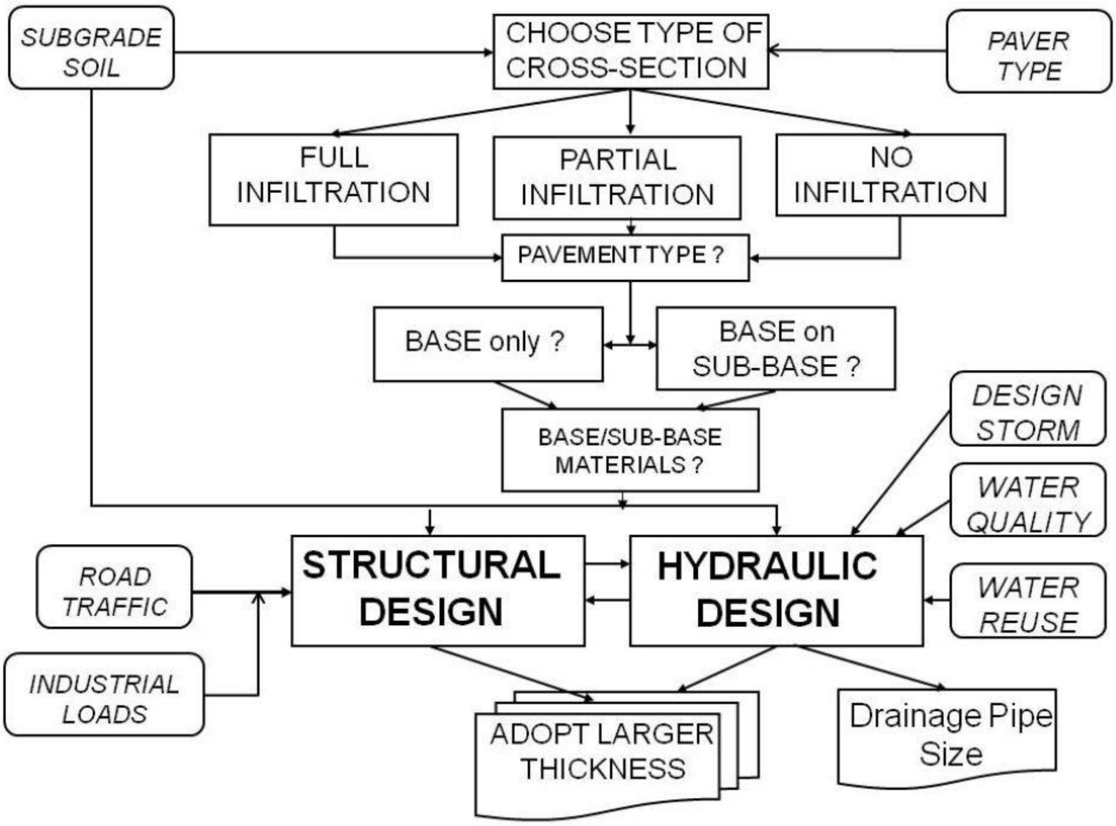

Figure 3.11 - Recommended methodology of permeable pavement design (Shackel et al. 2008)

Figure 3.11 shows the methodology used to design a permeable pavement system. Several computer programs have been developed over the years to aid design. PERMPAVE is used for the hydraulic analysis and design of PPs and LOCKPAVE is used in the structural design of the pavers (Shackel 2010, p. 3). PERMPAVE is run first which will provide a result for the required pavement thickness that will be satisfactory for the hydraulic requirements of the pavement. Following this the LOCKPAVE software is then run which will recommend a pavement thickness that will provide the required structural integrity for the intended use. It is more than likely that these two thicknesses will be different, therefore the greater of the two should be adopted (Shackel 2010, p. 7).

3.2.3(b) Construction methods

Once the sub-base has been prepared, the PICPs can be laid and filled with a highly permeable jointing aggregate. Care must be taken during construction to prevent sediment infiltration and early clogging. Therefore the site should be prepared with temporary silt fences and water diversion structures (if required). Construction traffic must also be minimised to preserve the surface and layers of the system which may be vulnerable to damage during construction (Gold Coast City Council 2007). Once installation is completed however, the surface can be opened immediately for traffic.

Permeable pavers can be mechanically laid by a machine such as that shown in Figure 3.12. These machines can lay 500 m^2 per machine per day (Interlocking Concrete Pavement Institute 2008, p. 6).

Figure 3.12 - This machine provides a mechanical means of laying blocks of pavers (Interlocking Concrete Pavement Institute 2008).

3.2.3(c) Advantages

- Does not require curing time. That is, the surface can be opened immediately upon completion.
- Can be easier to repair if severe clogging occurs when compared to PA and PC (North Carolina Department of Environment and Natural Resources 2012).

3.2.3(d) Disadvantages

- Materials and installation costs can be higher than PA and PC surfaces (North Carolina Department of Environment and Natural Resources 2012; Shackel 2010) .
- Maintenance costs can be higher than PA and PC due to having to refill the joints with aggregate after cleaning, albeit an easy process. Weed growth in between joints of PICPs is also very common which translates to increased maintenance costs (North Carolina Department of Environment and Natural Resources 2012).
- Not ideal for high-density populated areas, as many of these locations will require frequent access to underground services, in which case replacement is not as simple as other pavements (Shackel et al. 2008, p. 10).
- Areas in close proximity to deciduous trees should be avoided if at all possible, as decomposing organic matter can cause clogging (Shackel et al. 2008).
- The use of pavers which have a gap at each corner like that shown in Figure 3.9 should be limited to roads with speed limits of less than 30 mph (48kph) as tyre noise can be loud above this speed (City of Portland 2008).
- Installation is labour intensive if installed manually.
- Has the potential to be less stable in-situ when compared to PA and PC as the pavers can settle non-uniformly.

4 Case studies

4.1 Portland, Oregon

Case study information has been sought from The City of Portland, Oregon. As part of the city's sustainable stormwater management efforts, they introduced the 'Green Streets' program which has various initiatives designed to enable the city to become more sustainable in terms of stormwater management. As part of the program, they have installed various permeable surfaces around the city in order to further evaluate the widespread feasibility of permeable urban surfaces, so as to relieve the strain on Portland's combined sewer system. Two thirds of Portland's streets are considered low volume. Two of these pilot projects have been documented well and have been included and analysed in this report.

4.1.1 North Gay Avenue

The North Gay Avenue project is a residential street which required a new sewerage pipe to be installed. Rather than resurfacing the road with a conventional asphalt surface, the city installed PC and PA in separate sections of the road. This project was completed in 2005 and was to be used as a pilot study over the following years.

The total cost of the project was US$400,000 (porous pavement construction totalled $256,000) and extended for four blocks along North Gay Avenue. Each block was paved in a different manner as outlined below:

- One block curb-to-curb PC
- One block curb-to-curb PA
- One block conventional concrete in the driving lanes with PC in the parking lanes (shoulders)
- One block conventional asphalt in the driving lanes with PA in the parking lanes (shoulders)

4.1.1(a) Design

General

The following are some general design details that apply to both the PC and PA surfaces:

- Each pavement has a design life expectancy of 40 years (American Public Works Association 2008).
- Infiltration tests revealed rates of 1 to 3 in/hr into the subgrade. The pavement systems have therefore been designed using a conservative 1 in/hr (City of Portland 2010).
- The design storm used 1/3 of a 2 year average recurrence interval (ARI) storm, which in this area is 0.83 in (21.2 mm) in a 24 hour period. The sub-base thickness required to meet this standard was 6 inches (City of Portland 2010).
- The facility footprint, or total area of road considered part of the project is 32,000 sq. ft. (2,973 m^2). The catchment area served, including roofs, driveways, lawns, sidewalks and streets is 50,000 sq. ft. (4,645 m^2).
- An estimated average traffic volume of less than 300 vehicles per day (American Public Works Association 2008).
- Contrary to recommendations in some literature, the top 12 inches of the sandy gravel subgrade was compacted to 95% maximum density to prevent settlement issues. The sub-bases were compacted with an 8 tonne roller performing four passes (American Public Works Association 2008).
- The road surfaces are crowned, however the subgrade was graded flat to encourage infiltration through the soil (American Public Works Association 2008).
- No underdrain system in the substructure (American Public Works Association 2008). Any excess water drains to the existing inlet.

Pervious Asphalt

The asphalt mix used was the standard Oregon Department of Transportation (ODOT) ½ inch open-graded mix, of which according to the 1993 AASHTO Guide for Design of Pavement Structures, produced a required pavement thickness of 8 inches with 17% voids (City of Portland 2010). The aggregate mix used in this design is shown in Table 4.1.

Table 4.1 - ODOT 1/2 in open-graded asphalt mix (City of Portland 2010)

Sieve Size	Minimum	Maximum
¾”	99	100
½”	90	98
No. 4	18	32
No. 8	3	15
No. 200	1	5

The PA surfaced was laid in two 4 inch (102 mm) lifts, rolled with four passes (American Public Works Association 2008). A stiffer asphalt cement binder (PG70-22) was used to prevent the binder from liquefying and filling in the voids during hot summers (American Public Works Association 2008).

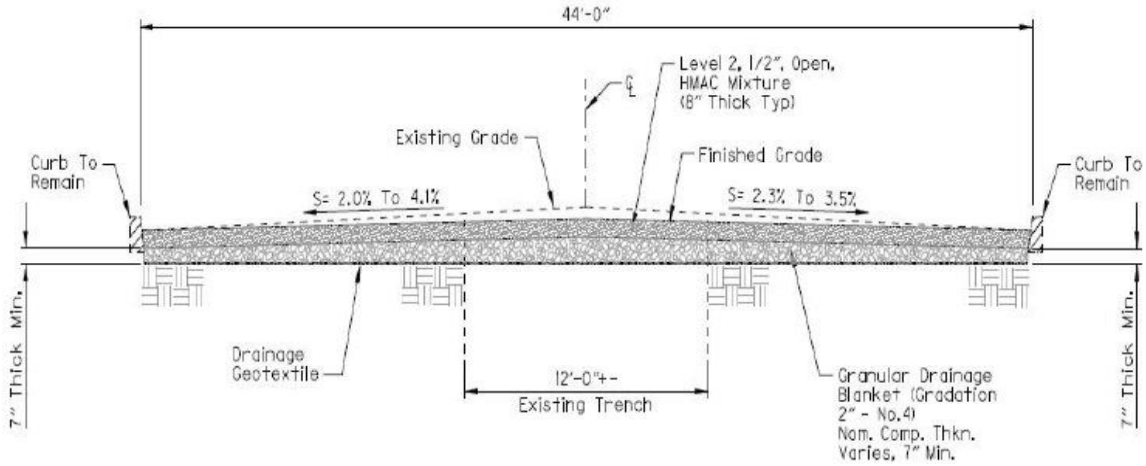

Figure 4.1 - Full width PA design schematic (City of Portland 2010)

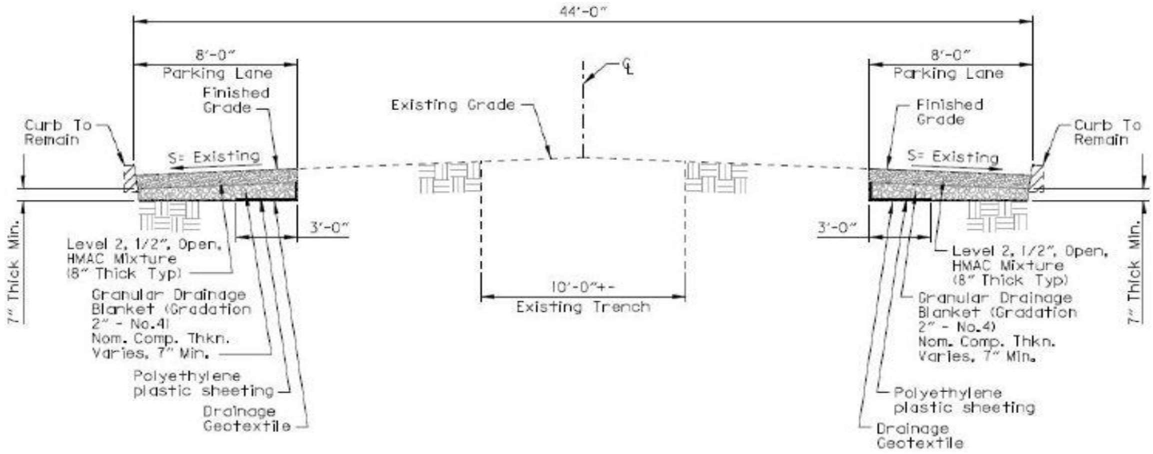

Figure 4.2 - Shoulder-only PA design schematic (City of Portland 2010)

Photos of the completed projects can be found in Appendix C.

Porous Concrete

- Using the 1993 American Association of State Highway and Transport Officials (AASHTO) Pavement Design Guide, the pavement thickness required was 9.2 inches, which was rounded up to 10 inches (254 mm) (City of Portland 2010). The concrete was cured with a plastic poly sheet (American Public Works Association 2008).
- Some fines were added to the PC to reduce the void space from 29% to 17% (American Public Works Association 2008).
- Due to the 17% void ratio, no air entrainment additives were required in the mixture (American Public Works Association 2008).
- The City of Portland used an identical joint spacing as all of their conventional concrete roads, that being every 10-12ft (3-3.7m) (American Public Works Association 2008).
- A vibratory screed was used to aid in striking off the surface, however care must be taken as vibration in general will consolidate the concrete layer and reduce its final porosity (American Public Works Association 2008).

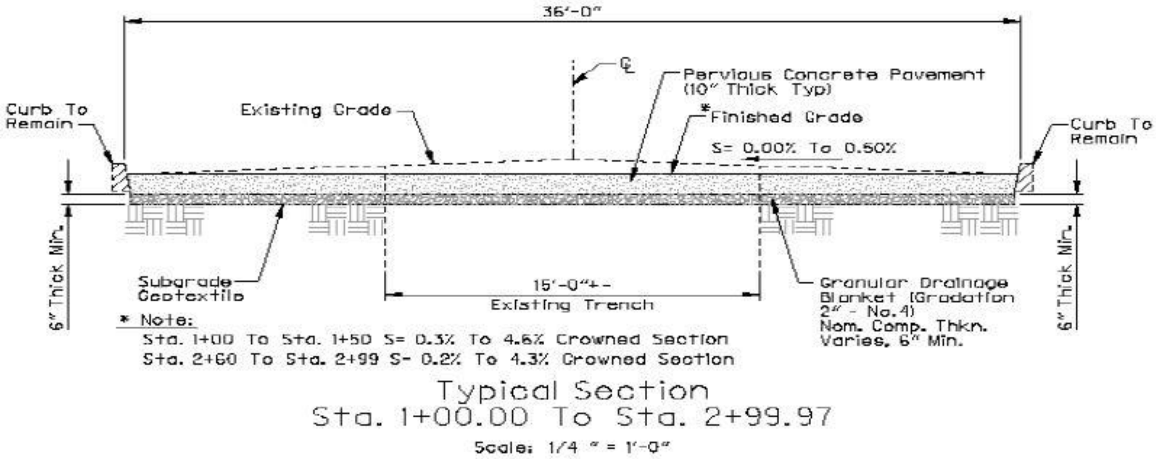

Figure 4.3- Full width PC design schematic (City of Portland 2010).

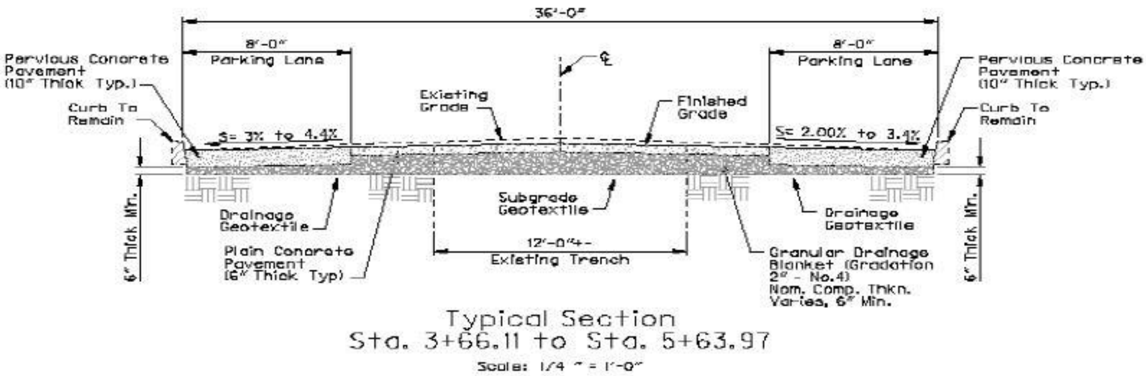

Figure 4.4 - PC shoulder-only design schematic (City of Portland 2010).

Photos of the completed projects can be found in Appendix C.

4.1.1(b) Costing

Pervious Asphalt

The cost of the PA pavement (per 8 inch thickness) was $22.00/sq. yd., which is very similar to the cost of conventional asphalt - $21.00/sq. yd. (American Public Works Association 2008). These costs are for the surface material only.

Porous Concrete

Porous Concrete (10 inch thickness) - $72.00/sq. yd., compared to conventional concrete (6 inch thickness) - $40/sq. yd. (City of Portland 2010). These costs are for the surface material only.

4.1.1(c) Maintenance Techniques Used

Vacuum sweeping is performed four times per year, which is the same as all Portland streets are swept with a standard sweeper (American Public Works Association 2008). The cost of the vacuum air sweeper was US$190,000, compared to $150,000 for a standard street sweeper (American Public Works Association 2008). The Tymco 500x was selected over the Schwarze A7000 and the Elgin Crosswind J-Plus sweepers.

4.1.1(d) Performance

The 28-day strength of the PC was 2000 psi (13.8MPa) (American Public Works Association 2008). The final compressive strength achieved was an average of 2500 psi (17.2MPa), which is higher than the 2000 psi anticipated in the design. At a compressive strength of 2500 psi, the pavement requirements could have been satisfied with an 8 inch (203 mm) PC layer instead of the 10 inches (254 mm) that was constructed (American Public Works Association 2008).

Pervious Concrete

The following are the results from periodic infiltration tests:

- 46 in/hr (2008)
- 10 in/hr (2009)
- 20 in/hr (2009) – after power wash
- 15 in/hr (2012)

Pervious Asphalt

The following are the results from periodic infiltration tests:

- 43 in/hr (2008)
- 10 in/hr (2009)
- 10 in/hr (2009) – after power wash
- < 2 in/hr (2012)

All infiltration rates are averages of tests performed in four separate and random locations within each pavement section. Each of the four random test locations consisted of three tests each, giving a total of 12 tests per surface type.

4.1.1(e) Lessons Learned and Recommendations

General

- The City of Portland recommends that porous road pavements be designed with a crown due to ease of maintenance with regard to road sweeping. The slope from the crown aids in forcing the debris towards the gutter (American Public Works Association 2008).
- Must be wary of underground basements of buildings adjacent to permeable roads, as water can seep through cracks in underground basements (American Public Works Association 2008).
- Some damage has occurred to the pavements caused by tree roots but none of the damage is due to the use of permeable surfaces. The City Forester in Portland believes that tree roots damage pavements because they are seeking air, therefore permeable surfaces should help in this aspect (American Public Works Association 2008).
- On the sections with the shoulder design, the ratio of impervious to pervious surface area is roughly 1.25. This design has not caused any drainage issues (American Public Works Association 2008).
- Traffic volumes and weight should not be a factor for PA and PP roads when properly designed (American Public Works Association 2008). PC may experience surface ravelling when exposed to heavier loads, however none has been observed after 8 years of use (Magee, M 2013, pers. comm., 16 October).
- The roads were snow-ploughed once as an experiment with no issues, however there are no results from this case study showing the effects of repetitive ploughing, as the City of Portland does not plough their streets due to minimal snow precipitation. However because of its rougher surface, PC may have issues with aggressive plough blades. The edges created by PPs may also pose a problem when using aggressive blades. In addition to this, there are also no outcomes in regards to chemicals used to de-ice roads, as the City of Portland does not use them (American Public Works Association 2008).
- It is advisable to take hot weather into consideration when evaluating pavement type. For example, there is a thought that the binder in a PA surface may soften and leak into the pores, in turn decreasing the porosity and infiltration potential. As in this Portland case study, a higher grade of bitumen should be used in the

design in an attempt to prevent this from happening (American Public Works Association 2008). UV degradation has not been an issue thus far (Magee, M 2013, pers. comm., 16 October).

- A water collection system was included in the design to enable water sampled to be extracted for quality testing. However the perforated pipe used in the design did not capture any water, therefore there is no water quality data from these case studies. The water collection system for a pavement should be designed differently and tested if possible (American Public Works Association 2008).

Porous Asphalt

- PA surface is roughly as smooth as conventional asphalt surface (City of Portland 2010).
- Pressure washing the PA surface did not increase the infiltration rate – see infiltration results in section 4.1.1(d) (City of Portland 2010). Further research in this area is recommended.
- Ravelling or cracking has not occurred on the PA surface thus far (Magee, M 2013, pers. comm., 16 October).
- UV degradation has not been an issue (Magee, M 2013, pers. comm., 16 October).
- As pressure washing did not improve the PA infiltration rates, it has been recommended that in similar circumstances the top 2 inches be cold planed off and replaced with a new lift. This is because the clogging happens in the top section of the surface layer (American Public Works Association 2008).

Pervious Concrete

- The contractor must have training and be certified in placing PC for a successful project (American Public Works Association 2008).
- Plastic should be laid over PC immediately after placement to help curing. The day after placement, water should be sprayed on the surface and then re-covered with plastic sheeting (American Public Works Association 2008).
- It is believed that pervious concrete is a better distributor of traffic loads into the subgrade, therefore it may be better to use PC where soils may be weakened by water saturation (American Public Works Association 2008).

- PC surface requires pressure washing every 3 years, which will increase the infiltration rate of the pavement (City of Portland 2010).
- Care must be taken when pouring PC in hot weather, as the surface dries fast which can cause it to ravel (American Public Works Association 2008).
- PC surfaces are not as smooth as conventional concrete surfaces (City of Portland 2010).
- Ravelling or cracking has not occurred on the PC surface thus far (Magee, M 2013, pers. comm., 16 October).

4.1.2 Westmoreland

This project was similar to the North Gay Avenue project in that it also required replacement of the sewer pipes. It was therefore decided that this project would be used as a pilot project incorporating permeable pavers into the road construction. The total cost of this project was US$412,000, of which $85,000 was funded by the Environmental Protection Agency (EPA) and it was completed in November 2004. The construction extended for four blocks along SE Rex Street, which were each paved differently as follows:

- One block paved curb-to-curb with permeable interlocking concrete paving blocks (PICP). This block is crowned.
- Two blocks with conventional asphalt in the driving lanes only, with PICP in the parking lanes (shoulders). One block has the asphalt section crowned and the other is not. The PP shoulders on both blocks are flat.
- One block curb-to-curb with conventional asphalt.

4.1.2(a) Design

The following are some key design parameters of this project:

- The pavement has a design life expectancy of 40 years (American Public Works Association 2008).
- Infiltration tests revealed rates of 1 to 3 inch/hour into the subgrade. The pavement system has therefore been designed using 1 in/hr (City of Portland 2010).

- The subgrade consists of a sandy gravel (American Public Works Association 2008).
- The total area of PICP used was 19,000 sq. ft. (City of Portland 2005).
- 10 inch open-graded sub-base was provided (City of Portland 2005).
- Southeast Rex Street has an estimated average traffic volume of less than 200 vehicles per day (American Public Works Association 2008).
- Mutual Materials Uni-Ecoloc PICPs with the following dimensions were used on a 3 inch bedding with a geotextile separating the two layers: 225 mm x 225 mm x 79.4 mm).

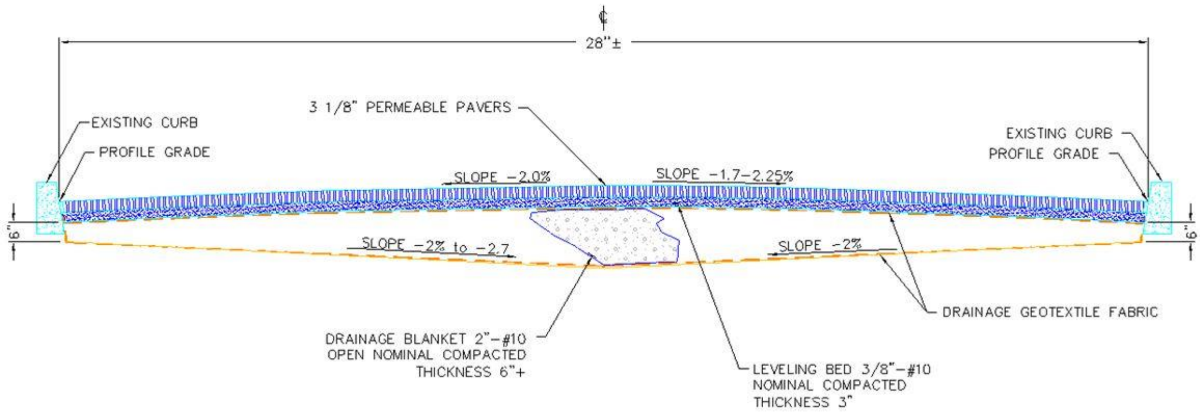

Figure 4.5 - Full street width PP design schematic (City of Portland 2010)

The shoulder-only design incorporates a conventional asphalt mix for the driving lanes, with PPs used in the shoulders of the road. An impervious concrete ribbon was included to separate the two materials and help provide a solid edge to lay the pavers against and help prevent movement (American Public Works Association 2008). See Figure 4.6.

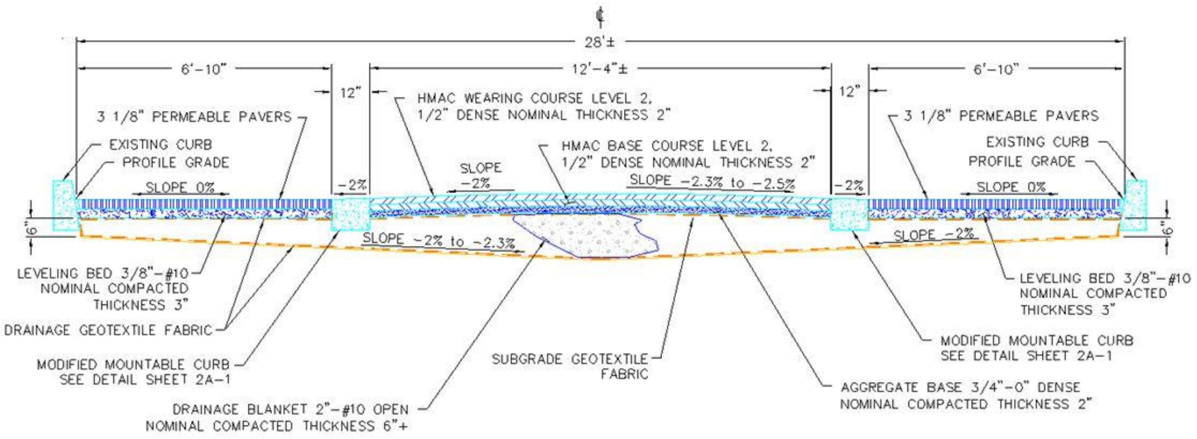

Figure 4.6 - Shoulder-only PP design schematic (City of Portland 2010)

Photos of the completed projects can be found in Appendix C.

4.1.2(b) Costing

The following is a breakdown of the costs:

- Pavers - $6.16/sq. ft., which includes sand bedding and 1 inch square opening filler in the pavers
- Geotextile - $0.14/sq. ft.
- Concrete band - $12.00/sq. ft.
- Asphalt Pavement - $1.22/sq. ft.

The cost of the PP surface (not including the aggregate base and construction costs) for this project was $55.44/sq. yd.

4.1.2(c) Maintenance techniques used

The same vacuum sweeping schedule used for the North Gay Avenue project is applied to this project – 4 times per year.

Weeds developed in the 1 inch holes between pavers in the year following installation. Weeds are now sprayed twice a year – autumn and spring (American Public Works Association 2008). The full maintenance matrix for this project can be found in Appendix D.

4.1.2(d) Performance

The following are the results from periodic infiltration tests:

- 63 in/hr (2008)
- 30 in/hr (2009)
- 22 in/hr (2011)
- 40 in/hr (2012)

All infiltration rates are averages of tests performed in four separate and random locations within the one site, each consisting of three tests each.

4.1.2(e) Lessons Learned and Recommendations

- There has been some subsidence of the pavers, however it is uniform across the surface therefore it does not affect driving conditions. The settling is evident at the gutter interface (Magee, M 2013, pers. comm., 16 October).
- A 3600 psi (25,000 kPa) hand pressure washer was tested for removing the weeds from the 1 inch holes in the corner of each paver. It was tested with a vertical, tilted and almost-horizontal angle of attack. Shooting each hole vertically was the only successful method, albeit very time consuming and it is consequently deemed unfeasible. Infiltration tests revealed that the weeds had no effect on infiltration rates (City of Portland 2008). Therefore it was concluded that the weeds were only a hindrance to the aesthetic values of the pavement. It has been determined that the best maintenance technique for weeds (if any) is to spray them twice per year – autumn and spring (American Public Works Association 2008).
- PP surfaces should not be used on roads with a speed limit greater than 25-30 mph (40-48 kph) as the noise from tyres can be loud (American Public Works Association 2008).
- Feedback from the public indicates that they prefer the shoulder-only design over the full-width construction (American Public Works Association 2008; City of Portland 2005).
- The shoulder-only design was 25% cheaper than the full-street width design (American Public Works Association 2008).
- The full-street width design with a crown was more difficult to construct compared to the shoulder design (City of Portland 2005).
- In this design, there was a geotextile fabric included in between the sub-base and the bedding layer. This was included due to the thought that the finer bedding

layer may potentially be transported into the sub-base over time by the flow of water, causing clogging of the voids. The Interlocking Concrete Pavement Institute does not require this layer to be installed, therefore for future projects under similar design conditions to that used in the Westmoreland project, it may be worth omitting the geotextile as "choking" between the sub-base and bedding layer should not be a problem (City of Portland 2005).

4.1.3 Infiltration rate comparison

Infiltration rates for all three surfaces are compared in Table 4.2. The results clearly show the best performing surface material in terms of infiltration rates is permeable pavers. PA is by far the worst performing and interestingly power washing did not seem to restore the permeability of the surface. Despite the severe reduction in permeability, all pavements are still allowing infiltration rates higher than what they were designed for.

Table 4.2 - Comparison of surface infiltration rates

	Infiltration rate (in/hr)				
Surface	**2008**	**2009 – pre-power wash**	**2009 post-power wash**	**2011**	**2012**
PA	43	10	10	N/A	< 2
PC	46	10	20	N/A	15
PP	63	30	N/A	22	40

4.1.4 Developments due to pilot study success

Due to the success of the North Gay Avenue and Westmoreland pilot projects, the City of Portland and the Bureau of Environmental Services (BES) have decided to proceed with using pervious concrete on a full-scale low volume road application. Some of the key technical factors that resulted in selecting PC over other treatments are (Magee, M 2013, pers. comm., 16 October):

- There is a state specification that is able to be simply mirrored – *USP7575: Plain Pervious Concrete Pavement.*

- The design is able to specify the national standard requirement that the contractor be fully certified for the placement of pervious concrete as per 757.31.
- The use of ½ inch rock in the PC gives a better ride.
- The ability to utilise PerviousPave – a modelling software developed by the American Concrete Pavement Association to evaluate the flexural strength as well as the stormwater management requirements and verify that the design will withstand the expected loadings.

Some of the key non-technical factors that resulted in selecting PC over other treatments are (Magee, M 2013, pers. comm., 16 October):

- From the infiltration rates seen in the North Gay Avenue pilot study, PC shows a better trend for maintaining infiltration rates over time.
- They believe it is important that maintenance crews can distinguish the surface from the surrounding asphalt roadways. This may help prevent future problems whereby crews may mistake the surface as a conventional road surface.
- There is a grocery store nearby that will take deliveries, therefore the loads will be higher than a regular low volume residential street. The city engineers believe that the concrete will hold up better to the truck turning over time.

4.2 Shoreview, Minnesota

The City of Shoreview, Minnesota's Capital Improvement Plan for 2009 included a road reconstruction project for a residential neighbourhood situated in the NE corner of Lake Owasso. Streets within the project area consisted of approximately 3,800 linear feet (1158 m) of asphalt roadway varying in width from 16 to 22-feet (4.9-6.7 m) with no curb and gutter. The existing storm sewer consisted of one catch basin located on the north end of the project that discharged directly into the lake. The project consisted of replacing the existing asphalt roadway with a new street surface, concrete curb and gutter, a storm sewer collection system, and miscellaneous water and sewer improvements.

Figure 4.7 - Aerial view of the Woodbridge neighbourhood in Shoreview that has been retrofitted with pervious concrete roads (Maloney 2013).

The main aspect of the project was the management of stormwater. This residential area drained directly towards Lake Owasso, therefore there had been concern from residents and the City regarding the water quality of the lake. After a 2007 study on the water quality of Lake Owasso, it was advised that all stormwater be treated or preferably not deposited into the lake.

A feasibility study revealed that due to a lack of space, treatment ponds were not an option. Underground treatment units and filtration chambers were also considered but were deemed unfeasible due to costs, space and odour issues. The study showed that the best option for this project would be a pervious concrete system based on the following factors (City of Shoreview n.d.):

- In 2007 the City constructed a 900-foot long x 12-foot wide pervious concrete alley as part of different road reconstruction project and was familiar with the design and installation of pervious concrete. During that project the City established strong relationships with the concrete industry, suppliers, and installers.

- The neighbourhood is located in a portion of town that is isolated with low traffic volumes.
- The location has a sandy soil subgrade with infiltration rates of 3+ in/hr
- The rock sub-base drainage layer could be designed such that it would eliminate the need for a discharge pipe to the lake.
- The pavement system would eliminate the need for traditional stormwater management infrastructure such as catch basins, manholes and underground piping.
- Project site is relatively flat therefore suitable for a pervious pavement system.
- Advancements in mix designs and installation could produce a road surface that is freeze-thaw durable.
- The initial capital cost of the project was approximately 10% higher than the infiltration chamber option, but when life cycle costs were considered between an asphalt and concrete roadway, the costs were equal.
- Reduced urban heat island effect when compared to asphalt.
- Other concerns surrounding the lack of documented experience of previous applications of PA and PPs to low volume roads (Maloney, M 2013, pers. comm., 22 October).

4.2.1 Design

At the time, this was the largest amount of pervious concrete placed for a public street project in the world, at a total of 8,600 sq. yd. (7,190 m^2) (Metropolitan Council 2012; Maloney, M 2013, pers. Comm., 22 October). Some key design specifications are as follows (Maloney 2013):

- Pavement system designed to be able to handle a 10-year ARI storm – 4.2 inches (107 mm) of precipitation in 24 hours
- 7 inch thick PC surface
- 18-24 inch (460-610 mm) open-graded sub-base
- 21% air voids
- Finished with a tri-roller screed

- 7 day cure with a curing blanket instead of the standard PC practice – a poly sheet

The details of the concrete mix design can be found in Appendix E.

A single roller screed was specified in the design to be used to finish the surface. This aligns with the standard for finishing pervious concrete, however the contractor advised that using a tri-roller screed would produce a superior surface.

In order to minimise accessibility issues for the residents, the project area was broken up into sections such that on small segments of the neighbourhood were inaccessible. This construction method was designed such that any resident could park within two houses of their own property at all times. The removal of the existing asphalt road, grading, installation of the curb and gutter and the sub-base installation of the sub-base for the new pavement are completed in one day, followed by the concrete pour and finishing the next day. Therefore, residents were usually impeded for a maximum of 8 days.

Three groundwater monitoring wells were installed within the project area and one additional well installed up-gradient of the project so that water samples could be gathered every six months and the groundwater levels could be measured.

4.2.2 Costing

Below is a cost comparison of the adopted pervious concrete road against the alternative of a standard asphalt road with an underground infiltration tank.

<u>Pervious concrete</u>

Common excavation – 11,000 cu yd. ($6.00/cu yd.)	= $66,000
Fabric – 11,000 sq. yd. ($1.00/sq. yd.)	= $11,000
1 ½ inch Crushed rock – 5000 cu yd. ($52.00/cu yd.)	= $260,000
7 inch pervious concrete – 8470 sq. yd. ($46.50/sq. yd.)	= $394,000
Total cost of PC system	= $731,000
Total cost per sq. yd.	**= $86.30**

Asphalt alternative

Estimated asphalt road cost	=	$257,000
Estimated underground infiltration	=	$417,500
Total estimated cost	=	$674,000
Total estimated cost per sq. yd.	**=**	**$79.60**

This cost comparison shows that the capital costs of the pervious concrete system were estimated to be 8.4% higher than the asphalt alternative. It is evident that when taking into account the whole lifecycle costs and the benefit of this alternative to Lake Owasso, pervious concrete was a superior option.

4.2.3 Maintenance

After the road construction, a side-by-side test was performed using a standard mechanical brush sweeper, a vacuum sweeper and a regenerative air sweeper. Based on the tests, an Elgin Crosswinds Regenerative air sweeper was purchased. The City of Shoreview claims that it used a trial and error method of determining the best sweeping maintenance program due to a lack of definitive maintenance protocols. Using this technique they arrived at a sweeping frequency of approximately once every six weeks (City of Shoreview n.d.).

Important to note is that the City's engineer for the project, Mark Maloney highly discourages the use of mechanical brush sweepers on permeable surfaces of any type.

> "I cannot stress this enough: Do not use mechanical brush sweepers on a permeable pavement of any type! The circular motion of the brushes grinds material down into the pore structure (Maloney, M 2013, pers. comm., 22 October)."

Maloney also believes that the main cause for clogging is organic material such as leaves and pine needles and that organic material is much more problematic than inorganic material. This agrees with a study completed by Shackel et al. (2008).

A regular power washing schedule has not been set up for this project, however some power washing has just been completed in August 2013. The only obtainable information for this was that the results are encouraging (Maloney, M 2013, pers. comm., 22 October). Maloney briefly described the power washing technique as being

> "…a fine line between getting enough water and force into the pavement pore structure to loosen things up, and using too much and actually driving the clogging materials deeper into the pavement structure (Maloney, M 2013, pers. comm., 22 October)."

He explained that the cores that they have taken of the surface show that the clogging occurs in the top ¼ inch of the pavement structure and stated that he best method of removal from their experiences is getting the clogging material loosened up in a slurry and quickly vacuuming it out of the pavement.

4.2.4 Performance

Concrete compressive strengths were not measured in this case study as they measured their PC in terms of void space and uncompacted density (Maloney, M 2013, pers. comm., 22 October).

Due to this project being primarily a city infrastructure project as opposed to a controlled and funded research initiative, there has been little testing performed on infiltration rates and water quality compared to what was initially planned. However initial infiltration rates were around 500 in/hr. A recent 2013 test performed shows a current average of approximately 100 in/hr. The infiltration rate is expected to plateau from this point in time (Maloney, M 2013, pers. comm., 22 October).

A 1 tonne 4x4 pickup truck with a regular blade is used to plough the roads. So far there is no evidence of damage due to ploughing (Maloney, M 2013, pers. comm., 22 October).

4.2.5 Lessons Learned and Recommendations

As stated in section 4.2.3, the engineer highly emphasis his disapproval of the use of a standard street sweeper with a mechanical brush.

Saw cut joints appear to be more durable than rolled in joints. These should be cut 24-48 hrs after the pour (Maloney 2013).

Cores taken from the pavement showed that the top 2 inches of the concrete was slightly more compacted than the remaining section, which should improve and prolong the durability of the surface (Maloney, M 2013, pers. comm., 22 October).

The construction sequence method used shows that although concrete requires a minimum 7 days of curing, the effect on the public can be minimised. Overall the City received a positive response from the residents in respect to the scheduling and coordination of the project (City of Shoreview n.d.).

The City of Shoreview recommends implementing an education program for the residents of a neighbourhood that has a permeable surface installed in order to increase awareness and encourage proper best management practices. The City created information brochures which warned against practices such as dumping grass cuttings on the road, getting mulch delivered and dumped on the road among other things (Maloney, M 2013, pers. comm., 22 October).

After four years in operation and enduring Minnesota's harsh winters, the PC surface is wearing well and is still performing above standard. The pavement also performed well through some severe rain events experienced in 2011 in which other areas of Shoreview experienced flooding (City of Shoreview n.d.).

4.3 Chicago Green Alley Program

Chicago has the most extensive network of alleys in the world with approximately 13,000 alleyways stretching for 1,900 miles in total length. The alleys are publicly owned and are used primarily for garbage and recycling pickup as well as points of access for vehicles. In 2005, the City of Chicago estimated that 20% of these alleys had deteriorated and were experiencing localised flood and therefore required repairing. Consequently after six successful pilot projects, the City developed the Green Alley program – a green initiative designed primarily to deal with the stormwater resulting from the 3,500 acres of impervious alleys, while also addressing the urban heat island effect and energy conservation.

Since 2006, over 200 alleys have been converted to Green Alleys at a rate of 20-40 per year. The program has utilised all three pavement types assessed in this study – PA, PC and PICPs. Figure 4.8 and Figure 4.9 shows the surface improvements to a Chicago laneway.

Figure 4.8 - A Chicago alley before conversion into a ‘Green Alley’ (Chicago Department of Transportation 2010).

Figure 4.9 - The same alley after conversion into a 'Green Alley' (Chicago Department of Transportation 2010).

4.3.1 Design

The City of Chicago tends to avoid PA where possible as it does not reduce the heat island effect like PC and PPs do, however they have used it on a number of alleys. Another factor that has resulted in a low adoption rate of PA is the availability of materials. For example all of the recent conversions have utilised PC or PPs as it is not economical for the local asphalt plant to produce a batch of open-graded asphalt for such small applications. This is because plant has to alter its whole production in order to produce an open-graded mix (Leopold, D 2013, pers. comm., 17 October).

The following are some design parameters used on Chicago’s Alleys:

- 8 inch thickness for both PA and PC layers.
- 2 year ARI design storm (Attarian, J 2013, pers. comm., 23 October).
- The concrete mix design incorporates blast furnace slag to reduce industrial waste, increase the durability and lighten the colour of the concrete (Leopold, D 2013, pers. comm., 17 October). The mixes also include recycled concrete whenever possible (Chicago Department of Transportation 2010).

- The open-graded asphalt mix incorporates ground tyre rubber to increase the cohesion of finished product to prevent binder drain-down (Attarian, J 2013, pers. comm., 23 October).
- Recycled concrete has been used for the sub-base bedding whenever possible (Chicago Department of Transportation 2010).

4.3.2 Costing

The cost of 8 inch PC in 2010 was $54.00/sq. yd. Unit costs of PA and PPs were unavailable.

4.3.3 Maintenance

After experimentation with both a normal street sweeper and a vacuum sweeper, the City found that the best results were produced by a dry sweep using normal street sweeper (Leopold, D 2013, pers. comm., 17 October). Therefore the current maintenance practice utilized is two passes of a standard street sweeper, twice per year for all three surface types.

Interesting to note is that there has not been any significant weed growth in the PP surfaces. This differs to what the City of Portland has experienced with their Westmoreland PP pilot project, where they have had significant weed growth that requires biannual spraying. However as previously stated weed growth is only a hindrance to the aesthetic values of the pavement and therefore do not affect the infiltration rate of pavers.

4.3.4 Performance

Infiltration rates have been omitted from this case study as they were unavailable. In terms of visual observations, all three pavement types are wearing well with no settling or damage (Leopold, D 2013, pers. comm., 17 October; Attarian, J 2013, pers. comm., 23 October). Chicago does not plough their alleyways so there is nothing to report in regards to potential damage due to ploughing. The City is very happy with the success of the program and is therefore continuing as planned.

4.3.5 Lessons Learned and Recommendations

The following are the lessons learned thus far from the Chicago Green Alley program:

- Chicago has also implemented an education program including brochures outlining the best practices to members of the public and highly recommends this to increase awareness and proper usage (Leopold, D 2013, pers. comm., 17 October).
- Normal street sweeper is more effective than the vacuum sweeper.
- The City has found that the clogging has only occurred in the top ½ inch of the pavements (Leopold, D 2013, pers. comm., 17 October).
- The local residents seem to prefer the aesthetics of the pavers but they have been receptive to all surfaces (Attarian, J 2013, pers. comm., 23 October).

Though the performance of the pavements cannot be quantified and compared numerically in this study due to the lack of available data, verbal communication with one of the City's engineers David Leopold, confirms that the Green Alley program has proven to be a successful application of pervious road surfaces to low-volume roads, even under heavy loads such as the stop-start nature of that experienced from the frequent use of garbage collection trucks.

5 Maintenance

An important requirement of an effective and successful porous pavement surface is maintenance. The primary objective of maintaining a porous pavement is to minimise clogging of the porous structure. However it is worth noting that clogging does not create an impermeable surface. Studies have shown that a rapid reduction from high initial infiltration rates occurs due to clogging, followed by a stabilisation over time (Bean et al., 2007 cited in US EPA 2009b). Younger, Hicks and Gower (1994) agree with this with respect to PA surfaces and believe that this is due to compression of the porous structure, in addition to clogging of the voids with debris. They do note that soil particles and debris are less prevalent in the wheel tracks of the road because the wheels tend to create a suction effect in the pores. Ultimately a successful maintenance program for all surface types will maximise infiltration rates and extend the life of the pavement.

Current maintenance techniques being employed on PC, PA and PP surfaces have been outlined within each of the case studies in this report. These methods include mechanical, regenerative and vacuum air sweeping, power washing and weed spraying where appropriate on PPs. Each case study shows that there is not one practice or frequency that is an accepted standard. Each of the projects had used some form of a trial and error method to arrive at a maintenance program which showed beneficial results.

There are some alternative maintenance techniques that have been studied in a laboratory-type setting of recent times. Shirke and Shuler (2009) undertook a study which evaluated the possibility of reverse flushing the pavement in order to remove clogged particles. The theory of this method is that reverse-flushing the pavement should avoid driving the clogged particles deeper into the pavement structure. They evaluated four different variables: water pressure, clogging material, pavement porosity and the number of flushes. Ultimately the study revealed that the only significant variable affecting the percentage of clogging material removed was the water pressure (Shirke & Shuler 2009). The results are shown below.

Table 5.1 - Percentage removal of clogging vs. water pressure (Shirke & Shuler 2009)

Pressure (kPa)	Percentage removal of clogging material (%)
21	80
14	73
3.5	66

The full-scale practical application of this method was beyond the scope of the study, however it is worth reporting to show the ongoing research efforts in the area of maintenance of porous surfaces.

As stated in the Westmoreland and Chicago case studies, clogging tends to happen in the top ¼ - ½ inch of the surface. For PPs, this occurs in the jointing aggregate. If after all other maintenance techniques fail to prevent this clogging from becoming too severe, the top portion of the aggregate should be replaced. However some experiences from in-situ tests performed in Europe show that the reduction in permeability of PICPs stabilises over time, reaching somewhat of an equilibrium condition 5 to 10 years after construction (Shackel 2010, p. 10). This may provide an argument for the suggestion that maintenance may be reduced after this period. Satisfactory infiltration rates have still been achieved on PICPs that have not been subjected to regular maintenance (Shackel 2010, p. 11).

In summary, from the case studies analysed in this research it is evident that there are contradicting experiences between each of the projects and it is clear that there is a need for more research with respect to maintenance of porous surfaces.

6 Discussion

6.1 Design

The results from these case studies show that there is no ‘one size fits all’ design for a particular pavement system. Each case study has used different design parameters for their pavement systems. For example, the Portland case studies designed their pavement systems to be able to accept 1/3 of a 2 year ARI storm. The Shoreview case study utilized a 10 year ARI storm for the sub-structure design and Chicago is different again utilising a 2 year ARI storm. Of course the ARI storm varies depending on geographical location, but there is still no rule of thumb in that aspect of design.

It is also interesting that there is a vast amount of literature stating that compaction of the subgrade should be avoided for permeable surfaces, but then find that each of these case studies did compact the subgrade. Compaction certainly will provide a more stable substructure for a road.

6.2 Cost

Initial capital costs of each surface vary and are of course a factor in selection criteria. PA is the overwhelmingly cheapest surface option, the next expense being PC followed closely by PPs. It should be noted that although asphalt may be the cheapest unit price, it may be difficult to source as experienced in Chicago.

In terms of comparing the cost of a traditional road and drainage system against a permeable pavement system, the Shoreview case study is evidence that permeable pavement systems are a competitive option, where the initial capital costs alone of the PC alternative are only 8.4% higher than a traditional asphalt road and underground infiltration system. This is before evaluating any cost benefits on the environment. Similarly, the cost of the actual PA and PC surfaces in the Portland case study are very competitive with their conventional alternatives.

6.3 Maintenance

As evident from the case studies, there does not seem to be any common practice for maintenance. Each city has tried and tested the three main types of street sweepers – vacuum, regenerative air and standard street sweepers with varied results. Each case study utilises a different type of street sweeper as shown below:

- Portland case studies – vacuum sweeper
- Shoreview, Minnesota – regenerative air sweeper
- Chicago – standard mechanical brush street sweeper

It is difficult to draw conclusions on why each city has had different experiences with the sweeper types. Factors such as the type of debris clogging the pavement as well as the porosity of surface could determine the effectiveness of a particular type of street sweeper. It is worth noting that Mark Maloney, the engineer on the Shoreview project is adamant that the use of a standard street sweeper with a mechanical brush is detrimental to the function of a permeable pavement. He believes that the wire brush grinds material down into the pavement surface.

The frequency of maintenance varies vastly between the case studies also. It is unknown whether this is due to the fact that each city is utilising a different type of street sweeper as previously mentioned. The Portland case studies are vacuum swept four times per year compared to Shoreview's frequency of once every six weeks and Chicago's frequency of twice per year. Therefore the range of maintenance frequency between the projects is between two and roughly nine times per year on average.

Portland also recommends power washing PC surfaces every three years. Interesting, the Portland project also revealed that their PA surface did not respond to power washing. For PPs they recommend power washing only if there is a significant reduction in infiltration rates. In comparison, the Shoreview PC project does not have a regular power washing schedule and has only just recently used this technique with encouraging results. The Chicago engineers also did not mention any regular power washing schedule.

PPs have the added potential to grow weeds in the gaps between pavers. This has occurred in the Westmoreland case study, however David Leopold P.E. made it clear that they have not had any significant issues with weed growth on the PP alleys in Chicago.

There is also an aspect of these projects where communities have to 'buy in' to the concept in order to give the project its best chance at long-term success. From the case studies analysed in this research project, residents seem to have a sense ownership and pride in their street and enjoy the green concept of permeable surfaces. Education of the locals is very important also as the way they use the streets will have a direct effect on maintaining the long-term performance of the pavements. Signage should also be posted on streets where permeable surfaces have been installed to ensure that the public is aware of the best management practices.

Maintenance is clearly an area that requires more thorough research to determine the best practices.

6.4 Performance

From the case studies analysed, PPs seem to have the highest infiltration rates, followed by PC and then PA. Specific infiltration rates from Chicago were not available so a comparison was not able to be made. However all pavements from each case study are draining precipitation at rates deemed satisfactory, even with reduced infiltration rates due to clogging.

In terms of structural performance, PPs do have the potential to settle which has occurred in the Westmoreland case study in Portland. There is also the potential for pavers to crack and come loose from their position. In the Westmoreland case study the pavers have settled uniformly thus far, however any form of settlement is undesirable and this should be taken into account when selecting a pavement type.

From observations by the engineers on each of the projects, the PA and PC surfaces are wearing as expected and no differently to conventional road surfaces, proving thus far permeable road surfaces are feasible on low volume roads.

7 Conclusion

Although this study has not evaluated projects that have been in place for their full design life, the road surfaces in these case studies are ageing as designed. Porous pavement can provide cost savings in overall lifecycle costs by reducing the need for other expensive stormwater infrastructure and land acquisition.

This study has revealed four case studies which are only some of many projects worldwide currently being trialled in the hope of advancing permeable surfaces on low volume road applications. This study has shown that assuming a well-designed design mix and that the site selection is appropriate in terms of maximum slope and average daily traffic volume, permeable road surfaces are a feasible option for low volume residential roads. Until more thorough research is performed the long-term performance of permeable pavements and their response to maintenance techniques, the choice of surface at this point in time becomes a decision based upon factors such as materials and installation cost, the cost and ease and effectiveness of maintenance, climate, water filtration effectiveness, availability of materials, secondary benefits such as reducing the urban heat island effect and aesthetics.

Therefore without a specific project in mind to evaluate against the above listed criteria, it is difficult to recommend a pavement type that is best suited to low volume road applications. However when considering the pavement type that performs best in cost, ease and effectiveness of maintenance, secondary benefits such as reducing the urban heat island effect, early indications are that porous concrete is the most well-rounded candidate.

8 Recommendations

From the results of this study, further research is recommended on maintenance techniques and frequency. Research into the underlying reasons why PA may not respond to power washing is also highly recommended.

A study that revisits the case studies included in this research project would be highly beneficial to the objectives of this study and the overall advancements in porous pavement technologies.

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10 Appendices

10.1 Appendix A

University of Southern Queensland

<u>ENG 4111/4112 Research Project</u>

Project Specifications

FOR: Harrison Spurling

TOPIC: Water Sensitive Urban Design for Sustainable Road Development

SUPERVISORS: Dr. David Thorpe

ENROLMENT: ENG4111 – S1, EXT, 2013
ENG4112 – S2, EXT, 2013

PROJECT AIMS: This project is set out to review and analyse the current pavement options that can be used in water sensitive urban design, as well as determine the feasibility of their use on low volume residential roads

PROGRAMME: <u>Issue 2B, 17 April 2013</u>

1. Undertake a literature review of existing research articles examining the potential of water sensitive urban design for road pavements.

2. Examine current uses and specific types of pavements that utilise water sensitive urban design principles, such as permeable pavements. This step will outline the basic design of such pavements, as well as the advantages and disadvantages of their use.

3. Explore three (3) to five (5) case study examples. Ideally each case study will have been performed on a specific type of pavement or for a specific type of project. These case studies will hopefully give an insight into the future potential of such pavements.

4. Analyse the existing variations of pavements incorporating water sensitive urban design principles to determine the best type for potential use on low volume roads such as those in new housing estates.

5. Investigate current maintenance techniques and how these can potentially be improved.

6. Analyse results and develop conclusions and recommendations.

7. Combine these topics into a synthesised report ready for submission as per USQ requirements.

If time permits:

8. Investigate the use of recycled and environmentally friendly materials.

AGREED:

…………………………………. (Student) ………………………………………;
……………………………………… (Supervisors)

….. /….. /………. ….. /….. /……….
….. /….. /……….

10.2 Appendix B

Table 10.1 - Information requirements for a WSUD evaluation (BMT-WBM 2009)

Total Score	Implementation Risk	Local Scale Assessment Level	Information requirements
7 - 9	Low	Demonstrate implementation of best practice techniques	(i) Site Plan showing location, size and dimensions of measures (ii) Detailed design calculations (compliant with relevant guidelines) (iii) Public Health and Safety Issues considered and addressed
10 - 16	Medium	Demonstrate how relevant WSUD objectives are achieved (e.g. load based reduction targets achieved, peak flows compliant with hydraulic objectives)	Overall Water Management Plan provided, including: (i) Site Plan showing location, size and dimensions of measures (ii) Detailed design calculations (compliant with relevant guidelines) (iii) Estimates provided to show how WSUD targets are achieved (e.g. MUSIC modelling, Hydraulic assessments, compliance with planning codes for landscape elements etc, % of potable water demand satisfied by alternative sources) (iv) Public Health and Safety Issues considered and addressed
17 -21	High	Demonstrate how relevant WSUD objectives are achieved (e.g. load based reduction targets achieved, peak flows compliant with hydraulic objectives) Demonstrate how high risk factors addressed	Overall Water Management Plan provided, including: (i) Site Plan showing location, size and dimensions of measures (ii) Detailed design calculations (compliant with relevant guidelines) (iii) Estimates provided to show how WSUD targets are achieved (e.g. MUSIC modelling, Hydraulic assessments, compliance with planning codes for landscape elements etc, % of potable water demand satisfied by alternative sources) (iv) Detailed assessment of risk factors and proposed mitigation (v) Public Health and Safety Issues considered and addressed

10.3 Appendix C

Photos of completed projects from the North Gay Avenue and Westmoreland Portland case studies

Figure 10.1 - Completed full-width PA street

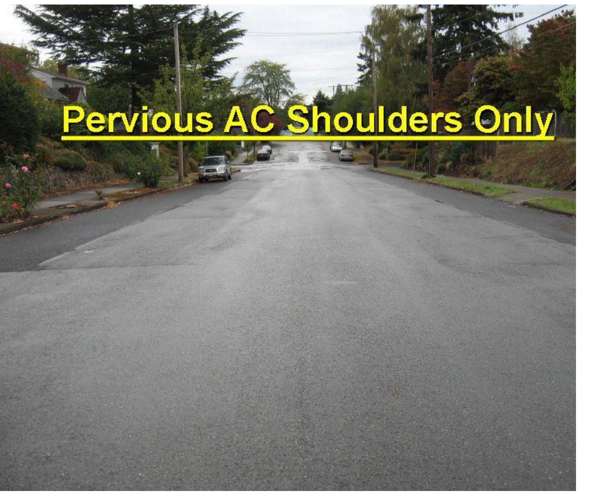

Figure 10.2 - Completed shoulder-only PA street

Figure 10.3 - Completed full-width PC street

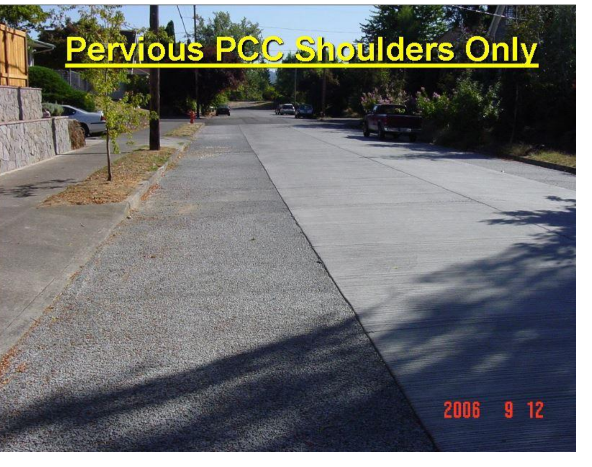

Figure 10.4 - Completed shoulder-only PC street

Figure 10.5 - Completed full-width PP street

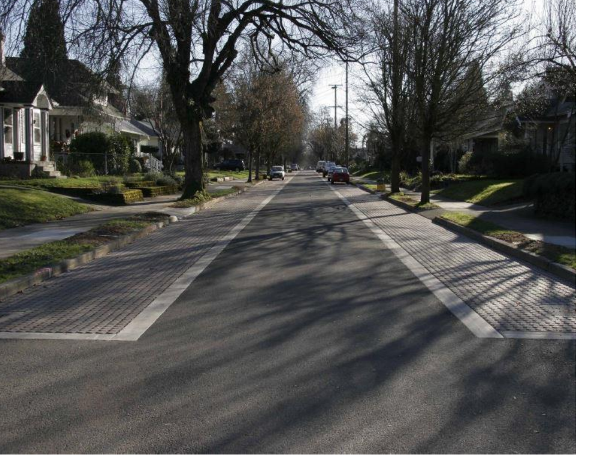

Figure 10.6 - Completed shoulder-only PP street

10.4 Appendix D

Westmoreland Permeable Pavement Pilot Project Operations and Maintenance Plan Activity Schedule

ACTION	Every spring	Every August	Every fall	Every winter	Every 4-5 years	When infiltration is slow
sweep	2x		2x	2x		
Sweep and suction	1x	1x				
Spray for weed control (Rodeo etc.)	1x after suctioning	1x after sweep ing				
Observe condition, Test for infiltration				1x, write summary report (PDOT)	Write status report, assess maintenance activities (PDOT)	
Pressure wash surface						If test report shows significant decrease in infiltration
Top off gravel/sand in voids					When top of surface lower than 1" below surface	

Repair and partial Replacement needed

- If paver voids are already empty and/or water ponds inside the voids and on majority of the surface, the blocks and leveling course in that area need to be removed. Replace rock with approved sand/ gravel, compact and replace block. Refill Core holes and compact.
- If there are areas of noticeable settlement, remove blocks and leveling course, and try to find the reason for settling. Replace and compact any soil, rock with approved sand/ gravel and replace block. Refill Core holes and compact.

System Replacement needed

If blocks are cracking and breaking to create an uneven surface, the whole system needs replacing. We expect this to happen every fifty to eighty years.

Westmoreland Permeable Pavement Pilot Project

Figure 10.7 - Maintenance schedule for the Westmoreland permeable paver pilot project

10.5 Appendix E

CEMSTONE™
CONCRETE SOLUTIONS
BUILDING THE FUTURE TOGETHER

Cemstone Products Company
Cemstone Ready Mix, Inc.
phone 1-800-Cemstone or (651) 688-9292
fax (651) 688-0124
2025 Centre Pointe Boulevard, Suite 300
Mendota Heights, MN 55120-1221
www.cemstone.com EOE/AA

CONCRETE MIXTURE DESIGN

MIX ID: FKSPERV Flexural Strength: 500 psi at 28-Days Revised On: Aug-22-07

MIX TYPE: Aggregate Specific
APPLICATION: Pervious Concrete with Falkstone Dolomite
PLACEMENT: Truck Discharge

CEMENT,	(ASTM C 150/TYPE I)	552 lbs. (85%)	2.81 ft^3
FLY ASH,	(ASTM C 618/CLASS F)	98 lbs. (15%)	0.61 ft^3
3/8" DOLO., Falkstone	(ASTM C 33/#89)	2,567 lbs. SSD	15.35 ft^3
WATER,		175 lbs. = 21.0 gal.	2.80 ft^3
VOIDS CONTENT,		21.0 % +/- 3.0%	5.73 ft^3
			27.30 ft^3
MRWRA,	(ASTM C 494/TYPE A)	26 oz. (4.0 oz/cwt)	
AEA,	(ASTM C 260)	4.0 oz.	
RETARDER,	(ASTM C 494/TYPE B)	10 oz. (1.5 oz/cwt)	
VISCOSITY MODIFYING ADMIXTURE,		26 oz. (4.0 oz/cwt)	

WATER-CEMENTITIOUS RATIO,	0.27
SLUMP,	0.00 in.
CONCRETE UNIT WEIGHT,	124.3 pcf
MIX SUITABILITY FACTOR,	14.6

MIXTURE ADJUSTMENT: Material variation and job site conditions may require mixture adjustments to maintain strength, water-cementitious ratio, slump, air content, and yield.
DISCLAIMER: Cemstone disclaims and negates any warranty whatsoever of this concrete mix design if it is provided to, or used by, another concrete producer.
CONFIDENTIALITY: This concrete mix design is proprietary to, and confidential information of, Cemstone. Its disclosure to a third party or entity, or permitting it to be used in competition with Cemstone, is strictly prohibited and will subject you to an injunction and damages.

PREPARED BY:

Kevin D. Heindel, P.E.

Document Printed On: Jun-15-09

Figure 10.8 - Cemstone mix design details for the Shoreview, MN pervious concrete project

10.6 Appendix F

Figure 10.9 - Example of community education taken from the Shoreview project (Maloney 2013).