Porous Asphalt Pavement Designs: Proactive Design for Cold Climate Use

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Porous asphalt pavements offer an alternative technology for stormwater management. A porous asphalt pavement differs from traditional asphalt pavement designs in that the structure permits fluids to pass freely through it, reducing or controlling the amount of run-off from the surrounding area. By allowing precipitation and run-off to flow through the structure, this pavement type functions as an additional stormwater management technique. The overall benefits of porous asphalt pavements may include both environmental and safety benefits including improved stormwater management, improved skid resistance, reduction of spray to drivers and pedestrians, as well as a potential for noise reduction. With increasing environmental awareness and an evolving paradigm shift in stormwater management techniques, this research aims to provide guidance for Canadian engineers, contractors, and government agencies on the design of porous asphalt pavement structures. One of the keys to the success of this pavement type is in the design of the asphalt mix. The air void percentage, which is ultimately related to the effectiveness of the pavement to adequately control the runoff, is a critical component of the mix. However, special consideration is required in order to obtain higher air void percentages while maintaining strength and durability within a cold climate.

The objectives of this study were to evaluate several laboratory porous asphalt mix designs for durability and strength in cold climate conditions. The porous asphalt mixes consisted of a porous asphalt Superpave mix design method whereby the asphalt binder type was varied. Performance testing of the porous asphalt including draindown susceptibility, moisture-induced damage susceptibility, dynamic modulus, and permeability testing were completed. Based on the preliminary laboratory results, an optimal porous asphalt mix was recommended for use in a Canadian climate. Initial design guidelines for porous asphalt were provided based on preliminary findings and hydrological analysis.

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Chapter 1
Introduction

The following chapter provides an introduction to and background into porous/permeable/pervious pavements with respect to asphalt and concrete pavement structures as well as for interlocking concrete pavers. It will also discuss the purpose and motivation of this research including the thesis scope and objectives. Finally this chapter will provide the contents of this thesis.

1.1 Background

Three categories of pavement structures exist in modern pavement design. Flexible pavements composed of asphalt cement concrete, rigid pavement composed of portland cement concrete, and interlocking concrete pavers. In most paving applications dense graded mixes are used for roadway and parking lot surfaces. Porous pavements are an emerging technology constructed for low volume roads and parking lots as an alternative stormwater management technique or best management practice.

Traditionally pavements are designed to allow fluid to flow along the surface and drain towards catch basins and/or ditches along the side of the roads or parking lots. Porous pavements are distinct pavement types that actually permit fluids to flow through the structure. The objective of the system is to reduce or control the amount of run-off from the surrounding impermeable area as well as providing additional benefits such as noise reduction, improved safety measures for drivers and pedestrians due to reduced spray during rain, and reduced potential for black ice/ice due to improper drainage [Thelen 1978, EPA 1999, Ferguson 2005]. Disadvantages of this technology may include: lack of technical expertise (particularly in cold climates), clogging potential, potential risk of groundwater contamination, potential for toxic chemicals to leak into the system, and potential for anaerobic conditions to develop in underlying soils if unable to dry out between storm events [EPA 1999].To date there has not been extensive research into the performance of porous pavements in cold climate applications. Little research has been conducted on porous asphalt to investigate the actual performance of these mixes in colder climates.

1.2 Purpose/Motivation

The purpose of this research was to investigate the potential use of an emerging stormwater management technology as it applies to the Canadian climate. With increasing environmental awareness and an evolving paradigm shift in stormwater management techniques, this research aims to provide guidance for Canadian engineers, contractors, and government agencies in dealing with porous asphalt as a stormwater management technique. The goal of the research is to be proactive by providing an initial framework for technical expertise for the porous asphalt mixes and performance measures. This research was established as a three way partnership between Golder Associates Ltd, the Natural Science and Engineering Research Council (NSERC) and the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo.

1.3 Scope and Objectives

The purpose of this thesis is summarized as the following objectives:

1. Review literature on porous asphalt, pervious concrete, and permeable interlocking concrete pavers with respect to applications, design, construction, and maintenance.
2. Evaluate several laboratory porous asphalt mix designs for durability and strength in cold climate conditions.
3. Recommend an optimal mix design to be used in a Canadian climate
4. Provide initial design guidelines for porous asphalt based on preliminary findings and hydrological analysis.

The laboratory component of the thesis will consist solely of work with porous asphalt, whereas a discussion of pervious concrete and permeable interlocking concrete pavers will be provided in Chapter 2 Literature Review.

1.4 Methodology

The methodology used for this research included an in depth review of current porous literature, and a Superpave mix design was then done to provide alternative porous asphalt mixes. Performance tests were then conducted on the chosen mixes. After completion of the performance testing, a hydrological analysis was conducted to determine appropriate pavement designs. Finally, recommended pavement designs were provided based on subgrade type and traffic levels. Figure 1 shows the overall methodology of the research study and details of this will be explained in Chapter Three.

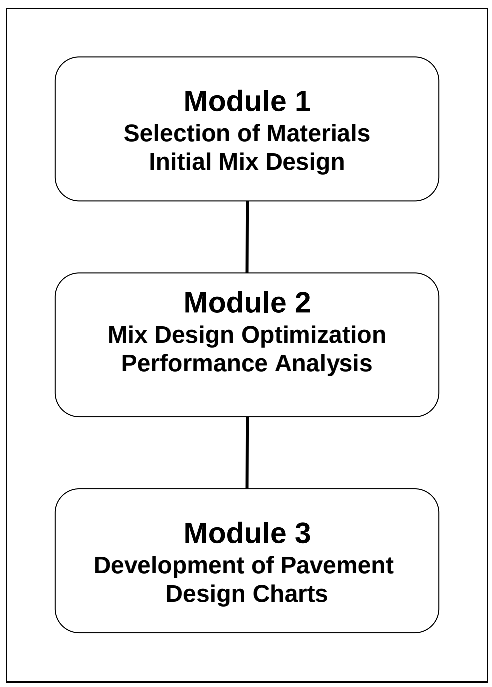

Figure 1.1 Overall Research Methodology

1.5 Organization of Thesis

Chapter One provides an introduction to the research project. It provides a general background and provides the scope and objectives of the work.

Chapter Two provides a literature review into pavements and porous pavement technology.

Chapter Three describes the experimental methodology used to conduct this research.

Chapter Four presents the mix design procedures and recommendations for the porous asphalt.

Chapter Five presents the porous asphalt performance test results.

Chapter Six recommends porous pavement designs based on hydrological considerations.

Chapter Seven provides the research conclusions and recommendations for future work.

Chapter 2
Literature Review

2.1 Introduction

The following chapter presents a literature review of porous/permeable/pervious pavements with respect to asphalt, cast in place concrete pavement structures, and interlocking concrete pavers. For the purpose of this thesis, and based on recent industry developments, porous asphalts will be the terminology used for asphalt systems, pervious for cast in place concrete systems and permeable for interlocking concrete pavers respectively. All three of the aforementioned pavement types are designed to allow free draining through the structure. The literature review will investigate the history of traditional pavement designs and design principles associated with porous pavement technology. This will include material selection, design, construction and the various maintenance and management considerations. Although the primary focus of this research is on the asphalt porous system, a brief review of the cast in place pervious concrete and interlocking concrete paver/permeable technologies will be explored.

2.2 Flexible Pavements

The Transportation Association of Canada (TAC) defines a flexible pavement as a pavement structure composed of asphalt concrete layers constructed on unbound aggregates or stabilized bases [TAC 1997]. There are various types of asphalt concrete mixtures which combine asphalt cement with coarse and fine aggregates. The following are accepted traditional asphalt concrete mixtures (or treatments) [TAC 1997]:

Mixtures:

- Hot mixed asphalt concrete and cold mix
- Hot and cold mixed treated or stabilized base
- Recycled hot mixed asphalt concrete and recycled cold mix
- Mobile plant or road cold mixes
- Stone matrix/mastic asphalt (SMA)

Thin Layer Surfaces:

- Asphalt surface treatments, including seal coats and microsurfacing
- Open-graded friction course

2.3 Porous Pavements

In the late 1960's, research into a new type of pavement structure was commencing at The Franklin Institute Research Laboratories in the United States. With the support of the United States Environmental Protection Agency (EPA), a porous pavement program was developed. This new pavement structure was initially installed in parking lots [Thelen 1978].

A porous pavement is a distinct pavement type that permits fluids either from precipitation or elsewhere, to pass freely through the structure reducing or controlling the amount of run-off from the surrounding area. By allowing precipitation and run-off to flow through the structure, this pavement type can be applied as a stormwater management practice. These particular types of pavements may also result in a reduction in the amount of pollutants entering the ground water by filtering the runoff. They are generally designed for parking areas or roads with lighter traffic [EPA 1999]. The original proposed structure of a porous pavement consisted of an open-graded surface course placed over a filter course and an open-graded base course (or reservoir) all constructed on a permeable subgrade [Thelen 1978].

There are, however, some disadvantages of this pavement type. In general there is a lack of technical expertise in theses types of pavements particularly in cold climates. Clogging potential is of concern due to the open structure of the pavement. There is a potential risk of groundwater contamination as well as a potential for toxic chemicals to leak into the system.

Porous pavements are not currently designed to treat pollutants. Finally, there is a potential for anaerobic conditions to develop in underlying soils if the systems is unable to dry out between storm events [EPA 1999].

Figure 2.1 presents an example of a typical porous section (for parking lots and light-weight vehicle pavements) that was provided in an Environmental Protection Agency study.

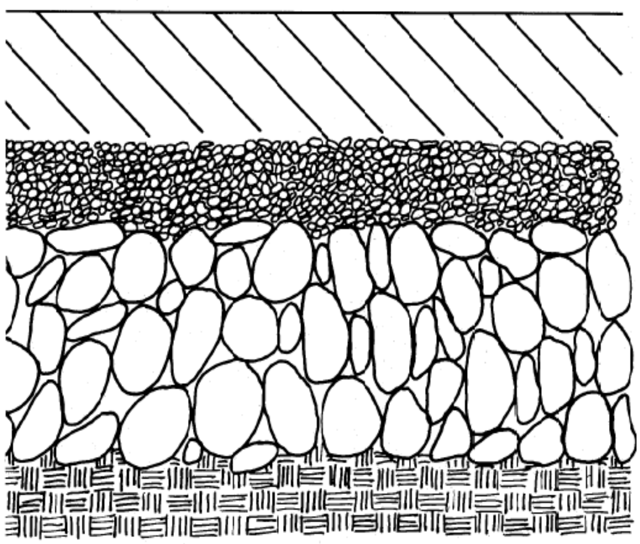

Figure 2.1 Porous Asphalt Paving Typical Section [Diniz 1980]

The EPA had identified two major types of porous pavements: porous asphalt and pervious concrete. Each type of porous pavement is a variation of the respective conventional or traditional impermeable pavement design. Porous asphalt consists of an inter-connected void system containing open-graded coarse aggregates bonded with asphalt cement and fibres, whereas the pervious concrete pavement consists of portland cement, uniformly open-grade coarse aggregates, and water combined using special porous mix designs [EPA 1999].

The literature indicates that porous pavement may also be referred to as pervious or permeable pavement. As indicated earlier, the term "porous" is often used when referring to asphalt mixes and the term “pervious” is used for cast in place concrete pavement structures. Both terms have, however, been used interchangeably [MDEQ 1992].

2.3.1 Proposed Benefits

The proposed benefits of porous pavements range from key environmental benefits to safety benefits. Some of the benefits associated with porous pavement include but are not limited to: utilization of technology to provide additional stormwater management measures or best practices, reduction in noise levels, improved safety measures for drivers and pedestrians due to reduced spray during rain, and reduced potential for black ice or ice due to improper drainage. This reduction of ice might also lead to reduced needs for certain winter maintenance activities [Thelen 1978, Ferguson 2005]. The American Concrete Institute (ACI) also provides some additional benefits over traditional pavement designs including: reduction of water-retention areas thereby increasing parking facility areas, creating additional lift to the aircraft during takeoff due to the cooling effect, and allowing air and water to reach roots of trees more efficiently [ACI 2006].

2.3.1.1 Stormwater Management

“The aim of porous pavement is to enhance and use the natural capacity of soil to absorb runoff and to replenish the earth with it” [Thelen 1978].

In comparison to a traditional dense-graded pavement, porous pavement is typically installed as an urban “Best Management Practices” (BMPs) within government agencies for an alternative practice to stormwater management and run-off control [Dunn 1995].
Porous pavement offers the potential to collect and/or slow the rate of run-off from other impervious surfaces. The National Asphalt Pavement Association (NAPA) suggests that with respect to stormwater management, porous pavement can increase permeability, potentially improve the water quality through filtering capabilities, and in certain applications, reduce the need for additional stormwater management systems [NAPA 2003]. The EPA also states that porous pavements can potentially provide the following benefits with respect to

stormwater management: water treatment by pollutant removal, reduce the need for curbing and storm sewers, and recharge local aquifers [EPA 1999].

2.3.1.2 Water Quality

Porous pavement systems can provide an excellent system for the removal of pollutants. Two long term monitoring pavements in Maryland and Virginia provide an estimate of porous asphalt's ability to remove pollutants. The studies have observed that 82% to 95% of sediment is removed as well as 65% of total phosphorus, and 80% to 85% of total nitrogen [EPA 1999]. The storage capacity and efficiency of the system is dependent on the degree of clogging within the porous system. With proper maintenance the porous system should be able to effectively remove pollutants [Balades 1995].

2.3.1.3 Safety

One of the benefits of a porous pavement is that it can provide an improvement in road safety for both drivers and pedestrians due to the potential for improved skid resistance especially when there is heavy precipitation and excess runoff conditions [EPA 1999]. Since the surface course of porous asphalt exhibits similar properties to open-graded friction courses, properly functioning porous asphalt surfaces may prevent hydroplaning on roadway surfaces as water is allowed to percolate through the system. As the standing water is eliminated from the surface spray and splash is reduced therefore improving driver visibility [NAPA 2002]. Similarly, pervious concrete also improves driver safety by reducing hydroplaning on pavement surfaces as well as reducing glare on the road surfaces specifically during wet night conditions [ACI 2006].

2.3.1.4 Noise Attenuation

Similar to an open-graded friction course, porous pavements can assist in reducing the noise generated by the tire and road contact [NAPA 2002]. Porous asphalt trials in the United Kingdom in the mid 1980's concluded that when a porous surface course was placed, a reduction of somewhere between 5.5 and 4 decibels (dB(A)) for dry conditions was observed over conventional dense-graded surfaces [Colwill 1993]. In France, in the late 1980's, researchers illustrated that porous asphalt was 1 to 6 dB(A) superior to dense-graded asphalt due to the absorbent capabilities of porous asphalt [Berengier 1990].

2.3.2 Installations

One of the earliest (scientifically monitored) systems installed was the Woodlands Parking lot near Houston, Texas in 1975 [Thelen 1978, NAPA 2003].

Porous pavements have been installed since the early 1980's throughout the United States. Cahill Associates Inc. have installed over one hundred porous pavements including parking lots, pathways, and trails for universities, libraries, religious centers, prisons, industrial parks, commercial plazas, and municipal buildings [Adams 2006].

2.3.3 Durability and Strength

One of the major concerns with porous pavement systems specifically the surface course is durability and strength characteristics. Specifically, these issues are related to the freeze-thaw performance, ravelling and coarse aggregate loss particularly with snow plow exposure, the potential for clogging due to winter maintenance applications as well as the possibility of draindown of the asphalt cement.

2.3.3.1 Freeze-Thaw Performance

Early experiments conducted by The Franklin Institute in the late 1970's suggested that when properly designed, installed, and maintained, freeze-thaw damage was not observed. Through several hundred laboratory freeze-thaw cycles, no damage or stresses were observed. Thelen stated that the freeze-thaw resistance was achieved through larger voids allowing for sufficient expansion of the water [Thelen 1978].

2.3.3.2 Clogging

The functionality of porous pavements is related to the degree to which the pavement is clogged with silt and/or other fine debris. Excessive clogging of the system can inhibit its infiltration capabilities and therefore potentially trap water in the system [Brown 2003]. NAPA suggests that neither sand nor de-icing salt should be applied to porous surfaces as it can clog the structure inhibiting the infiltrating capabilities. It is recommended that inspections be conducted for possible clogging [NAPA 2003].

2.3.3.3 Asphalt Draindown

One of the concerns with porous asphalt is the potential for asphalt draindown. The nature of porous mixes can lead to the asphalt binder draining down and out of the mix. This could be the result of gravity, transportation of the mix, as well as construction practices. To prevent draindown from occurring in porous mixes, fibres are recommended. The fibres aid in stabilizing the asphalt binder during production and placement [Cooley 2000].

2.4 Porous Asphalt: Structure, Properties, and Design

The U.S Department of Transportation and the Federal Highway Administration (FHWA) recommend that porous pavement structures consist of three components: a surface course, a filter course, and a reservoir course, all constructed on a permeable subgrade base. The surface course typically consists of a 50-100 mm (2-4 inches) of an open-graded asphalt mix. The filter course ranges between 25-50 mm (1-2 inches) consisting of crushed aggregate that provides filtering capabilities as well as a providing a suitable platform for paving. A 40 – 80 mm (1.5 – 3 inches) reservoir course is typically constructed as a storage facility. The depth of the reservoir course varies depending on the storage volume required [FHWA 2004]. Figure 2.2 illustrates a general porous asphalt structure.

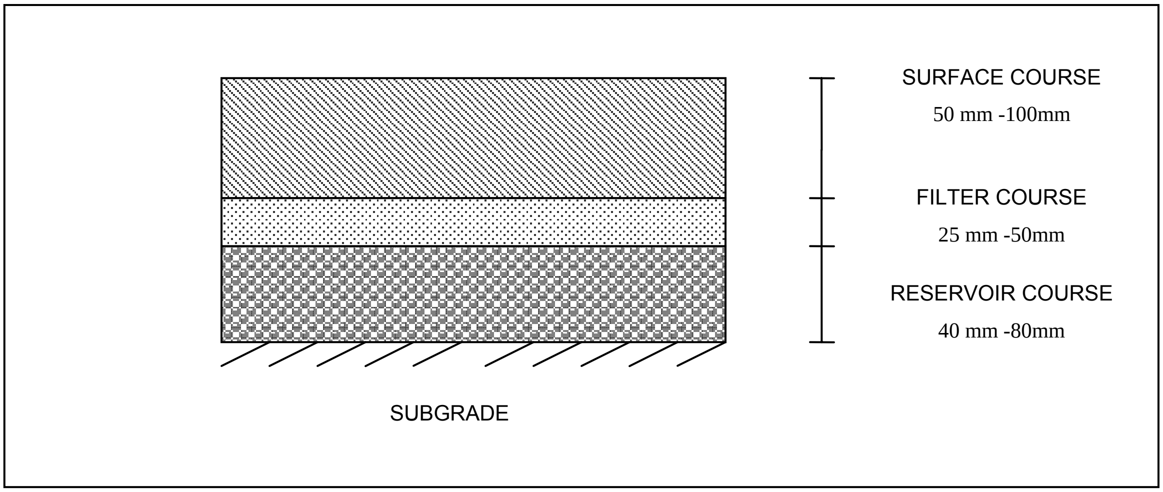

Figure 2.2 Recommended Porous Asphalt Pavement Structure

2.4.1 Surface Course Material Characteristics

Porous asphalt and traditional dense-graded asphalt surface courses generally consist of asphalt cement (binder) and various coarse and fine aggregate gradations. Modifiers as well as additives may be included to improve the material's performance [TAC 1997]. The purpose of the surface course is to provide a loading platform, ride quality and safety, and to be aesthetic pleasing [Ferguson 2005]. Currently the design guidelines for surface courses for porous asphalt are equivalent to the guidelines recommended for an open-graded friction (surface) course [NAPA 2003].

2.4.1.1 Air Void Requirements

One of the critical components of porous pavements is the permeability or infiltration capabilities of the structure. The porosity of the pavement is critical in order for the structure to remain functional.

In traditional dense-graded asphalt mix designs, a typical in-place air void percentage is between 3% and 8%. Air void percentages less then 3% have been shown to result in rutting and percentages greater then 8% can lead to oxidization of the asphalt binder resulting in cracking and/or ravelling [NCAT 1996]. Porous asphalt mixtures have significantly higher percentages of air voids in order to promote adequate infiltration. An air void percentage ranging from 16% to 22% (or greater) has been recommended [NAPA 2003, Backstrom 2000, FHWA 2004]. In Belgian applications, air void percentages have ranged on average between 19% and 25% [Van Heystraeten 1990].

2.4.1.2 Selection of Asphalt Cement

The asphalt binders typically used in asphalt concrete pavements in Ontario are performance graded asphalt cements (PGACs). Three variables are considered when specifying a PGAC: temperature, traffic loading, and percentage of recycled materials. The Ontario Ministry of Transportation has divided the Province of Ontario into three separate zones, each with a different PGAC [OHMPA 1999]. Figure 2.3 illustrates the respective zones in Ontario.

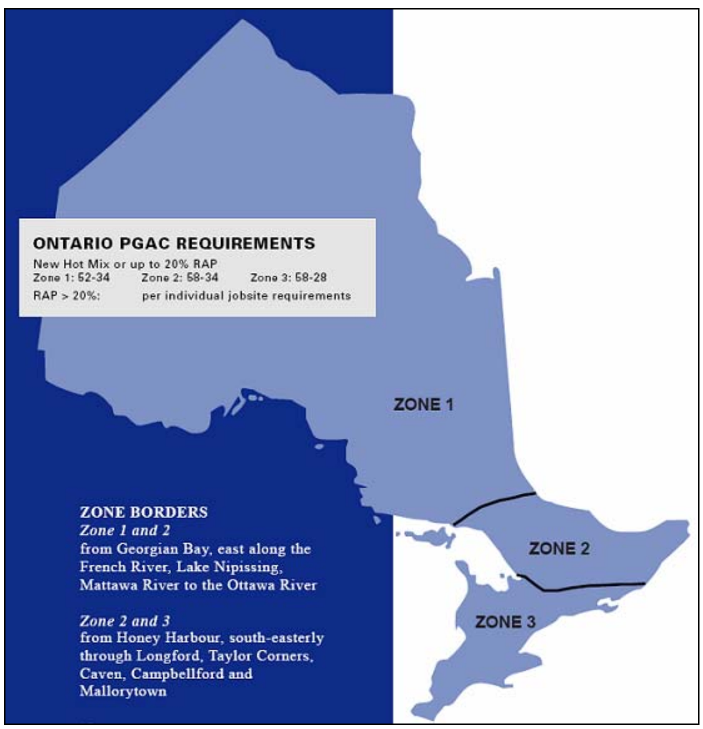

Figure 2.3 Ontario PGAC Requirements

The southernmost region of the province is considered "Zone 3". The corresponding PGAC for zone 3 is a PG 58-28 (penetration grade 150/200). A PG 58-28 has an average 7 day maximum design temperature of 58°C and a minimum design temperature of -28°C. The northern region of the province is considered “Zone 1” with a PG 52-34, and the central region in the province is “Zone 2” with a PG 58-34 [OHMPA 1999]. One of the issues in the past with porous asphalt is the lack of stiffness in the mix. Therefore it has been recommended that the grade of binder be increased two grades higher then what is normally specified for a specific region [NAPA 2003]. Using the southern region of Ontario (zone 3) as a case study, this would correspond in a performance graded asphalt cement PG 70-58. Previously, The Franklin Institute recommended that 5.5 percent of asphalt cement by weight be used in the porous mixes [Thelen 1978]. Currently, recommendations on asphalt cement content have been given ranging between 5.5%-6.5% [NAPA 2003, Cahill 2003].

2.4.1.3 Modification and Additives

One of the major failures associated with porous pavement is due to the lack of stiffness of the binder [NAPA 2003]. Asphalt modifiers can assist in reducing the temperature susceptibility of the mix. Additives such as anti-stripping agents help to promote adhesion between the binder and the aggregates [TAC 1997]. Modification and additives (specifically fibres) are required in order to prevent draindrown and improve the performance of the mix [Esenwa 2006].

2.4.1.4 Aggregates and Grading

The grading and properties of the aggregates used in the surface course are important components of the mix design to attain the proper air voids in the mix. In order to provide a high air void percentage, a high proportion of coarse aggregate and few fine aggregates are required. The coarse aggregate content is classified as the portion or percent passing of aggregates retained on a 4.75 mm (No.4) sieve [TAC 1997]. Examples of past and current design gradations for porous asphalt surface courses are provided in Table 2.1 and shown in Figure 2.4.

Table 2.1 Various Recommended Design Gradations for Porous Asphalt Surface Course

Sieve Size		Percent Passing (%)		
Metric	**Imperial**	**The Franklin Institute [Thelen, 1978]**	**National Asphalt Pavement Association [NAPA, 2003]**	**Cahill Associates [Cahill 2003]**
37.5 mm	0.5 "	100		
19 mm	0.75 "		100	
12.5 mm	0.5 "		85-100	100
9.5 mm	0.375 "	95	55-75	95
4.75 mm	**No. 4**	**35**	**10-25**	**35**
2.36 mm	No. 8	15	5-10	15
1.18 mm	No. 16	10		10
0.6 mm	No. 30			2
0.075 mm	No. 200	2	2-4	

As indicated above, The Franklin Institute and Cahill Associates recommend similar single gradations, where as the National Asphalt Pavement Association recommends a gradation envelope. The percent passing on a 4.75 mm sieve ranges between 10-35% with a small proportion of fine aggregates in the mix.

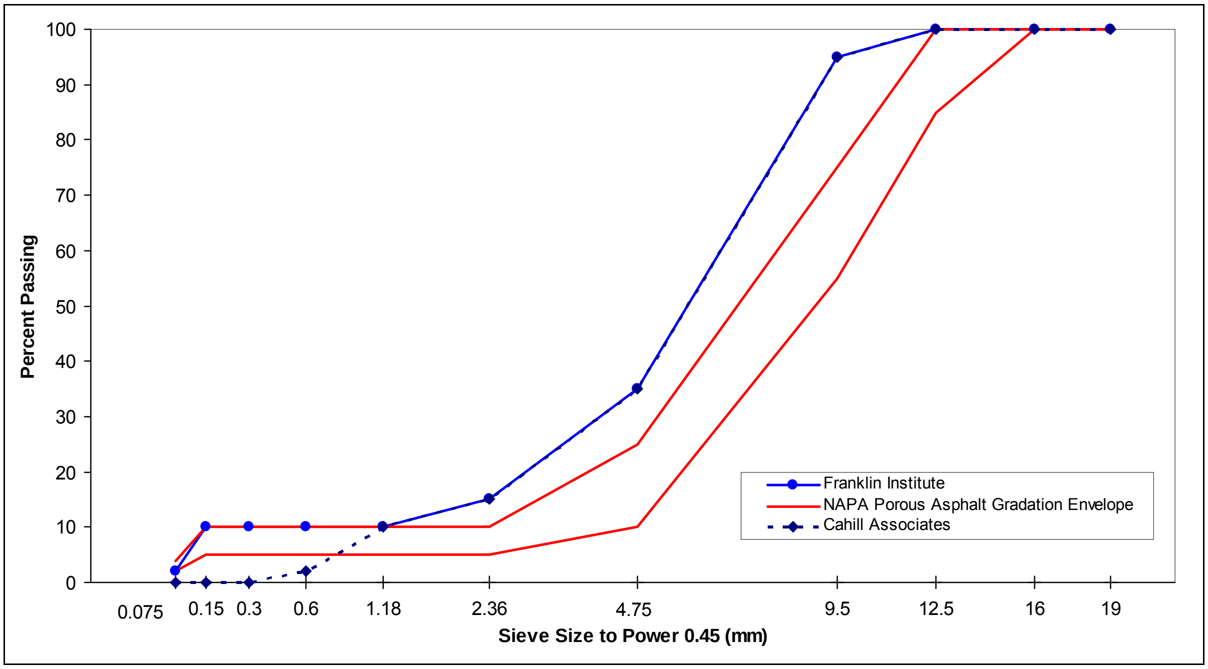

Figure 2.4 Various Recommended Design Gradations for Porous Asphalt Surface Course

The following properties of the coarse and fine aggregate are recommended by NAPA for the porous asphalt surface course [NAPA, 2003]:

Coarse Aggregate:

L.A Abrasion	≤ 30%
Fractured Faces	≥ 90% two fractured faces, 100% one fractured face
Flat and Elongated	≤ 5% 5:1 ratio
	≥ 20% 2:1 ratio

Fine Aggregate:

Fine Aggregate Angularity (FAA) ≥ 45

As noted earlier, the freeze-thaw concern should be addressed, and therefore, testing should be carried out on this concern although it is not currently addressed in the NAPA guidelines.

2.4.2 Reservoir Course Material Characteristics

The purpose of the reservoir course is to store the infiltrated water until the water can penetrate the underlying soil. This engineering layer in the pavement structure acts similarly to a retention basin [Thelen 1978]. The reservoir course ensures the material performs well under saturated conditions given that water could be trapped in this layer for a substantial period of time depending on its ability to drain. For example, the underlying subgrade soil condition could act as a barrier for drainage.

The reservoir course functions as a holding tank until the water can infiltrate into the underlying soil or sub-drains. The storage capacity requires that the porosity of the reservoir course be significantly higher then the surface asphalt course at approximately 40% air voids [Cahill 2003]. Similarly, The Franklin Institute recommended that the percentage of voids in the reservoir should be equal to or greater than 40% in order to collect the precipitation [Thelen 1978].

High air voids are critical for the reservoir course. This engineered layer must provide sufficient storage capacity for the infiltrated fluids. To obtain the appropriate high air void in the reservoir course, Table 2.2 and Figure 2.5 indicate the recommended gradations for the reservoir course.

Table 2.2 Recommended Design Gradation for Reservoir Course

Sieve Size		**Percent Passing (%)**
Metric	**Imperial**	
75 mm	3 “	100
	2.5 “	90-100
50 mm	2 “	35-75
37.5 mm	1.5 “	0-15
19 mm	0.75 “	0-5
12.5 mm	0.5 “	
0.150 mm	No. 100	0-2

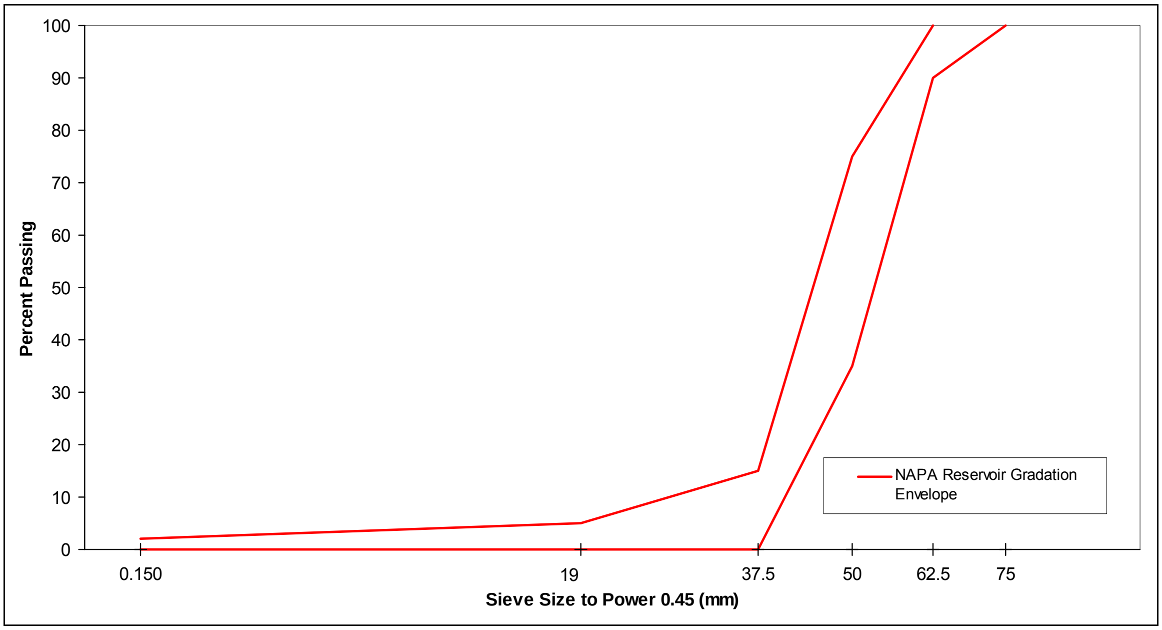

Figure 2.5 Recommended Gradation for Reservoir Course

2.4.3 Filter Course Material Characteristics

The purpose of the filter or choker course in the structure is to provide a working/ construction platform for the surface course and provide limited filtering capabilities [Ferguson 2005, NAPA 2003]. Table 2.3 provides recommended gradations for the filter course.

Table 2.3 Recommended Design Gradation for Filter Course

Sieve Size		Percent Passing (%)
Metric	**Imperial**	
12.5 mm	0.5 “	100
9.5 mm	0.375 “	0-5

2.5 Pervious Concrete: Structure, Properties, and Design

In the early 1950's, pervious concrete was used in the United States and Europe as surface overlays and drainage layers. In the State of Florida in the 1970's, the first applications of pervious concrete were installed for environmental and stormwater benefits [Ferguson 2005]. The American Concrete Institute (ACI) defines pervious concrete as zero-slump, open-graded concrete that consists of portland cement, coarse aggregate, water, as well as admixtures. Pervious concrete typically contains few to no fine aggregate [ACI 2006]. To provide high permeability, the mixes typically contain higher air voids ranging between 15% and 35% [ACI 2006, Tennis 2004].

2.5.1 Mix Design

Pervious concrete mixes have few fine aggregates and consist of narrow graded coarse aggregates. It has been suggested that both rounded and crushed aggregates can be used in pervious mixes; however, higher strengths have been achieved with rounded aggregates [Tennis 2004].

The water to cementitious ratio recommended ranges from 0.27 to 0.30. The relationship between the strength of the pervious concrete and the water to cementitious ratio isn't fully understood for pervious concrete [Tennis 2004].

Similarly to traditional conventional concrete pavements, supplementary cementitious materials can be added to a pervious mix in order to improve performance. These materials may include fly ash and pozzolans [Tennis 2004]. In addition, air entraining agents are used to provide additional protection for freeze-thaw. Although it is uncertain as to their quantifiable impact on performance, adding air entraining agents is generally desirable for extra protection against freeze-thaw damage.

Pervious concrete tends to be stiff during placement. Pervious mixtures are considered to be zero-slump mixes and do not flow freely during placement; thus, raking of the material is often required. To assist with placement, chemical admixtures (water-reducing agents) are usually added in order to make the mix more workable by increasing the slump [Ferguson 2005].

2.5.2 Strength

The compressive strength of pervious concrete has been stated to range between 3 and 28 MPa [ACI 2006, Tennis 2004]. Steel reinforcement should not be installed in pervious concrete mixtures as the steel does not bond properly within the mix. Steel reinforcement would be easily subjected to corrosion due to the porous nature of the mix and thus is generally not recommended [Ferguson 2005].

2.5.3 Cold Climate Durability

One of the initial concerns regarding the durability of pervious concrete is its resistance to freeze-thaw damage. If a pervious pavement system is designed appropriately with the higher air void percentage, then water should be able to pass freely through the system and into the underlying soils leaving no remaining water available to freeze. If the pervious concrete is saturated though, any additional water attempting to pass through the system will remain and potentially freeze causing damage to the pervious concrete. It has been suggested that pervious concrete may become saturated under the following conditions [NRMCA 2004]:

- Clogging of the air voids
- Areas where the average daily temperature stays below the freezing point for a long period throughout the year thus preventing drainage
- When the ground water table is less than approximately one metre from the top of the pavement surface

The National Ready-Mixed Concrete Association has stated that partially saturated pervious concrete systems have shown good freeze-thaw durability and that limited amounts of clogging are not expected to inhibit its freeze-thaw resistance [NRMCA 2004].

For a region such as Ontario, the National Ready-Mixed Concrete Association would classify the area as a “Hard Wet Freeze” region. This is defined as an area where the ground remains frozen for long periods of time. These areas have the potential for pervious concrete to become fully saturated. To enhance the freeze-thaw resistance in these areas it is recommended that a layer of clean aggregate base be constructed below the concrete. Air-entraining admixtures may be added to the mix, and additional drainage may be provided to assist in drainage as well [NRMCA 2004]. Testing has indicated that air-entraining agents have improved the freeze-thaw ability of pervious concrete whereas pervious concrete without air-entraining has failed in laboratory testing [ACI 2006].

2.5.4 Site Condition

Pervious concrete is best suited for areas where the underlying soils have permeability greater then 13 mm per hour with a soil layer of 1.2 m, as recommended by the ACI [ACI 2006].

The ACI suggests that the site be prepared in a specific manner in order to ensure good performance. The top 150 mm of subgrade/subbase should be constructed of selected subgrade material or granular subbase with less then 10% silt or clay. Prior to placement of the pervious concrete, the subgrade should not be saturated or frozen; however, the subgrade should be moist at time of placement [ACI 2006].

2.5.5 Construction and Placement of Surface Layer

The Portland Cement Association (PCA) recommends the following practices for the placement of pervious concrete [Tennis 2004]:

- Placement should be continuous, and spreading and strikeoff rapid
- Conventional formwork can be used
- Compaction can be accomplished with both mechanical and vibratory screeds
- Edges should be compacted with a 300 mm by 300 mm steel tamp

- Consolidation is accomplished with a steel roller and should be completed within 15 minutes of placement
- Normal floating and troweling finishing practices should not be done as they may fill up the surface voids. (Typically, compaction practices will “finish” most pervious concrete pavements)
- 6 to 13.5 m joint spacing based on geometry
- Curing should commence 20 minutes after placement; fog misting covered by plastic sheeting is recommended.
- Curing should last a minimum of 7 days.

2.5.6 Maintenance

The primary goal of the maintenance activities for pervious concrete is concerned with the prevention of clogging within the structure. Vacuuming of the structure annually (or as required) is recommended to ensure that void structure is clear of dirt and debris [Tennis 2004]. The Mississippi Concrete Industries Association (MCIA) indicates that pressure washing of pervious concrete can restore 80%-90% of the permeability of the pervious concrete [MCIA 2002]. The ACI provides a suggested maintenance schedule for pervious concrete [ACI 2006]. Table 2.4 provides the recommended maintenance activities specifically for pervious concrete.

Table 2.4 Recommended Maintenance Activities for Pervious Concrete

Maintenance Activity	Frequency
-Ensure that paving area is clean of debris -Ensure that the area is clean of sediments	Monthly
-Seed bare upland areas -Vacuum sweep to keep the surface free of sediment	As needed
-Inspect the surface for deterioration	Annually

The above mentioned maintenance activities do not necessarily represent all of the maintenance activities and/or frequencies that may be required especially in cold climate applications. The type of activity may need to be changed and frequency may have to be increased for colder climates that are subjected to de-icing activities. Further research is required to explore the clogging potential of pervious concrete pavements.

2.6 Permeable Interlocking Concrete Pavers

Permeable precast interlocking concrete pavers offer an additional type of paving material to be installed as a best management practice for stormwater management. The permeable pavers consist of infiltration trenches with a paving material over top to support vehicle and pedestrian loads [Burak 2004]. For the general paver design, the interlocking geometry provides regular void spacing throughout the system. The voids are typically filled with sand allowing for appropriate drainage while maintaining a suitable surface. The infiltrated precipitation is collected within a drainage layer and transported to a storm water collection system or reservoir designed to infiltrate precipitation into the subgrade below. Typical application sites include low traffic roadways, mainly local streets and parking facilities. Pavers provide an improved esthetic pavement whereby grass growth can be supported due to the design of the structure [FHWA 2004]. Figure 2.6 illustrates a typical permeable paver structure.

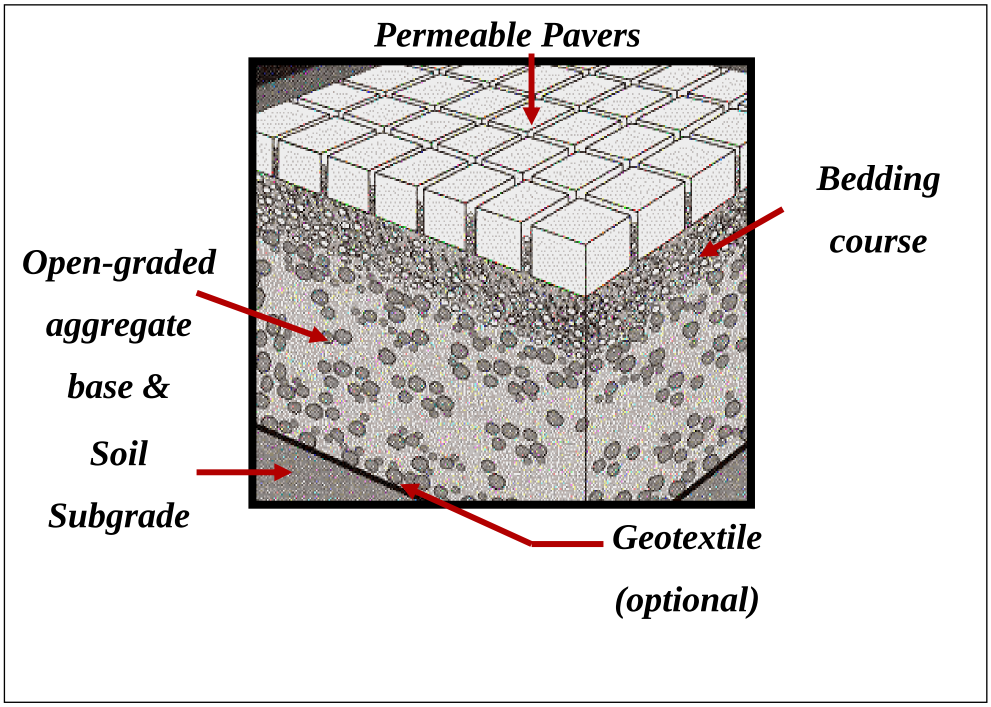

Figure 2.6 Permeable Paver Structure

2.6.1 Types of Permeable Concrete Pavers

The Interlocking Concrete Pavement Institute (ICPI) suggests four various types of permeable pavers. Interlocking shapes with openings are designed with specific patterns allowing fluid to drain through the openings. The specific shape of the units creates the drainage openings while maintaining high side-to-side contact between the units. Enlarged permeable joints are constructed with large joints allowing fluid to penetrate the system. These enlarged joints may be as wide as 35 mm. Porous concrete pavers are similar to pervious concrete pavements. The pavers are placed directly beside one another, and fluid is able to penetrate directly through the concrete. Concrete grid pavers are similar to the above mentioned pavers; however, these types of pavers have different applications. They are typically used in lower volume traffic areas whereas the above pavers may be used for higher traffic volumes [ICPI 2006]. Figure 2.7 illustrates the various types of permeable pavers.

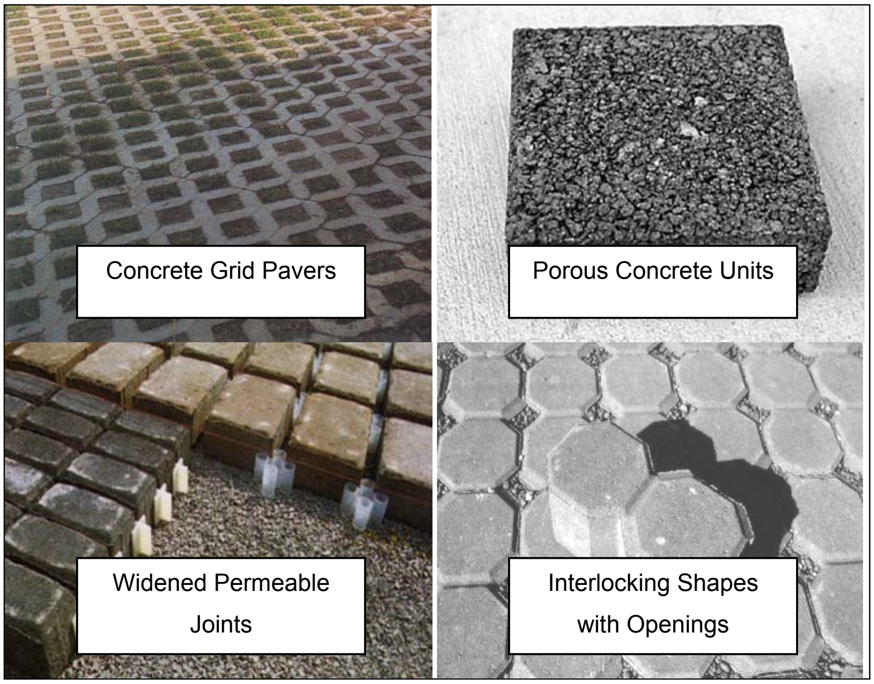

Figure 2.7 Types of Permeable Pavers

2.7 Pavement Design Theory

There are several theories associated with pavement design; experience based, empirical, and the Mechanistic-Empirical Pavement Design Guide (MEPDG).

Experience based pavement design employs standard sections that are derived from successful past designs. Experience based pavement designs provide standard layer thicknesses based on site conditions including but not limited to: soil types, traffic levels, roadway classifications, and drainage properties. However, experience based designs are limited in providing future properties such as increased traffic, new materials, and improved construction and maintenance activities [TAC 1997].

Empirically based pavement design has been the primary pavement design theory used in the United States between the 1970's and the 1990's through the releases of the American Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures, 1972, 1986, and 1993. The AASHTO guides were based on empirical principles developed from data obtained from the 1950's AASHO Road Test. Due to some of the limitations within the guides with respect to traffic loading, foundations, material characterization, pavement performance, and environment, it was determined that an improved guide that dealt with these limitations was required [NCRHP 2004]. Empirically based designs rely on the results of measured responses (i.e. deflection). These responses are used to provide limits for pavement design. Similar problems arise with future properties as observed with experience based designs [TAC 1997].

The goal of the new design guide is to provide designers with a state-of-the-practice guide for designing new and/or rehabilitated pavements based on mechanistic-empirical theory. According to the National Cooperative Highway Research Program (NCHRP), the objective was obtained through the following [NCHRP 2004]:

1. The Design Guide itself, which is based on comprehensive pavement design procedures that use existing mechanistic-empirical technologies.
2. User-oriented computational software and documentation based on the Design Guide procedure.

The general design approach is summarized as follows: initially site conditions such as traffic, climate, subgrade, existing pavement condition, and construction conditions are evaluated, and a proposed trial design is determined. Prediction of key distresses and smoothness are used to evaluate the sufficiency of the trial design. If the trial design is determined to be inadequate, the design is re-evaluated, and the process can be repeated. The objective of the design process is to optimize the design and to eliminate the development of pavement distresses such as cracking, rutting, etc. [NCHRP 2004].

2.8 Summary

This chapter presented a literature review of porous/permeable/pervious pavements with respect to asphalt, interlocking concrete pavers, and cast in place concrete pavement structures. All of these pavements are designed to allow free draining through the structure. The literature review also provided a summary of the history of traditional pavement designs and the specific design principles associated with porous pavement technology. Porous pavements are generally designed for parking areas or roads with lighter traffic. By permitting fluids to pass freely through the structure it can assist in reducing or controlling the amount of run-off from the surrounding area, and therefore, it can be applied as a stormwater management practice. These particular types of pavements may also result in a reduction in the amount of pollutants entering the ground water by filtering the runoff [EPA 1999]. Additional benefits may include a reduction in noise levels, improved safety measures for drivers and pedestrians due to reduced spray during rain, and reduced potential for black ice/ice due to improper drainage [Thelen 1978, Ferguson 2005]. This chapter also stated the major concerns with porous pavement systems. These included durability and strength concerns with respect to the surface course. Specifically these issues are related to the freeze-thaw performance, ravelling and loss of coarse aggregate, clogging potential, and asphalt cement draindown.

Porous asphalt pavement structures generally consist of a porous asphalt surface course (a filter course may be installed) and a reservoir course all placed on the subgrade material. One of the key components to the success of porous pavements is the permeability or infiltration capabilities of the structure. High porosity is required for the structure to remain functional. Typical dense-graded asphalt mix designs have an in-place air void percentage is between 3% and 8%. Porous asphalt mixtures have significantly higher percentages of air voids ranging from 16% to 22%. Failures of porous asphalt pavements have been associated with lack of stiffness of the binder [NAPA 2003]. Asphalt modifiers can assist in reducing the temperature susceptibility of the mix. Porous asphalt mixes consist of coarse aggregate with a percent passing on the 4.75 mm sieve that ranges between 10% and 35%, with a small proportion of fine aggregates in the mix. The reservoir course must store a significantly higher amount of fluid within the structure, and therefore, the porosity of the reservoir course should be approximately 40% air voids [Cahill 2003].

Finally the chapter concluded with a brief summary of the theories associated with pavement design including experience based, empirical, and the Mechanistic-Empirical Pavement Design Guide (MEPDG).

Chapter 3
Experimental Methodology

The purpose of this chapter is to present the research methodology employed in this study. The experimental methodology for this research was divided into three modules. Module one was to determine a suitable mix for porous asphalt based on Canadian conditions using southern Ontario as a case study. Module two was to examine the performance of the mixtures through specific performance testing. The final module, module three, was to provide porous pavement designs based on hydrological considerations. Figure 3.1 provides a flow chart of the modules.

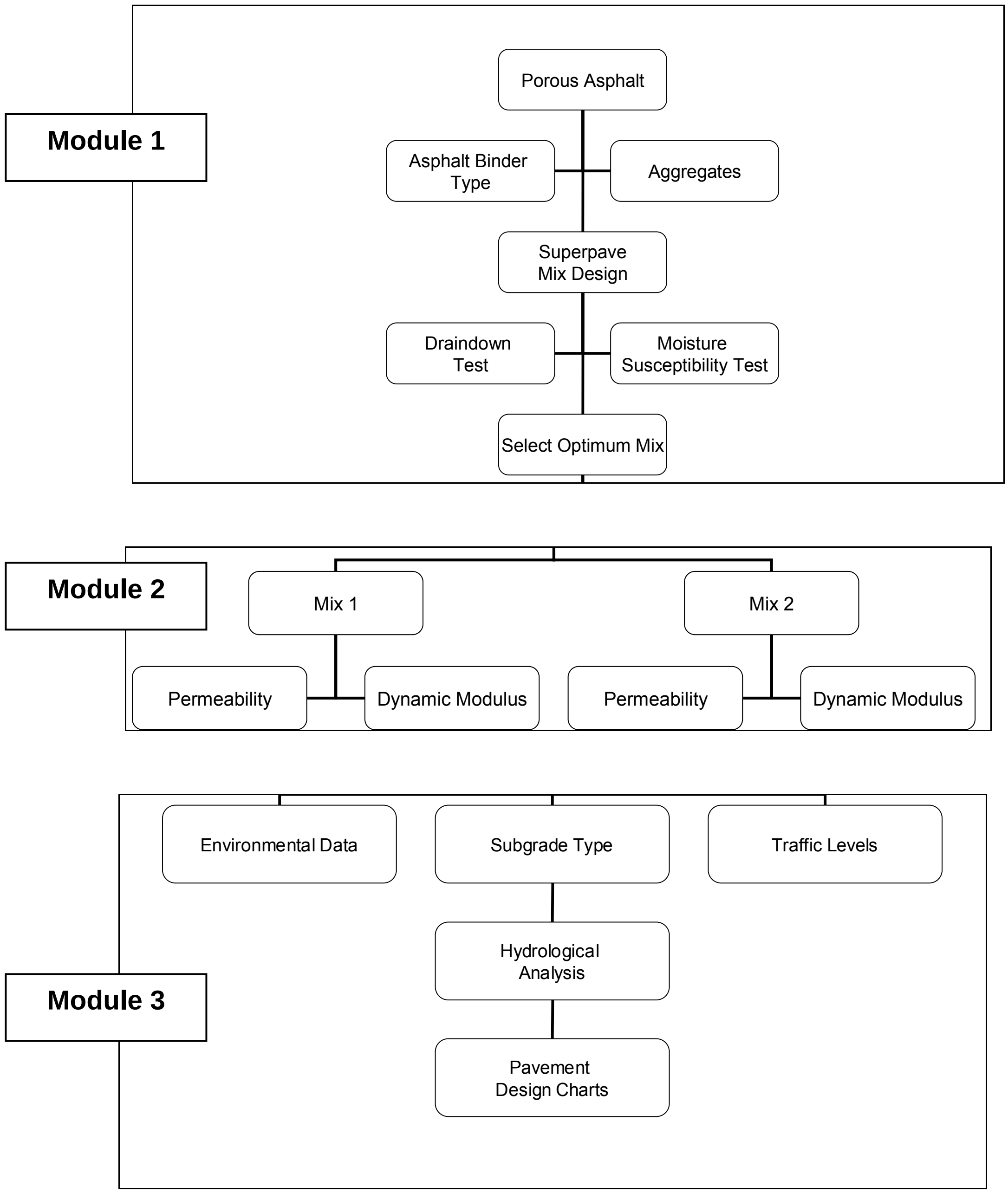

Figure 3.1 Research Module Flow Chart

3.1 Experimental Mixes

The objective of the porous asphalt mix design was to determine the optimum binder content and air void percentage to be used in the porous mixes. In addition to basic mix design procedures, the Modified Lottman Test (AASHTO T-283) and draindown tests were performed on the porous mixes. The detailed mix design will be discussed in Chapter 4. Two porous asphalt mixtures were designed with similar properties to each other; however, different binder types were incorporated. NAPA recommended that due to lack of stiffness, the asphalt binder should be increased by two grades [NAPA 2003]. Based on these recommendations for a southern Ontario mix, a polymer modified asphalt (PMA) PG 70-28 binder was chosen as well as a PG 64-28. The objective was to evaluate their effect on performance when used in a porous asphalt mixture. In total two experimental mixes were examined in this research. Performance tests including permeability and dynamic modulus tests were completed on the mixes. Table 3.1 summarizes the specific mix design tests and performance tests conducted in this research.

Table 3.1 Porous Asphalt Tests

Test	Standard	Purpose
Draindown	ASTM D6390-99	To determine whether the asphalt draindown of the mixes were within acceptable limits.
Modified Lottman Test	AASHTO T-283	To examine the resistance of the asphalt mixtures to moisture-induced damage.
Permeability	Gilson Asphalt Permeameter and The Florida Department of Transportation Designation FM 5-565	To assess the effectiveness of the mixes to transport fluid through the structure.
Dynamic Modulus	AASHTO TP62-03	To determine dynamic modulus values for characterization of the asphalt for both pavement design and in-service performance purposes.

3.2 Mix Design Tests

The initial phase of the experimental matrix included the investigation of durability and strength in cold climate conditions. In addition to general mix design procedures, the draindown characteristics of the mixes were determined. The Modified Lottman Test was also performed on the mixes in order to evaluate their susceptibility to moisture induced damage.

3.2.1 Draindown Characteristics

The determination of the draindown characteristics was completed using the ASTM standard test method (ASTM D6390-99). The acceptable draindown for the porous asphalt has been recommended at less then 0.3% [NAPA, 2003]. A summarized method for determination of draindown involves preparing laboratory uncompacted samples. These samples were placed in a standard draindown basket and placed in the oven for one hour. The amount of asphalt draindown from each mix was then determined. The draindown test was completed on a PG 64-28 porous mix at 5.5%, 6.0%, and 6.5% asphalt content, as well as on a PG 70-28 polymer modified asphalt porous mix at 5.5%, 6.0%, and 6.5% asphalt content.

3.2.2 Modified Lottman Test (AASHTO T-283)

The Modified Lottman Test or AASHTO T-283 Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage was used to investigate the effects of saturation and accelerated water conditioning under freezing and thawing cycles [AASHTO 2004d]. The American Association of State Highway and Transportation Officials (AASHTO) summarizes the test method as the following: [AASHTO 2004d]

Each mixture condition specimen is divided into two subsets. The first subset is tested for indirect-tensile strength in a dry condition. The second subset is subjected to a vacuum saturation and a freeze cycle, followed by a warm-water soaking cycle, and then the indirect-tensile strength is determined. Once the test data is determined for both the dry and conditioned subsets, numerical indices of retained indirect-tensile strength properties are calculated, and the tensile strength ratio (TSR) is determined. As recommended due to the higher porosity, this test was completed at five freeze-thaw cycles [NAPA 2003]. Previous research at the National Center for Asphalt Technology (NCAT) has indicated that for the higher air void percentages observed in both an open graded friction course as well as porous asphalt, the samples should be tested under more severe cases, therefore the number of cycles in the Modified Lottman Test should be increased [Mallick 2000].

3.3 Performance Testing

The second phase of the laboratory component of the research included the performance testing of the porous asphalt mixtures. This testing was carried out in the state of the art CPATT laboratory. Two performance tests were conducted on the specimens: dynamic modulus and permeability. These tests are particularly important for comparisons to other new and innovative asphalt pavement designs.

3.3.1 Dynamic Modulus

The dynamic modulus values determined in this research can assist in the characterization of the asphalt for both pavement design and in-service performance purposes. The test was performed in accordance with AASHTO TP 62-03. The dynamic modulus test was performed over a range of temperatures and frequencies of loading to simulate real world environmental and traffic loading conditions. The measurements observed can be further used for performance criteria [AASHTO 2003]. The AASHTO summary of method is as follows: a sinusoidal axial compressive stress is applied to a specimen of asphalt concrete at a given temperature and loading frequency. The applied stress and the resulting recoverable axial strain response of the specimen is measured and used to calculate the dynamic modulus and phase angle [AASHTO 2003]. The dynamic modulus is a fundamental property required for Level 1 of the Mechanistic Empirical Pavement Design Guide (MEPDG) design.

3.3.2 Permeability

One of the critical properties of the porous asphalt is the ability to properly drain the fluid (i.e. rainfall, etc) through the system. Permeability tests were performed on the porous asphalt samples using the Gilson Asphalt Field Permeameter and procedure. All of the samples tested for dynamic modulus were first tested using the permeameter in order to determine the coefficient of permeability.

3.4 Air Void Confirmation

The air void percentages for the porous mixes were difficult to determine due to the open structure of the mix. Several methods were employed and finally the air voids were confirmed using a CoreLok® apparatus performed by DBA Engineering Ltd. The various methods for determining the air voids and the final air void analysis are discussed in Chapter 4.

3.5 Summary

This chapter presented the research methodology. The research included three experimental modules: porous asphalt mix design, performance testing, and hydrological pavement design. The objective of the porous asphalt mix design was to determine the optimum binder content and air void percentage of the porous mixes. Two porous asphalt mixtures were tested using different binder types. A polymer modified asphalt (PMA) PG 70-28 binder and a PG 64-28 were chosen. Performance tests included draindown characteristics and the Modified Lottman Test (moisture-induced damage susceptibility) that were performed during the initial mix design stage and permeability and dynamic modulus tests that were performed on the final mixes.

Chapter 4
Mix Design

The following chapter describes the procedures followed in determining the porous asphalt mix designs. It briefly discusses classical mix design theory including Marshall Mix design and Superpave Mix design. The chapter details the design procedure including the determination of the design gradations, air void analysis, draindown characteristics, and asphalt content. The Modified Lottman Test procedure and results will also be discussed. Finally, the final porous asphalt job-mix formula is provided.

4.1 Mix Design Background

There are three major methods for designing hot-mix asphalt. Between the 1940's and the mid 1990's the Marshall or Hveem methods were the most common mix design method used. More recently, there has been a shift to the Superpave mix design method [NCAT 1996]. The Asphalt Institute states that the objective of asphalt mix design is to "determine a cost-effective blend and gradation of aggregates and asphalt that yields a mix having [Asphalt Institute 1997]:

1. Sufficient asphalt cement binder to ensure a durable pavement.
2. Sufficient mix stability to satisfy the demands of traffic without distortion or displacement.
3. Sufficient voids in the total compacted mix to allow for a slight amount of additional compaction under traffic loading and a slight amount of asphalt expansion due to temperature increases without flushing, bleeding, and loss of stability.
4. A maximum void content to limit the permeability of harmful air and moisture into the mix.
5. Sufficient workability to permit efficient placement of the mix without segregation and without sacrificing stability and performance.

For surface mixes, proper aggregate texture and hardness to provide sufficient skid resistance in unfavourable weather conditions.”

4.2 Marshall Mix Design Theory

The original concept for the Marshall Mix design was initiated by Bruce Marshall in 1943 with the Mississippi State Highway Department. Using these concepts the U.S Army Corps of Engineers developed the mix design criteria, and finally the American Society of Testing and Materials (ASTM) standardized the test procedures [Asphalt Institute 1997]. The Marshall method attempts to provide similar laboratory densities as those exhibited in the field due to the densification induced by traffic loading. A 4.54 kg (10 lbs) hammer with a 98.4 mm (3.875 in) foot plate was selected for compaction. A compacted effort of 50 blows per each specimen side has become standard practice [NCAT 1996]. This serves as the primary method of mix design in Ontario and elsewhere in Canada.

4.3 Superpave Mix Design Theory

Superpave mix design is a newer system for specifying asphalt materials for asphalt concretes that was developed as part of the Strategic Highway Research Program (SHRP) in the late 1980’s. The system provides a method for selecting and specifying asphalt binders and includes various aggregate requirements. According to the Asphalt Institute, the unique feature of the Superpave system is that it is considered a performance-based system. The theory is that the tests and analysis performed in the laboratory will have direct relationships to field performance of the asphalt mixtures. The Superpave system of designing mixes begins with the selection of asphalt and aggregates that meet Superpave specifications, and a volumetric analysis is conducted of the mix specimens that have been compacted with a Superpave gyratory compactor [Asphalt Institute 2001].

4.4 Materials

The following section describes the materials used to produce the porous asphalt samples for this research. The materials used for this research included two different types of aggregate, two different asphalt binder types, as well as cellulose fibres. All the materials were provided from local suppliers within the Province of Ontario to represent typical materials that would be available for porous asphalt applications within Ontario.

4.4.1 Aggregates

The aggregates used in the porous asphalt mixtures consisted of limestone coarse aggregate and a screenings fine aggregate. A small percentage of filler was also used in this particular mix design. Limestone was chosen as the coarse aggregate as it is a common higher quality aggregate available in Ontario. Figure 4.1 provides a photograph of the aggregates.

Figure 4.1 Coarse and Fine Aggregates

Table 4.1 summarizes the aggregate properties as provided by the supplier. Figure 4.2 illustrates the aggregate gradations.

Table 4.1 Aggregate Properties

Aggregate Type	Aggregate Data	Aggregate Specific Gravity	Aggregate Absorption (%)	Fractured Faces	Flat and Elongated	Micro-Deval
19 mm clear stone	CA#1	2.686	1.5	100	3	10.5
Screenings	FA#1	2.769	0.79	--	--	--

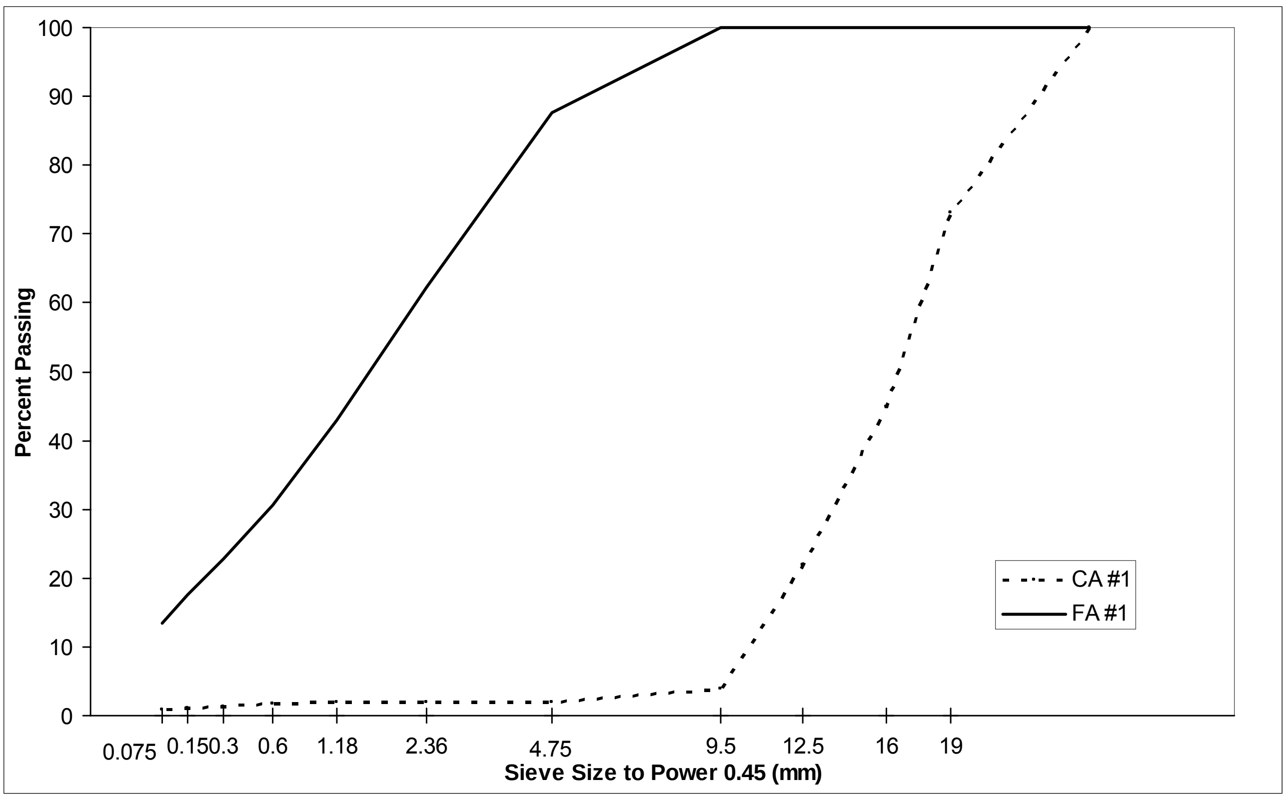

Figure 4.2 Coarse and Fine Aggregate Gradations

4.4.2 Asphalt

Two different types of asphalt binders were used in the design of the mixes. It has been recommended that high stiffness binders be used in porous asphalt mixes, specifically two grades higher then what is typically placed in a region. It is also recommended that polymer modified binders may be used to enhance stiffness. [NAPA 2003]. A PG 64-28 and a PG 70-28 polymer modified asphalt (PMA) binder were chosen to be used in the porous mixes.

The PG 70-28 PMA as provided by the supplier had a recommended mixing temperature of 165°C and a recommended compaction temperature of 150°C. The PG 64-28 binder as provided by the supplier had a recommended mixing temperature between 155°C -162°C and a recommended compaction temperature between 142°C -148°C.

4.4.3 Fibres

Porous asphalt because of the nature of the mix design, can be susceptible to draindown of the asphalt binder. Cellulose fibres were added to the mix in order to prevent draindown from occurring during mixing and placement. Fibres may assist with the mix's durability as the fibres may allow for the asphalt content to be increased allowing for an increased film thickness around the aggregates [Cooley 2000].

4.5 Porous Superpave Mix Design

The design method used for determining the mix design for porous asphalt using Superpave methodology for this research combined the general Superpave method as provided by the Asphalt Institute [Asphalt Institute 2001] as well as the method and recommendations provided from the National Asphalt Pavement Association for porous asphalt pavements [NAPA 2003]. The following sections describe the procedure used in this research to determine the suitable design gradation and optimal asphalt content to batch the final mixes to be used for porous asphalt. These mixes were then used to batch specimens for specific performance testing.

4.5.1 Design Procedure

The determination of the final job-mix formula for the porous mixes required several initial design steps to be completed. Initially trial blends were used to determine the design gradation. Using the determined design gradation, several specimens were prepared using three different asphalt contents. Air void and draindown analyses were then conducted and the optimal asphalt content was determined.

4.5.2 Design Gradation

The design gradation was determined by evaluating three trial blend gradations. The trial blends were classified as middle, fine, and coarse gradations that all were within the NAPA recommended gradation limits. Figure 4.3 illustrates the three trial gradations.

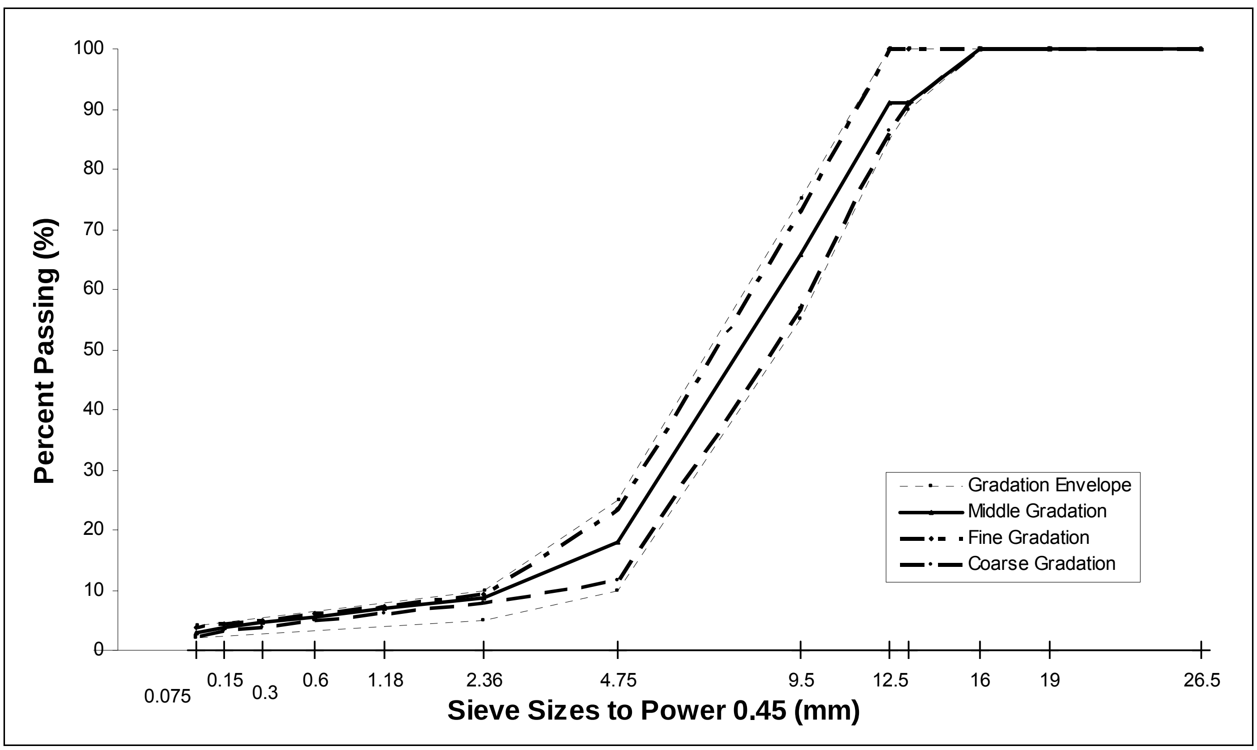

Figure 4.3 Porous Asphalt Trial Gradations

Two specimens for each of the trial gradations were compacted using the Rainhart Superpave Gyratory Compactor (SGC), and a third sample was prepared to determine the maximum relative density (G_{mm}) of the mixture. The compacted samples were compacted at N_{des} equal to 50 gyrations. The mixtures were prepared using the PG 64-28 asphalt binder at an asphalt content of 6.0%. Each specimen was short-term aged for two hours in a force draft oven. The compaction temperatures ranged between 138°C – 145°C. The dry-rodded voids in coarse aggregate of the coarse aggregate fraction (VCA_{DRC}) and the voids in coarse aggregate of the mixture (VCA_{MIX}) were then determined for all of the specimens. A second set of trial blends were completed using the procedure as above; however, the PG 70-28 PMA was used. The air voids were determined using the Ministry of Transportation, Ontario's former Method of Test for Bulk Relative Density of Compacted Bituminous Mixtures Using Paraffin Coated Specimens (Test Method LS-306). There were some issues in determining the air voids and these will be discussed in detail later in the chapter. The design gradation was determined by comparing the VCA_{MIX} and VCA_{DRC} values for each of the trial specimens. Table 4.2 summarizes the VCA_{MIX} and VCA_{DRC} and air void percentages obtained.

Table 4.2 VCA_{MIX} and VCA_{DRC} Values for Trial Gradations

AC Type	Trial Blend	VCA_{DRC}	VCA_{MIX}	AV%
PG 64-28	Fine	40.7	23.4	9.0
	Medium	40.7	23.4	9.0
	Coarse	40.7	23.7	8.9
PG 70-28	Fine	40.7	22.9	8.5
	Medium	40.7	24.4	11.2
	Coarse	40.7	23.1	10.0

It was recommended that the design gradation be determined by the trial blend where the VCA_{MIX} was less then VCA_{DRC} and achieved the highest air voids. [NAPA 2003]. Based on the results, the middle gradation was chosen as the design gradation for both binder types.

4.5.3 Asphalt Content

Once the design gradation was determined, it was then used to prepare several specimens at various asphalt contents in order to determine the optimum asphalt content. Three asphalt contents were evaluated, 5.5%, 6.0%, and 6.5% asphalt cement. These three were selected based on engineering best practice after consultation with public and private sector experts. The specimens were evaluated based on an air void analysis and the draindown characteristics. The results for each were utilized to determine the final or optimum asphalt content.

4.5.4 Air Void Analysis

The air void percentages of the porous asphalt samples were very difficult to determine due to the higher porosity. Three specimens were prepared for each percentage of asphalt contents to evaluate the maximum relative density (G_{mm}), and three specimens were prepared to evaluate the bulk relative density (G_{mb}). The G_{mm} was determined using the AASHTO T209-99 standard method [AASHTO 2004b]. The bulk relative density was the more difficult of the two densities to determine. In order to determine G_{mb}, three methods were employed. The first two methods were conducted to attempt to determine the G_{mb}, and finally, the third method was conducted to anticipate the true $G_{mb.}$

The first attempt at the air void determination was completed using the AASHTO T166 Standard Method [AASHTO 2004a]. However, due to the increased porosity of the mixtures, the results were suspect as a substantial amount of water was lost in the handling process resulting in inaccurate values. A second method was attempted using the Ministry of Transportation, Ontario's former Method of Test for Bulk Relative Density of Compacted Bituminous Mixtures Using Paraffin Coated Specimens (Test Method LS-306) [MTO 1996]. This method consisted of coating the specimens with paraffin wax and then determining the bulk relative density similarly to the procedure as completed in AASHTO T166. However, in an investigation into the samples, it was concluded that once again due to the high porous nature of the mixtures, an accurate determination of the air voids could not be determined using this G_{mb} as a significant amount of wax filled the pores. Due to laboratory constraints, in order to determine the asphalt content, the MTO method for G_{mb} determination was employed since the relative difference in air voids between the various asphalt contents was required. The results obtained from this method were used to determine the final asphalt content. The final method for the air void determination will be discussed further in the chapter. Figure 4.4 illustrates the air voids analysis results using the AASHTO T269-97 and MTO methods for air void determination.

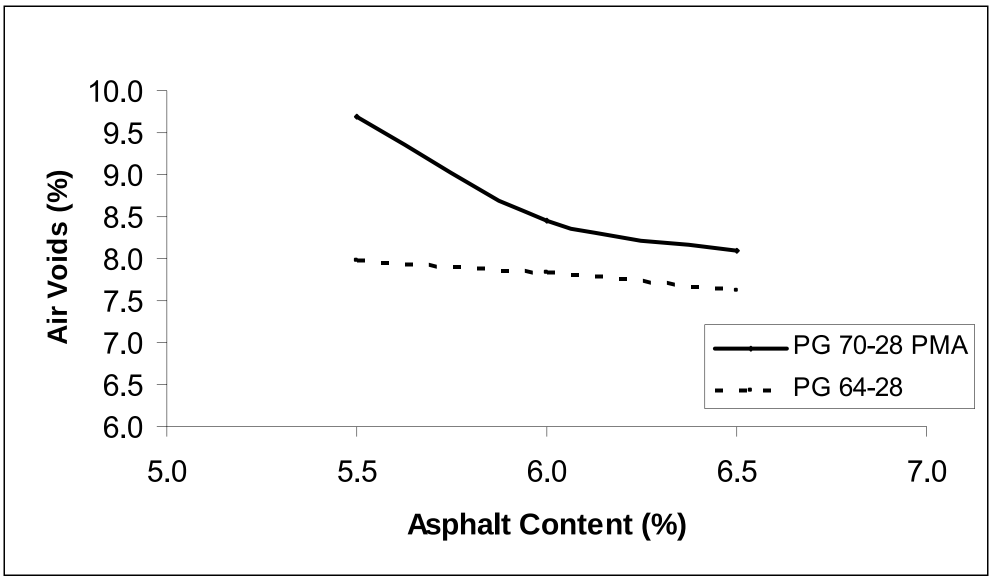

Figure 4.4 Asphalt Content Determination Air Void Analysis

As illustrated in the figure, higher air voids were achieved when the asphalt content was lower. Although there is minimal difference between the air voids between the 5.5% and 6.0% asphalt cement content for the PG 64-28 mix, 5.5% may provide a better value. The above analysis was used in order to determine the optimal asphalt content to be used in the preparation of the final samples for the performance testing. Results from this were also verified and checked with industry experts.

4.5.5 Asphalt Draindown Analysis

The draindown analysis was completed as per ASTM D6390-99 [ASTM 2005]. This test was performed on uncompacted porous asphalt samples using the PG 64-28, and the PG 70-28 PMA, binder types. The same asphalt contents of 5.5%, 6.0%, and 6.5% were used to perform this test. The draindown test was conducted at 15^{o}C higher then the mixing temperature for each of the binder types as recommended by NAPA. [NAPA 2003]. Table 4.3 indicates a summary of the draindown results.

Table 4.3 Porous Asphalt Draindown Results

Sample	PG	AC%	Temperature (^{o}C)	Average Draindown (%)
1	64-28	5.5	175	0.01
2	64-28	6.0	175	0.01
3	64-28	6.5	175	0.02
4	70-28	5.5	180	0.02
5	70-28	6.0	180	0.02
6	70-28	6.5	180	0.02

It was recommended that the draindown of a porous asphalt sample be limited to less then 0.3% [NAPA 2003]. As indicated above, for each of the asphalt content increments the average draindown was within the 0.3% limit. Therefore, in terms of the draindown characteristics any one of the asphalt contents could be chosen as the final asphalt content.

4.5.6 Optimum Asphalt Content

The National Asphalt Pavement Association recommends that the optimum asphalt content for porous asphalt be determined by the asphalt content the meets the following requirements: air voids greater then 18% and draindown less then 0.3% [NAPA 2003].

Based on the results of the air void analysis and the draindown characteristics the final asphalt content was chosen to be 5.5% asphalt cement.

4.6 Final Job-Mix Formula

After completing all the mix design procedures stated above the final job mix formula was obtained. This job-mix formula was then used to batch samples required for the performance testing. Figure 4.5 illustrates the final job-mix gradation.

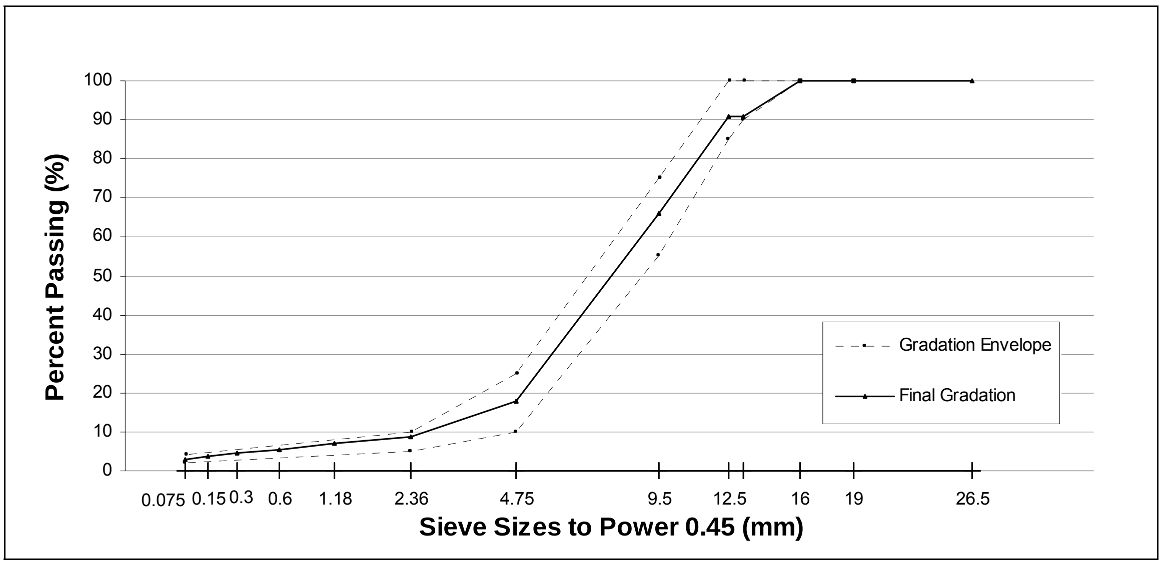

Figure 4.5 Final Job-Mix Gradation Porous Asphalt

Two different mixes were prepared using the above gradation for performance testing. The first mix consisted of 5.5% PG 64-28 asphalt cement with 0.3% fibres and the second mix consisted of 5.5% PG 70-28 PMA cement with 0.3% fibres.

4.7 Modified Lottman Test

To determine the resistance of the porous samples to moisture-induced damage, the Modified Lottman test (AASHTO T 283) was conducted. As stated in Chapter 3, this test is used to investigate the effects of saturation and accelerated water conditioning under freezing and thawing cycles [AASHTO 2004d]. Given the fact that the purpose of the porous asphalt structure is to allow fluid to flow through the system, it was important to evaluate the effect of the water (moisture) on the asphalt mixes. The test was performed on the mixes as per AASHTO T 283. Five freeze–thaw cycles were used in this test, because given the higher air voids exhibited by porous asphalt it was recommended that the samples be tested in more severe conditions [Mallick 2000]. Therefore, the freeze-thaw cycles were increased. Although this test is typically conducted to assist in the determination of appropriate final mix designs, in this research the test was performed after the determination of the final job-mix formula. The samples were batched from the final job-mix formula as stated above using both the PG 64-28 and the polymer modified PG 70-28 binders. The Modified Lottman test was performed by Golder Associates Ltd. The test evaluates the ratio of the tensile strength of two different subsets, a dry subset and a wet (freeze-thaw) subset. The tensile strength ratio is calculated using the following equation [AASHTO 2004d]:

$$TSR = S_2 / S_1 \qquad (4.1)$$

Where:

TSR = tensile strength ratio

S_1 = average tensile strength of the dry subset, kPa

S_2 = average tensile strength of the conditioned subset (wet, freeze-thaw), kPa

The tensile strength of each of the subsets was calculated using the following equation [AASHTO 2004d]:

$$S_t = 2000\ P / \pi\ t\ D \qquad (4.2)$$

Where:

S_t = tensile strength, kPa

P = maximum load, N

t = specimen thickness, mm

D = specimen diameter, mm

π = 3.14

Three subsets for each of the binder types were used in the dry condition and three subsets for each binder type was saturated and subjected to five freeze-thaw cycles. The indirect tensile strengths were determined and the resulting TSR was determined for each binder type. Table 4.4 summarizes the results of the Modified Lottman Test.

Table 4.4 Modified Lottman Test Results

Mix	Dry Subsets	Wet Subsets	t (mm)	D (mm)	P (N)	S_t (kPa)	Average S_t (kPa)	TSR (%)
PG 64-28	1		103	150	5338	220.0	280.2	**65.0**
	2		102	150	7206	299.8		
	3		103	150	7784	320.7		
		4	103	150	4181	172.3	182.1	
		5	103	150	4270	175.9		
		6	103	150	4804	197.9		
PG 70-28	1		101	150	8006	336.4	384.8	**84.6**
	2		100	150	9608	407.8		
	3		104	150	10052	410.2		
		4	104	150	8785	358.5	325.6	
		5	102	150	5827	242.5		
		6	103	150	9118	375.7		

As indicated above, the TSR for the PG 64-28 was determined to be 65%, whereas the TSR for the PG 70-28 was determined to be 84.6%. Comparing the two results, the mix containing the PG 70-28 binder maintains approximately 85% of its original dry tensile strength, as compared to only 65% of the mix containing the PG 64-28 binder. NAPA recommends that the TSR values for porous asphalt should be greater then 80% [NAPA 2003]. In order for porous asphalt to be installed and to be successful in wet and colder climates such as in Ontario, one of the issues that is critical is maintaining a certain level of strength when subjected to these conditions. It is important that the loss of strength under these harsh conditions be minimized. It can be concluded that since the TSR value for the PG 70-28 binder is greater than 80%, the PG 70-28 binder should be recommended for porous asphalt to minimize the tensile strength lost under freeze-thaw conditions. However, further performance testing was completed on both binder types and will be discussed in Chapter 5.

4.8 Air Void Confirmation

Once the mixes were completed, additional samples were prepared and the percentages of air voids were anticipated using a CoreLok® apparatus performed by DBA Engineering Ltd. The CoreLoK® can be used to determine the air voids of Superpave, Stone Matrix (SMA), and Coarse mix asphalts. It follows ASTM D6752, D6857, and D7063. It provides the most reliable method for the determination of bulk specific gravity of this special type of mix. The system works by sealing the samples and the densities are then measured by the water displacement method. The samples are sealed in puncture resistant polymer bags [InstroTek 2007]. Figure 4.6 depicts the apparatus.

(Source: InstroTek http://www.instrotek.com/corelok.htm)

Figure 4.6 Corelok® Apparatus

Table 4.5 indicates the confirmed final air void percentages as well as a summary of results based on the various test methods used to determine the bulk relative densities.

Table 4.5 Air Void Comparison

Mix Type	Air Void %		
	Corelok®	MTO	AASHTO T166
PG 70-28	16.5	10.1	14.1
PG 64-28	17.1	7.9	12.6

As indicated the Corelok® confirmed the air void percentage for the mixes at 17.1% and 16.5% for the PG 64-28 and PG 70-28 respectively for a number of samples. It is also apparent that due to the higher porosity of these specific types of asphalt mixes that the typical methods for determining the bulk relative densities are not suitable methods for measuring the air voids of porous mixes and it is recommend that the Corelok® or a similar apparatus be employed when determining the air voids of porous asphalt.

4.9 Summary

This chapter presented the procedures followed to determine the porous asphalt mix designs. A brief discussion of classical mix design theory including Marshall Mix design and Superpave Mix design was presented. Superpave mix design theory was employed to design the porous asphalt with additional guidance provided by the National Asphalt Pavement Association. The materials used for the porous asphalt mixes were presented including, the coarse and fine aggregates, the asphalt cement, and the fibres. The general procedures for the determination of the design gradations, air void analysis, draindown characteristics, the Modified Lottman test, and asphalt content were also presented. The design procedure included determination of design gradation by testing trial gradations and the determination of asphalt content by evaluating asphalt contents between 5.5% and 6.5%. The air voids were determined using three methods for determination. The final job-mix formula was presented. The Modified Lottman test results and the air void confirmation were also discussed.

Chapter 5
Performance Testing

The following chapter discusses the performance testing completed on the porous asphalt specimens. Two performance tests were completed on the porous asphalt samples including permeability and dynamic modulus. The procedures and results of the tests for both mix types are presented. The sample preparation and testing equipment used to conduct the experiments will also be discussed.

5.1 Sample Preparation and Equipment

The samples were prepared using the Rainhart Superpave Gyratory Compactor (SGC) in the CPATT John J Carrick Pavement Laboratory at the University of Waterloo using the job mix formula as previously stated in chapter 4. Figure 5.1 depicts the Rainhart Superpave Gyratory Compactor.

Figure 5.1 Rainhart Superpave Gyratory Compactor

Four samples for each mix type were prepared for the dynamic modulus test for a total of eight samples. These samples were cored and trimmed from the gyratory sample to fulfill the specimen dimensions required for dynamic modulus testing procedure. Figure 5.2 depicts the coring equipment and Figure 5.3 illustrates the cored samples.

Figure 5.2 Coring Apparatus

Figure 5.3 Cored Samples for Dynamic Modulus Test

The dynamic modulus testing was completed using the Interlaken Universal Test Machine. This testing system is a computer controlled system that contains an integrated load frame (including hydraulic power supply), a triaxial cell, and environmental chamber [Uzarowski 2006]. Figure 5.4 depicts the Interlaken testing system.

Figure 5.4 Interlaken Testing System

Three Linear Variable Differential Transducers (LVDT's) were used to measured deformations on the samples. Each LVDT had a gage length of 75 mm. Figure 5.5 depicts the LVDT configuration on the specimen.

Figure 5.5 Sensor Configuration for Dynamic Modulus Testing

5.2 Permeability

The permeability of the samples was evaluated using a Gilson Asphalt Field Permeameter in the CPATT Laboratory. Figure 5.6 depicts the configuration of the test apparatus.

Figure 5.6 Permeameter Apparatus

The permeability test was conducted using the above mentioned permeameter. The test procedure was performed based on the falling head principle of permeability. It should be noted that the test was adapted to be used in a laboratory setting. The permeability test was conducted on eight samples in total. Four samples consisted of the PG 64-28 asphalt binder and the remaining four samples consisted of the PG 70-28 PMA binder. Each sample tested for permeability was then used to conduct the dynamic modulus test. The permeability test was conducted on 150 mm diameters gyratory samples prior to any coring or trimming procedures. Figure 5.7 depicts the apparatus with the sample in place.

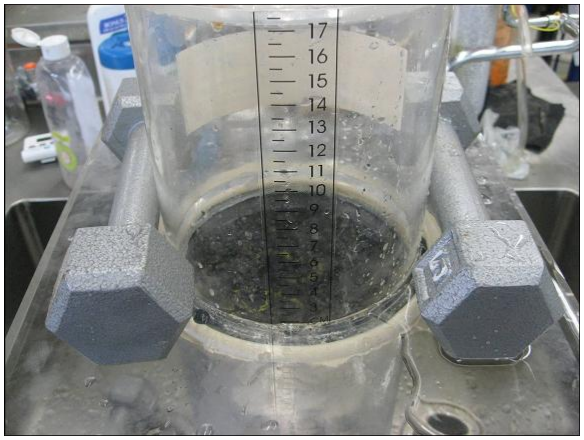

Figure 5.7 Permeameter With Sample in Place

The procedure was completed as per the manufacturer's procedure. The procedure summary was as follows: each sample was wrapped securely with a thin plastic wrap, and then secured in a metal mould. The permeameter was then placed on the top surface of the sample in the mould. The moldable sealant was then applied around the base of the permeameter. Four five pound weights were placed on the base to prevent a break in the sealant. Once the apparatus was secured with a sample, the permeameter was filled with water at a steady rate. Once the water reached the top of the meter and was allowed to settle, the rate at which the water level dropped was determined. A water level change of 10 cm was measured for each time trial. The time was recorded over a change in head of 10 cm. The change in head height (10cm) and the time (s) was recorded for each sequence. The sequence was completed five times per sample and an average coefficient of permeability was calculated. The coefficient of permeability was calculated using the following equation:

$$K = (a\,L / At)\ ln(h_1/h_2) \qquad (5.1)$$

Where:

K = coefficient of permeability

a = inside cross-sectional area of the standpipe (cm^2)

L = length of the sample (cm)

A = cross-sectional area of permeameter through which water can penetrated the pavement area (cm^2)

t = elapsed time between h_1 and h_2 (s)

h_1 = initial head (cm)

h_2 = final head (cm)

The permeability test was conducted at a water temperature of 17^{o}C, therefore a temperature correction factor of 1.08 was applied to each of the coefficient of permeability measurements from the Florida Department of Transportation (FDOT) Method test for Measurement of Water Permeability of Compacted Asphalt Paving Mixtures [FDOT 2006]. The permeability testing results are found in Table 5.1.

Table 5.1 Average Coefficient of Permeability for Porous Asphalt

Mix Type	Average Coefficient of Permeability (cm/s)	Number of Samples	Standard Deviation
PG 64-28	0.99	4	0.20
PG 70-28	1.00	4	0.19

The coefficient permeability for both mix types was determined to be approximately 1.00 cm/s. As stated in Chapter 4, the confirmed air void percentage for the mixes was 17.1% and 16.5% for the PG 64-28 and PG 70-28 respectively. With the mixes exhibiting similar air void percentages, comparable coefficients permeability was expected. Table 5.2 summarizes a comparison of coefficient of permeability rates of various other materials to the porous asphalt.

Table 5.2 Coefficient of Permeability Rate Comparison

Mix/Material	Average Air Voids (%)	Average Coefficient of Permeability (cm/s)
Porous Asphalt		
PG 64-28	16.5	0.99
PG 70-28	17.1	1.00
Soils/Aggregates		
Gravel*	--	1.00
Sand**	--	3.53×10^{-4}
Silt**	--	7.06×10^{-5}
Clay**	--	7.06×10^{-6}
Dense-Graded Laboratory Mixes*		
SP 9.5 mm fine (surface)	8.3	1.94×10^{-3}
SP 9.5 mm coarse (surface)	5.5	3.95×10^{-4}
SP 12.5 mm coarse (surface)	5.0	1.02×10^{-3}
SP 19 mm coarse (base)	7.1	2.34×10^{-3}
SP 25 mm coarse (base)	6.6	2.19×10^{-5}

* [Elgamal 2002] ** [PCA 2006] *** [Mallick 2003]

The porous asphalt mixes exhibit identical permeability rates to traditional gravel which was to be expected due to the open void structure of the mix. The rates were also compared to laboratory permeability testing of five different Superpave dense-graded mixes from the National Center for Asphalt Technology [Mallick 2003]. The porous asphalt exhibited significantly higher rates then the dense graded mixes as was to be expected as dense-graded mixes are designed to be relatively impermeable.

5.3 Dynamic Modulus Testing

The dynamic modulus is a linear viscoelastic test conducted on asphalt specimens. The FHWA defines the dynamic modulus (E*) as the "viscoelastic test response developed under sinusoidal loading conditions. It is the absolute value of dividing the peak-to-peak stress by the peak-to-peak strain from material subjected to a sinusoidal loading" [FHWA, 2001]. The Mechanistic Empirical Pavement Design Guide (MEPDG) incorporates the dynamic modulus in order to characterize the various asphalt mixtures used in the design of high-volume roads and highways [FHWA, 2001]. The purpose of the dynamic modulus testing on the porous asphalt samples was to evaluate the mixes for cold weather conditions as well as to compare their performance to traditional asphalt mix types. The procedure for testing the dynamic modulus of the porous asphalt samples was provided by the AASHTO TP62-03 standard for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures [AASHTO, 2003].

5.3.1 Dynamic Modulus Test Results

The dynamic modulus test was performed as per the AASHTO TP 62-03 designation at six loading frequencies, 0.1 Hz, 0.5 Hz, 1 Hz, 5.0 Hz, 10 Hz, and 25 Hz and at five different temperatures, -10^{o}C, 4.4^{o}C, 21.1^{o}C, 37.8^{o}C, and 54.4^{o}C. Three samples of each mix type were tested. The axial strain for the test was approximately 50 microstrains. Through the testing, the dynamic modulus (E*) and phase angle (φ) were determined for both mix types. For each of the test conditions, the loading stress, σ_o, was calculated over the last five loading cycles [AASHTO 2003].

$$\sigma_o = P / A \qquad (5.2)$$

Where:

P = average peak load (N)

A = area of specimen (mm^2)

σ_o = average peak stress (kPa)

The recoverable axial strain was calculated individually for each LVDT over the last five loading cycles for each test condition as follows [AASHTO 2003]:

$\varepsilon_o = \Delta / GL$ (5.3)

Where:

Δ = average peak deformation (mm)

GL = gage length (mm)

ε_o = average peak strain (unitless)

For each test condition and over the last five loading cycles, the dynamic modulus, E* individually for each LVDT was calculated as follows [AASHTO 2003]:

$E^* = \sigma_o / \varepsilon_o$ (5.4)

For each test condition and over the last five loading cycles, the phase angle individually for each LVDT was calculated as follows [AASHTO 2003]:

$\Phi = (t_i / t_p)*(360)$ (5.5)

Where:

t_i = average lag time between a cycle of stress and strain (sec)

t_p = average time for a stress cycle (sec)

Φ = phase angle (degree)

Tables 5.3, Table 5.4, Table 5.5, and Table 5.6 summarizes the dynamic modulus at three temperatures and five frequency ranges, phase angle, stress, and strain results for the two porous asphalt mixes. Samples of the testing system outputs for the dynamic modulus testing can be found in Appendix A. The dynamic modulus testing could not be completed at the last two higher temperatures as the mixes became unstable and the strain levels were outside the range of the LVDT's. Cracking and permanent deformation failure was observed during loading, therefore, the dynamic modulus, phase angle, stress, and strain values could not be accurately determined for the 37.8°C, and 54.4°C temperatures. These were therefore excluded from the results.

Table 5.3 Summary of Dynamic Modulus Testing Results for Porous Asphalt

Mix	Frequency (Hz)	Average Dynamic Modulus (kPa)		
		-10.0°C	4.4°C	21.1°C
PG 64-28	25	11,754,487	5,009,317	3,368,547
	10	10,663,827	4,058,505	2,572,734
	5	9,889,343	3,411,361	2,091,725
	1	7,948,256	2,268,055	1,295,305
	0.5	7,403,895	1,772,012	1,060,941
	0.1	5,853,597	1,206,048	725,819
PG 70-28	25	15,113,332	8,830,763	4,213,873
	10	13,673,313	7,526,869	3,203,280
	5	12,729,398	6,633,168	2,558,477
	1	10,478,204	4,758,141	1,529,181
	0.5	9,761,238	4,071,540	1,229,439
	0.1	7,852,756	2,766,339	800,608

As indicated in the dynamic modulus table, higher values were observed for the mix containing the PG 70-28 asphalt binder. The overall higher values on the PG 70-28 mix were observed due to the increase stiffness that the 70-28 binder type provides. The binder is also a polymer modified binder that also increased the stiffness of the mix. Higher dynamic modulus values were observed at the lower temperatures and decreased as the testing temperature increased.

Table 5.4 Summary of Phase Angle Testing Results for Porous Asphalt

Mix	Frequency (Hz)	Average Phase Angle		
		−10.0°C	4.4°C	21.1°C
PG 64-28	25	10.34	17.88	21.58
	10	10.23	18.44	22.39
	5	10.77	19.97	23.35
	1	12.59	23.21	25.59
	0.5	13.52	25.01	25.96
	0.1	16.21	27.19	24.59
PG 70-28	25	8.91	15.33	22.44
	10	9.43	15.80	23.95
	5	9.87	16.86	25.82
	1	11.85	20.95	28.82
	0.5	12.77	22.78	29.27
	0.1	15.22	26.94	27.63

Higher phase angles were observed for the PG 64-28 mix then the PG 70-28 mix. The phase angles observed increased as the test temperature increased. The phase angles above indicate that at the lower temperatures the porous asphalt behaved more elastic as compared to at the higher temperatures. The PG 70-28 mix was behaved more elastic then the PG 64-28 mix.

Table 5.5 Summary of Stress Testing Results for Porous Asphalt

Mix	Frequency (Hz)	Average Stress		
		−10.0°C	4.4°C	21.1°C
PG 64-28	25	14,423.66	12,896.51	12,037.20
	10	13,058.51	12,724.40	12,312.39
	5	12,685.05	12,413.86	12,392.77
	1	12,341.08	12,118.57	11,800.60
	0.5	12,402.28	11,909.77	11,822.39
	0.1	12,155.79	11,697.07	11,746.57
PG 70-28	25	14,340.43	13,522.98	12,054.75
	10	12,976.62	12,680.15	12,360.95
	5	12,537.05	12,362.60	12,288.34
	1	12,552.70	12,089.02	11,561.76
	0.5	12,439.12	12,063.49	11,598.56
	0.1	12,214.50	11,708.07	11,674.96

The stresses observed in the two mixes were relatively the same with the PG 64-28 mix exhibiting slightly higher stresses. There were slight changes in the observed stresses over the testing temperatures with a slight decrease in stress as the temperature increased.

Table 5.6 Summary of Strain Testing Results for Porous Asphalt

Mix	Frequency (Hz)	Average Strain		
		-10.0°C	4.4°C	21.1°C
PG 64-28	25	0.00167	0.00159	0.00155
	10	0.00159	0.00160	0.00157
	5	0.00155	0.00154	0.00154
	1	0.00150	0.00146	0.00145
	0.5	0.00154	0.00149	0.00144
	0.1	0.00149	0.00144	0.00147
PG 70-28	25	0.00157	0.00153	0.00153
	10	0.00150	0.00152	0.00153
	5	0.00150	0.00146	0.00150
	1	0.00146	0.00145	0.00146
	0.5	0.00147	0.00145	0.00144
	0.1	0.00145	0.00144	0.00145

The average strain values for the mixes were once again relatively the same between the two different mixes. The strain values slightly decreased as temperature values increased.

5.3.2 Master Curve Development

Asphalt is a viscoelastic material and therefore the mechanical behaviour of the material is dependent on the temperature and time of loading. In order to compare the results of the two mixes the temperatures are normalized or shifted relative to the time loading so that the various curves form a single master curve [AASHTO 2003]. The shift factors for the master curves were calculated using the following equation [AASHTO 2003]:

$$t_r = t/a(T) \qquad (5.6)$$

Where:

t_r = reduced time, time of loading at the reference temperature,

t = time of loading, the reciprocal of the loading frequency,

a(T) = shift factor a function of temperature,

T = Temperature

Figure 5.8 and Figure 5.9 shows the master curve and shift factor plot for PG 64-28 porous mix.

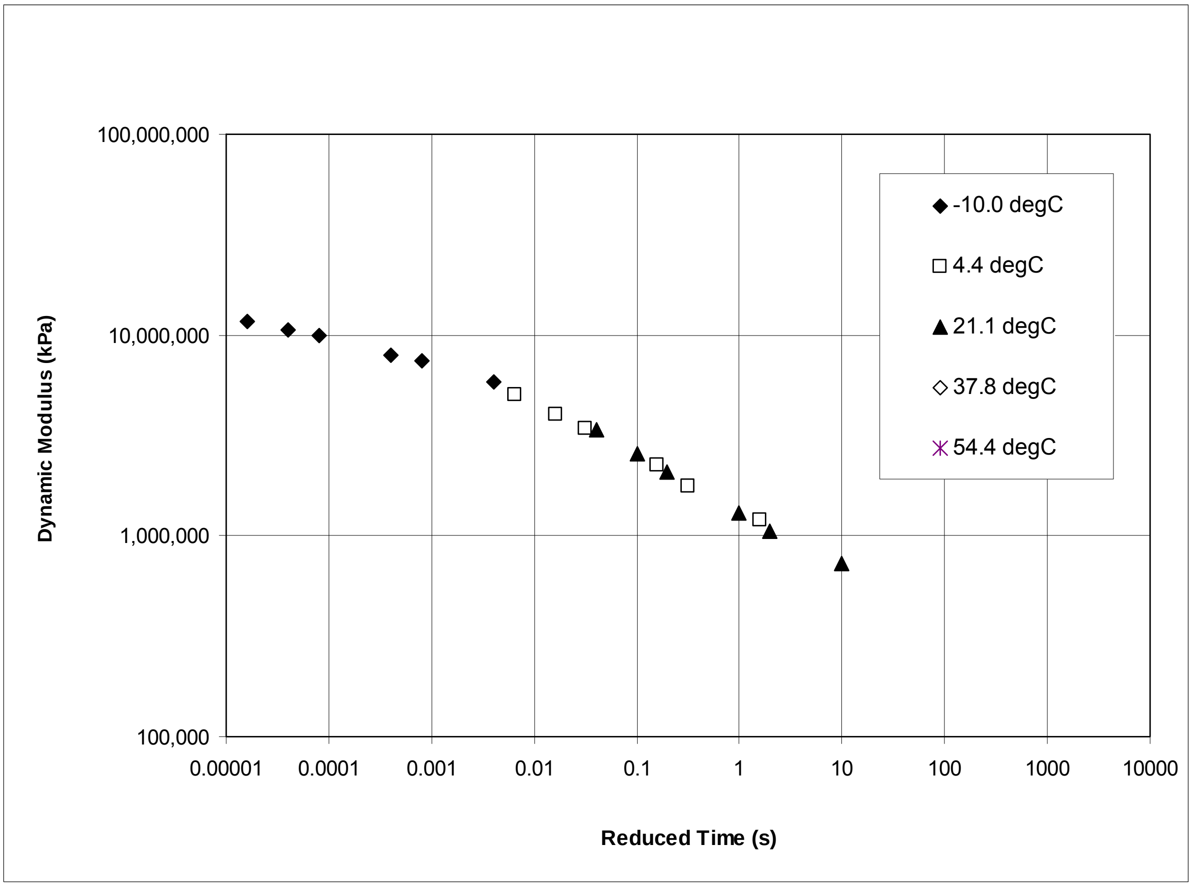

Figure 5.8 Master Curve for the Porous Asphalt PG 64-28 Mix

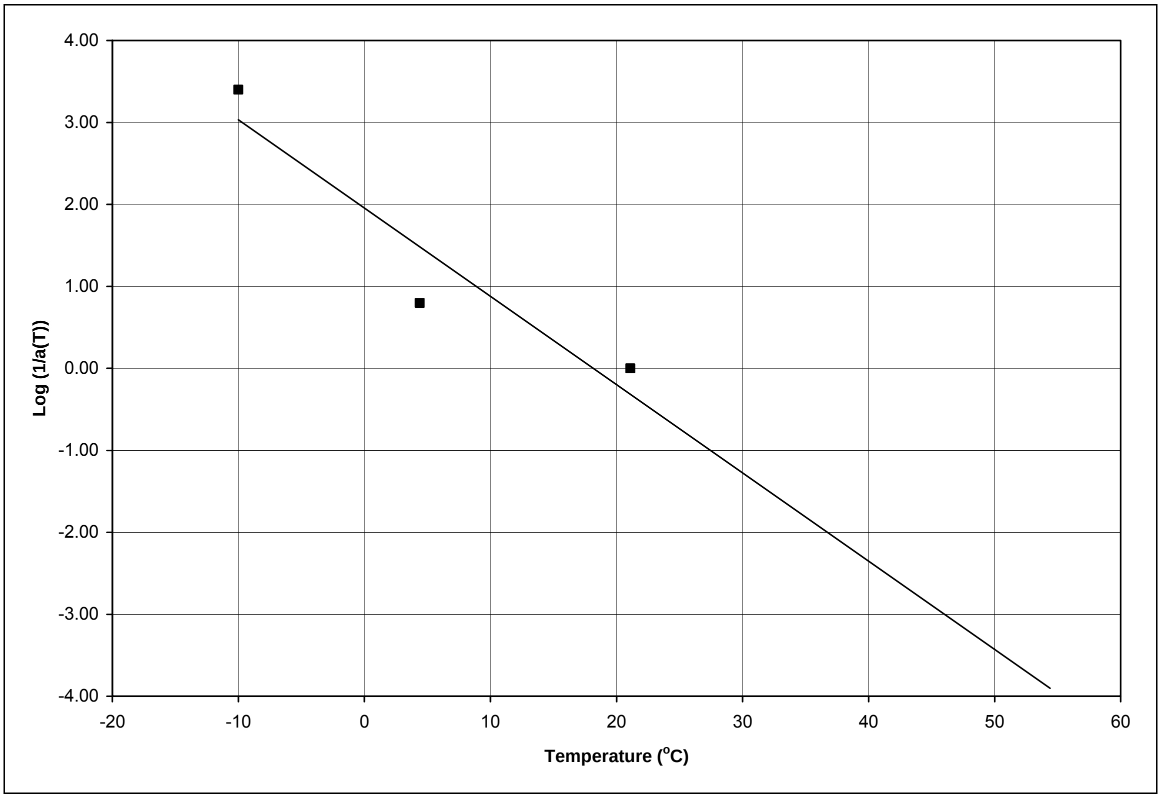

Figure 5.9 Shift Factor for the Porous Asphalt PG 64-28 Mix

Figure 5.10 and Figure 5.11 shows the master curve and shift factor plot for the PG 70-28 porous mix.

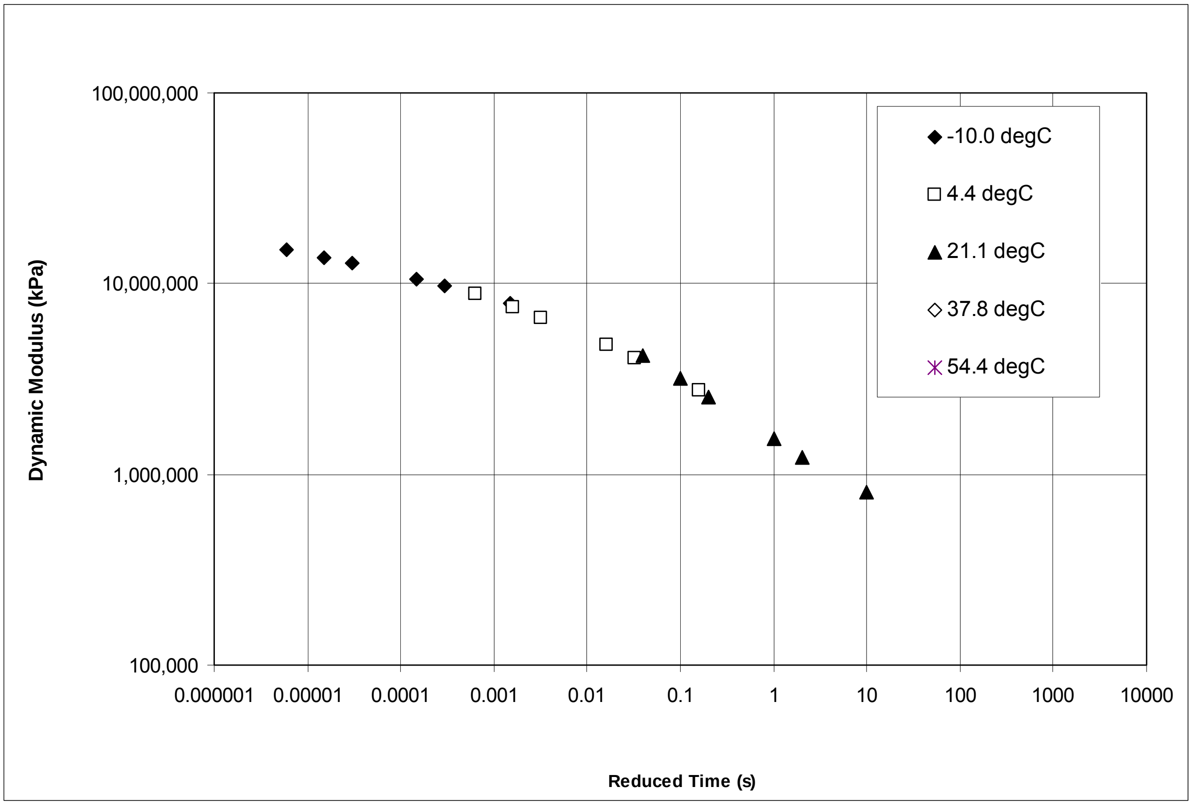

Figure 5.10 Master Curve for the Porous Asphalt PG 70-28 Mix

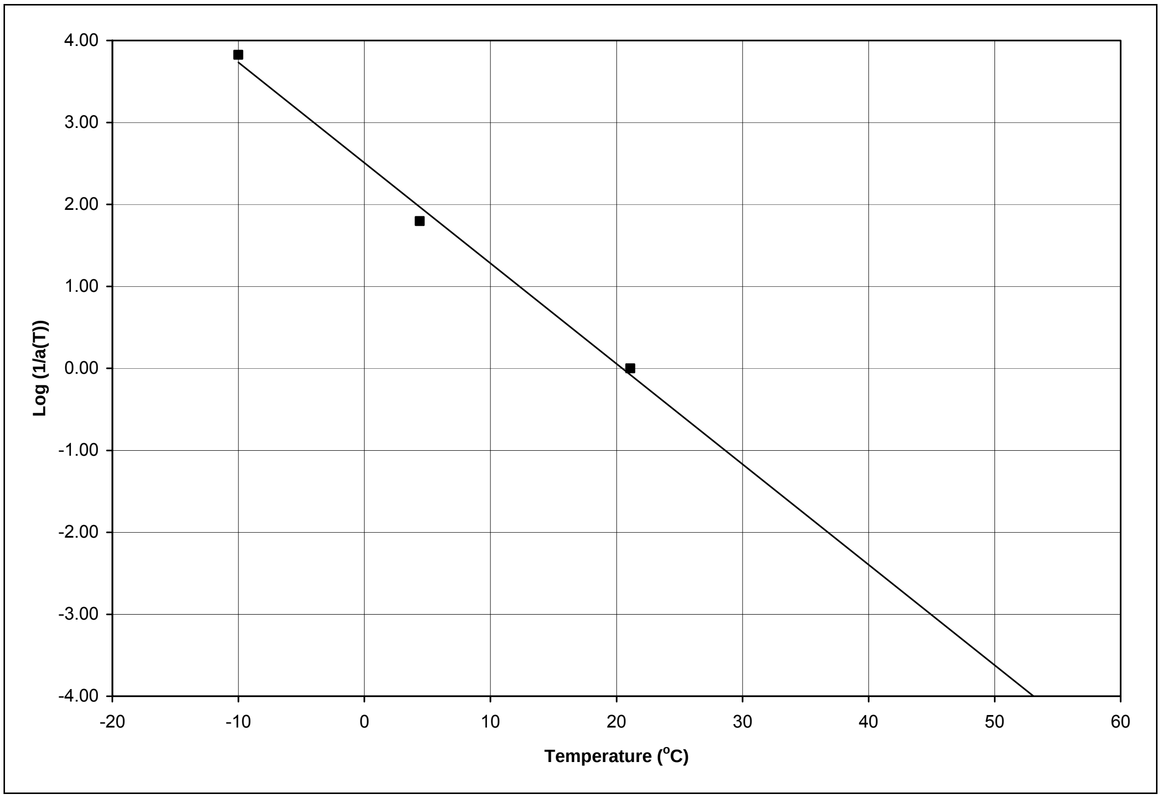

Figure 5.11 Shift Factor for the Porous Asphalt PG 70-28 Mix

Figure 5.12 illustrates the two different master curves for the porous asphalt mixes.

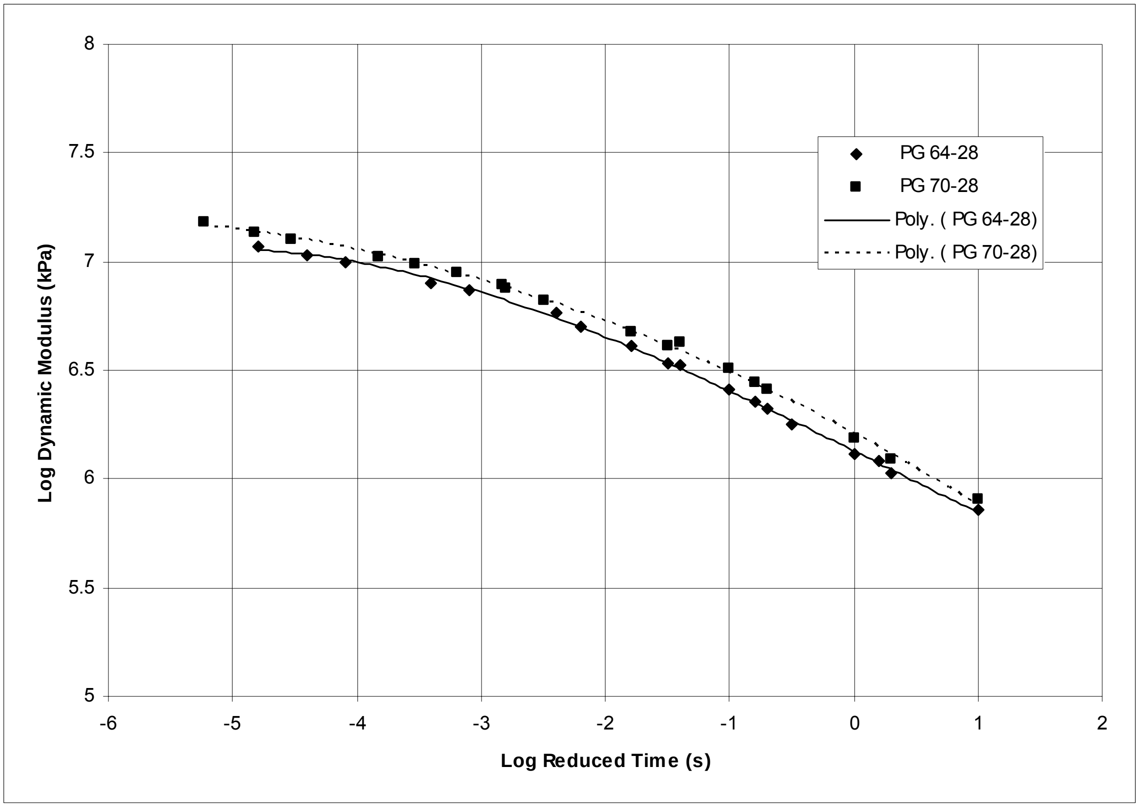

Figure 5.12 Combined Master Curves for the Porous Mixes

The above figure graphically illustrates that PG 70-28 porous mix exhibits overall higher dynamic modulus results then the PG 64-28 mix. Once again this was to be expected as the binder is a stiffer binder type.

5.3.3 Statistical Analysis

An analysis of variance (ANOVA) was conducted on the dynamic modulus master curve results for the two porous asphalt mixes to determine whether there was a statistical difference between the results of the two different mix types. Table 5.7 summarizes the statistical summary.

Table 5.7 ANOVA Summary of Dynamic Modulus for Porous Asphalt

ANOVA: Single Factor	**SUMMARY**					
Asphalt Type	*Count*	*Sum*	*Average*	*Variance*		
PG 64-28	18	117.4	6.523	0.137		
PG 70-28	18	120.4	6.690	0.141		
ANOVA						
Source of Variation	*SS*	*Df*	*MS*	F_{obs}	*P-value*	F_{crit}
Between Asphalt Types	0.250	1	0.250	1.795	0.189	4.130
Within Asphalt Types	4.734	34	0.139			
Total	4.984	35				

The above table illustrates that the F_{obs} value of 1.795 is less than the F_{crit} value of 4.130. Therefore the dynamic modulus results exhibit no statistical significant difference between the different asphalt types used for porous asphalt.

5.4 Mix Comparisons

One of the objectives of the performance testing of the porous mixes was to compare the dynamic modulus results to dynamic modulus test results of traditional asphalt mixes. The comparison mixes represent a range of applications used in Ontario. The five mixes used to compared against included a conventional HL 3 Marshall surface course, two stone mastic asphalt 12.5 mm gap-graded surface courses (SMA L and SMA G), and finally two Superpave 19.0 mm dense graded binder courses (SP 19 D, and SP 19 E). These mixes were prepared by Golder Associates Ltd and tested for dynamic modulus using the Interlaken Universal Test Machine/Simple Performance Tester at the CPATT laboratory at the University of Waterloo [Ludomir 2007]. Figure 5.13 illustrates the combined master curves for the five traditional Ontario mixes as well as the two porous asphalt mixes.

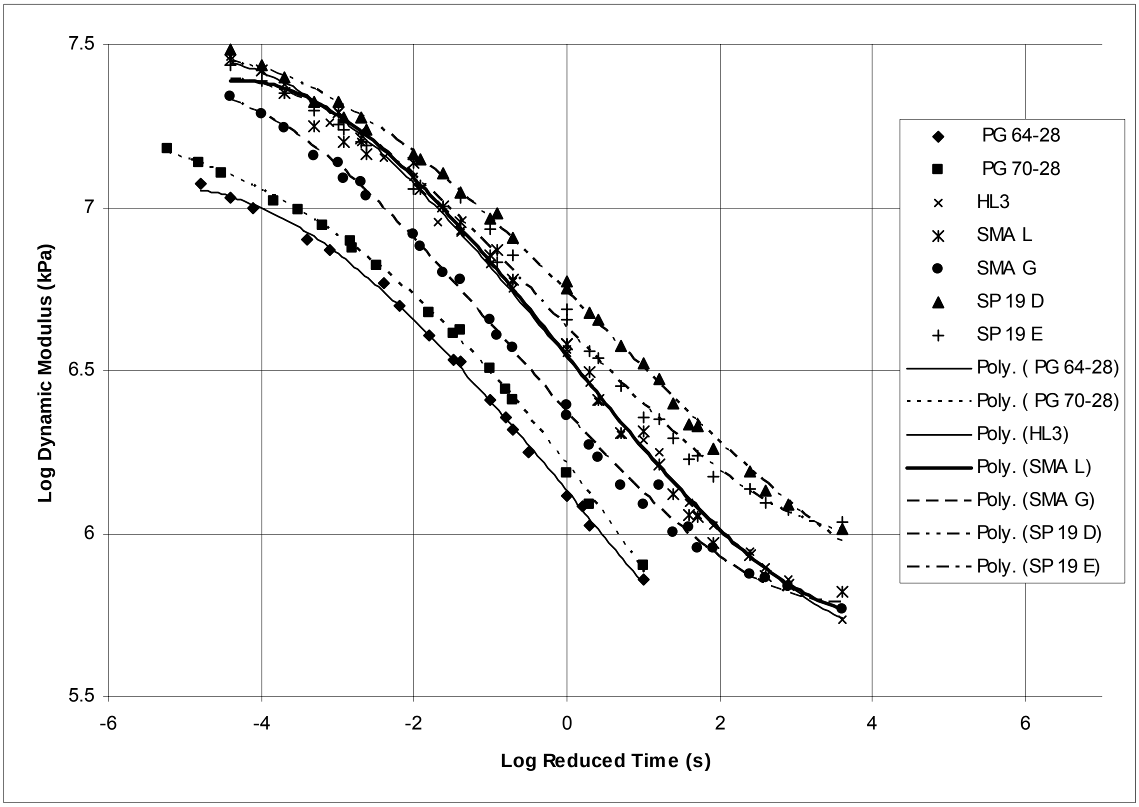

Figure 5.13 Comparison of Porous Asphalt to Traditional Asphalt Mixes

The comparison of the various mixes illustrates that the porous asphalt exhibited lower dynamic modulus values as compared to the traditional mixes. The Stone Mastic Asphalt exhibits the most similar results to the porous asphalt samples. The lower results compared to traditional mixes were to be expected due to the nature of the mix type.

5.5 Summary

This chapter presented the performance tests that were completed on the porous asphalt specimens. The performance tests included permeability and dynamic modulus. The preparation of the specimens as well as a brief summary of the testing equipment was discussed. The coefficient of permeability results were determined to be 0.99 cm/s and 1.00 cm/s for the PG 64-28 and PG 70-28 respectively. The dynamic modulus testing results were presented including the dynamic modulus, phase angle, stress, and strain values. The dynamic modulus values were then used to create master curves. The master curves indicated that the PG 70-28 exhibited higher dynamic modulus values; however, after completion of a statistical analysis it was determined that there was no significant difference between the values obtained from either mix. The porous asphalt master curves were then compared to traditional mix master curves and it was determined that the porous mixes exhibited lower dynamic modulus values then the traditional mixes. The porous asphalt mixes were most similar to a Stone Mastic Asphalt.

Chapter 6
Porous Pavement Design

The following chapter discusses the structural pavement design for porous asphalt. The porous asphalt pavement designs were determined based on hydrological analysis using various layer thicknesses and subgrade types. The hydrological analysis was performed using the porosity determined in mix design procedure of the porous asphalt mixes.

6.1 Pavement Structure

The pavement structure used for designs consisted of the porous asphalt surface course and a reservoir course, all constructed on subgrade. Figure 6.1 illustrates a schematic of the typical pavement design.

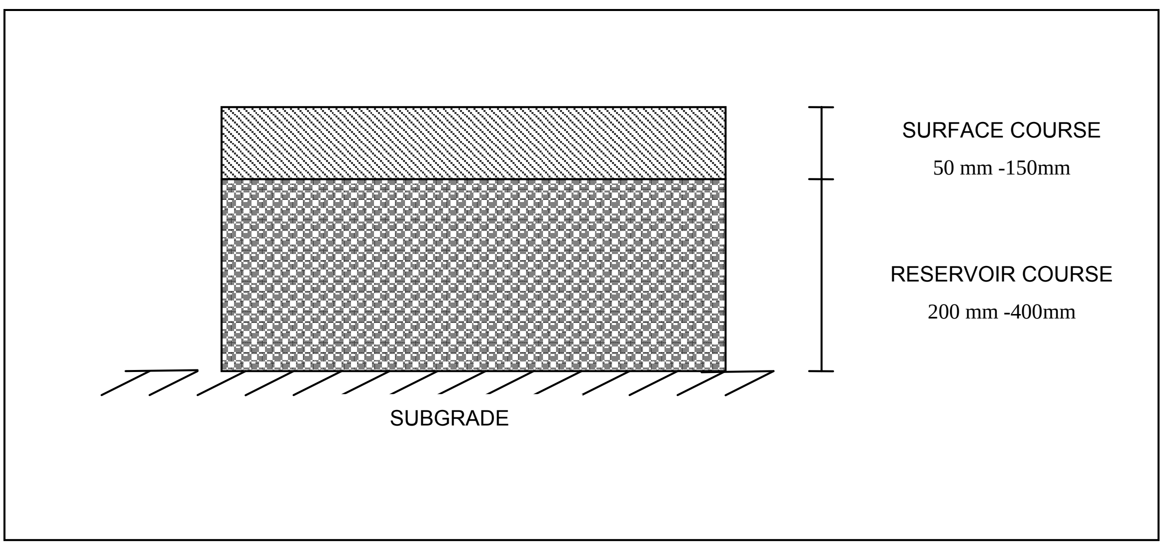

Figure 6.1 Typical Porous Asphalt Pavement Design

In order to complete the hydrological pavement design various layer thickness and subgrade exfiltration rates were analyzed. Three surface course thicknesses were analyzed: 50 mm, 100mm, and 150mm. The surface course thicknesses were recommended by the FHWA and industry practices [FHWA 2004]. The reservoir course is one of the key components to the storage of the precipitation passing through the structure and ultimately the performance of the system. The reservoir thicknesses analyzed were chosen to be: 200 mm, 300 mm, and 400 mm.

6.2 Hydrological Analysis

The hydrological analysis for the porous pavement design was completed using an analysis program provided by the Portland Cement Association and the National Ready-Mixed Concrete Association (NRMCA) [PCA 2006]. Table 6.1 summarizes the design inputs and assumptions for the design analysis.

Table 6.1 Design Inputs and Assumptions

		Metric	Imperial
Surface Course	Thickness	50 mm	2 in
		100 mm	4 in
		150 mm	6 in
	Porosity (Air Voids)	17%	
Reservoir Course	Thickness	200 mm	8 in
		300 mm	12 in
		400 mm	16 in
	Porosity	40%	
Subgrade	Exfiltration Rate		
	Clay	0.254 mm/hr	0.01 in/hr
	Silt	2.54 mm/hr	0.1 in/hr
	Sand	12.7 mm/hr	0.5 in/hr
Permeable Area	Parking Lot *	40,000 (mm^2)	430,560 ft^2
Impermeable Area	Surrounding Area **	40,000 (mm^2)	430,560 ft^2
Rainfall Information		121.4 mm	4.8 in
Ponding Limit		0.0 mm	0.0 in

* Assumed: 200 m x 200 m parking lot

** Assumed: Impermeable area equal to permeable area

The porosity of the surface course was assumed to be 17% as per the air void analysis conducted in the porous asphalt mix design. The reservoir course was assumed to have 40% porosity as per the recommendations [Thelen 1978]. Three different subgrade materials, clay, silt, and sand were analyzed with exfiltration rates as recommended by the analysis program. In order to perform the analysis a parking lot pavement structure was chosen with an area of 200 m by 200 m. The impermeable area surrounding the parking lot was assumed to be equal to the permeable area. The precipitation data used in the analysis was obtained from Environment Canada for the City of Toronto. To ensure that the pavements would be able to function under extreme hydrological conditions, an extreme daily precipitation of 121.4 mm was assumed and was applied as a 2-year return period [EC

2007]. A surface ponding limit of zero was chosen as ponding on the pavement surface could potentially result in major safety concern for drivers and pedestrians.

There are a few key outputs of the analysis that were the considered critical factors for appropriate pavement designs. From a pavement perspective it is important that the hours of ponding be equal to zero to ensure driver and pedestrian safety. However, since this pavement technology is primarily to be used as an additional stormwater management technique, the additional key outputs that were examined included: the estimated runoff (5 days), available storage after 24 hour (%), and available storage after 5 days (%).

6.2.1 Hydrological Results

After completing the analysis, three pavement thickness designs were chosen for each subgrade type. The remaining analyses can be found in Appendix B. Table 6.2 summarizes the hydrological analysis results.

Table 6.2 Hydrological Results for Selected Pavement Designs

Surface Thickness (mm)	50	100	150	50	100	150	50	100	150
Surface Area (m^2)	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000
Surface Porosity (%)	17	17	17	17	17	17	17	17	17
Reservoir Thickness (mm)	300	300	200	400	400	400	400	400	400
Reservoir Porosity (%)	40	40	40	40	40	40	40	40	40
Exfiltration Type	Sand	Sand	Sand	Silt	Silt	Silt	Clay	Clay	Clay
Exfiltration Rate(mm/hr)	12.7	12.7	12.7	2.54	2.54	2.54	0.254	0.254	0.254
Impervious Area (m^2)	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000
Estimated Runoff (5 days) (mm)	0	0	0	5.84	1.52	0	33.27	28.96	24.64
Available Storage used (%)	82	77	97	100	100	97	100	100	100
Hours of Ponding	0	0	0	0	0	0	0	0	0
Maximum Ponding Depth (mm)	-88.9	-139.7	0	0	0	-33.02	0	0	0
Available Storage After 24hr (%)	83	84	80	0	0	3	0	0	0
Available Storage After 5 days (%)	100	100	100	100	100	100	14	13	13
Stage After 5 days (mm)	0	0	0	0	0	0	367.7	389.3	416.9
Additional Time To Drain Completely (hr)	0	0	0	0	0	0	579	613	647
Total Drained Surface Area (m^2)	80,000	80,000	80,000	80,000	80,000	80,000	80,000	80,000	80,000
Storage Capacity (porous) (m^3)	345.4	690.9	1036.3	345.4	690.9	1036.3	345.4	690.9	1036.3
Storage Capacity (reservoir) (m^3)	4,877	4,877	3,251	6,502	6,502	6,502	6,502	6,502	6,502
Storage Capacity (ponding) (m^3)	0	0	0	0	0	0	0	0	0
Total Stormwater Drainage (m^3)	5,222.3	5,567.7	4,287.6	6,847.9	7,193.3	7,538.8	6,847.9	7,193.3	7,538.8
Total Precipitation Volume (m^3)	9,754	9,754	9,754	9,754	9,754	9,754	9,754	9,754	9,754
5 Day Exfiltration Volume (m^3)	9,754	9,754	9,754	9,286	9,632	9,754	1,209	1,209	1,209
Total Runoff (overflow) (m^3)	0	0	0	467	122	0	2,662	2,316	1,971
Water Stored after 5 (m^3)	0	0	0	0	0	0	5,883	6,228	6,574

The pavement designs were determined by ensuring that the hours of ponding equaled zero, and that the estimated runoff, available storage after 24 hours, and the available storage after 5 days were minimized.

6.3 Pavement Structure Design

The final pavement designs were chosen by minimizing the hydrological considerations as discussed as well as providing different designs for various site conditions and traffic levels. The surface course thickness should be determined for the appropriate traffic levels. Table 6.3 summarizes the required thicknesses for the pavement structure based on subgrade and surface course thicknesses.

Table 6.3 Porous Asphalt Design Table

Subgrade Type	Surface Thickness* (mm)	Reservoir Thickness** (mm)
Sand	50	300
	100	300
	150	200
Silt	50	400
	100	400
	150	400
Clay	50	400
	100	400
	150	400

* Based on approximately 17% porosity

** Based on approximately 40 % porosity

Using the hydrological analysis, the recommended pavement structure thickness indicated illustrates that when a higher permeable subgrade such as sand is present, the reservoir thickness can be decreased. For a sand subgrade as the surface thickness increases, the reservoir thickness can be decreased based on the higher permeability that the sand subgrade provides. The reservoir thickness for a structure constructed on sand can range between 200mm and 300 mm. However, when lower permeable subgrade materials are present such as silt and clay the reservoir thicknesses are greater due to the slower rate in subgrade permeability. The reservoir course thickness is recommended to be at least 400 mm for sand and silt subgrades in order for the structure to perform adequately.

6.4 Summary

This chapter presented the pavement designs for porous asphalt structures. A hydrological analysis was conducted and pavement structure designs were recommended. The analysis was conducted by varying the subgrade conditions and traffic levels (i.e. surface course thicknesses). The analyses were performed for a 200 m x 200 m porous asphalt parking lot. The surface course was assumed to have a porosity of 17% as determined in the air void analysis of the porous asphalt mixes. Higher permeable subgrades such as sand require a reservoir course thickness between 200mm and 300mm, where as lower permeable subgrades such as silt and clay require a reservoir thickness of at least 400 mm.

Chapter 7
Conclusions and Recommendations

7.1 Summary

Porous pavements offer an additional technology for stormwater management and best practices by controlling run-off from surrounding impervious areas. The materials used in this research included all typical local materials obtained from local Ontario suppliers. A polymer modified asphalt (PMA) PG 70-28 binder and a PG 64-28 binder were chosen. Superpave mix design was used to determine the optimum binder content and air void percentage of the porous mixes. The mix design resulted in two porous asphalt mixtures using different binder types (polymer modified PG 70-28 and a PG 64-28).

Based on the results of the air void analysis and the draindown characteristics, two different mixes were prepared using the design gradation that consisted of 5.5% PG 64-28 asphalt cement with 0.3% fibres and 5.5% PG 70-28 PMA cement with 0.3% fibres. The air void percentages were confirmed at 17.1% and 16.5% for the PG 64-28 and PG 70-28 respectively. Conventional methods for the determination of the air voids analysis are not suitable for porous mixes and care should be taken when determining the bulk relative density of a porous mix.

The Modified Lottman tests indicated that the TSR value for the PG 64-28 was determined to be 65%, whereas the TSR for the PG 70-28 was determined to be 84.6%. Based on the recommendations that the TSR value for porous asphalt should be greater then 80% [NAPA 2003], the PG 70-28 binder should be recommended for porous asphalt since it maintains 84.6% of its tensile strength under freeze-thaw conditions.

Permeability tests were conducted on the porous asphalt samples using the Gilson Asphalt Field Permeameter. The test was performed based on the falling head principle of permeability. The test was adapted to be used in a laboratory setting.

Dynamic modulus tests were performed at six loading frequencies: 0.1 Hz, 0.5 Hz, 1 Hz, 5.0 Hz, 10 Hz, and 25 Hz and at only three different temperatures: -10^{o}C, 4.4^{o}C, and 21.1^{o}C. The test could not be competed at the two highest temperatures as the mixes became unstable and the strain levels were outside the range of the LVDT's. Cracking and permanent deformation was observed during loading.

Finally, recommended pavement designs for porous asphalt structures were presented based on hydrological analysis. Subgrade types, surface course thicknesses, and reservoir thicknesses were varied in the analysis and a porosity of 17% was assumed as determined in the air void analysis of the porous asphalt mixes.

7.2 Conclusions

The coefficient of permeability was found to be 0.99 cm/s and 1.00 cm/s for the PG 64-28 and PG 70-28 respectively. When compared to traditional soils, porous asphalt exhibited a coefficient of permeability similar to gravel and significantly higher rates then traditional dense-graded mixes.

The dynamic modulus results indicated higher values for the porous mix containing the PG 70-28 asphalt binder. The overall higher values on the PG 70-28 mix were observed due to the increased stiffness that the 70-28 polymer modified binder type provides. Higher dynamic modulus values were observed at the lower temperatures and decreased as the testing temperature increased.

Higher phase angles were observed for the PG 64-28 mix than the PG 70-28 mix. The phase angles observed increased as the test temperature increased. The results indicated that at the lower temperatures the materials were more elastic as compared to the higher temperatures. The PG 70-28 mix exhibited more elastic performance then the PG 64-28 mix.

Dynamic modulus master curves were developed to compare the results between the two mixes. The master curves provided further consistent results that the PG 70-28 mix exhibited stiffer physical properties then the PG 62-28 mix. A statistical analysis indicated that there was no significant difference between the dynamic modulus values of the two different mixes.

The porous master curves were compared against a range of typical Ontario mixes. The comparison illustrated that the porous asphalts exhibited lower dynamic modulus values as compared to the traditional mixes. The porous asphalts exhibited dynamic modulus master curves most similar to the Stone Mastic Asphalts.

7.3 Recommendations

Further performance testing should continue on porous asphalt including indirect tensile testing, resilient modulus, beam fatigue, and detailed freeze-thaw testing. Additional dynamic modulus testing could be conducted in attempt to determine the dynamic modulus values at the two higher temperatures. Field trials should be constructed to evaluate field performance of the porous asphalt mixes in all climates but especially in cold climates.

The high porosity of these pavements increases the clogging potential. If the pavements are completely clogged then the entire system cannot function properly and fluid may collect on the surface providing a hazardous situation for drivers and increasing the stormwater run-off. Further research needs to be conducted on the clogging potential especially in colder climates where the pavements are subjected to de-icing activities such as salt and sand.

Asphalt pavements are the most recycled material in North America. Approximately four out of every five tonnes of asphalt pavements removed during a construction project is recycled. The United States of America recycles approximately 73 million tonnes of asphalt per year [OHMPA 2003]. However, the behaviour of recycled asphalt pavements in a porous mixture is unknown. Further laboratory investigations should be completed in order to examine the effects of including a percentage of reclaimed asphalt pavements (RAP) in a porous mix.

The high porosity of porous asphalt mixtures may lead to higher levels of contaminates such as gasoline, oil and various other chemicals in the environment. Research should be conducted to determine whether a porous asphalt mix can be recycled and reused in further porous or traditional asphalt mixes.

A detailed life cycle cost analysis should be conducted to examine the economic aspects of this technology. Furthermore it would be suggested that detailed maintenance evaluation be incorporated in the life cycle cost analysis.

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Appendix A

Sample Dynamic Modulus Reports

Dynamic Modulus Standard Report

Date: 5/22/2007
Time: 4:11:51 PM

Dynamic Modulus: 7510095. KPa
Phase Angle: 13.9 Deg

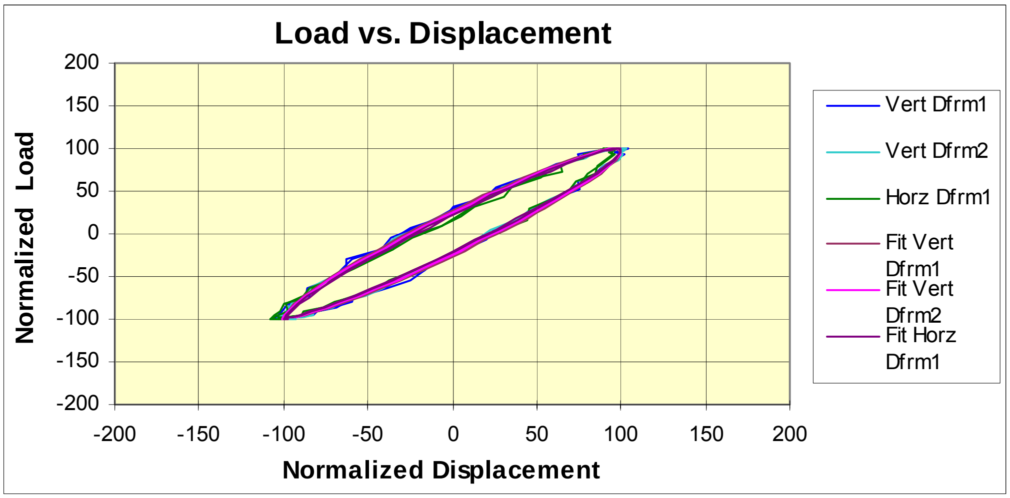
Specimen ID: **D61**
Project: **Lori**
Test Freq: **0.4999 Hz**
Specimen Gauge Length: **70 mm**
Operating Technician: **jn**
File Name: C:\Documents and Settings\Interlaken\My Documents\TestData\DynMod\LORI\-10.0\D61Atrial1Freq6
Specimen Dia.: **99.71 mm**
Specimen Hieght: **148.49 mm**
Cross Sec. Area: **7808.495 mm^2**
Target Test Temp: **-10.0 C**
Target Confining Pressure: **0. KPa**

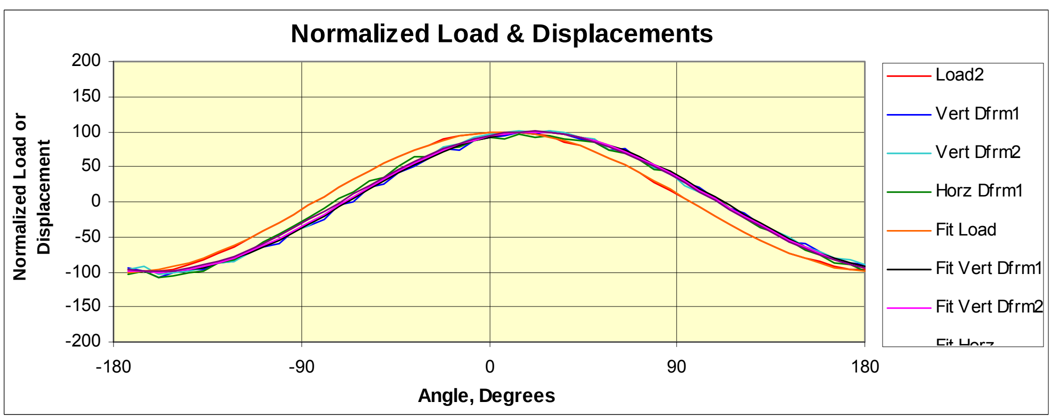
Data Quality Indicators
Drift for Load (%): **0.55**
Std. Error for Load (%): **1.25**
Average Drift for Deformations (%): **36.44**
Avg. Std. Error for Deformations (%): **3.26**
Uniformity Coef. for Deformations (%): **29.65**
Uniformity Coef. for Phase Angles (Deg): **1.22**

Specimen Conditioning Time: **720 Min**
Remarks: D61A -10.0 degrees celcius
Post Test Remarks: May 22

Average Actual Temperature: **-10.6 C**
Average Actual Confining Stress: **0. KPa**

Warnings
Temperature Tolerance exceeded at 4:08:35 PM During Frequency 5





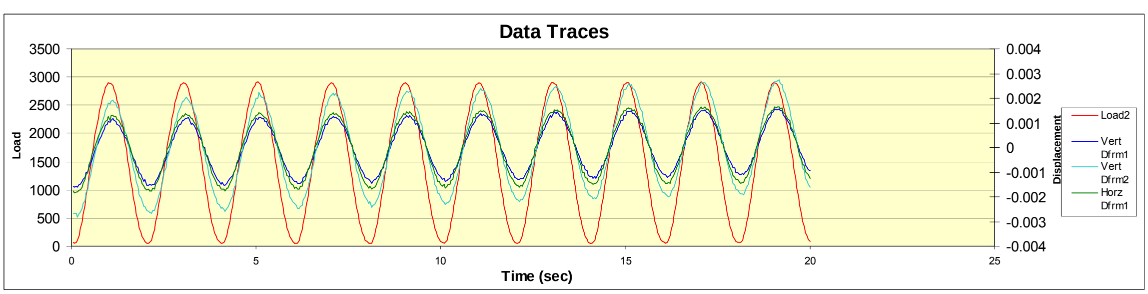


Figure A1: Dynamic Modulus Report for PG 64-28 @ -10.0°C, 0.5 Hz

Dynamic Modulus Standard Report

Date: 5/23/2007
Time: 2:42:09 PM

Dynamic Modulus: 1226552. KPa
Phase Angle: 29.31 Deg

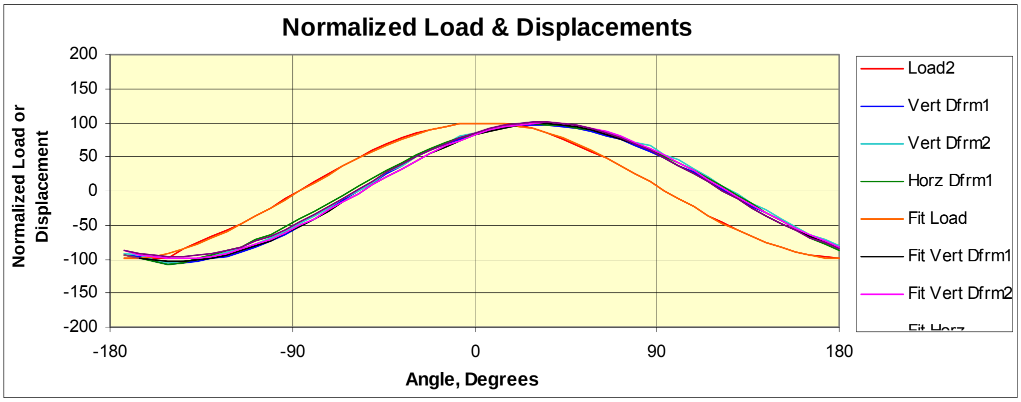
Specimen ID: **D61**
Project: **Lori**
Test Freq: **0.0998 Hz**
Specimen Gauge Length: **70 mm**
Operating Technician: **jn**
File Name: C:\Documents and Settings\Interlaken\My Documents\TestData\DynMod\LORI\4.4oc\44D61trial2Freq7
Specimen Dia.: **99.71 mm**
Specimen Hieght: **148.49 mm**
Cross Sec. Area: **7808.495 mm^2**
Target Test Temp: **-10.0 C**
Target Confining Pressure: **0. KPa**

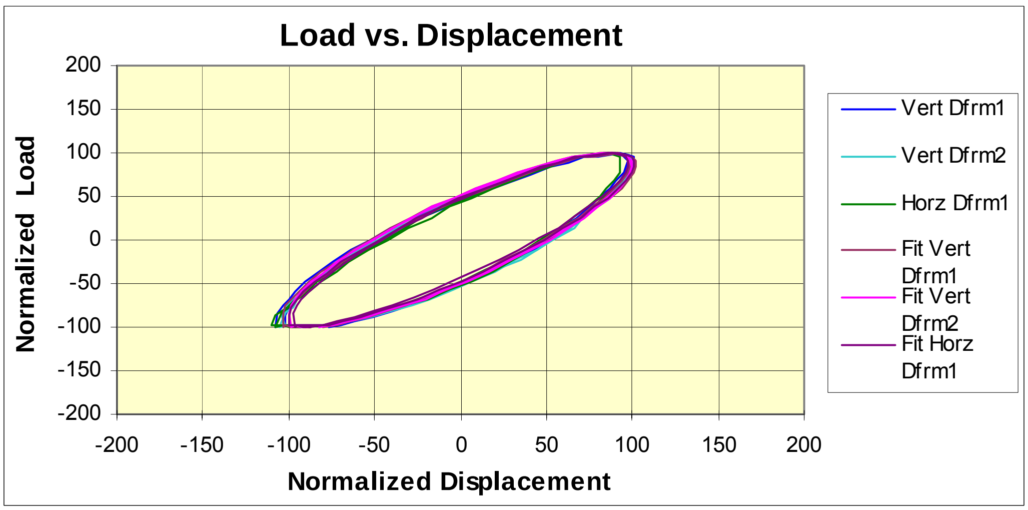
Data Quality Indicators
Drift for Load (%): **0.53**
Std. Error for Load (%): **3.28**
Average Drift for Deformations (%): **36.02**
Avg. Std. Error for Deformations (%): **3.99**
Uniformity Coef. for Deformations (%): **34.51**
Uniformity Coef. for Phase Angles (Deg): **0.98**

Specimen Conditioning Time: **720 Min**
Remarks:
Post Test Remarks: Used the bearing apparatus

Average Actual Temperature: **4.4 C**
Average Actual Confining Stress: **0. KPa**

Warnings
Temperature Tolerance exceeded at 2:30:11 PM During Frequency 10





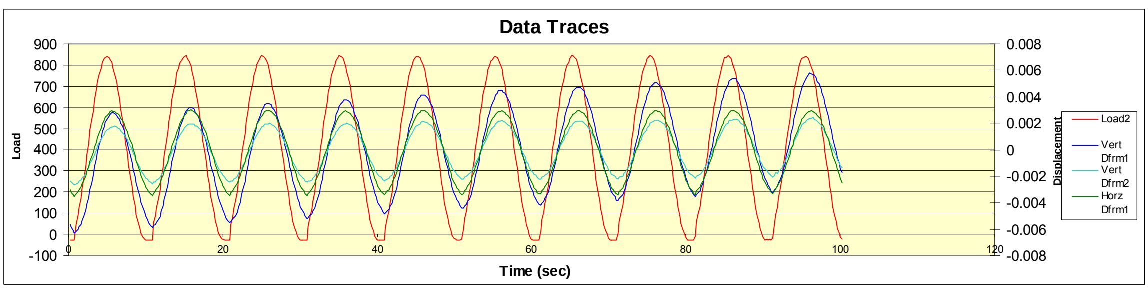


Figure A2: Dynamic Modulus Report PG 64-28 @ 4.4°C, 0.1 Hz

Dynamic Modulus Standard Report

Date: 5/28/2007
Time: 2:33:57 PM

Dynamic Modulus: 1601741. KPa
Phase Angle: 28.53 Deg

Specimen ID: **D74**
Project: **Lori**
Test Freq: **0.9996 Hz**
Specimen Gauge Length: **70 mm**
Operating Technician: **jn**
File Name: C:\Documents and Settings\Interlaken\My Documents\TestData\DynMod\LORI\21.1 oc\21D74trial1Freq5
Specimen Dia.: **99.45 mm**
Specimen Hieght: **150.52 mm**
Cross Sec. Area: **7767.826 mm^2**
Target Test Temp: **21.1 C**
Target Confining Pressure: **0. KPa**

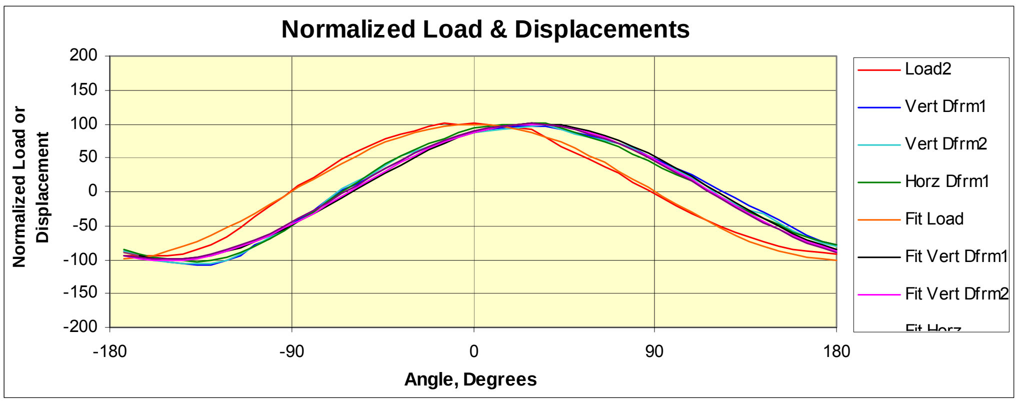
Data Quality Indicators
Drift for Load (%): **1.15**
Std. Error for Load (%): **5.86**
Average Drift for Deformations (%): **69.52**
Avg. Std. Error for Deformations (%): **6.32**

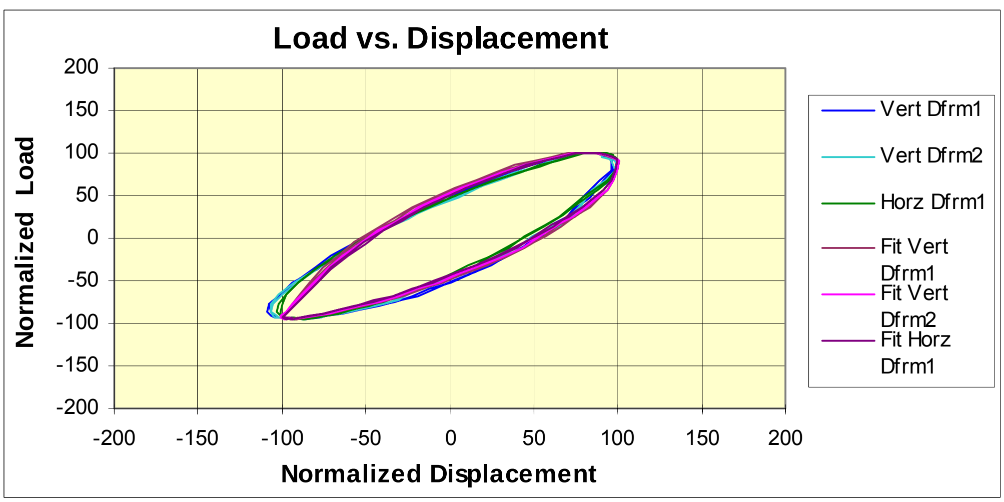
Uniformity Coef. for Deformations (%): **22.79**
Uniformity Coef. for Phase Angles (Deg): **1.53**

Specimen Conditioning Time: **720 Min**
Remarks:
Post Test Remarks:

Average Actual Temperature: **21.0 C**
Average Actual Confining Stress: **0. KPa**

Warnings





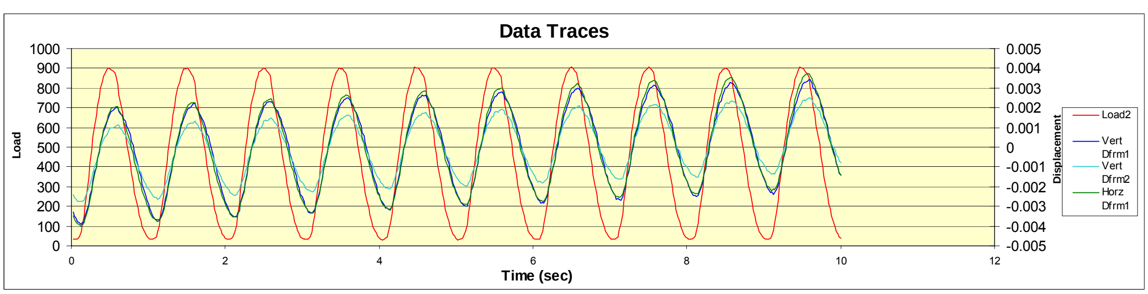


Figure A3: Dynamic Modulus Report PG 70-28 @ 21.1°C, 1.0 Hz

Appendix B

Complete Hydrological Analysis

Surface Thickness (mm)	**50**	**50**	**50**	**100**	**100**	**100**	**150**	**150**	**150**
Surface Area (m^2)	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000
Surface Porosity (%)	17	17	17	17	17	17	17	17	17
Reservoir Thickness (mm)	**200**	**300**	**400**	**200**	**300**	**400**	**200**	**300**	**400**
Reservoir Porosity (%)	40	40	40	40	40	40	40	40	40
Exfiltration Type	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand
Exfiltration Rate (mm/hr)	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7
Impervious Area (m^2)	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000
Estimated Runoff (5 days) (mm)	8.6	0.00	0.00	4.3	0.00	0.00	0.00	0.00	0.00
Available Storage used (%)	100	82	62	100	77	59	97	72	57
Hours of Ponding	0	0	0	0	0	0	0	0	0
Max Ponding Depth (mm)	0.0	-88.9	-190.5	0.0	-139.7	-241.3	0.0	-190.5	-292.1
Available Storage After 24hr (%)	95	83	87	86	84	88	80	85	88
Available Storage After 5 Days (%)	100	100	100	100	100	100	100	100	100
Stage After 5 Days (mm)	0	0	0	0	0	0	0	0	0
Additional Time to Drain Completely (hr)	0	0	0	0	0	0	0	0	0
Total Drained Surface Area (m^2)	80,000	80,000	80,000	80,000	80,000	80,000	80,000	80,000	80,000
Storage Capacity (porous) (m^3)	345	345	345	691	691	691	1,036	1,036	1,036
Storage Capactiy (reservoir) (m^3)	3,251	4,877	6,502	3,251	4,877	6,502	3,251	4,877	6,502
Storage Capacity (ponding) (m^3)	0	0	0	0	0	0	0	0	0
Total Stormwater Drainage (m^3)	3,597	5,222	6,848	3,942	5,568	7,193	4,288	5,913	7,539
Total Percipitation Volume (m^3)	9,754	9,754	9,754	9,754	9,754	9,754	9,754	9,754	9,754
5 Day Exfiltration Volume (m^3)	9,326	9,754	9,754	9,416	9,754	9,754	9,754	9,754	9,754
Total Runoff (overflow) (m^3)	683	0	0	337	0	0	0	0	0
Water Stored After 5 days	0	0	0	0	0	0	0	0	0
Water Balance Error (m^3)	0	0	0	0	0	0	0	0	0

Table B1: Hydrological Pavement Analysis- Sand Subgrade

Surface Thickness (mm)	**50**	**50**	**50**	**100**	**100**	**100**	**150**	**150**	**150**
Surface Area (m^2)	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000
Surface Porosity (%)	17	17	17	17	17	17	17	17	17
Reservoir Thickness (mm)	**200**	**300**	**400**	**200**	**300**	**400**	**200**	**300**	**400**
Reservoir Porosity (%)	40	40	40	40	40	40	40	40	40
Exfiltration Type	Silt	Silt	Silt	Silt	Silt	Silt	Silt	Silt	Silt
Exfiltration Rate (mm/hr)	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54
Impervious Area (m^2)	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000
Estimated Runoff (5 days) (mm)	46.5	26.2	5.8	42.2	21.8	1.5	37.8	17.5	0.00
Available Storage used (%)	100	100	100	100	100	100	100	100	97
Hours of Ponding	0	13	0	0	0	0	0	0	0
Max Ponding Depth (mm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-33.0
Available Storage After 24hr (%)	0.0	0.0	0.0	0.0	0.0	0.0	0	0	3
Available Storage After 5 Days (%)	100	100	100	100	100	100	100	100	100
Stage After 5 Days (mm)	0	0	0	0	0	0	0	0	0
Additional Time to Drain Completely (hr)	0	0	0	0	0	0	0	0	0
Total Drained Surface Area (m^2)	80,000	80,000	80,000	80,000	80,000	80,000	80,000	80,000	80,000
Storage Capacity (porous) (m^3)	345	345	345	691	691	691	1,036	1,036	1,036
Storage Capactiy (reservoir) (m^3)	3,251	4,879	6,502	3,251	4,879	6,502	3,251	4,879	6,502
Storage Capacity (ponding) (m^3)	0	0	0	0	0	0	0	0	0
Total Stormwater Drainage (m^3)	3,597	5,222	6,848	3,942	5568	7,193	4,288	5,913	7,539
Total Percipitation Volume (m^3)	9,754	9,754	9,754	9,754	9,754	9,754	9,754	9,754	9,754
5 Day Exfiltration Volume (m^3)	6,035	7,661	9,286	6,381	8,006	9,632	6,726	8,351	9,754
Total Runoff (overflow) (m^3)	3,719	2,093	467	3,373	1,748	122	3,028	1,204	0
Water Stored After 5 days	0	0	0	0	0	0	0	0	0
Water Balance Error (m^3)	0	0	0	0	0	0	0	0	0

Table B2: Hydrological Pavement Analysis- Silt Subgrade

Surface Thickness (mm)	**50**	**50**	**50**	**100**	**100**	**100**	**150**	**150**	**150**
Surface Area (m^2)	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000
Surface Porosity (%)	17	17	17	17	17	17	17	17	17
Reservoir Thickness (mm)	**200**	**300**	**400**	**200**	**300**	**400**	**200**	**300**	**400**
Reservoir Porosity (%)	40	40	40	40	40	40	40	40	40
Exfiltration Type	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay
Exfiltration Rate (mm/hr)	0.254	0.254	0.254	0.254	0.254	0.254	0.254	0.254	0.254
Impervious Area (m^2)	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000
Estimated Runoff (5 days) (mm)	73.9	53.6	33.3	69.6	49.3	29.0	65.3	45.0	24.6
Available Storage used (%)	100	100	100	100	100	100	100	100	100
Hours of Ponding	0	13	0	0	0	0	0	0	0
Max Ponding Depth (mm)	0	0	0	0	0	0	0	0	0
Available Storage After 24hr (%)	0	0	0	0	0	0	0	0	0
Available Storage After 5 Days (%)	27	18	14	24	17	13	23	16	13
Stage After 5 Days (mm)	165.1	266.7	368.3	185.4	287.0	388.6	200.0	300.0	400.0
Additional Time to Drain Completely (hr)	259	419	579	293	453	613	327	487	647
Total Drained Surface Area (m^2)	80,000	80,000	80,000	80,000	80,000	80,000	80,000	80,000	80,000
Storage Capacity (porous) (m^3)	345	345	345	691	691	691	1,036	1,036	1,036
Storage Capactiy (reservoir) (m^3)	3,251	4,879	6,502	3,251	4,879	6,502	3,251	4,879	6,502
Storage Capacity (ponding) (m^3)	0	0	0	0	0	0	0	0	0
Total Stormwater Drainage (m^3)	3,597	5,222	6,848	3,942	5,568	7,193	4,288	5,913	7,539
Total Percipitation Volume (m^3)	9,754	9,754	9,754	9,754	9,754	9,754	9,754	9,754	9,754
5 Day Exfiltration Volume (m^3)	1,209	1,209	1,209	1,209	1,209	1,209	1,209	1,209	1,209
Total Runoff (overflow) (m^3)	5,941	4,288	2,662	5,568	3,942	2,316	5,222	3,597	1,971
Water Stored After 5 days (m^3)	2,631	4,257	5,883	2,977	4,603	6,228	3,322	4,948	6,574
Water Balance Error (m^3)	0	0	0	0	0	0	0	0	0

Table B3: Hydrological Pavement Analysis- Clay Subgrade

Appendix C

Glossary

ACI	The American Concrete Institute
AASHTO	American Association of State Highway and Transportation Officials
BMPs	Best Management Practices
CPATT	Centre for Pavement and Transportation Technology
EPA	United States Environmental Protection Agency
FDOT	Florida Department of Transportation
FHWA	U.S Department of Transportation and the Federal Highway Administration
ICPI	Interlocking Concrete Pavement Institute
LVDT	Linear Variable Differential Transducers
MCIA	Mississippi Concrete Industries Association
MEPDG	Mechanistic Empirical Pavement Design Guide
MTO	Ministry of Transportation, Ontario
NAPA	National Asphalt Pavement Association
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NRMCA	National Ready-Mixed Concrete Association
OHMPA	Ontario Hot Mix Producers Association
PCA	Portland Cement Association
PGAC	Performance Graded Asphalt Cement
PMA	Polymer Modified Asphalt
SGC	Superpave Gyratory Compactor
SHRP	Strategic Highway Research Program
TAC	Transportation Association of Canada