Permeable Asphalt Paving:

Environmental Impacts and Performance of an Urban Permeable Pavement Parking Lot in Milwaukee, Wisconsin

by

Alexandra Gilgenbach

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Abstract

The purpose of this project is to investigate the effectiveness of an installation of permeable asphalt pavement almost a decade after its installation. The study performed sought to determine the installation's effects on stormwater discharge quantity and quality from the site. The goal was to draw conclusions on the overall system benefits that can be seen by implementing green infrastructure in stormwater control design as opposed to a more traditional grey water system. Study protocols and original water quality and quantity values were obtained from a previous study performed at the same site and were used for comparison purposes to evaluate the change in performance of the pavement over time. Volumes of water that were collected in carboys installed under the pavement at the site were measured and recorded. Data pertaining to the quantity of water that was infiltrated into the pavement instead of running off into a municipal combined sewer were obtained. The infiltration data were compared to rainfall data collected from the site in order to evaluate the infiltration efficiency of the permeable asphalt pavement system. Water samples were collected from the carboys and tested for BOD and TSS to assess water quality. Findings suggest that though the surface of the pavement has degraded significantly over time, the permeable asphalt pavement system is still allowing a significant amount of water to infiltrate into the subgrade soil, resulting in positive downstream effects on the municipal system. Water quality results were not quite as useful, but still suggest positive impacts on water quality resulting from infiltration through the permeable surface.

This paper is dedicated with the utmost affection and gratitude to Adam Rohde,
Who pumped out a lot of carboys,
Bought a lot of pumps, broke a lot of pumps, cleaned a lot of pumps,
Held my hand through a lot of emotional outbursts &
Even wore an awful orange vest for me.
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Nomenclature

Abbreviations

BOD – Biochemical oxygen demand

COD – Chemical oxygen demand

DRO – Diesel range organics

GRO – Gasoline range organics

LCC – Life Cycle Costing

TSS – Total suspended solids

Glossary

Evapotranspiration – “Water evaporation together with plant transpiration. Evaporation is the movement of water to the air from soil, plants, the built environment and bodies of water. Transpiration is the movement of water within a plant and the loss of water through plant leaves.”[1]

Permeable Asphalt Paving – “Porous asphalt, also known as pervious, permeable, "popcorn," or open-graded asphalt, is standard hot-mix asphalt with reduced sand or fines and allows water to drain through it. Porous asphalt over an aggregate storage bed will reduce stormwater runoff volume, rate, and pollutants.”[2]

Infiltration – “The process by which water on the ground surface enters the soil. This term is also used to describe stormwater that leaks into pipes. When this occurs, infiltration is not considered beneficial.”[1]

Storage – “The practice of capturing and holding stormwater on a temporary or permanent basis. Storage can be on a rooftop, at the ground level or underground.”[1]

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[1] “Weaving Milwaukee’s Green and Grey Infrastructure into a Sustainable Future.” 01 October, 2012. Fresh Coast Green Solutions. [Internet, WWW]. Available: MMSD Fresh Coast Website; ADDRESS: http://www.freshcoast740.com/Learn/Green-Alleys-Streets-And-Parking-Lots/-/media/H2OCapture/PDF/SustainBookletWeb1209.pdf. [Accessed: 12 April 2015].

[2] United States Environmental Protection Agency. Best Management Practices. 03 July, 2014. Porous Asphalt Pavement. [Internet, WWW]. Available: EPA.gov; ADDRESS: http://water.epa.gov/polwaste/npdes/swbmp/Porous-Asphalt-Pavement.cfm. [Accessed: 12 April 2015].

Introduction

Permeable asphalt paving is a type of green infrastructure practice associated with low impact design. Permeable asphalt has larger pores than traditional asphalts, meaning that there is more area between the aggregate and the binder through which water can drain through the paving to the substrate beneath [1]. The large voids between the constituent parts of the layers make the drainage of water through the asphalt possible.

Given the critical nature of these voids to the performance of the permeable paving, it stands to reason that if the voids became plugged, the asphalt would lose its favorable drainage characteristics. Normal wear and tear generally causes the surface layer of the pavement to degrade over time. The surface layer slowly becomes clogged with particulate matter and the functionality of the permeable surface gradually decreases. For this reason, permeable pavement is much more effective in applications with large surface areas, such as parking lots, as opposed to applications like the lining in drainage ditches. This is because the larger the surface area of the pavement compared to the volume of water runoff, the better the pavement will perform [2]. Conversely, the smaller the surface area compared to the total volume of runoff, the more likely that the pavement will become clogged, which will adversely impact performance [2]. The life span of these permeable pavement parking lots is still being determined. Research has been done to attempt to establish the amount of time permeable pavements remain functional, as well as to determine maintenance strategies to rehabilitate installed systems when they become clogged [2].

Research Question

Stormwater transport and treatment are important considerations for a civil engineer when designing a parking lot, developing a site, or master planning for a community. The amount of runoff that is expected to be generated by large weather events, the amount of water that must be transported from the site to a downstream receiving water or a treatment works, and the amount of runoff that must be retained on the site, must all be carefully estimated, investigated, and planned. In order to allow more complete utilization of the footprint of the site in terms of rainwater retention, permeable pavements have been developed to reduce runoff and to allow more natural infiltration of rainwater into the groundwater table. This design helps to preserve the natural ability of the ground at the site to absorb rainwater, instead of discharging it into adjacent storm sewers. Not only does this design help to meet regulatory requirements for runoff, it cuts the cost of transporting and treating stormwater. It is especially important in cities like Milwaukee that utilize combined storm and sanitary sewers, which can be more susceptible than traditional sewers to sewer overflows because of the volume of rainwater that must be handled by the system.

The City of Milwaukee has installed permeable pavement in a parking lot at Ward Street. The pavement was installed in order to study the reduction of runoff that can result from this surface and the impact of the levels of selected pollutants in the water that may flow to the groundwater, in order to verify that the design meets relevant water quality standards. Though it functioned very well at installation, this lot has been unmonitored for nearly a decade, and it is not known whether it is still allowing rainwater to infiltrate into the site and what level of pollutants are currently infiltrating through the surface.

This project investigated the current functionality of this site, including the amount of water captured by the permeable pavement and testing of certain water quality markers such as the levels of total suspended solids (TSS) and the biochemical oxygen demand (BOD) of the infiltrated rain water.

Project Overview

Permeable asphalt paving is a not a new technology, but it is a technology that seems to be coming back into vogue with the emphasis on sustainable development and the industry-wide push to move away from environmentally irresponsible building practices and towards ecologically maintainable practices such as green infrastructure. Green infrastructure is defined by the US Environmental Protection Agency as “an approach to wet weather management that is cost-effective, sustainable, and environmentally friendly. Green infrastructure management approaches and technologies infiltrate, evapotranspire, capture and reuse stormwater to maintain or restore natural hydrologies.” [3] Permeable asphalt paving is one such technology that can be used to further the goal of designing for the efficient and sustainable management of stormwater. Permeable asphalt -- also known as pervious, porous or open-graded asphalt -- is a conventional hot mix asphalt designed to create interconnected pores upon setting that allow stormwater to infiltrate first into the pavement and then into a gravel bed below [4]. The open graded gravel bed provides up to 40% voids, or in other words, 40% of the volume of the gravel fill can be used as stormwater storage. Water is stored in the gravel bed until it can infiltrate into the site’s subgrade, eventually rejoining the natural water table or drain out slowly through an underdrain, if one is installed. A typical cross section of porous asphalt is shown in Figure 1.

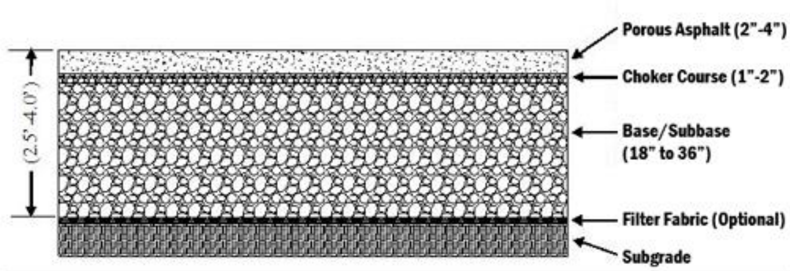

Figure 1: Typical Porous Asphalt Cross Section [4].

Water that infiltrates and is captured by the gravel sub-base infiltrates at the location where it fell, helping to reduce peak stormwater flows to municipal treatment facilities as well as reducing volumes that must be treated or stored until treatment capacity is available. Allowing rainfall to infiltrate as close as possible to the location that it falls helps reduce the potential for the water to be contaminated by pollutants along its route to the nearest stormwater practice and also reduces the potential of erosion of natural soils by the falling water. The infiltration process by which the water passes through the asphalt to the subgrade also helps to remove pollutants and suspended solids from the stormwater before it reaches the ground water table. The Environmental Protection Agency (EPA) observes that "the runoff volume and rate control, plus pollutant reductions, allow municipalities to improve the quality of stormwater discharges." [4] That being said, permeable paving can also be used effectively in residential development applications, as well as on municipal development projects [4].

Previous studies have shown that permeable pavement systems "have outperformed their conventionally paved counterparts in terms of both parking-lot durability and stormwater management." [5] This project compared permeable asphalt paving to traditional asphalt paving in an attempt to determine which is the most economically feasible by using direct and indirect costs of the pavements, costs of maintenance and upkeep, and the costs of downstream effects of each type of pavement as well as looking at other, less tangible factors such as the overall environmental impacts and life spans of each pavement to evaluate which is the better solution.

Background

The larger area of interest that motivated this investigation is, simply stated, the use of permeable pavement systems in stormwater management. Why is this important? In an ecosystem that has not been impacted by human development, the majority of the water that falls to the earth as rain is absorbed by the ground where it falls. Runoff from an undeveloped site is minimal compared to the amount of runoff from the same site post-construction. Urbanization creates impervious surfaces through which rainfall cannot infiltrate. For typical urban development, it is estimated that up to 75% of all surface area is comprised of impervious surfaces [6]. In highly impervious locations such as strip malls and large shopping centers, the impervious surface cover can be as high as 95% of the total area [6]. Thus, in urban areas, water does not have as much surface area to infiltrate into the ground as it would in nature. This leads to increased runoff from developed areas.

To put it in perspective, “1 inch of rain falling on an average home’s 1,500 square feet produces approximately 900 gallons of runoff.” [7] If one inch of rain falling on one typical residential home can produce 900 gallons of runoff, it becomes a bit overwhelming to imagine the amount of water that would run off of a typical city block. It becomes mind boggling to consider that the total amount of pavement in the US is almost 38,000 square miles or an area the size of the state of Indiana [6]. This information helps to describe the magnitude of the volume of water that can be created by rainfall, which becomes runoff, which in turn must be collected and conveyed by municipal stormwater systems. But water running downhill doesn’t seem like it should be that big of a problem. After all, it’s not like all 900 gallons of the water that fell on a

1,500 square foot home are all being poured downhill at one time. So why is stormwater management such an issue? In addition to flooding and sewer overflows that can accompany heavy rains, when water travels, it rarely travels alone. All that runoff flowing over generally impervious ground picks up particulate matter and chemical pollution on its journey downhill.

As rainwater flows over parking lots and paved areas, it collects dirt and debris, entrapping them and carrying them along as it flows. Imagine a rain gutter in the fall. The gutter is full of leaves. This is because water picks up anything small enough to be swept away in its path. The most significant direct result of this tendency is soil erosion. Free flowing runoff will collect top soil and carry it away from its original location. This strips the soil of its minerals and causes problems for farmers and other individuals who use soil as a growing medium, and it also creates a problem downstream. The rate at which water is flowing has a large impact on the size of particle it can carry. Particles suspended in the flow will drop out of the stream if the velocity of the water becomes low enough. A good example of this scenario on a large scale is the sediment that builds up behind a dam. A swiftly flowing river can carry a large amount of rocks and sediment along with it, but when the water reaches an impoundment, its velocity is significantly reduced and much of the suspended particulate drops out of the flow and builds up behind the dam. Similarly, the Mississippi River leaves a large pile of sediment at its mouth as it enters the Gulf of Mexico. The flow of the river slows significantly as it enters the ocean, causing much of the suspended solid load it is carrying to drop out. Soil erosion is a significant environmental problem in itself, but dirt isn't the only particulate matter relocated by stormwater flow. Chemical contaminants are also collected by the runoff and carried along to its final destination.

Since dirt, leaves, oil drippings, etc. accumulate on parking lots, it is also easy to imagine that the water that runs off of these lots into the local stormwater system isn't very clean. Grease, oil, gasoline and it byproducts, diesel and its related byproducts are all commonly found on the surface of parking lots. When rain falls onto this impermeable area and runs off, everything that it collects is taken with it. Particulate matter, along with many other chemicals, can dissolve into the water stream, causing problems for the environment if this water is not treated before it rejoins a natural river or stream. How significant is the effect of polluted runoff to the environment? Cohen reports that stormwater runoff is known to be responsible for 83% of non-point source pollution [8]. This pollution "most often occurs when oil and other residues from cars run off parking lots into nearby watersheds." [8] Not only can permeable pavement reduce runoff, but in doing so, it can significantly reduce other environmental issues associated with runoff, such as erosion and pollution of local watersheds. Basically, permeable pavement can act as a decentralized stormwater treatment facility.

Studies report that, "unlike traditional asphalt, porous pavement acts like a sponge, soaking up water into an infiltrating sub surface of increasingly finer particles" [8]. This action allows permeable pavement to treat the rainwater where it falls, avoiding the additional costs and energy that will be required downstream if this water must be intercepted by a more traditional 'grey' stormwater management system. A grey stormwater management system is one that is primarily made of concrete like a traditional gutter and stormsewer system. In contrast, permeable pavement is a 'green' infrastructure practice that creates “a network of decentralized stormwater management practices” [9] that can treat stormwater in a more sustainable way.

Project Background

The primary focus of this study is the Ward Street Parking Lot, an approximately 1,000 square foot permeable asphalt parking lot installed by the City of Milwaukee in 2007 [10]. The permeable pavement was originally installed with the aid of an EPA grant to study the potential for permeable installations to reduce the loading on the Milwaukee Metropolitan Sewerage District (MMSD) combined sewer system during large flow events [10]. During the initial study, no event during the monitoring period produced a rainfall volume large enough to create runoff from the installation. That is, all of the water that fell at the site was able to infiltrate into the subgrade [10]. The study also showed that levels of monitored contaminants as well as total suspended solids (TSS) and biological oxygen demand (BOD) were well under the permitted limits for infiltration into the groundwater table [10]. “This pavement technology is approved by the U.S. Environmental Protection Agency as a best management practice, and has been proven to reduce the rate of runoff and levels of associated pollutants in addition to increasing the ground water recharge rate.” [11]

These results proved conclusively that permeable asphalt paving could be a very effective solution for minimizing stormwater volumes in the combined sewer system. The next step was to see how long the installation would remain functional. The impact of these studies and others like it are far reaching and important, especially to developers and municipalities looking for sustainable ways to manage the stormwater runoff from their sites.

Permeable asphalt can help reduce peak runoff rates and volumes from large storm events, which brings an energy and cost savings to the municipality by reducing the amount of stormwater that must be treated or discharged directly into downstream water bodies, but this is far from the only benefit it can provide. Permeable pavement has many additional benefits that can be seen both by the municipality in the amount and quality of stormwater runoff as well as benefits for the individual parking lot owners and operators.

Permeable pavement can also help protect water quality as well as reduce runoff quantities. Permeable pavement can result in significant pollutant reduction such as an "80 percent total suspended solids reduction" [4]. One of the contaminants that permeable pavements do not reduce are the chlorides that come from the application of road salts, but permeable pavements also require less applied deicers [4]. Gunderson reports that "research findings showed that salt application for porous asphalt could be reduced by 75%, based on snow and ice cover." [12] Since "deicing treatments are a significant expense and chlorides in stormwater runoff have substantial environmental impacts" [4], the reduction of the need for these products has a benefit both for the owner and operator of a parking lot and for the municipality that will receive the runoff from the lot.

Porous pavement also has added environmental impacts at the soil level. According to Baume, “it decreases impervious land coverage, provides a more stable load-bearing surface, and allows the water to go into the ground.” [13]

It also has the benefit of decreasing or eliminating the need for other on site storage practices, such as detention ponds, which take up a significant amount of site square footage and therefore decrease potential revenue from the parking lot, as there is less usable area in the project site [13].

Lastly, pervious pavements provide benefits to the people who will be using them. Such driver benefits “include decreased hydroplaning and glare,” as well as “increased visibility and traction.” [11] Since the surface of a pervious asphalt is rougher, the friction coefficient is greater. This is what contributes to the need for less deicers, but it also benefits drivers by providing traction and the more uneven surface helps to cut down on the potential of glare from ponded water limiting visibility. Basically, permeable pavements also create a safer driving environment than their traditional counterparts.

The Wisconsin Department of Natural Resources (WDNR) now allows developers to use permeable pavement as a stormwater practice as required to meet their construction permit requirements to limit site runoff and to “mitigate any negative impacts that a project will have on streams and wetlands.” [14] The WDNR has stated that “research has shown that permeable pavement is able to reduce the quantity of pollutants, such as sediments and phosphorus, from stormwater that passes through the pavement system.” [14] This, along with the fact that permeable paving “also recharges more water into the ground, aquifers and streams” [14], has created a strong case for adding it to the regular tool box of stormwater management practices commonly employed by developers and municipalities.

At the local level, MMSD has “proposed an ultimate goal of eliminating all sewer overflows by the year 2035” [15], and has stated that “green infrastructure will be a critical component of meeting this goal” [15]. Permeable asphalt pavement is a simple way to increase the amount of green infrastructure in a community, as it helps reduce impervious area in parking lots and sideways, which create some of the interconnected impervious areas in an urban development and therefore lead to the most runoff [16].

Pervious asphalt pavement can “promote stormwater *infiltration*, groundwater recharge, and stream baseflow preservation” as well as “reduce the discharge of stormwater pollutants to surface waters, reduce stormwater discharge volumes and rates, and reduce the temperature of stormwater discharges.” [17] This makes it an excellent solution to the problems that can be caused by excessive stormwater runoff in urban areas, especially those similar to the system in downtown Milwaukee, where sanitary waste and stormwater flow in the same ‘combined’ sewer system.

In the greater Milwaukee area, “The Milwaukee Metropolitan Sewerage District (MMSD) is a regional government agency that provides water reclamation and flood management services for about 1.1 million customers in 28 communities.” [15] In an attempt to limit overflows and releases of untreated sewage into the Lake Michigan watershed, “MMSD invested $3 billion in grey infrastructure over three decades through the mid-1990s. From the late 1990s to 2010, the MMSD spent an additional $900 million in grey infrastructure” [15]. This was necessary because though the MMSD has developed “one of the most advanced” municipal wastewater management systems “in the world” [3] and has “excess dry weather capacity” [3], there are still events that occur that create “huge amounts of precipitation or snow melt” that “can overwhelm the system.” [3] These events typically occur several times a year and during such events “combined and/or sanitary sewer overflows occasionally are then necessary to protect public health, protect against property damage and protect the system itself” [3]. Despite the necessity of these untreated releases, “MMSD and the communities it serves seek to avoid this whenever possible.” [3]

One critical part of MMSD’s grey infrastructure system is a colossal underground storage system known as the “Deep Tunnel” or Inline Storage System (ISS). “The Deep Tunnel is 300 feet underground and has a total capacity of 521 million gallons. Under extreme storm events, the Deep Tunnel temporarily stores wastewater until the water reclamation facilities have available treatment capacity.” [3] Before the Deep Tunnel and other improvements came online in the early 1990s, “the MMSD sewer system had between 50 and 60 overflows per year, with an annual average volume of 8 billion to 9 billion gallons of overflow” [15]. After the completion of the Deep Tunnel that number is down to only “about two overflows per year, with an annual average of one billion gallons of overflow.” [15] The Deep Tunnel project “has prevented more than 80 billion gallons of wastewater from polluting Lake Michigan.” [3]

Though the Deep Tunnel is clearly a very important piece of MMSD’s grey infrastructure, it has not been sufficient to prevent all occurrences of combined sewer overflow in the system. After MMSD spent approximately 2 billion dollars on its creation, the Deep Tunnel is still not large enough to provide storage capacity during the largest rainfall events of the year. The largest problems arise when one large rain event follows another large event very closely and the tunnel cannot be emptied before the next wave hits. Because of the extremely high cost of constructing this large volume storage and the lack of resources to continue adding capacity to the system in this way, MMSD has turned to green infrastructure as a less conventional solution to minimizing stormwater runoff volumes. Especially in combined sewer areas, MMSD believes that green infrastructure could help capture water "that might have otherwise contributed to a combined sewer overflow." [3] They go on to state that "reducing the amount of water needing to be treated *(and the resultant energy cost savings)* is a benefit to everyone." [3]

MMSD describes their method for evaluating the benefits of green infrastructure as a "Triple Bottom Line" analysis. "Potential benefits are measured based on environmental outcomes (e.g., overflow, peak stream flow, and pollutant loading reductions) as well as economic (e.g., new jobs created, property values) and social (e.g., quality of life, aesthetics) outcomes." [15] This holistic approach provides a good measuring tool for evaluating the effectiveness of a permeable pavement application, as it looks not only at straight cost, but also less tangible associated benefits that weigh into the value of an installation, but may not be accounted for in a more traditional methodology.

Technical Data

Stormwater Infrastructure

The first topic that should be discussed in detail when getting into the technical aspects of this report is not actually related to permeable pavement directly. It is important to take a step back to put the practice into perspective by examining the existing stormwater infrastructure in the surrounding community and by analyzing the potential impacts of stormwater runoff that permeable pavement can help to address.

Within their jurisdiction, MMSD has two types of sewer systems that are used to convey wastewater from buildings in the MMSD service area to the Jones Island and South Shore treatment plants [3]. The first type, a separated sewer system, conveys about 95 percent of the municipal wastewater separately from stormwater. The separated sewer system carries wastewater to either the Jones Island or the South Shore facility for treatment [3] and discharges stormwater directly to local creeks and rivers. “In the older, more densely developed part of the service area (about five percent), sewers convey wastewater combined with stormwater. Combined sewers eventually convey wastewater to the Jones Island Water Reclamation Facility.” [3] Figure 2 illustrates the difference between these two types of sewer systems.

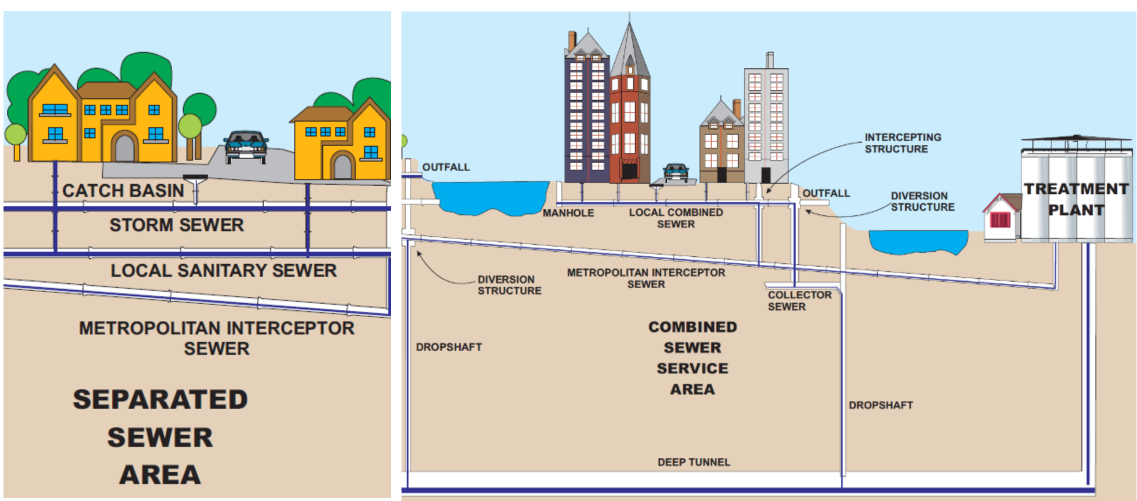

Figure 2: Types of Municipal Sewer Systems [3].

The water reclamation facilities at Jones Island and South Shore can treat up to 600 million gallons of water per day. This means that in dry weather conditions, the system has excess capacity, but during severe wet weather events, the plants can be overwhelmed by the increased flow caused by stormwater [3]. The problems created by runoff vary slightly depending on the type of municipal sewer system that is receiving the water. In a separated sewer system, rainwater can infiltrate into the sanitary sewer system, increasing the amount of flow that must be conveyed and treated. “In the Milwaukee region municipal sanitary sewer systems carry between two and 40 times the amount of water when it rains.” [3]

Therefore the benefit of keeping rainwater out of sanitary sewers is that it can “help to minimize treatment costs at the water reclamation facilities.” [3] Green infrastructure can aid in this goal by helping to store stormwater and thereby “keeping it from leaking into sanitary sewer pipes.” [3] The added benefit of this storage is that water conveyed in separate stormwater systems is discharged directly into receiving waters. “When rainwater flows by gravity across rooftops, lawns, parking lots and roads, it picks up pollutants deposited from the air, fertilizers and pesticides, petroleum products and metals from cars, and any host of particles” [3], all of which are deposited directly into the Milwaukee river or Lake Michigan. Green infrastructure can remove “significant amounts of pollution” including up to 50 percent removal of nitrogen, phosphorus, copper, lead, zinc, ammonium and calcium, according to MMSD documentation and the EPA [3]. In combined sewer areas, the benefit of green infrastructure is that the storage it provides “could help capture enough rainwater that might have otherwise contributed to a combined sewer overflow” [3], a direct benefit to receiving waters.

As previously discussed, MMSD’s Deep Tunnel project, a civil engineering feat and an example of traditional ‘grey’ stormwater infrastructure, was able to reduce combined sewer overflows and “has prevented more than 80 billion gallons of wastewater from polluting Lake Michigan.” [3] While this is a significant accomplishment, MMSD wishes to improve even further, with a goal of reducing combined sewer overflows from approximately two overflows and an annual average of about one billion gallons of flow to zero by the year 2035 [15]. In order to do this, MMSD will rely on green infrastructure, including porous pavement. According to their 2020 facilities plan, MMSD plans to implement porous pavement to create ‘green alleys’ that will be able to treat runoff from an area that is about four times that of the alley [15]. Portions of local streets would also be converted to porous pavements as well as certain parking lots identified using 2000 MMSD imagery [15]. This added permeable area, along with a number of other green infrastructure measures that are to be implemented -- such as bioretention swales, rain gardens, green roofs and stormwater trees -- will help meet the zero overflow goal.

Permeable Pavement Overview

Permeable asphalt pavement is a green infrastructure technology that “reduces impervious areas, recharges groundwater, improves water quality, eliminates the need for detention basins, and provides a useful purpose besides stormwater management.” [5] The pavement is relatively simply derived, a “standard hot-mix asphalt with reduced sand or fines and allows water to drain through it.” [4] “The reduced fines leave stable air pockets in the asphalt. The interconnected void space allows stormwater to flow through the asphalt and enter a crushed stone aggregate bedding layer.” [4] The bedding layer consists of a “uniformly graded and clean-washed aggregate with a void space of 40%.

Stormwater drains through the asphalt, is held in the stone bed, and infiltrates slowly into the underlying soil mantle." [5] This method of green infrastructure "will reduce stormwater runoff volume, rate, and pollutants." [4] On top of its other benefits, the manufacturers and retailers of permeable asphalt pavement boast that, "when properly constructed, porous asphalt is a durable and cost competitive alternative to conventional asphalt." [4]

The WDNR provides guidance for permeable pavement systems in order to ensure that they are used properly, safely and effectively. They recommend that "permeable pavement systems are most effective in areas where subsoil and groundwater conditions are suitable for stormwater infiltration, and the risk for groundwater contamination is minimized." [17] In order to protect ground water from contamination, the WDNR standard for permeable pavement installation dictates that "permeable pavement may not be used in industrial storage and loading areas or vehicle fueling and maintenance areas." [17]

It is also recommended that measures be "taken to protect permeable pavement from high sediment loads, particularly fine sediment" [4] in order to protect the pavement and prevent clogging. The WDNR states "permeable pavement surfaces are highly susceptible to clogging from source area runoff containing significant sediment or particulate loads." [17] Because of this, they suggest "limiting runon to source areas such as other pavements, sidewalks or roofs" [17] so that dirt and fine particles are not carried into the pavement and allowed to clog its pores. Figure 3 illustrates the WDNR suggested cross section of a permeable pavement installation in order to receive pretreatment credits.

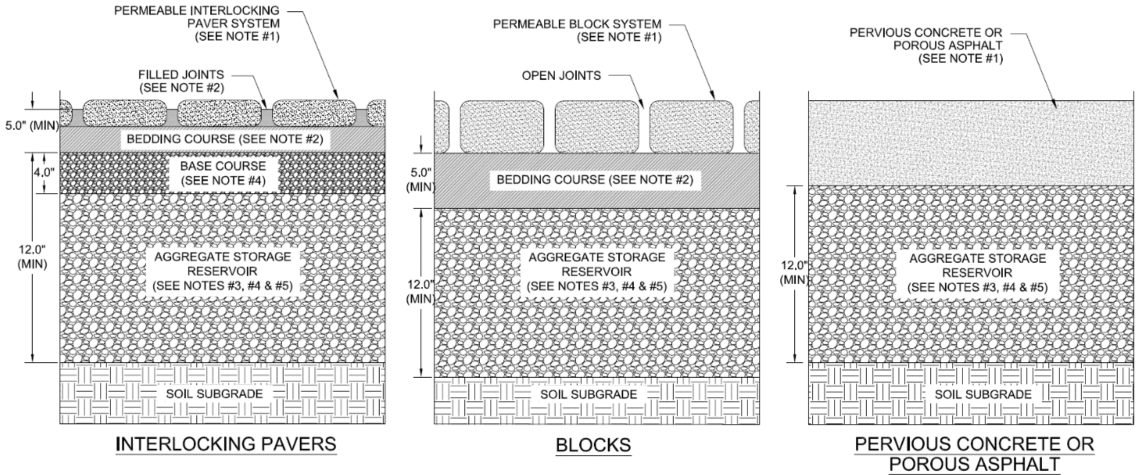

Figure 3: Criteria for Underdrain Discharge and Infiltration Pretreatment Credits [17].

Figure 4 shows the effective infiltration area of a permeable paving system in cross section and plan views. It also demonstrates that the aggregate storage layer can serve more pervious area than just the pavement surface.

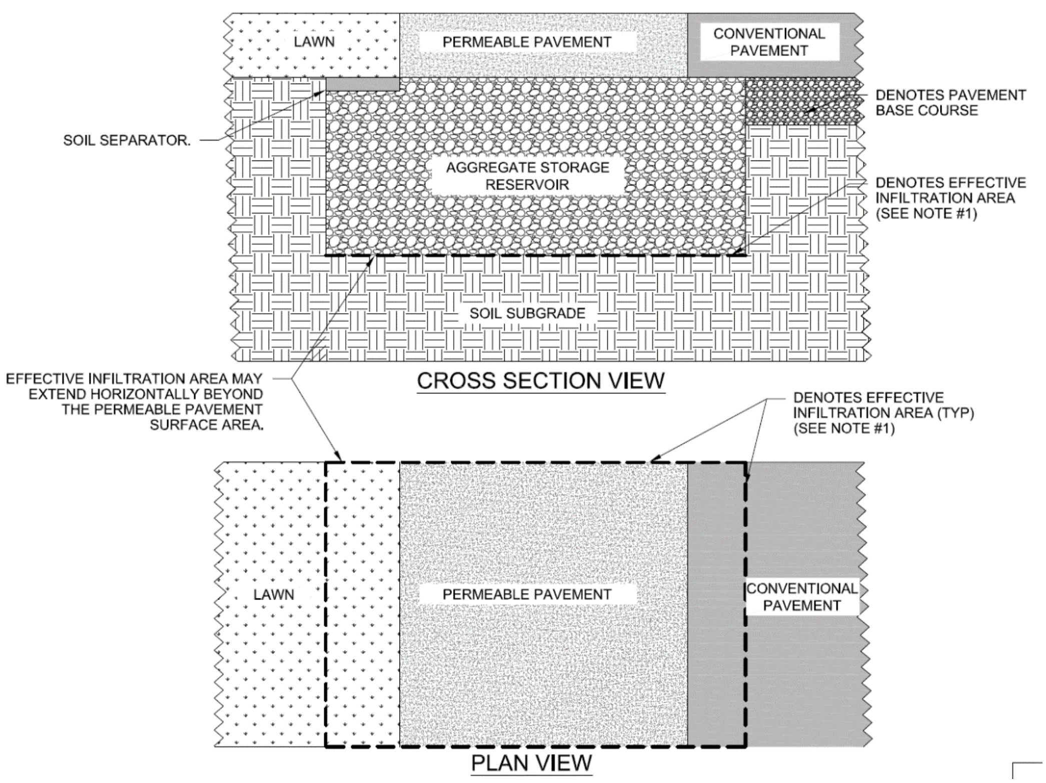

Figure 4: Effective Infiltration Area of a Permeable Installation [17].

Permeable asphalt is prepared and placed without the fines found in conventional asphalt paving. The lack of fines allows for the interconnected voids that promote infiltration through the pavement. The downside of this is that asphalt without fines has a lower shear strength than traditional asphalt pavement [11]. Because of this, it is recommended that the use of permeable asphalt pavement “should be limited to highways with low traffic volumes, axle loads, and speeds (less than 30 mph); car parking areas; and other lightly trafficked or non-trafficked areas.” [11] Parking lots and sidewalks are very good applications for permeable asphalt, as are highway shoulders or parking lanes, but driving lanes should be constructed of conventional materials to avoid excessive wear and deterioration of the asphalt surface.

The WDNR specifies surface infiltration rates for permeable pavement in order to meet the infiltration requirement for post-construction permitting. They specify that “the surface infiltration rate upon completion of the installation shall be at least 100 in/hr” [17] and that “the in-service surface infiltration rate shall be no lower than 10 in/hr.” [17] They consider any permeable surface with an infiltration rate of less than 10 in/hr to be failed [17].

Operations and Maintenance

Permeable pavements have more rigorous maintenance standards than typical asphalt pavements. The EPA notes that “the most prevalent maintenance concern is the potential clogging of the porous asphalt pores. Fine particles that can clog the pores are deposited on the surface from vehicles, the atmosphere, and runoff from adjacent land surfaces.” [4] In most cases, “the long-term infiltration capacity remains high even with clogging” though “clogging does increase with age and use.” [4] Clogs can be removed and “permeability can be increased with vacuum sweeping” [4], which is the primary maintenance difference between permeable asphalt pavement and traditional asphalt.

Maintenance suggested by MMSD for pervious pavement includes checking for potential obstructions and damage that may have been done to the surface of the pavement, vacuum sweeping to prevent clogging and maintaining surrounding vegetation to prevent dirt and small particulate from infiltrating and clogging the previous surface [18]. The DNR also recommends that maintenance staff “clean the pavement surface using industry recommended methods, such as regenerative air or vacuum sweeping, at least twice per year.” [17] The vacuuming is done “to remove and dispose of sediment in the gravel media.” [19] This maintenance “requires heavier equipment” [18] and the “more intensive maintenance may require technical training” [19] that traditional pavements do not. Additional maintenance requirements of permeable pavements “should include checking infiltration rates” [19], sweeping debris from around the pavement area, and collecting trash and other refuse that may have accumulated around the site to prevent future clogging.

The WDNR also suggests “minimizing the use of road salt (sodium chloride) on permeable pavement and run-on surfaces to reduce … conditions that could reduce subgrade soil infiltration rates.” [17] This is possible due in part to the fact that “research findings showed that salt application for porous asphalt could be reduced by 75%, based on snow and ice cover.” [12] It has been showed that “with only 25% of the salt, the snow and ice cover on the porous asphalt was the same as on the dense-mix asphalt parking lot, and even with no salt, porous asphalt has higher frictional resistance than dense-mix asphalt with 100% of the normal salt application. Therefore, a sizable reduction in salt application rate is possible for porous asphalt without compromising braking distance or increasing the chance of slipping and falling." [12] So less salt and winter maintenance are needed than would be required with a traditional asphalt parking lot. This reduced winter maintenance could in part help to offset the additional maintenance costs of sweeping and caring for the increased needs of the permeable asphalt.

Usable Life of an Installation

Permeable pavement has been argued to have a reduced lifespan in northern climates, but recent research shows that may not be the case. The EPA states that "the lifespan of a northern parking lot is typically 15 years for conventional pavements; porous asphalt parking lots can have a lifespan of more than 30 years." [4] This is "because of the reduced freeze/thaw stress" [4], on a permeable asphalt pavement, which freezes in stages because of its porous, non-rigid nature as opposed to a traditional asphalt pavement which freezes as a single solid unit [12].

A 600-space parking installation in Pennsylvania has continued to function well after 20 years of service and has not needed to be resurfaced or repaved, which a traditional system would have required at this life stage [5]. Even more impressively, even though the area where the parking lot is installed is naturally very prone to sinkholes, "far fewer sinkholes have occurred in the porous asphalt areas than in the conventional asphalt areas, which the site manager attributes to the broad and even distribution of stormwater over the large areas under the porous pavement parking bays." [6]

Testing should be done throughout the life of an installation to monitor its operation, as mentioned above, but for the most part, it seems that with proper care and maintenance, these applications can stand the test of time and continue to perform in some cases even longer than their traditional asphalt counterparts.

Literature Review

Permeable pavements and other types of green infrastructure have many inherent environmental benefits. Permeable pavements and their benefits are well documented. Despite this, permeable pavement is not commonly used throughout much of the United States and Canada [20]. In many respects, it seems that there is simply a lack of mainstream attention concerning this topic [20]. Basically, all of the data exist to prove that permeable pavements are useful, but these existing data need to be more widely publicized. Similarly, more awareness is necessary concerning the consequences of urban runoff and the negative effects of not using green practices to better manage stormwater.

There has historically been a lack of guidance from professional societies and local authorities having jurisdiction on how to properly install and to maintain permeable paving systems [20]. Recently, however, with the rise of the popularity of sustainable design bringing green infrastructure to the forefront of the design world, many municipalities have been generating guidance and literature to help inform the public about the benefits of permeable pavements and to encourage their use. The EPA now considers permeable concrete and permeable asphalt to be best management practices in dealing with stormwater, and have published very useful standards and guidance on the topic [4]. The Wisconsin Department of Natural Resources (WDNR) has also published permeable pavement practice standards [14, 17] and now considers permeable pavement a method of gaining compliance with state required infiltration standards [14].

In addition to state and national level attention, permeable pavement and green infrastructure are being promoted, perhaps most successfully, by local municipalities.

The Milwaukee Metropolitan Sewerage District (MMSD) has published a large amount of literature on green infrastructure and on how they plan to utilize green infrastructure to help manage stormwater locally [19]. MMSD has long been at the forefront of water treatment technology and they plan to stay ahead of the curve by promoting green development [15]. In order to operate in the most economically efficient manner, as well as taking an active role in caring for the environment and promoting social and economic growth in the Milwaukee Metropolitan area, MMSD is seeking to meet their future infrastructure improvement goals mostly by implementing more infiltration practices. Such practices will limit stormwater runoff both in peak flow and in total flow volume and will help take pressure off the existing municipal sewer system as well as limiting the impacts of future expansion on the existing system [15]. All of these examples help to illustrate that the most environmentally responsible practices are also becoming known for being the more cost effective methods.

This review is meant to build a knowledge base of facts about the topic of permeable pavements as well as to aid in the analysis of the existing information about permeable asphalt and draw conclusions based on the combined knowledge of these works. If necessary, areas where further study may be necessary will be addressed after a review of the current knowledge base is complete. Because the topic of permeable pavement is quite broad, it was determined that it would be most useful to focus on a few key topics in the existing body of work that specifically pertain to this research project. These main themes should help to paint a clear picture of the existing knowledge of permeable pavement and help to identify a direction in which the development of study of the topic should progress in the future.

As they relate to this study, several themes stand out in the available literature as being particularly applicable to the project. First, the literature provides insight into the environmental impacts of permeable pavement. Potential environmental impacts of permeable pavement include stormwater management benefits such as reduced peak flow and flow volume, pollution control benefits such as solids removals, and additional benefits of promoted infiltration such as positive impacts on native soils. The second major theme in the literature is the performance of permeable pavement surfaces over time. These key research points focus on aspects of permeable pavement that relate directly to the Ward Street research project, and were useful in providing an outline of what to expect when conducting the project experiment described in this report.

Most of the paving in an urban area is done to create roads, sidewalks and parking lots, "which play a major role in transporting increased stormwater runoff and contaminant loads to receiving waters." [16] As a solution, alternative paving materials such as permeable asphalt "can be used to locally infiltrate rainwater and reduce the runoff leaving a site." [16] Green stormwater practices that create pervious paved surfaces to allow for the infiltration of stormwater can "decrease downstream flooding, the frequency of combined sewer overflow events, and the thermal pollution of sensitive waters." [16] "Asphalt porous pavements, first developed in the 1970s at the Franklin Institute in Philadelphia" [11], are one such solution. Permeable pavements can also "eliminate problems with standing water, provide for groundwater recharge, control erosion of streambeds and riverbanks, facilitate pollutant removal, and provide for a more aesthetically pleasing site." [16] Alternative paving systems can even "eliminate the requirement for underground sewer pipes and conventional stormwater retention /

detention systems.” [16] All of these environmental benefits help make the case for using permeable pavements instead of conventional paving systems.

The basic definition of a permeable pavement is “a pavement system designed to achieve water quality and quantity benefits by allowing movement of stormwater through the pavement surface and into a base/subbase reservoir.” [17] The open graded gravel bed under the asphalt allows water that has infiltrated into the pavement to be stored in the voids of the gravel until it can infiltrate into the native soil beneath [4]. This storage capacity gives permeable asphalt the ability to naturally manage stormwater and to prevent excessive runoff from urban areas.

The environmental impact of this measure is that permeable paving can reduce peak flows and runoff volumes, drastically lowering the impact of rainfall on municipal sewer systems and receiving waters [3]. The effect of this in the Milwaukee area is that permeable pavements can be used in combined sewer areas in order to reduce the frequency of combined sewer overflows or prevent them entirely [3]. In separated sewer systems, permeable pavements can limit the amount of flow that finds its way into the sanitary system, limiting the multiplicative effect that storm events can have on sanitary base flow [3]. Permeable pavement also lowers the volume of flow entering surface water bodies, limiting the potential for flooding. In all cases, by limiting the amount of flow that must be handled downstream, the pavement takes pressure off the municipal system, saving energy and money that would have otherwise had to be invested into treating the increased amount of flow [3].

As well as letting water infiltrate into the native soils, permeable pavements promote evaporation, another natural part of the water cycle which can contribute to reduced flow in downstream sanitary, stormwater or combined systems. Evaporation from the storage layer and soil under a permeable pavement is greatly affected by the color of the surface layer, and somewhat affected by the type of base that is underneath [21]. By leveraging the properties of the permeable paving system, an ideal paving system that fosters the highest amount of infiltration ability and evaporative characteristics can be created.

Permeable asphalt pavement captures stormwater and retains it in inside of its storage layer, allowing water to slowly infiltrate into the substrate and ground beneath, or to evaporate out of the surface layer. The ability of the pavement to absorb and retain a large amount of rainwater reduces the runoff peak in a rainfall events. The fact that water is allowed to infiltrate or evaporate means that the total volume of runoff for the storm event can also be significantly reduced. In fact, most studies show that there is virtually no runoff whatsoever from a functional permeable pavement [22]. This result is that water that would normally run off of urban paved areas into municipal sewers instead infiltrates and evaporates similar to natural processes prior to paving.

Permeable pavement can be used instead of a traditional retention basin, which would otherwise be necessary to reduce peak flows, effectively saving all of the surface area these practices would use to be more productively utilized by the development. “The effective imperviousness of any given project is reduced while land use is maximized.” [16] Permeable pavements basically allow land to be used for two purposes at the same time: it can be used both as a paving system and as a stormwater management system [23]. This is illustrated in Figure 5.

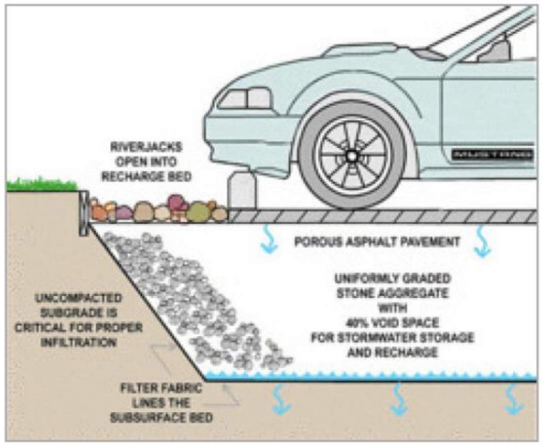

Figure 5 – Permeable Asphalt Parking Lot [6].

The hydraulic properties of permeable pavements have been studied quite thoroughly with respect to how they can be most effectively used to assist in the creation of low impact designs [24]. “The drainage of paved areas and traffic surfaces by means of permeable systems is an important building block within an overall Low Impact Development scheme that seeks to achieve a stormwater management system close to natural conditions.” [16]

According to Drake, Bradford and Van Seters, during significant rainfall events, permeable pavement systems can reduce “overall stormwater outflow by 43% and completely captured most rainfall events.” [25] Permeable pavement can “reduce the volume, peak flow and frequency of storm flows” [25], especially in cold climates with low permeability soils [25]. If their finding hold true in Milwaukee, the City of Milwaukee could benefit greatly from the utilization of permeable pavement systems, as Wisconsin is located in a cold climate with soils that are high in clay, which therefore have relatively low permeability. These factors mean that the natural soil of the region allows for more stormwater runoff than places that are less subject to subfreezing temperatures and that have soils that feature better infiltration characteristics. As a result, even in places where impervious surfaces do not cover native soils, there is still a large amount of water that runs off these surfaces. Thus, capturing and dispersing as much rainwater as possible becomes even more important.

The infiltration of water through the surface of a permeable pavement has many benefits. It clearly has positive effects on water quantity, reducing the amount of runoff by capturing rainwater where it falls and storing it until it can infiltrate into the local soil. In addition, infiltration can also reduce pollution in runoff by removing and trapping it [26]. When water runs off of impervious surfaces such as buildings and parking lots, it picks up loose particles and chemical contaminants from these surfaces. The more ground that the runoff must cover before reaching a storm sewer, the more contaminants it can collect. The lack of permeable ground area in urban areas leads to increased erosion of native soils as well as to pollutants being carried in runoff, and stormwater overflow into sewage systems [27].

The lack of pervious area to retain rainfall can create many issues relating to the transfer of pollutants in the stormwater. This problem can easily be solved, however, by simply introducing more area for infiltration [27]. Adding permeable parking lots is a relatively simple way to achieve this goal. Infiltration into the permeable pavement reduces runoff, and the water is filtered as it travels through the courses of asphalt. This filtration traps contaminants and removes them from the stormwater. Permeable pavements can act as a pretreatment system, filtering sediment and contaminants out of the flow and lessening the pollutant loadings downstream that will enter a receiving water or be treated at a municipal waste water treatment facility [28].

According to the EPA, “permeable pavement reduces pollutant concentrations through several processes.” [4] First “the aggregate filters the stormwater and slows it sufficiently to allow sedimentation to occur.” [4] This means that large particles will drop out of suspension and be left behind in the pavement while the water moves downward. The capture of these particles is one of the reasons that pavements must be maintained by vacuuming, to remove particles that become entrapped in the lots surface. Next, the subgrade soils play a role in treating the runoff. The type of soil can have a large impact on its treatment capacity. The EPA states that “Sandy soils will infiltrate more stormwater but have less treatment capability. Clay soils have a high cation exchange capacity and will capture more pollutants but will infiltrate less.” [4]

In addition to solids removal, the voids in the permeable surfaces as well as the aggregate base of the permeable pavement can create an environment that can foster the growth of bacteria that help to process and treat runoff that passes through these surfaces, The EPA states that their studies have shown “beneficial treatment bacteria in the soils,” as well as the fact that “beneficial bacteria growth has been found on established aggregate bases.” [4] They go on to note that “in addition, permeable pavement can process oil drippings from vehicles” [4], thus lowering the concentrations of gasoline and diesel range organics in the runoff.

Permeable pavements can remove a fairly large range of particle and chemical contaminants. Drake, Bradford, and Van Seters state in the *Journal of Environmental*

Management that “permeable pavement systems provide excellent stormwater treatment for petroleum hydrocarbons, total suspended solids, metals (copper, iron, manganese and zinc) and nutrients (total-nitrogen and total phosphorus) by reducing event mean concentrations (EMC) as well as total pollutant loadings.” [29] Geotextiles can be added to permeable paving systems to reduce pollutant concentration to an even greater extent [30]. There have been a number or studies that have yielded similar results. For example, Brattebo and Booth studied sampling water that had passed through a permeable asphalt pavement and found that the infiltrated water had lower levels of copper, lead, zinc and no motor oil content at all compared to 89% of the runoff from non-permeable pavements having motor oil [22]. The EPA suggests that permeable pavements can provide “water quantity and pollutant reduction characteristics such as 80 percent total suspended solids reductions.” [4] EPA studies show that in some cases, up to 99% total suspended solids (TSS) removal is possible, as well as heavy metals removal from 76-93% and the removal of other measured pollutants such as copper, zinc and nitrogen up to 79%, 83% and 72%, respectively [4].

Infiltration promoted by permeable pavements can have positive impacts on both the quantity and quality of stormwater that is infiltrated instead of being allowed to run off, but there are even more environmental benefits to implementing permeable pavement systems. Infiltrating rainwater where it falls can have positive effects on native soil and plant life conditions, as well as replenishing local water tables.

The infiltration enabled by permeable pavement can have a very favorable effect on urban plant life. When studying the belowground effects of porous pavement, Morgenroth, Bucheur, and Scharenbroch discovered that the type of paving used can alter the physical and chemical properties of the soil beneath based on how much water is allowed to infiltrate into the soil [31]. This result can affect urban plant life, especially under stressful conditions such as drought [31]. Basically, the more water that is allowed to infiltrate into the ground on to which it falls as rain, the more favorable that ground will be for plant life. The fact is that the more water that runs off of an area which is covered by an impervious surface, the less moisture the soil beneath that surface will be able to collect. As a result, exposed urban soils will be much drier than soils exposed to similar environmental conditions that are surrounded by pervious surfaces. Permeable pavements allow paved surfaces to remain pervious, allowing rainwater to reach the soil beneath and to be retained by the plant life there.

Based on the large amount of water permeable pavements are able to collect and to introduce into the soil below, it has even been suggested that these pavements could be utilized to collect rainwater and to store it for reuse [32]. This result could be achieved by incorporating some kind of catch basin underneath a permeable asphalt surface, which would collect rainwater that was captured by the pavement and store it, instead of allowing it to fully infiltrate into the ground beneath. This design would allow rainwater to be better managed in climates that have infrequent rainfall or that are subject to droughts. The MMSD notes that "in addition, permeable paving can be made lighter in color, which reduces the urban heat island effect." [15] The many environmental benefits provided by permeable pavements make a good case for installing this system instead of a more traditional asphalt paving.

Permeable asphalts also have benefits associated with the added porosity of the system. Since it lacks the fine aggregate used in traditional hot mix asphalt, the surface of a permeable asphalt is much coarser. This provides several benefits to drivers while operating a motor vehicle in the parking lot. The “benefits of porous pavement include decreased hydroplaning and glare, increased visibility and traction.” [11] There are similar advantages for bicyclists as well. Using a permeable asphalt “takes that film of water off the ground that makes it slippery.” [15] “Past installations indicate that applications across the country have been primarily in the construction of parking lots. However, this method also has been extended successfully to sidewalks, bike paths, and playground surfaces.” [11]

Permeable asphalt is not infallible, however. There are problems associated with using permeable asphalt in some conditions and locations, and permeable pavements and other green infrastructure systems cannot replace traditional grey infrastructure entirely. Traditional infrastructure is still necessary to provide an overflow path for green systems to handle excessive loading or to protect downstream areas from flooding in the event of a failure in the system.

The largest factor to consider is that most types of green infrastructure have a relatively small storage capacity. “The use of swales and permeable pavers has the most influence on runoff during small storms. For high intensity rainfalls or when soil conditions are saturated, runoff is not reduced as substantially.” [16] Permeable pavements will have the largest impact on the quantity of runoff during small storms. Figure 6 shows two scale graphs. “The first is for a rain event that produced just over 0.5 inch of rain in about 75 minutes, while the second is for an event producing almost 2.5 inches in under 2 hours and occurring less than 24 hours after four preceding days with rain.” [16]

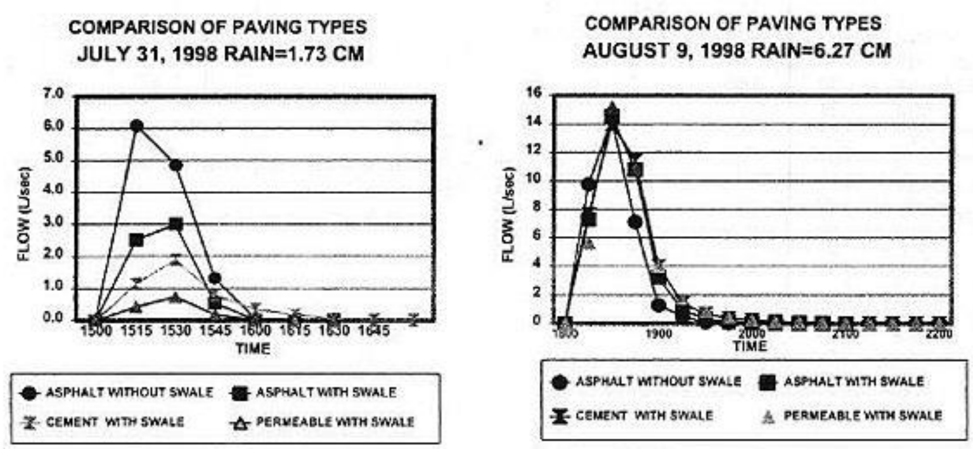

Figure 6: Effect of Storm Size and Intensity on Green Infrastructure [16].

That being said, just because permeable pavement and green infrastructure practices are most effective in small storm conditions doesn't mean they are not useful during large storms. Data collected from one site in the Northeastern part of the United States showed that even after a significant service life "during a 25-year precipitation event, there was no surface discharge from the stone beds." [5] Infiltration into native soils will still reduce runoff volume even in large events, and that reduced runoff does have energy and cost saving impacts downstream. In addition, green infrastructure practices have a multiplicative effect in terms of storage volume. One infiltration practice may not have a large amount of storage when compared to an entire system, but a city full of green infrastructure practices can see drastic results in terms of runoff reduction. Cities such as San Francisco and Chicago are taking active steps to improve their urban watershed. The MMSD notes that Chicago has a city-wide goal to "convert flood-prone asphalt into hydrologically sensitive conduits that include permeable surfaces, strategically-placed drainage pipes, and recycled pavement." [15]

MMSD has helped Milwaukee to become a leader in green development in an attempt to improve municipal systems and promote better stormwater management. The MMSD Greenseams program allows 1.4 billion gallons of rainwater to infiltrate around the city every year. Porous pavements in the service area account for an additional 2.2 million gallons of runoff that are diverted away from city sewers. Figure 7 provides a chart of various green infrastructure practices in the MMSD Service area.

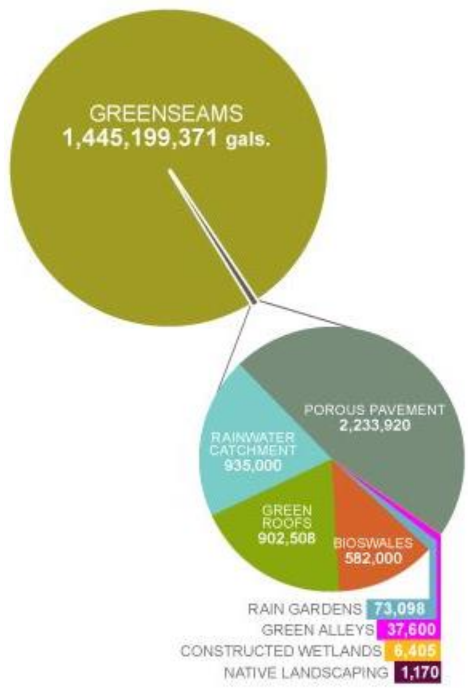

Figure 7: MMSD's Green Infrastructure by Volume [33].

Figure 8 shows the locations of various green infrastructure practices around the Milwaukee Metropolitan area.

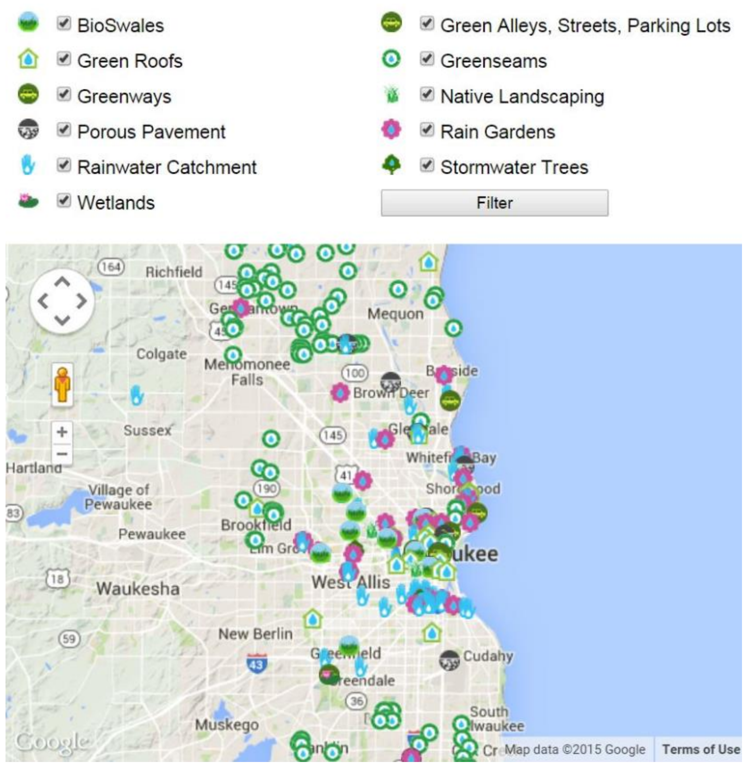

Figure 8: Green Infrastructure Practices Around Milwaukee [34].

The effect of winter conditions on permeable asphalts is another concern for many developers looking to install permeable pavements. A "widespread misconception exists in the industry about pervious pavement systems, specifically about their functionality in cold-weather environments." [12] It seems that "the prevalent belief is that pervious pavements are not an effective stormwater management option for cold-weather climates because of concerns related to diminished permeability during freezing and that the material is not durable enough to withstand freeze-thaw conditions." [12] This misconception is one that has been closely studied by the civil engineering community in order to determine the truth about the effectiveness of permeable pavements in cold environments and in locales where they are exposed to extreme freeze thaw conditions.

The findings of these studies show that permeable asphalt may in fact surpass traditional asphalt in performance in freeze thaw conditions. Gunderson states that “findings from the four year porous asphalt in New England study have demonstrated functionality that exceeds conventional practices by measures of both water quality and hydraulics.” [12] The same study showed that over a three year time period, a consistent pattern emerged in the behavior of the behavior of the asphalt binder, which was identified as the “weak link in the system” [12] as far as asphalt performance. This is because the binder “is petroleum based and becomes sticky and tacky during the hot summer months.” [12] The effect of the slight molecular loosening in the binder is most likely the cause of “swelling and reduced pore size” [12] within the asphalt in the warmer months of the year. “Then, when the winter season arrives, the cycle is reversed” [12], which leads to the conclusion that asphalt may actually be more permeable in colder months, when the lower temperatures keep the binder stable.

The most important finding of the study was that the infiltration capacity of the pavement” remained high during the winter, even when there was significant frost penetration—sometimes in excess of 12 inches.” [12] Researchers noted that “the porous asphalt does freeze; however, it generally freezes as a porous medium and not a solid block. Freezing rain and rain on snow can freeze the material at the surface, but minor salting and plowing at such times can return the surface to high infiltration.” [12]

Such studies have led the EPA to conclude that “cold weather and frost penetration do not negatively impact surface infiltration rates.” [4] They note that the drainage of water through the pores is preserved by the open void spaces in the binder and gravel sub-base, keeping infiltration rates high even in freezing conditions [4]. The only recommendation that they note is that “plowed snow piles should not be left to melt over the porous asphalt as they can receive high sediment concentrations that can clog them more quickly.” [4]

In order to preserve the high drainage and favorable characteristics of permeable pavements in cold climates, several recommendations have been made for the construction of permeable pavements in cold climates. First, the gravel sub-base selected for the parking lot should be appropriate for the applications. “The use of proper sub-bases will greatly reduce the occurrence and severity of frost heaves.” [35] Secondly, “the top of the subgrade must be below the frost line” [11] to ensure that the soil beneath the pavement system remains passable and unfrozen to allow for infiltration in subfreezing surface conditions. The depth of gravel aggregate base -- in order to ensure that there is enough depth of cover over the soil to prevent it from freezing -- is determined by the climate conditions in which the system is being installed.

There are three different classifications given to area in which freezing conditions occur for determining the appropriate sub-base depth for a permeable asphalt system. Areas “located in the higher elevations of the western United States” receive little precipitation in the winter and are classified as areas of “dry freeze and hard dry freeze.” [11] “These areas experience 15 or more freeze-thaw cycles in a year.” [11] In such areas pervious pavements should be “placed over a 4- to 8-inch thick layer of clean aggregate base.” [11] Areas in the eastern United States receive “precipitation throughout the winter accompanied by 15 or more freeze-thaw cycles” and are classified as areas of wet freeze.” [11] In these areas should also see a “4- to 8-inch thick layer of clean aggregate base” installed below permeable pavements [11]. Lastly, areas that “experience below freezing temperatures for an extended length of time causing the ground to remain continuously frozen throughout much of winter” are classified as areas of “hard wet freeze.” [11] In order for a pervious pavement to be successful in such locations, it is recommended that “an 8- to 24-inch layer of clean aggregate base” is used, as well as use of an underdrain system such as a “perforated pipe system in the base to carry water away from the pavement” [11] to prevent water from standing in the storage layer in case of freezing conditions in the subgrade that make infiltration impossible. With these precautions, it is possible to successfully install permeable asphalt in a wide range of climate areas.

Research findings have also shown “that salt application for porous asphalt could be reduced by 75%, based on snow and ice cover.” [12] “With only 25% of the salt, the snow and ice cover on the porous asphalt was the same as on the dense-mix asphalt parking lot.” [12] More impressively, “even with no salt, porous asphalt has higher frictional resistance than dense-mix asphalt with 100% of the normal salt application,” which allows for “a sizable reduction in salt application rate is possible for porous asphalt without compromising braking distance or increasing the chance of slipping and falling.” [12] So both the drainage capability and the surface characteristics of permeable asphalt improve winter performance.

The EPA notes that though permeable pavements "do not treat chlorides from road salts" and that "removal of chloride with stormwater BMPs is not effective," they still have a positive environmental impact on the level of chlorides in receiving waters, because they "require less applied deicers." [4] The result of the reduction in deicing treatment is a significant savings both in the expense of applying and then subsequently treating "chlorides in stormwater runoff" and a "substantial environmental impact" from the removal of deicers that would otherwise impact receiving waters and downstream conditions. This gives another strong environmental reason to choose to install a permeable pavement over a traditional system.

As a response to the assertion that permeable asphalt is not useful in climates with subfreezing or freeze thaw conditions, it is important to note "that porous pavements have been used successfully in Norway" as well as "parts of North America with very cold climates" [35], and have been proven effective in these locations. In addition it should be noted that "freeze/thaw cycling is a major cause of pavement breakdown, especially for parking lots in northern climates" [4], and that the use of a permeable pavement, which freezes as a porous medium instead of in a solid block, actually survives better in freeze thaw environments. The EPA observes that "the lifespan of a northern parking lot is typically 15 years for conventional pavements; porous asphalt parking lots can have a lifespan of more than 30 years because of the reduced freeze/thaw stress." [4] So increased lifespan in freezing conditions compared to traditional asphalt and reduced winter maintenance make an argument for the use of permeable pavement over traditional asphalt. Seasonal maintenance, however, makes a slightly different suggestion.

Studies have shown that the expected life of a permeable paving system will be shorter than a non-permeable alternative because of the degradation of the pavement by oxidation [36]. Oxidation is able to damage the interior of the permeable pavement because the voids in the asphalt make it possible for oxidative agents to gain access to the interior of the paving surface and to break it down from the inside. The larger the voids in the asphalt media, the more damage can potentially be done by oxidation [36]. In order to avoid damage by oxidation, a good permeable surface should have voids that are large enough to allow for the retention and infiltration of the maximum amount of rainwater, while being as small as possible to prevent excess space for the invasion of unwanted foreign materials. Clearly, it is important to acknowledge some maintenance challenges associated with a pervious pavement over a more traditional type.

According to the EPA, "the most prevalent maintenance concern is the potential clogging of the porous asphalt pores. Fine particles that can clog the pores are deposited on the surface from vehicles, the atmosphere, and runoff from adjacent land surfaces." [4] The more frequent the use of the paving, the more quickly clogging will occur [4]. The age of the application will also increase the rate at which the pores become clogged [4]. Whereas "maintenance for a traditional pavement normally consists of patching and sweeping", the "maintenance operations for porous pavements are focused on keeping voids in the surface open." [11] To this end, it is recommended that "all pervious pavements should be swept twice a year with an industrial vacuum." [11] The WDNR states that "regenerative air or vacuum sweeping" performed twice per year is the industry standard method of cleaning permeable pavements surfaces [17]. Other maintenance recommended to keep permeable pavements from clogging is regular sweeping and trash clean up as well as inspection to ensure the pavements are functioning as intended [17]. Inspection of a permeable pavement system “shall be conducted at least once per year to evaluate” the condition of the pavement, the surface infiltration rate, drainage through the aggregate base and outfall conditions to ensure that the underdrain, if applicable, is functioning as expected [17].

Another difference in the care of a porous pavement and that of a traditional asphalt pavement includes the winter maintenance requirements. As previously mentioned, permeable asphalt paving requires less salt to be applied for deicing. This salt reduction can be attributed in part to the drainage characteristics of the pavement. The EPA states that “porous asphalt has been found to work well in cold climates as the rapid drainage of the surface reduces the occurrence of freezing puddles and black ice. Melting snow and ice infiltrates directly into the pavement facilitating faster melting.” [4] Another difference to note is that “sand should not be applied” to a permeable surface “for snow or ice conditions”, as it may clog the pores of the parking surface [4]. However, “snow plowing can proceed as with other pavements and salt can be used in moderation” [4]. So for the most part maintenance is similar between porous systems and traditional systems. The main differences are that permeable systems require vacuum sweeping, which involves heavier equipment and more worker training than the maintenance done on a traditional system, and that permeable systems require less winter maintenance than traditional systems based on their infiltration and surface characteristics [19].

In pavements where proper maintenance is not performed, damage can occur to the pavement surface, which leads to clogging of the asphalt pores. Clogging can drastically reduce infiltration rates and has a cumulative effect, meaning that the more the pavement becomes clogged, the easier it will be for clogging to continue. This can lead to functional failure of the pavement. The WDNR defines failure of an infiltration practice as a "measured surface infiltration rates of less than 10 in/hr." [17] Though a pavement with less then 10 in/hr of infiltration capacity is considered failed, systems can still provide significant flow reduction even with just 1 in/hr of infiltration capacity.

If the level of infiltration is not sufficient to meet the needs of the system, remediation techniques can be used to restore functionality, such as vacuum and air sweeping. The EPA states that "in areas where extreme clogging has occurred, half inch holes can be drilled through the pavement surface every few feet or so to allow stormwater to drain to the aggregate base." [4] In case of extreme clogging or complete sealing of the pavement, "a stone apron around the pavement connected hydraulically to the aggregate base and subbase can be used as a backup." [4]

Given that even clogged permeable pavements can provide significant infiltration benefits, the question becomes at what point has a permeable application actually failed. The WDNR standards of 10 in/hr seems to be an overly conservative value as the EPA states that an infiltration rate of 1 in/hr is usually sufficient to handle even large storm events [4, 17]. According to the EPA, while clogging does decrease infiltration rates, clogged pavement systems can still be effective stormwater management tools. The EPA observes that "while more particles become entrained in the pavement surface, it does not become impermeable. Studies of the long-term surface permeability of porous asphalt and other permeable pavements have found high infiltration rates initially, followed by a decrease, and then leveling off with time." [4]

The EPA states that “with initial infiltration rates of hundreds of inches per hour, the long-term infiltration capacity remains high even with clogging. When clogged, surface infiltration rates usually well exceed 1 inch per hour, which is sufficient in most circumstances for the surface to effectively manage intense stormwater events.” [4] This suggests that even significantly clogged surfaces can still be considered functional infiltration practices. The disconnect between the various standards may be contributed to the fact that standards for infiltration best management practices (BMPs) have been introduced to the industry relatively recently, and it may take more studies to provide data that prove that even ‘failed’ permeable practices can still have a positive impact on stormwater management.

Studies on permeable surfaces in many different parts of the country have previously shown a wide range of results on the continued functionality of permeable surfaces over time. One parking lot was shown to function for three years without a need for maintenance, although infiltration rates had decreased in some areas [37]. Those permeable pavement systems near loose soil in heavily trafficked areas have experienced decreased infiltration [37]. Other systems have experienced no change in functional ability in both permeable and non-permeable pavements after six years of daily use [22]. Still other studies have found that the surface layer of permeable asphalt paving degraded significantly after nine years of service, but the base of the paving and its sub-base were still operating as installed [38]. The results of these studies are promising. Overall, they show that permeable pavements can still operate relatively efficiently for nearly a decade. They also suggest that though degradation of the surface of the asphalt is common, the gravel storage layers are largely unaffected over time. This suggests that in order to restore the system to its original infiltration characteristics, only the top layer of asphalt would have to be removed and replaced, a much less costly measure than replacing the entire bed.

The largest problem encountered when attempting to draw conclusions from the findings in these investigations is that the conditions were not consistent across the studies. That is, each surface experienced different local environmental and atmospheric conditions which affect service life. The variance in conditions makes it difficult to make generalizations about the service life of a general permeable pavement based on the lack of common factors between the studies. The amount of particulate in the immediate vicinity of a permeable paving parking lot, for example, is an important factor in how much clogging will occur in the pavement. A lot that is surrounded by grass or permeable surfaces would most likely function for a longer period of time than a lot surrounded by impervious surfaces or that served long run-on areas of interconnected impervious areas. There would be fewer particles that could be introduced in runoff to clog the voids in the pavement from a nearby pervious surface.

In an attempt to study the performance of an infiltration practice under more stable conditions, Mullaney, Rikalainen, and Jefferies performed a study using test rigs of permeable pavers and steady particulate additions to simulate the buildup of small particulate matter over a number of years [39]. Figure 9 shows the test rigs used in their experiment.

Figure 9: Test Rig Assembly [39].

The findings from this experiment showed that the infiltration ability of the test rigs was not significantly affected until an equivalent of 10 years of sediment was added to the system [39]. The test systems did not totally lose functionality until nearly 20 years of sediment was added. Figures 10 and 11 illustrate the results of the experiments.

Figure 10: Pooling in Rig after 3 Years [39].

Figure 11: Overflowing after 20 Years [39].

Experiments like this and studies of permeable pavements in the field will help to further establish functionality guidelines and create rating criteria for infiltration practices that can then be applied to practice standards and BMP documentation. This process of assessing the validity of practice standards such as those issues by the WNDR is important, as further study will help to establish standards that give fair credit to infiltrating practices. Once the function of infiltration practices is more clearly understood, function and failure rating can be adjusted to adequately reflect what infiltration a pavement is responsible for and the downstream impacts of the installation post-construction and during its service life. In order to extend that service life, various maintenance techniques can be performed to clear clogged pavement. Clearing the voids can be achieved by vacuuming out trapped particulate or shaking it out with a sonic device [40]. These methods allow for the extension of the useful life of permeable pavement systems by improving infiltration rates. Given all of the data available, it can be observed that “many of these systems have outperformed their conventionally paved counterparts in terms of both parking-lot durability and stormwater management.” [5]

In summary, permeable pavement systems feature many benefits over traditional paving systems. Permeable pavement can be used as a stormwater management tool, retaining rainfall and allowing it to infiltrate into the ground below instead of running off to a municipal storm sewer. This infiltration reduces stormwater runoff, and in doing so, reduces the necessary capacity of the municipal treatment works. The process of infiltration also acts as a pretreatment, filtering particulate and contaminants out of the stormwater. These benefits reduce erosion as well as pollution caused by stormwater runoff contacting and carrying pollutants, such as gasoline, to nearby lakes and streams. The lifespan of permeable pavement systems has also been much extended by engineering innovation in recent years.

Materials and Methods

For the purposes of this study, data and samples were collected from the Ward Street parking lot and tested in the lab to obtain the concentration of TSS and biological oxygen demand (BOD) present in the infiltrate from the parking surface. Samples were collected using procedures outlined in the lab manual from CV-320, Environmental Engineering adapted from the Standard Methods of the Examination of Water and Wastewater, Sections 2540D and 2540E and Section 5210B [41, 42]. Data collected included the amount of rainfall that fell in the course of a given event and the depth of water collected in the buried, under-pavement carboys on site after each event.

The monitoring infrastructure from the original installation of the Ward Street parking lot was used to collect water samples that infiltrated during each storm event. Three stainless steel funnels installed under the surface of the pavements collected water from the 4 square feet of pavement directly above three 20 L (5 gallon) carboys installed below the lot's surface. The layout and numbering of these carboys can be seen in Figure 12.

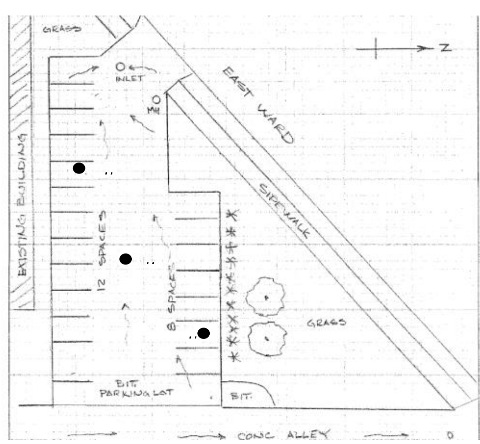

Figure 12: Parking Lot Carboy Configuration [10].

The installation detail of the funnels and carboys can be seen in Figure 13.

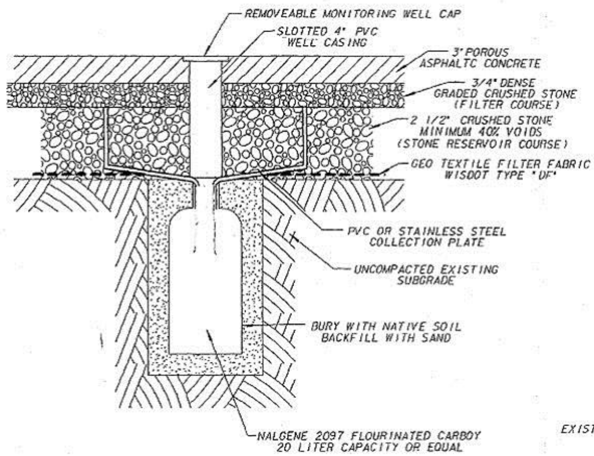

Figure 13: Carboy Installation Detail [10].

Rainfall data were collected using a manual 10-inch rain gage installed at the site. The rain gage was installed on a pole with a 45 degree clear area around the collection orifice. The rain gage was read to an accuracy of a hundredth of an inch and rainfall readings were taken at the time of each sample collection. Events were each given a unique number associated with the date of the event in order to distinguish data and samples.

The depth of water in each carboy after an event was determined using a chalked pole, which was inserted into the carboy to determine the water depth by the amount of chalk that was removed from the pole. Measurements of collected rainwater depth were taken to the nearest 1/16th of an inch. Depths of collected water were then converted to volumes using the rating curve developed by pouring a known amount of water into carboy #3 and measuring the resulting depths. The rating curve that was developed and used to determine the volume of water collected in each carboy is detailed in Table 1 and

Figure 14. Collection efficiency of the permeable pavement as determined by the depth of water collected in the carboy can be found in Appendix A.

Table 1: Carboy Rating Curve.

Volume (gal)	Depth (in)
.528	1.375
1.057	3
2.055	5.75
5.283	18

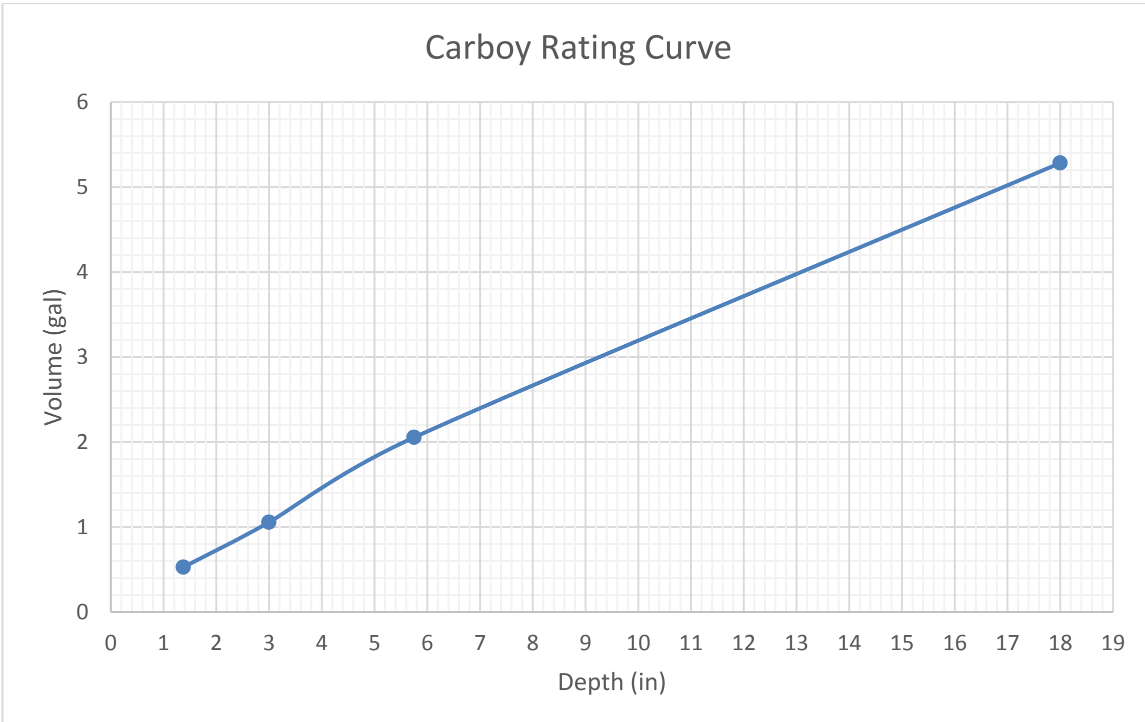

Figure 14: Carboy Rating Curve.

After depth measurements were taken from the carboys, samples for water quality testing were collected from the reservoir inside each carboy. Samples were collected following a similar procedure to that used in the original Ward Street study [10]. Samples were removed from wells after rainfall events using a hand pump and collected in sample bottles for transport back to the lab. Samples were collected within 1 hour of the end of each rainfall event and kept refrigerated until the time of use as recommended by Dr. Mahuta and standard testing procedures outlines in the CV-320 lab manual [41].

Samples were stored, prepared and tested for five-day BOD and TSS concentration at the environmental lab CC 50 at the Milwaukee School of Engineering. TSS testing was performed in accordance with MSOE lab standards and CV-320 course manual recommendations as provided by Dr. Mahuta [43]. Five-day BOD testing was performed to the same quality criteria [41]. After testing, sample data were recorded. Recorded data can be found in Appendix A.

The parking surface was also tested for permeability in compliance with ASTM C1701, *Standard Test Method for Infiltration Rate of in Place Pervious Concrete*, which is the primary technique for measuring infiltration or the amount of water captured by a permeable pavement system [2, 42]. The significance of this test as described by ASTM is that "tests performed at the same location across a span of years may be used to detect a reduction of infiltration rate of the pervious concrete, thereby identifying the need for remediation." [42] ASTM Standard C1781, *Standard Test method of Surface Infiltration Rate of Permeable Unit Pavement* Systems [44], could have also been applied to obtain similar data and results. In compliance with ASTM C1701, a 12-inch infiltration ring was used to perform a constant head infiltration test. A known amount of water was poured into the ring and the amount of time it took to infiltrate into the pavement was measured.

The test was used to determine whether or not the parking surface complied with the WDNR standard for permeable pavement infiltration practices, which considers a pavement failed if its infiltration rate is determined to be less than 10 in/hr [17]. Test data can be found in Table 2.

Table 2: ASTM C1701 Results.		
Carboy Location	Pour	Infiltration Rate (in/hr)
1	1 – Pre Wet	2
	2 – Wet	< 1
2	1 – Pre Wet	< 1
	2 – Wet	< 1
3	1 – Pre Wet	1.2
	2 – Wet	< 1

Results and Discussion

Testing determined that the permeable asphalt pavement at Ward Street has failed with respect to WDNR standards, even though the carboys had collected water during all rainfall events. An infiltration rate of between .5in/hr and 1 in/hr was found to be a consistent infiltration rating of wet pavement across the parking surface. This rate is not surprising, as it appears that no regular maintenance, such as vacuum sweeping, has even been performed at the site. But despite these low infiltration values, the parking lot was seen to have an effect on stormwater runoff during rainfall events.

Evaluation of data collected from the site pertaining to water quantity reveals a trend concerning the efficiency of capture during small storms as compared to the large storms. The capture efficiencies of the carboys during large storm events are relatively high. In some cases, the capture efficiencies of the carboys during larger storms reflect that they captured more than 100% of the rainfall that fell on the surface above them. This most likely means that the carboys collected water that flowed over the surface of the pavement that otherwise would have run off.

During small storms, however, the capture efficiencies of the carboys are very low -- a great deal lower, in fact, than the collection efficiency of large storms. The hypothesis that explains this difference in the performance involves the lack of accounting for an initial loss to evaporation and wetting. During small rainfall events there is a significant proportion of the event rainfall volume “captured” by evaporation, and therefore, less water is able to pass all the way through the pavement and aggregate base layer into the carboys. The field capacity is the moisture that can be absorbed by the asphalt pavement and the aggregate base before the system discharges by gravity into the carboys. During large storm events, only a small proportion of the event rainfall volume is absorbed onto the surface and into the pores of the asphalt and the aggregate in the base course, which results in a higher percentage of the rainfall volume draining into the carboys.

This understanding of rainfall during a small storm event also explains the previously mentioned facts about the fact that permeable paving makes a large difference in the total amount of runoff in smaller storms than it does in large storms. This is because the storage capacity of the pavement can handle all runoff in a small storm, whereas in a large storm, the system can become saturated. Based on these results, it seems that the Ward Street permeable pavement functioned as intended throughout the study and did make a difference in the amount of runoff that was allowed to leave the parking surface, especially in the case of small storms. The pavement also performed well during large storms, capturing at least 57% of the water that fell on the parking surface, and potentially more, as determined by measuring the depth collected by the carboys, though the carboys were not large enough to store and record any additional captured rainfall.

As for the water quality data, testing showed that that levels of biochemical oxygen demand were less than or equal to those found in the original study. These results, though they have limited statistical reliability based on the relatively small number of successful tests performed, seem to indicate that the parking lot has not experienced a degradation in its ability to pretreat runoff over time. The levels of contaminants measured as indicated by BOD were found to be minimal, and still are within allowable limits for infiltration into the subgrade soil.

Solids testing, however, showed significantly higher levels of solids present in the carboys than during the original study. The author believes that this can be attributed to the fact that sediment has been allowed to collect in the bottom of the carboys over time, skewing the solids results. The sediment has accumulated because of the limited ability to remove sediment from the carboys as a result of their underground location. Sediment running over the surface of the parking lot has also been found to directly enter the neck of the carboy through the well cap, which is not completely tight. Logic would suggest that the more clogging that has occurred in the pavement, the less ability the solids would have to infiltrate into the sub-base. However, because of limitations in lab testing, the amount of the captured solids cannot be determined, so it is difficult to develop a more accurate evaluation at this time.

Overall, water quantity and quality testing for the most part agrees with the results of the previous study. Testing shows that the permeable asphalt at Ward Street did in fact have a positive impact on water quality in terms of BOD and it did reduce the volume of stormwater runoff from the site. Future testing should be performed to further investigate the high TSS concentrations, which will be discussed further in the conclusions section of this report. Table 3 shows the average collected levels of BOD and TSS levels in the rainwater that has infiltrated through the permeable pavement.

Table 3: Average Infiltrate Values.

	Original Study	**Current Study**
TSS (mg/L)	65.9	437.5
BOD (mg/L)	9.4	2.78

Life Cycle Costing

There are a two main factors to consider when putting together the cost of permeable pavement compared to traditional asphalt. First, it is necessary to evaluate the direct installation and maintenance costs of permeable asphalt paving versus conventional asphalt paving. Next, it is necessary to evaluate the added value of extra parking spots that can be constructed in a parking lot that utilizes a permeable pavement instead of a traditional detention basin, which minimizes the usable area of the project site. In this report, each factor is given an approximate dollar value so that the two options can be compared to each other and life cycle conclusions can be drawn concerning which is more cost effective.

Adams argues that “porous pavement does not cost more than conventional pavement.” [5] Adams states that “on a yard-by-yard basis the asphalt cost is approximately the same as the cost of conventional asphalt.” [5] There are several main factors that influence the cost of permeable pavement. The “material availability and transport”, the “site conditions including accessibility by construction equipment, slope and existing buildings and uses”, and the condition of the subgrade soils as “clay may result in additional base material needed for structural support or added stormwater storage volume” [4] are all important factors. Other secondary considerations with respect to cost include the stormwater requirements because “the level of control required for the volume, rate, or quality of stormwater discharges will impact the volume of treatment needed”; the size of the project is also important as “larger porous asphalt areas tend to have lower per square foot costs due to construction efficiencies.” [4]

In summary, “costs vary with site activities and access, porous asphalt depth, drainage, curbing and underdrains (if used), labor rates, contractor expertise, and competition." [4] The typical "cost of the porous asphalt material ranges from $0.50 to $1 per square foot." [4] These factors and asphalt costs are very similar to those of conventional asphalt paving.

The largest cost difference between typical asphalt and permeable asphalt is that the "underlying stone bed is usually more expensive than a conventional compacted sub-base." [5] The open graded gravel is necessary to fill the sub-base of a permeable lot, as opposed to a traditional lot, which would only require the compacting of the existing soils. Excavation is also required to create the storage cavity to fill with gravel, which adds another cost to the permeable installation. Excavation costs usually range from $50 to $200 per yard for material removal [45]. Costs for crushed stone are about $20 per cubic yard for backfilling with an open graded aggregate sub-base [46].

These costs are generally offset, however, by the "significant reduction in stormwater pipes and inlets." [5] EPA studies show that the cost of an LID practice is on average 40% less expensive than a traditional installation based on lower discharge flow volumes [47]. In addition, "porous pavement is designed to "fit into" the topography of a site, there is generally less earthwork and no deep excavations" [5], despite the added excavation of space for the gravel sub-base. In addition, "when the cost savings provided by eliminating the detention basin are considered, porous pavement is always an economically sound choice." [5] A number of studies have been done in the past on the cost of installing a permeable pavement system instead of a traditional system and "on those jobs where unit costs have been compared, the porous pavement always has been the less expensive option." [5] For this site, however, it seems that more excavation would be required for permeable asphalt paving because of the site topography and the depth of the gravel sub-base required to prevent freezing of the subgrade soils.

As far as the added values for added parking spaces, studies show that “current jobs are averaging between $2,000 and $2,500 per parking space for parking, aisles, and stormwater management.” [48] Given the fact that the ‘maximum extent practicable’ for an infiltration basin is defined as 1% of the project site based on WDNR practice standards, a safe assumption is that a detention basin with some infiltration potential will take up no more than 1% - 5% of the project site. The Ward Street parking lot has an approximate area of 1,000 square feet and approximately 20 parking spots. Five percent of this area would take up approximately four parking spots.

Based on these costs, a life cycle analysis can be conducted to deduce which option offers a more attractive payback period. Factors to be considered in the Life Cycle Costing exercise are listed in Table 4 and 5. Less tangible factors that should be weighed into the decision, but do not have specific costs associated with them, are listed in Table 6.

Table 4: Life Cycle Costing Considerations – Traditional Pavement.

Cost	***Value***	***Year***
Materials	$.5/sf - $1/sf	0
Excavation	$200/yd	0
Material Excavated	1,000sf*.75ft = 750 ft^3 => 28cy	0
Pond Excavation	8*12*2 ft = 192 ft^3 = 21 cy	0
Installation	$2,000/space to $2,500 /space	0
Worker Training	0	1-15
Maintenance Costs	40 hr/yr*$30/hr = $1,200	1-15
Deicing Cost	$550	1-15
Maintenance Equipment Costs	0	1-15
Parking Capacity	16 cars	1-15
Parking Income	$80/mo/car	1-15

Table 5: Life Cycle Costing Considerations – Permeable Asphalt.		
Cost	***Value***	***Year***
Materials	$.5/sf - $1/sf	0
Excavation	$200/yd - $1,200/yd	0
Gravel	$20/yd	0
Material Excavated	1,000sf*4ft = 4,000ft^3=>148 cy	0
Installation	$2,000/space to $2,500 /space	0
Worker Training	6 hr*20 workers*$30/hr = $3,600	1-15
Maintenance Costs	80hr/yr*$30/hr = $2,400	1-15
Deicing Cost	$550*.25 = $140	1-15
Maintenance Equipment Costs	$500/year	1-15
Parking Capacity	20 cars	1-15
Parking Income	$80/mo/car	1-15

Table 6: Less Tangible Life Cycle Costing Factors to Consider.	
1	Impact of using less road salt on rivers and streams
2	Environmental impact of runoff pollution
3	Public perception of the city and municipal program
4	Worker pride in their organization
5	City image on a local and global scale
6	Impacts of driver safety caused by better visibility and traction
7	Environmental impacts of longevity of permeable pavement

Before drawing conclusions from the life cycle costing exercise, it is important to take into account the possible changes in outcome of this analysis based on changes in the parameters used. Parameter values are somewhat uncertain and so these items were tested to study their effect on the results of the costing study. Alternates -- indicated in Table 7 -- represent the difference in the costs of the baseline traditional asphalt parking lot and the alternative permeable paving if the sensitivity measure described was adjusted.

Table 7: Life Cycle Costing Outcomes – Net Present Values.			
LCC Option	***Sensitivity Measure***	***Baseline Cost***	***Alternative Cost***
Original	None	$28,846	$10,920
Alternate 1	Lower Cost of Pervious Asphalt	$28,846	$11,314
Alternate 2	Discount Factor 15%	-$3,246	-$21,848
Alternate 3	Parking Income at $160/mo instead of $80/mo	$119,780	$124,587
Alternate 4	Pond Excavation 43 cy (8*12*4 ft)	$25,381	$10,920

Based on the results of the costing study, the initial cost of the permeable paving installation is too high to pay back in the 15 year cycle of the study unless the parking income of the parking lot can be significantly increased. With more income per parking space, the increased number of spaces added by the permeable paving system do provide a payback in the first year of operation. Despite this, it is clear that based on the lower salt costs and increased parking revenue of the permeable asphalt that there are significant yearly cost benefits to the owner of the parking lot. In conjunction, the wide range of environmental benefits make a strong case for the use of the more sustainable permeable asphalt over a traditional paving system based on its more intangible factors.

In addition to its environmental benefits and its increased revenue, which benefit the owner of a green installation, there are also benefits to the municipal system. The cost per gallon of storing water in the gravel sub-base of a permeable asphalt parking lot versus storing it in the deep tunnel system is arguably the largest factor that sets apart the cost of a permeable pavement parking system from traditional pavement. Storage in the deep tunnel had a capital cost of about $4 per gallon to construct which yields a capital cost of about twenty cents gallon of discharge captured per year [3]. This does not include the costs of operating and maintaining the system, and yearly capital improvement cost add more to the annual cost per gallon each year maintenance is required. The system requires a significant amount of monitoring and maintenance. Water stored in the ISS must be pumped out and back to the treatment works, whereas water stored in a green infrastructure simply drains by gravity. The larger the amount of storage that can be installed in green installations, the less that must be stored in grey infrastructure. This added benefit provides another argument for the installation of permeable asphalt and green infrastructure.

Based on the information presented in Table 5, pervious pavement has a capital cost of about $3.75 per gallon of discharge captured per year. Based on these values, pervious pavement has a greater capital cost than the deep tunnel based on the overall cost of storage per year. The key difference is the cost of excavation required to create a pervious pavement system. This means that over time, the capital cost of a pervious pavement system could theoretically be absorbed by the fact that a green infrastructure system such as a pervious parking surface requires much less maintenance, monitoring and energy to operate than a traditional grey infrastructure installation such as the deep tunnel.

Conclusions and Recommendations

Results of field observations, data collection and lab testing have shown that, though the Ward Street parking lot is technically considered to have failed as an infiltration practice by WDNR standards, it is still functional after seven years. The installation still has a positive effect on stormwater management, reducing the volume of runoff from the site and allowing captured rainwater to infiltrate into subgrade soils. The quality of the infiltrate meets standards for infiltration into the groundwater table, and the surface of the lot is still in relatively good condition, though no maintenance has been performed on the surface since the time of installation.

Permeable pavements have long had somewhat of a stigma in the construction and development industry based on poor performance of early systems and a general lack of knowledge of the environmental benefits that these installations can provide. Another factor that may have played a role is that in the past many developers and owners have been most interested in the bottom line cost of a project and were not especially interested in the environmental impacts of what was installed. Today, however, sustainably and environmental responsibility have become much more important to owners and constructors, as well as local and state governing agencies. This push for green building has forced the industry to take a second look at environmentally beneficial technologies such as green infrastructure, infiltration practices for stormwater managements and permeable pavements.

Permeable pavements have many potential applications beyond just parking lots. Despite this, “the use of porous pavement for roadway construction has not been overwhelmingly adopted by a large number of communities, most likely due to traffic volume and speed constraints.” [11] While it is true that permeable asphalt is not an ideal material for road surfaces, it can be used for shoulders, sidewalks and low traffic residential areas, which can still contribute to better stormwater management, as the impervious areas of vehicle related infrastructure could still be greatly reduced by the application.

There is also the concern “over performance during freeze-thaw cycles” in “cold weather regions.” [11] This issue has been well covered by extensive research and testing, and results show that contrary to the general assumption, permeable pavements can actually perform better than traditional pavements in cold weather conditions. The way that they freeze in sections instead of in a solid block contributes to less freeze thaw stress on permeable pavements, which contributes to a longer life. Surface characteristics of permeable asphalt also give it an advantage over traditional paving in freezing conditions. The reduced fines create a rougher surface that provides more traction and visibility to drivers and the porous nature of the surface allows water to infiltrate, reducing surface ponding that can lead to black ice and other hazardous driving conditions. The reduction in road salt necessary to deice permeable pavements also offers maintenance and environmental benefits. Basically, permeable pavements have a pretty long list of winter weather benefits.

Another factor may be that it is difficult for municipalities to assign monetary values to the amount of savings that is incurred by implementing green infrastructure practices [9]. The ways that a permeable pavement can pay back its installation costs are numerous, but not overly obvious. Permeable paving systems may be slightly more expensive than traditional systems to install, but where they pay back is in system costs. Higher annual maintenance costs of permeable asphalt attributed to the needs for vacuum sweeping and more rigorous inspection requirement can be made up for by the fact that winter maintenance and the cost of deicing materials are greatly reduced on permeable surfaces. The greatest savings, however, are the system-wide savings by not having to install additional grey infrastructure to store stormwater that has run off from the pavement. Green infrastructure creates a much less costly way to store stormwater. Add in the downstream environmental benefits that infiltration and pretreatment can provide, along with the reduction in risk of combined sewer overflow, and the payback of a permeable pavement becomes much clearer.

Along with the large driver of an increased awareness of environmental responsibility, the US EPA National Pollutant Discharge Elimination System (NPDES) Regulations are also a primary driver for the installation of green infrastructure such as permeable asphalt paving [47]. Permeable parking lots can also have favorable cost factors and can greatly optimize site dynamics by reducing or eliminating the need for retention ponds and other grey infrastructure such as curb and gutter system and storm sewers [47]. The EPA states that “porous asphalt can be used for municipal stormwater management programs and private development applications. The runoff volume and rate control, plus pollutant reductions, allow municipalities to improve the quality of stormwater discharges.” [4]

Based on these facts, it is pretty clear that as previous studies have shown, permeable pavement is not only the environmentally sustainable choice, it is also the more cost effective one. The costs of utilizing green infrastructure over traditional grey systems for stormwater storage are somewhat higher at installation, but their environmental benefits make a strong case for their installation. In addition, natural storage allows for infiltration, which recharges natural groundwater reserves, which has many benefits.

Permeable pavements are simple to install, and though they require slightly more frequent and complex maintenance than a traditional paving system, their maintenance costs are typically offset by the money they save in grey infrastructure and winter maintenance. From every angle, green infrastructure is the right choice for parking applications such as the Ward Street parking lot, and have a lot of promise for other applications such as green sidewalks, bike paths, parking lanes and highway shoulders.

Based on the relatively small scope and almost nonexistent budget of this project, there were some limitations to the study. The most significant of these would be the lack of equipment to measure the amount of stormwater that ran off the site and into the municipal sewer, both from the parking surface and the permeable pavement's underdrain. These data would have been helpful in creating an efficiency curve for the entire parking surface, allowing an estimate of just how much over every storm event was allowed to infiltrate. As there was no discharge from the permeable paving in the original Ward Street study [10], it would have been informative to compare those results to the parking lot functionality today.

The second largest limitation was the lack of ability to clean the carboys in the field. Solids in the bases of the carboys that were not able to be removed by the methods at hand most likely skewed TSS results in the study, resulting in a lack of useful data on the true amount of solids present in the infiltrate. It would have also been very helpful to have an offsite lab perform BOD testing, as the quality of seed obtained for use in the BOD_5 tests performed in the environmental lab at MSOE varied wildly, leading to difficulty obtaining meaningful and accurate BOD results.

Based on these limitations and other field observations, recommendations for future studies at this site to better determine performance are as follows. First, it is recommended that the weir on site be repaired and a depth sensor be installed in the manhole on site, to allow for a future study in which similar observations could be made, which could be paired with data about how much water was discharged from the site to the municipal combined sewer system. This would give a more complete picture of how much of an impact the installation is having on downstream conditions and how that impact has changed over time.

Secondly, a more advanced water quality study of the site infiltrate is suggested. Samples could be tested at a professional lab facility for a wider range of organic pollutants and heavy metals, to be able to draw better conclusions about the quality of the water infiltrating through the surface of the pavement. In order to estimate the pretreatment abilities of the pavement surface and aggregate sub-base, water quality samples need to be collected from the surface of the adjacent impervious asphalt application. These samples could be compared to see what effect, if any, infiltrating through the system had on the stormwater runoff.

As a side project, the field capacity of the asphalt needs to be determined in a small scale experiment. The test measure would involve isolating an area of pavement in the four square foot area that drains into a single carboy and then wetting that area until it began to discharge to the carboy. Pouring a known volume of water onto the pavement and measuring how much is collected in the carboys would reveal how much moisture the pavement surface and sub-base could absorb before discharging to the subgrade below. The result would be a clearer picture of the efficiency of the pavement in small storm conditions.

Lastly, measures could be taken to perform regenerative maintenance on the surface of the pavement, to see what effect it would have on the surface infiltration rate. Current infiltration rates could be compared to infiltration rates after restorative maintenance had occurred in order to draw conclusions about how much effect restorative measures can have on ‘failed’ pavement surfaces. Hopefully, restorative maintenance techniques would lead to a significant improvement in surface infiltration values, allowing the pavement to perform more effectively.

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Appendix A –

Experimental Data and Test Results

Appendix A

Appendix A features data collected from the field testing portion of this report. Experimental data were collected on site at the Ward Street Parking Lot and tested in the environmental lab at the Milwaukee School of Engineering.

Table A-1: Rainfall Event Data.											
Event		Rainfall (in)	Samples			Depth (in)			Volume/4 sq ft (gal)		
			#1	#2	#3	#1	#2	#3	#1	#2	#3
1	3/30-3/31/15	0.016	-	-	X	-	-	NA	-	-	0.069
2	4/2/15	0.087	X	X	X	0.4375	NA	3.875	0.396	-	1.321
3	4/6-4/8/15	0.455	-	X	X	-	> 18	2.5625	-	5.284	0.925
4	4/8-4/10/15	2.582	X	X	-	> 18	> 18	-	5.284	5.284	-
5	4/19-4/20/15	1.071	X	X	X	9.1875	> 18	4.375	2.840	5.284	1.532
6	4/23-4/24/15	0.180	X	X	-	2.5625	13.25	-	1.057	3.963	-
7	5/5-5/6/15	0.566	X	X	-	4.25	> 18	-	1.519	5.284	-
8	5/9-5/11/15	0.562	-	X	X	-	> 18	2.25	-	5.284	0.793

Table A-2: Rainfall Volume Data.											
	Volume Rainfall (ft^3)	Volume Rainfall (L)	Depth (in)			Volume Infiltrated (gal)			Infiltration Efficiency		
			#1	#2	#3	#1	#2	#3	#1	#2	#3
1	0.017	0.474	-	-	NA	-	-	0.069	-	-	0.21%
2	0.091	2.579	0.4375	-	3.875	0.396	-	1.321	1.08%	-	102.42%
3	0.476	13.487	-	> 18	2.5625	-	5.284	0.925	-	106.51%	9.99%
4	2.702	76.535	> 18	> 18	-	5.284	5.284	-	56.53%	56.53%	-
5	1.121	31.746	9.1875	> 18	4.375	2.840	5.284	1.532	21.00%	11.75%	25.95%
6	0.188	5.335	2.5625	13.25	-	1.057	3.963	-	1.34%	109.66%	-
7	0.592	16.777	4.25	> 18	-	1.519	5.284	-	11.03%	103.22%	-
8	0.588	16.659	-	> 18	2.25	-	5.284	0.793	-	103.34%	86.34%

Table A-3: BOD_5 Data.

Event	Sample Name/ Description	Sample Volume (mL)	Seed Volume (mL)	Seed Curve Used	SCF (mg/L)	Dilution H_20 Volume (mL)	DO_i (mg/L)	DO_f (mg/L)	DO Depletion (mg/L)	BOD (mg/L)	BOD Average (mg/L)
1											
	Storm #3	10	2	1	4.5	288	7.76	4.54	3.22	0.00	
	Storm #3	50	2	1	4.5	248	8.01	4.75	3.26	0.00	2.47
	Storm #3	100	2	1	4.5	198	8.69	1.67	7.02	7.41	
	Control 1	0	0	1	4.5	300	7.55	7.54	0.01	0.00	
	Control 2	0	0	1	4.5	300	7.55	7.54	0.01	0.00	0.00
	Control 3	0	0	1	4.5	300	7.56	7.56	0.00	0.00	
	Seed 1	0	5	1		295	7.69	2.42	5.27	316.20	
	Seed 2	0	10	1		290	7.43	0.03	7.40	222.00	194.74
	Seed 3	0	50	1		250	7.69	0.02	7.67	46.02	
2											
	Storm #1	10	2	1	4.5	288	7.57	4.61	2.96	0.00	
	Storm #1	50	2	1	4.5	248	7.60	3.88	3.72	0.00	0.51
	Storm #1	100	2	1	4.5	198	7.75	2.73	5.02	1.53	
	Storm #2	10	2	1	4.5	288	7.60	4.59	3.01	0.00	
	Storm #2	50	2	1	4.5	248	7.59	4.24	3.35	0.00	0.82
	Storm #2	100	2	1	4.5	198	7.64	3.06	4.58	0.24	
	Storm #2	200	2	1	4.5	98	7.73	1.19	6.54	3.03	
	Storm #3	10	2	1	4.5	288	7.72	4.50	3.22	0.00	
	Storm #3	50	2	1	4.5	248	7.91	3.70	4.21	0.00	3.68
	Storm #3	100	2	1	4.5	198	8.49	1.52	6.97	7.26	
	Storm #3	200	2	1	4.5	98	9.60	0.07	9.53	7.47	
	Control 1	0	0	1	4.5	300	7.55	7.55	0.00	0	0
	Control 2	0	0	1	4.5	300	7.62	7.62	0.00	0	

Table A-3: BOD_5 Data (cont.).											
Event	**Sample Name/ Description**	**Sample Volume (mL)**	**Seed Volume (mL)**	**Seed Curve Used**	**SCF (mg/L)**	**Dilution H_20 Volume (mL)**	**DO_i (mg/L)**	**DO_f (mg/L)**	**DO Depletion (mg/L)**	**BOD (mg/L)**	**BOD Average (mg/L)**
3											
	Storm #2	10	1	2	0.35	289	7.71	7.29	0.42	1.91	4.08
	Storm #2	50	1	2	0.35	249	7.79	6.58	1.21	5.03	
	Storm #2	100	1	2	0.35	199	8.08	5.95	2.13	5.29	
	Storm #3	10	1	2	0.35	289	7.66	7.08	0.58	6.27	5.04
	Storm #3	50	1	2	0.35	249	8.19	6.96	1.23	5.18	
	Storm #3	100	1	2	0.35	199	8.47	6.88	1.59	3.68	
	Seed 1	0	1	2		299	7.85	7.45	0.40	120.00	84.60
	Seed 2	0	3	2		297	7.68	7.02	0.66	66.00	
	Seed 3	0	5	2		295	7.76	6.63	1.13	67.80	
4											
	Storm #1	10	1	2	0.35	289	8.19	7.33	0.86	13.91	7.28
	Storm #1	50	1	2	0.35	249	8.17	7.06	1.11	4.47	
	Storm #1	100	1	2	0.35	199	8.53	7.02	1.51	3.45	
	Storm #2	10	1	2	0.35	289	7.85	7.44	0.41	1.64	3.10
	Storm #2	50	1	2	0.35	249	8.13	7.21	0.92	3.35	
	Storm #2	100	1	2	0.35	199	8.32	6.52	1.80	4.31	

Table A-3: BOD_5 Data (cont.).											
Event	**Sample Name/ Description**	**Sample Volume (mL)**	**Seed Volume (mL)**	**Seed Curve Used**	**SCF (mg/L)**	**Dilution H_20 Volume (mL)**	**DO_i (mg/L)**	**DO_f (mg/L)**	**DO Depletion (mg/L)**	**BOD (mg/L)**	**BOD Average (mg/L)**
5											
	Storm #1	25	1	3	1.89	274	7.96	0	7.96	70.04	
	Storm #1	75	1	3	1.89	224	7.79	0	7.79	23.29	35.37
	Storm #1	150	1	3	1.89	149	8.32	0	8.32	12.77	
	Storm #2	25	1	3	1.89	274	7.77	0	7.77	67.85	
	Storm #2	75	1	3	1.89	224	7.57	0	7.57	22.42	34.05
	Storm #2	150	1	3	1.89	149	7.87	0	7.87	11.88	
	Storm #3	25	1	3	1.89	274	7.55	0	7.55	65.31	
	Storm #3	75	1	3	1.89	224	7.99	0	7.99	24.08	34.02
	Storm #3	150	1	3	1.89	149	8.27	0	8.27	12.68	
	Seed 1	0	1	3		299	7.40	0	7.40	2220.00	
	Seed 2	0	5	3		295	7.24	0	7.24	434.40	
	Seed 3	0	3	3		297	6.91	0	6.91	691.00	883.45
	Seed 4	0	10	3		290	6.28	0	6.28	188.40	
6											
	Storm #1	25	0.5	3	6	274.5	7.90	6.13	1.77	0.00	
	Storm #1	75	0.5	3	6	224.5	8.40	6.19	2.21	0.00	0.00
	Storm #1	150	0.5	3	6	149.5	9.28	5.66	3.62	0.00	
	Storm #2	25	0.5	3	6	274.5	7.81	6.20	1.61	0.00	
	Storm #2	75	0.5	3	6	224.5	7.63	4.46	3.17	0.00	0.00
	Storm #2	150	0.5	3	6	149.5	7.54	2.42	5.12	0.00	
	Seed 1	0	0.25	3		299.75	7.71	5.82	1.89	2268.00	
	Seed 2	0	0.5	3		299.5	7.83	5.94	1.89	1134.00	1534.00
	Seed 3	0	0.75	3		299.25	8.06	5.06	3.00	1200.00	

Table A-3: BOD_5 Data (cont.).

Event	Sample Name/ Description	Sample Volume (mL)	Seed Volume (mL)	Seed Curve Used	SCF (mg/L)	Dilution H_20 Volume (mL)	DO_i (mg/L)	DO_f (mg/L)	DO Depletion (mg/L)	BOD (mg/L)	BOD Average (mg/L)
7											
	Storm #1	25	1.5	3		273.5	7.97	0.14	7.83	88.64	45.15
	Storm #1	75	1.5	3		223.5	8.06	0.16	7.90	30.98	
	Storm #1	150	1.5	3		148.5	8.17	0.18	7.99	15.82	
	Storm #2	25	1.5	3		273.5	8.03	0.12	7.91	89.55	45.39
	Storm #2	75	1.5	3		223.5	8.03	0.14	7.89	30.94	
	Storm #2	150	1.5	3		148.5	8.06	0.14	7.92	15.68	
	Seed 1	0	0.5	3		299.5	8.06	1.82	6.24	3744.00	2036.33
	Seed 2	0	1.5	3		298.5	8.01	0.11	7.90	1580.00	
	Seed 3	0	3	3		297	7.92	0.07	7.85	785.00	
8											
	Storm #2	25	0.5	3		274.5	8.32	0.14	8.18	96.24	49.03
	Storm #2	75	0.5	3		224.5	8.6	0.13	8.47	33.66	
	Storm #2	150	0.5	3		149.5	8.71	0.08	8.63	17.20	
	Storm #3	25	0.5	3		274.5	8.78	0.07	8.71	102.47	51.41
	Storm #3	75	0.5	3		224.5	8.68	0.08	8.60	34.17	
	Storm #3	150	0.5	3		149.5	9.01	0.18	8.83	17.60	
	Seed 1	0	0.25	3		299.75	8.86	4.92	3.94	4728.00	4258.00
	Seed 2	0	0.5	3		299.5	8.19	0.14	8.05	4830.00	
	Seed 3	0	0.75	3		299.25	8.15	0.11	8.04	3216.00	

Table A-4: Original Study Data.[1]

Event Number	Last Sample Bottle Cleaning	pre-BMP Sampler Start Time	Sample Transfer	TSS (mg/L)		BOD 5-day (mg/L)		COD (mg/L)		DRO (mg/L)		GRO (ug/L)		Copper (mg/L)		Zinc (mg/L)	
				Pre-BMP	Post-BMP	Pre-BMP	Post-BMP	Pre-BMP	Post-BMP	Pre-BMP	Post-BMP	Pre-BMP	Post-BMP	Pre-BMP	Post-BMP	Pre-BMP	Post-BMP
1	3/31/07 17:15	3/31/07 17:19	4/2/07 8:30	19	74	12	8.8	no sample	no sample	2.3	1.2	no sample	no sample	no sample	no sample	no sample	no sample
2	4/2/07 8:30	4/3/07 0:23	4/3/07 9:00	11	46	11	<3.5	64	9.4	1.4	0.24	<50	<50	<.018	<.018	0.039	0.19
3	4/5/07 0:00	4/11/07 10:33	4/14/07 18:15	4.0	74	9.6	3.2	94	45	1.4	0.82	<250	<50	<.018	<.018	0.025	0.51
4	4/18/07 9:10	4/18/07 10:43 & 4/18/07 13:39	4/19/07 7:50	6.0	43	14	12	no sample	no sample	no sample	no sample	no sample	no sample	no sample	no sample	no sample	no sample
5	4/19/07 13:40	not recorded	4/23/07 9:00	26	90	11	17	94	82	2.3	18	<200	<100	<.018	<.018	0.037	0.51
6	4/23/07 9:00	4/25/07 0:00	4/25/07 9:00	5.0	93	28	13	220	56	4.0	8.0	<400	<100	0.021	0.41	0.077	0.0066
7	4/25/07 9:00	4/26/07 5:34 & 4/26/07 10:34* & 4/26/07 10:50*	4/27/07 9:45	9.0	34	5.6	4.0	47	29	1.1	1.3	<250	<100	<.018	<.018	0.033	0.25
8																	
9	4/30/07 10:00	4/30/07 12:08	5/1/07 8:45	18	120	27	5.7	110	44	3.0	0.82	<250	<100	<.018	<.018	0.065	0.36
10	5/7/07 13:30	5/9/07 2:50	5/9/07 10:45	53	35	45	23	no sample	no sample	no sample	no sample	no sample	no sample	no sample	no sample	no sample	no sample
11	5/9/07 10:45	5/15/07 14:08	5/16/07 12:10	59	50	35	<3.6	180	27	4.8	0.70	<2000	<100	0.029	<.018	0.094	0.18
11**	5/9/07 10:45	5/15/07 14:08	5/16/07 12:10	64	49	31	<4.3	240	22	5.3	0.66	<2000	<100	0.028	<.018	0.091	0.17
AVERAGE				21.3	65.9	19.6	n/a	119.9	41.4	2.6	3.9	n/a	n/a	0.0	n/a	0.1	0.3

1 Symbiont. 02 August 2007. "US EPA Great Cities Partnership Program – City of Milwaukee Stormwater Parking Demonstration Project Final Project Report". Symboint. West Allis, Wisconsin. Available from the author.

Table A-5: BOD Seed Curves.				
Seed Curve	**Seed Volume (mL)**	**DO Depletion (mg/L)**	**Seed Volume Used (mL)**	**SCF (mg/L)**
1	5	5.27	2	4.5
	10	7.4	2	4.5
2	1	0.4	0.5	0.35
	3	0.66	0.5	0.35
	5	1.13	0.5	0.35
3	0.25	3.94	0.5	6
	0.5	6.24	0.5	6
	0.75	7.9	0.5	6

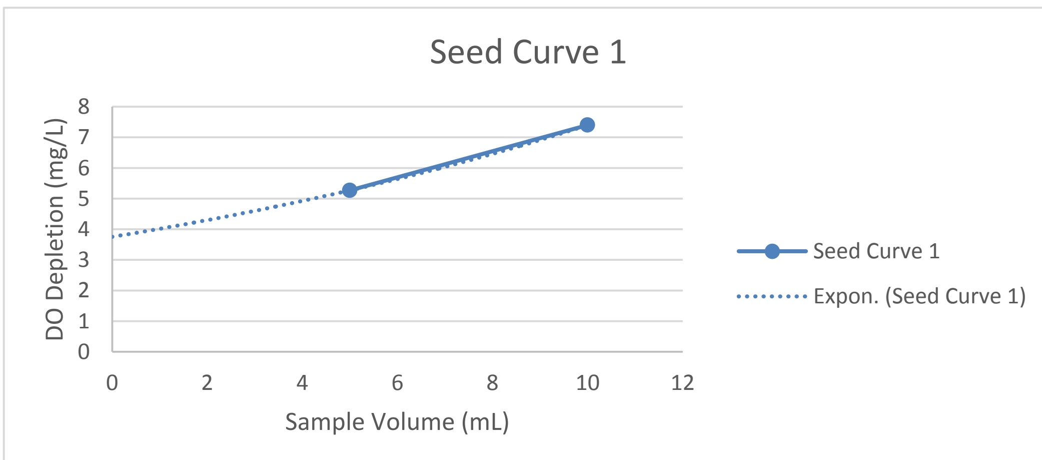

Figure A-1: Seed Curve #1.

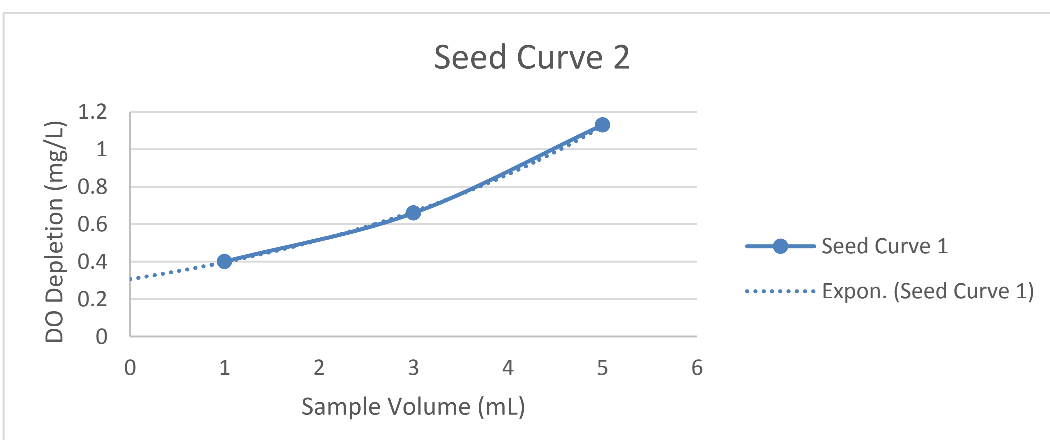

Figure A-2: Seed Curve #2.

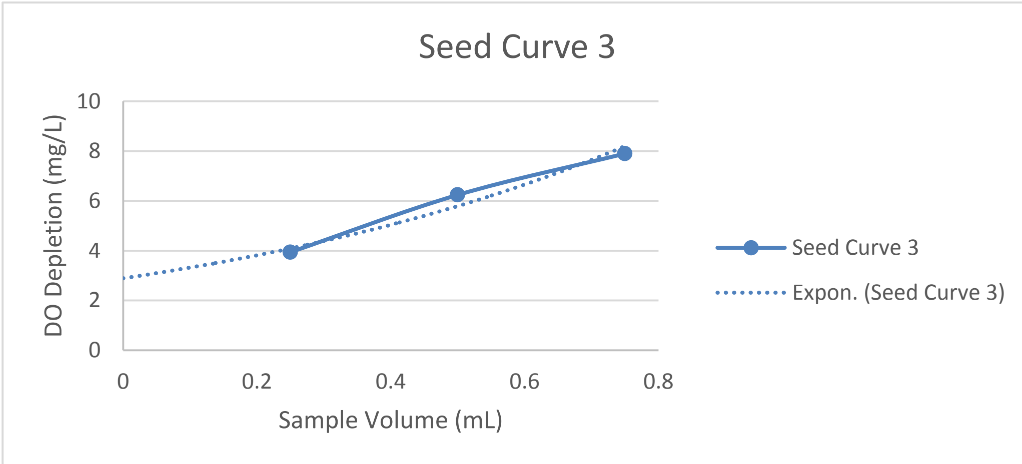

Figure A-3: Seed Curve #3.

Table A-6: BOD$_5$.

Event	Sample Name/ Description	Seed Curve Used	BOD (mg/L)
1			
	Storm #3	1	2.47
2			
	Storm #1	1	0.51
	Storm #2	1	0.82
	Storm #3	1	3.68
3			
	Storm #2	2	4.08
	Storm #3	2	5.04
4			
	Storm #1	2	7.28
	Storm #2	2	3.10
5			
	Storm #1	3	Bad Data
	Storm #2	3	Bad Data
	Storm #3	3	Bad Data
6			
	Storm #1	3	0.00
	Storm #2	3	0.00
7			
	Storm #1	3	Bad Data
	Storm #2	3	Bad Data
8			
	Storm #2	3	Bad Data
	Storm #3	3	Bad Data

Table A-7: TSS.

Event	Test Well	C (g)	A (g)	V (mL)	TSS (mg/L)
1					
	1	-	-	-	-
	2	-	-	-	-
	3	2.476	2.546	130	538
2					
	1	2.464	2.770	200	1,530
	2	2.480	2.571	100	910
	3	2.455	2.520	100	650
3					
	1	-	-	-	-
	2	2.436	2.508	100	720
	3	2.396	2.432	200	180
4					
	1	2.413	2.434	200	105
	2	2.419	2.455	200	180
	3	-	-	-	-
5					
	1	2.456	2.523	200	335
	2	2.449	2.522	100	730
	3	2.430	2.444	200	70
6					
	1	2.427	2.445	200	90
	2	2.475	2.555	150	533
	3	-	-	-	-
7					
	1	2.467	2.484	200	85
	2	2.452	2.529	150	513
	3	-	-	-	-
8					
	1	-	-	-	-
	2	2.484	2.518	200	170
	3	2.496	2.506	200	50

Appendix B –

Life Cycle Costing Data and Calculations

Appendix B

The following factors and measurements have been employed in the life cycle cost analysis in this project.

Tax Rate – 35%

Discount Factors – 7%

Salt Costs

$0.12/lb

1 cup covers 1/sf

50lb = 95.86114 cups

1000 sf = 1000 cups/95.86 = (11) 50 lb bags/event

4 months of winter, salt 2/mo = 11*8 = 88 50 lb bags = 4,400 lbs*$.12/lb = $528

Appendix C –

Life Cycle Costing Analyses

Appendix C

Appendix C features the Life Cycle Costing studies referenced in this report. LLC data were generated using the values defined in Appendix B and in the body of this report. Net present values for each paving option were reached using these calculational tables.

Table C-1: LCC Cost Study Baseline.

Traditional Asphalt Paving

	Year															
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Material	-$1,000															
Excavation Costs	-$9,800															
Install	-$50,000															
Worker Training		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Maintenance Costs		-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200
Equipment Costs		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Deicing Costs		-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200
Parking Income		$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360
Depreciation		-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053
Profit Before Taxes		$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907
Tax provision		-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117
Net Income		$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789
Add Back Depreciation		$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053
Cash Flow	-$60,800	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843
Discount factors	1.00	1.07	1.14	1.23	1.31	1.40	1.50	1.61	1.72	1.84	1.97	2.10	2.25	2.41	2.58	2.76
Present Value	-$60,800	$9,199	$8,597	$8,035	$7,509	$7,018	$6,559	$6,130	$5,729	$5,354	$5,004	$4,676	$4,370	$4,084	$3,817	$3,567
Net Present Value	$28,846															

Table C-2: LCC Cost Study Alternative.

Permeable Asphalt Paving

	Year															
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Material	-$1,000															
Excavation Costs	-$29,600															
Install	-$50,000															
Worker Training		-$3,600	-$3,599	-$3,598	-$3,597	-$3,596	-$3,595	-$3,594	-$3,593	-$3,592	-$3,591	-$3,590	-$3,589	-$3,588	-$3,587	-$3,586
Maintenance Costs		-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400
Equipment Costs		-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500
Deicing Costs		-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140
Parking Income		$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200
Depreciation		-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373
Profit Before Taxes		$7,187	$7,188	$7,189	$7,190	$7,191	$7,192	$7,193	$7,194	$7,195	$7,196	$7,197	$7,198	$7,199	$7,200	$7,201
Tax provision		-$2,515	-$2,516	-$2,516	-$2,516	-$2,517	-$2,517	-$2,517	-$2,518	-$2,518	-$2,518	-$2,519	-$2,519	-$2,520	-$2,520	-$2,520
Net Income		$4,671	$4,672	$4,673	$4,673	$4,674	$4,675	$4,675	$4,676	$4,677	$4,677	$4,678	$4,678	$4,679	$4,680	$4,680
Add Back Depreciation		$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373
Cash Flow	-$80,600	$10,045	$10,045	$10,046	$10,047	$10,047	$10,048	$10,049	$10,049	$10,050	$10,051	$10,051	$10,052	$10,052	$10,053	$10,054
Discount factors	1.00	1.07	1.14	1.23	1.31	1.40	1.50	1.61	1.72	1.84	1.97	2.10	2.25	2.41	2.58	2.76
Present Value	-$80,600	$9,388	$8,774	$8,201	$7,665	$7,164	$6,695	$6,258	$5,849	$5,466	$5,109	$4,775	$4,463	$4,171	$3,899	$3,644
Net Present Value	$10,920															

Table C-3: Sensitivity Analysis 1 Baseline.

Traditional Asphalt Paving

	Year															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Material	-$1,000															
Excavation Costs	-$9,800															
Install	-$50,000															
Worker Training		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Maintenance Costs		-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200
Equipment Costs		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Deicing Costs		-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200
Parking Income		$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360
Depreciation		-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053
Profit Before Taxes		$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907
Tax provision		-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117
Net Income		$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789
Add Back Depreciation		$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053
Cash Flow	-$60,800	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843
Discount factors	1.00	1.07	1.14	1.23	1.31	1.40	1.50	1.61	1.72	1.84	1.97	2.10	2.25	2.41	2.58	2.76
Present Value	-$60,800	$9,199	$8,597	$8,035	$7,509	$7,018	$6,559	$6,130	$5,729	$5,354	$5,004	$4,676	$4,370	$4,084	$3,817	$3,567
Net Present Value	$28,846															

Table C-4: Sensitivity Analysis 1 Alternative.

Permeable Asphalt Paving

	Year															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Material	-$500															
Excavation Costs	-$29,600															
Install	-$50,000															
Worker Training		-$3,600	-$3,599	-$3,598	-$3,597	-$3,596	-$3,595	-$3,594	-$3,593	-$3,592	-$3,591	-$3,590	-$3,589	-$3,588	-$3,587	-$3,586
Maintenance Costs		-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400
Equipment Costs		-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500
Deicing Costs		-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140
Parking Income		$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200
Depreciation		-$5,340	-$5,340	-$5,340	-$5,340	-$5,340	-$5,340	-$5,340	-$5,340	-$5,340	-$5,340	-$5,340	-$5,340	-$5,340	-$5,340	-$5,340
Profit Before Taxes		$7,220	$7,221	$7,222	$7,223	$7,224	$7,225	$7,226	$7,227	$7,228	$7,229	$7,230	$7,231	$7,232	$7,233	$7,234
Tax provision		-$2,527	-$2,527	-$2,528	-$2,528	-$2,528	-$2,529	-$2,529	-$2,529	-$2,530	-$2,530	-$2,531	-$2,531	-$2,531	-$2,532	-$2,532
Net Income		$4,693	$4,694	$4,694	$4,695	$4,696	$4,696	$4,697	$4,698	$4,698	$4,699	$4,700	$4,700	$4,701	$4,701	$4,702
Add Back Depreciation		$5,340	$5,340	$5,340	$5,340	$5,340	$5,340	$5,340	$5,340	$5,340	$5,340	$5,340	$5,340	$5,340	$5,340	$5,340
Cash Flow	-$80,100	$10,033	$10,034	$10,034	$10,035	$10,036	$10,036	$10,037	$10,038	$10,038	$10,039	$10,040	$10,040	$10,041	$10,041	$10,042
Discount factors	1.00	1.07	1.14	1.23	1.31	1.40	1.50	1.61	1.72	1.84	1.97	2.10	2.25	2.41	2.58	2.76
Present Value	-$80,100	$9,377	$8,764	$8,191	$7,656	$7,155	$6,688	$6,250	$5,842	$5,460	$5,103	$4,770	$4,458	$4,167	$3,894	$3,640
Net Present Value	$11,314															

Table C-5: Sensitivity Analysis 2 Baseline.

Traditional Asphalt Paving

	Year															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Material	-$1,000															
Excavation Costs	-$9,800															
Install	-$50,000															
Worker Training		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Maintenance Costs		-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200
Equipment Costs		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Deicing Costs		-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200
Parking Income		$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360
Depreciation		-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053
Profit Before Taxes		$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907	$8,907
Tax provision		-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117	-$3,117
Net Income		$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789	$5,789
Add Back Depreciation		$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053
Cash Flow	-$60,800	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843	$9,843
Discount factors	1.00	1.15	1.32	1.52	1.75	2.01	2.31	2.66	3.06	3.52	4.05	4.65	5.35	6.15	7.08	8.14
Present Value	-$60,800	$8,559	$7,442	$6,472	$5,628	$4,894	$4,255	$3,700	$3,218	$2,798	$2,433	$2,116	$1,840	$1,600	$1,391	$1,210
Net Present Value	-$3,246															

Table C-6: Sensitivity Analysis 2 Alternative.

Permeable Asphalt Paving

	Year															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Material	-$1,000															
Excavation Costs	-$29,600															
Install	-$50,000															
Worker Training		-$3,600	-$3,599	-$3,598	-$3,597	-$3,596	-$3,595	-$3,594	-$3,593	-$3,592	-$3,591	-$3,590	-$3,589	-$3,588	-$3,587	-$3,586
Maintenance Costs		-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400
Equipment Costs		-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500
Deicing Costs		-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140
Parking Income		$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200
Depreciation		-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373
Profit Before Taxes		$7,187	$7,188	$7,189	$7,190	$7,191	$7,192	$7,193	$7,194	$7,195	$7,196	$7,197	$7,198	$7,199	$7,200	$7,201
Tax provision		-$2,515	-$2,516	-$2,516	-$2,516	-$2,517	-$2,517	-$2,517	-$2,518	-$2,518	-$2,518	-$2,519	-$2,519	-$2,520	-$2,520	-$2,520
Net Income		$4,671	$4,672	$4,673	$4,673	$4,674	$4,675	$4,675	$4,676	$4,677	$4,677	$4,678	$4,678	$4,679	$4,680	$4,680
Add Back Depreciation		$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373
Cash Flow	-$80,600	$10,045	$10,045	$10,046	$10,047	$10,047	$10,048	$10,049	$10,049	$10,050	$10,051	$10,051	$10,052	$10,052	$10,053	$10,054
Discount factors	1.00	1.15	1.32	1.52	1.75	2.01	2.31	2.66	3.06	3.52	4.05	4.65	5.35	6.15	7.08	8.14
Present Value	-$80,600	$8,734	$7,596	$6,605	$5,744	$4,995	$4,344	$3,778	$3,285	$2,857	$2,484	$2,160	$1,879	$1,634	$1,421	$1,236
Net Present Value	-$21,848															

Table C-7: Sensitivity Analysis 3 Baseline.																
Traditional Asphalt Paving																
	Year															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Material	-$1,000															
Excavation Costs	-$9,800															
Install	-$50,000															
Worker Training		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Maintenance Costs		-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200
Equipment Costs		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Deicing Costs		-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200
Parking Income		$30,720	$30,720	$30,720	$30,720	$30,720	$30,720	$30,720	$30,720	$30,720	$30,720	$30,720	$30,720	$30,720	$30,720	$30,720
Depreciation		-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053	-$4,053
Profit Before Taxes		$24,267	$24,267	$24,267	$24,267	$24,267	$24,267	$24,267	$24,267	$24,267	$24,267	$24,267	$24,267	$24,267	$24,267	$24,267
Tax provision		-$8,493	-$8,493	-$8,493	-$8,493	-$8,493	-$8,493	-$8,493	-$8,493	-$8,493	-$8,493	-$8,493	-$8,493	-$8,493	-$8,493	-$8,493
Net Income		$15,773	$15,773	$15,773	$15,773	$15,773	$15,773	$15,773	$15,773	$15,773	$15,773	$15,773	$15,773	$15,773	$15,773	$15,773
Add Back Depreciation		$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053	$4,053
Cash Flow	-$60,800	$19,827	$19,827	$19,827	$19,827	$19,827	$19,827	$19,827	$19,827	$19,827	$19,827	$19,827	$19,827	$19,827	$19,827	$19,827
Discount factors	1.00	1.07	1.14	1.23	1.31	1.40	1.50	1.61	1.72	1.84	1.97	2.10	2.25	2.41	2.58	2.76
Present Value	-$60,800	$18,530	$17,317	$16,184	$15,126	$14,136	$13,211	$12,347	$11,539	$10,784	$10,079	$9,420	$8,803	$8,227	$7,689	$7,186
Net Present Value	$119,780															

Table C-8: Sensitivity Analysis 3 Alternative.																
Permeable Asphalt Paving																
	Year															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Material	-$1,000															
Excavation Costs	-$29,600															
Install	-$50,000															
Worker Training		-$3,600	-$3,599	-$3,598	-$3,597	-$3,596	-$3,595	-$3,594	-$3,593	-$3,592	-$3,591	-$3,590	-$3,589	-$3,588	-$3,587	-$3,586
Maintenance Costs		-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400
Equipment Costs		-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500
Deicing Costs		-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140
Parking Income		$38,400	$38,400	$38,400	$38,400	$38,400	$38,400	$38,400	$38,400	$38,400	$38,400	$38,400	$38,400	$38,400	$38,400	$38,400
Depreciation		-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373
Profit Before Taxes		$26,387	$26,388	$26,389	$26,390	$26,391	$26,392	$26,393	$26,394	$26,395	$26,396	$26,397	$26,398	$26,399	$26,400	$26,401
Tax provision		-$9,235	-$9,236	-$9,236	-$9,236	-$9,237	-$9,237	-$9,237	-$9,238	-$9,238	-$9,238	-$9,239	-$9,239	-$9,240	-$9,240	-$9,240
Net Income		$17,151	$17,152	$17,153	$17,153	$17,154	$17,155	$17,155	$17,156	$17,157	$17,157	$17,158	$17,158	$17,159	$17,160	$17,160
Add Back Depreciation		$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373
Cash Flow	-$80,600	$22,525	$22,525	$22,526	$22,527	$22,527	$22,528	$22,529	$22,529	$22,530	$22,531	$22,531	$22,532	$22,532	$22,533	$22,534
Discount factors	1.00	1.07	1.14	1.23	1.31	1.40	1.50	1.61	1.72	1.84	1.97	2.10	2.25	2.41	2.58	2.76
Present Value	-$80,600	$21,051	$19,674	$18,388	$17,185	$16,062	$15,011	$14,030	$13,112	$12,255	$11,453	$10,704	$10,004	$9,350	$8,739	$8,167
Net Present Value	$124,587															

Table C-9: Sensitivity Analysis 4 Baseline.

Traditional Asphalt Paving

	Year															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Material	-$1,000															
Excavation Costs	-$14,200															
Install	-$50,000															
Worker Training		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Maintenance Costs		-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200
Equipment Costs		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Deicing Costs		-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200	-$1,200
Parking Income		$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360	$15,360
Depreciation		-$4,347	-$4,347	-$4,347	-$4,347	-$4,347	-$4,347	-$4,347	-$4,347	-$4,347	-$4,347	-$4,347	-$4,347	-$4,347	-$4,347	-$4,347
Profit Before Taxes		$8,613	$8,613	$8,613	$8,613	$8,613	$8,613	$8,613	$8,613	$8,613	$8,613	$8,613	$8,613	$8,613	$8,613	$8,613
Tax provision		-$3,015	-$3,015	-$3,015	-$3,015	-$3,015	-$3,015	-$3,015	-$3,015	-$3,015	-$3,015	-$3,015	-$3,015	-$3,015	-$3,015	-$3,015
Net Income		$5,599	$5,599	$5,599	$5,599	$5,599	$5,599	$5,599	$5,599	$5,599	$5,599	$5,599	$5,599	$5,599	$5,599	$5,599
Add Back Depreciation		$4,347	$4,347	$4,347	$4,347	$4,347	$4,347	$4,347	$4,347	$4,347	$4,347	$4,347	$4,347	$4,347	$4,347	$4,347
Cash Flow	-$65,200	$9,945	$9,945	$9,945	$9,945	$9,945	$9,945	$9,945	$9,945	$9,945	$9,945	$9,945	$9,945	$9,945	$9,945	$9,945
Discount factors	1.00	1.07	1.14	1.23	1.31	1.40	1.50	1.61	1.72	1.84	1.97	2.10	2.25	2.41	2.58	2.76
Present Value	-$65,200	$9,295	$8,687	$8,118	$7,587	$7,091	$6,627	$6,193	$5,788	$5,410	$5,056	$4,725	$4,416	$4,127	$3,857	$3,605
Net Present Value	$25,381															

Table C-10: Sensitivity Analysis 4 Alternative.

Permeable Asphalt Paving

	Year															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Material	-$1,000															
Excavation Costs	-$29,600															
Install	-$50,000															
Worker Training		-$3,600	-$3,599	-$3,598	-$3,597	-$3,596	-$3,595	-$3,594	-$3,593	-$3,592	-$3,591	-$3,590	-$3,589	-$3,588	-$3,587	-$3,586
Maintenance Costs		-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400	-$2,400
Equipment Costs		-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500	-$500
Deicing Costs		-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140	-$140
Parking Income		$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200	$19,200
Depreciation		-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373	-$5,373
Profit Before Taxes		$7,187	$7,188	$7,189	$7,190	$7,191	$7,192	$7,193	$7,194	$7,195	$7,196	$7,197	$7,198	$7,199	$7,200	$7,201
Tax provision		-$2,515	-$2,516	-$2,516	-$2,516	-$2,517	-$2,517	-$2,517	-$2,518	-$2,518	-$2,518	-$2,519	-$2,519	-$2,520	-$2,520	-$2,520
Net Income		$4,671	$4,672	$4,673	$4,673	$4,674	$4,675	$4,675	$4,676	$4,677	$4,677	$4,678	$4,678	$4,679	$4,680	$4,680
Add Back Depreciation		$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373	$5,373
Cash Flow	-$80,600	$10,045	$10,045	$10,046	$10,047	$10,047	$10,048	$10,049	$10,049	$10,050	$10,051	$10,051	$10,052	$10,052	$10,053	$10,054
Discount factors	1.00	1.07	1.14	1.23	1.31	1.40	1.50	1.61	1.72	1.84	1.97	2.10	2.25	2.41	2.58	2.76
Present Value	-$80,600	$9,388	$8,774	$8,201	$7,665	$7,164	$6,695	$6,258	$5,849	$5,466	$5,109	$4,775	$4,463	$4,171	$3,899	$3,644
Net Present Value	$10,920															