8-2011

Evaluation of Warm Mix Open Graded Friction Course Mixtures

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EVALUATION OF WARM MIX OPEN GRADED FRICTION COURSE MIXTURES

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Civil Engineering

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by
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August 2011

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ABSTRACT

The goal of this study was to evaluate Evotherm™ (a chemical package) and foaming (a water-injection method) warm mix asphalt (WMA) technologies to determine their effectiveness in producing high quality open graded friction course (OGFC) mixes. Specifically, this study focused on the effect of the removal of stabilizing additives (fibers and polymers) on the optimum binder content and performance of WMA OGFC mixtures. By focusing on additive removal, this study attempted to evaluate practical production concerns and the possible benefits of WMA technologies combined with OGFC.

The Evotherm™ WMA and foaming WMA mixes were compared to traditional HMA OGFC by evaluating four main mix design criteria: draindown, moisture susceptibility, permeability, and abrasion resistance. Overall, 10 different mix designs were tested and evaluated for use in OGFC pavements. Both volumetric and performance properties were analyzed to assess the performance of each mix design. The results suggested that WMA technologies have the ability to enable the removal of fiber from OGFC mix designs without significant draindown and to improve the performance properties of OGFC mix designs. This study suggests that there is a high potential for the use of warm mix technologies in OGFC.

DEDICATION

To Dr. Brad Putman, my advisor, committee chair, professor, and friend, for his constant support, motivation, and guidance throughout my time at Clemson University. His high expectations and confidence in me fostered my passion for this work and my future career.

To Dr. Prasad Rangaraju and Dr. Leidy Klotz, my professors and committee members, for their instruction and guidance throughout my time at Clemson University. To Laura Kline, Andrew Neptune, Greg Bunting, Talat Mansour, Will Martin, and David Duncan for the comradery and knowledge that they shared with me as I conducted my research.

To Loc Sanders, Dane Rosier, Rhett Templeton, Matt Shuler, Neil Bolling, Tyler Gilstrap, Laura Rowe, Melissa Gende, and Jenny Yenawine for their time and effort given to this project in assisting me, without which this study would not have been possible.

To my parents, family, and friends for their love and vital role in forming me into the person I am today. Also for their confidence in me and unfailing encouragement throughout my entire academic career.

To my Savior, Jesus Christ, who guides me in all truth, to him be any credit that I receive from the accomplishments he has brought about through my life.

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CHAPTER ONE

INTRODUCTION

Open graded friction course (OGFC) is a type of porous asphalt mix designed to be placed in thin lifts over top of a typical impermeable pavement surface. This type of mix is characterized by having a coarse textured, open graded surface and a high, interconnected air void content throughout. These attributes are achieved by using a uniformly graded aggregate with very little fines in comparison to a dense graded pavement. Along with a uniformly graded aggregate, asphalt binder and additives are the primary ingredients in an OGFC mixture. Since the mid-1940s this type of pavement surface has been used in the United States with mixed success (Kandhal 2002). Two common problems have caused the inconsistency in OGFC performance: raveling and binder draindown.

Raveling is a phenomenon that occurs when individual aggregate particles at the surface of a pavement succumb to wear by breaking away from the pavement. This problem is thought to be caused by the open void structure typical of OGFCs which allows much more exposure to air and the elements than traditional dense graded mixes. With this added exposure, the asphalt binder can age prematurely causing raveling. When raveling begins to occur, additional aggregate particles begin to ravel away and the raveling builds exponentially upon itself. In the worst cases, entire full-depth sections of OGFC can degrade from a pavement.

Draindown is a phenomenon occurring in OGFCs that is attributed to the increased asphalt binder content and a lack of fines. Draindown can be seen as excess asphalt binder that drains out of an OGFC mixture and is deposited in the beds of trucks hauling the mix or on the surface of the supporting dense graded asphalt layer. Traditional dense graded asphalt mixes have a binder content around 5% while OGFCs, because of the uniformly graded aggregate, require additional binder to increase the binder film thickness with the aim of increasing durability (i.e., prevent raveling). If the binder content is arbitrarily increased without some other adjustment to the mix design, much of the added binder will be lost from the OGFC due to draindown. For engineers to design OGFCs with higher binder contents, additives are typically incorporated to stabilize the mix and prevent draindown. The stabilizing additives employed most commonly in OGFCs are polymers which stiffen the asphalt binder and fibers which absorb the additional binder creating a higher binder film thickness surrounding the aggregate particles without the subsequent draindown.

The production of hot mix asphalt (HMA) has long involved the combination of bitumen based asphalt binder and mineral aggregate. Lately, the asphalt paving industry has seen the need to develop more sustainable pavements and is making efforts to cut costs, reduce emissions, and recycle more old HMA into new pavements. These trends are now becoming the industry standard with hopes of reducing the need for virgin binder and aggregate, both nonrenewable resources. One of the technologies that has grown out of the need for more sustainable construction is warm mix asphalt (WMA).

The objective of WMA is to produce and construct asphalt pavements at lower temperatures (up to 100^{o}F lower) than conventional hot mix. Some technologies such as Mead Westvaco's (MWV) Evotherm™, directly alter binder properties with the use of carefully selected chemistry, while foaming technologies employ water to create steam in the binder which provides the desired change in binder properties. This alteration in binder properties is the primary goal of any warm mix technology and allows for warm mix asphalt to be mixed at much lower temperatures with results similar to HMA paving.

Warm mix asphalt is a relatively new technology aimed at reducing energy consumption and the emissions associated with asphalt paving. With the use of WMA technologies in asphalt paving, the energy consumption can be cut by 40%, subsequently reducing emissions (Vaitkus et al. 2009). This two-fold reduction has the added benefit of providing a better work environment for workers involved with paving operations. Today's WMA technologies were first developed in Europe in the mid-1990s, and the first warm mix asphalt pavements were placed in Europe from 1997 to 1999. After learning of the new European technology, the National Asphalt Paving Association (NAPA) performed a study tour in Europe to investigate the technologies. In 2004, the first US field trials were constructed in North Carolina and Florida, and since 2007 numerous research projects have been conducted on WMA technologies at state and federal levels. These studies have found numerous advantages for the use of warm mix asphalt (Prowell and Hurley 2007).

The environmental benefits of warm mix asphalt over hot-mix asphalt have been clearly demonstrated in the lab and field. Due to lower mixing temperatures, warm mix asphalt reduces energy consumption, CO_2 emissions, and other harmful byproducts of asphalt paving. Because of the significant reduction in emissions, WMA improves the project work environment and thereby improves the health of workers (Vaitkus et al.

2009). Some time related benefits provided by warm mix technologies include longer possible haul distances and less time after paving before opening a road to traffic (Vaitkus et al. 2009). WMA has also been shown to reduce cracking and early degradation by reducing binder aging during production and thereby increasing the binder film thickness around individual aggregate particles.

With the use of any new technology, there are drawbacks emanating from an industry’s unfamiliarity with a technology. The majority of concerns agencies seem to have over using WMA technologies is the relatively small knowledge base on the long term effects of the technology (Vaitkus et al. 2009). Hopefully, this knowledge base is being further developed through current lab and field studies. Meanwhile, contractors can be understandably resistant to changing to a new process and paying the cost for new technologies. This resistance indicates why the WMA technologies must be examined to determine their potential for cost-savings and pavement improvement. Studies like this are paramount as the paving industry must see WMA technologies as worth the investment.

In recent years, warm mix asphalt technologies have been tested in limited field performance trials with OGFC indicating promise. Many believe that warm mix technologies can help improve OGFCs by reducing the aging of the binder during the mixing process because of lower production temperatures. With this hypothesis, the reduction in binder aging could inhibit raveling which is so debilitating to OGFCs proving WMA OGFCs more durable than traditional OGFCs. In addition to reduced binder aging, some WMA technologies have the ability to increase the binder film thickness around the individual aggregate particles. Previously, raveling was introduced as the most physically destructive problem facing OGFCs. If this issue could be adequately addressed, OGFCs would gain desired durability and dependability. If the WMA technologies can indeed improve the mix performance, the fibers and polymers that are currently being added to OGFC mixes could be eliminated. This would reduce the cost of OGFCs and make them easier for asphalt plants to produce and for crews to construct.

There are currently a number of different warm mix technologies on the market, but they all work for the common goal of providing equivalent asphalt binder properties at lower temperatures to match the same binder properties of typical hot mix asphalt binder. There are four basic types of WMA technologies: chemical packages, zeolites, waxes, and water-injection methods.

With WMA technology and OGFC becoming increasingly popular, the combination of the two could provide a new, successful market for both. The potential for the expansion in the use of OGFCs is dependent on whether or not the most common problems with this mix can be mitigated by WMA: raveling and draindown. The current solution to OGFC draindown and stability issues is fibers. Although the introduction of fibers has been somewhat successful in addressing mix draindown and stability, fibers are a production hassle. The incorporation of fibers into a mix raises the cost and the variability of a mix as the introduction of fibers into a mix is difficult to monitor and control. Due to the aforementioned properties of WMA, there is the potential that raveling and draindown could be decreased dramatically with the use of warm mix

OGFC. If WMA technologies can provide this desired effect, contractors could eliminate the need for this additive.

Research Objectives

The primary objective of this study was to evaluate Evotherm™ (a chemical package) and foaming (a water-injection method) WMA technologies to determine their effectiveness in producing high quality OGFC mixes. Specifically, this study focused on the effect of the removal of stabilizing additives (fibers and polymers) on the optimum binder content and durability of WMA OGFC mixtures. This evaluation was based on the comparison of Evotherm™ WMA and foaming WMA mixes with traditional HMA OGFC using four main criteria: draindown, moisture susceptibility, permeability, and abrasion resistance. To accomplish this objective the following tasks were completed:

1. Conduct a detailed review of the literature related to WMA and OGFC.
2. Prepare mix designs using one aggregate source, one gradation, and two binder grades (76-22 and 64-22) for two WMA technologies (Evotherm™ and Foaming) and HMA.
3. Conduct draindown testing and develop draindown curves for each mix to determine the effect of the fiber and polymer removal.
4. Prepare specimens for 14 selected mix designs and evaluate the volumetric properties, moisture susceptibility, permeability, and abrasion resistance of each mix design.

5. Provide recommendations for the implementation of WMA OGFC and future research.

Organization of Thesis

This thesis is divided into five chapters. The first chapter is the introduction and provides some background information on the topic as well as the objectives of the study. In the second chapter, an extensive literature review is presented. This chapter includes additional background information on both OGFC and WMA including a history of both technologies, benefits and drawbacks of OGFC pavements, and some of the latest research conducted using both technologies. The third chapter details the experimental procedures. Within this chapter, the material selection and properties are specified as well as the experimental methods for both the design and testing procedures used to realize the research objectives. The fourth chapter of this thesis discusses the results of the research including both the first and second phase of the testing. Completing the manuscript, the fifth chapter outlines the conclusions of the research and provides recommendations for implementation and future research.

CHAPTER TWO

LITERATURE REVIEW

History of OGFC

Open Graded Friction Course (OGFC) is a thin layer of permeable asphalt pavement consisting of a uniformly graded aggregate and asphalt binder which is placed over a typical dense graded pavement in thin lifts. As researchers looked for better alternative to chip seals, a thin asphalt surface layer called a plant seal mix (PSM) was developed in the 1940's. First placed in California, these PSM layers improved skid resistance and were the precursor of today's OGFC. The California mixes were placed in thin layers using a smaller maximum aggregate size than typical asphalt mixes and slightly increased amounts of asphalt binder. Engineers found that, in addition to providing superior skid resistance, these mixes provided reduced noise, better durability, and better ride quality (Kandhal 2002).

The new asphalt layer began to grow in popularity in the United States as well as Europe and Japan by the 1970s. However, many agencies began to experience problems with the mixes such as draindown and raveling. These problems would become habitual hindrances to OGFC causing many agencies to discontinue use of the mixes in the 1980's. Some European countries as well as some states like Georgia, Texas, Florida, and Oregon persisted in using OGFCs by improving the mix design of this wearing course (Kandhal 2002). These agencies did so by using polymer modified binder, higher quality open graded aggregates and fiber additives. These changes were aimed at stabilizing the mix to decrease binder draindown. In reality, these changes increased binder content and air voids and made the mix more durable overall (Fitts 2002).

In Europe, porous asphalt was first used in the United Kingdom on runways in the 1960's to eliminate hydroplaning and improve skid resistance (Hwee et al. 2004). After some success, the mix was taken into the lab for study where it was modified by adding fibers and raising the binder content to make the pavement more durable. At this point, the mix was thought to be satisfactory for roads where the safety advantages afforded were found to outweigh the disadvantages (Nielsen 2006).

OGFC mixes in Europe developed similarly to their American counterparts but with some subtle yet noteworthy differences. The European version of these mixes became known as PEMs, Porous European Mixes (Watson et al. 1998). PEMs utilize polymerized binder almost exclusively and higher quality aggregates common in Europe (Huber 2000). These mixes are characterized by having an increased porosity, around 18-22%, compared to their American counterparts, typically about 15%. The higher porosity in PEMs most directly displays the differences in gradation in the two types of mixes as well as the higher quality of materials (Watson et al. 1998). The gradation comparison between American OGFCs and European PEMs can be seen in Table 2.1 below.

Table 2.1 – Gradation Comparison of OGFC and PEM
(Watson, et al. 1998)

Sieve Size	Percent Passing 12.5mm OGFC	Percent Passing 12.5mm PEM
3/4 inch (19 mm)	100	100
1/2 inch (12.5 mm)	85-100	90-100
3/8 inch (9.5 mm)	55-75	35-60
#4 (4.75 mm)	15-25	10-25
#8 (2.36 mm)	5-10	5-10
#200 (0.075 mm)	2-4	1-4

In France, the use of porous asphalt did not begin until 1976, but consistently increased until 1990 at which point agencies decided to discontinue the use because of the difficulty with winter maintenance. France did, however, strongly advocate the use of polymerized binder finding it necessary to limit draindown. French authorities also suggest that OGFC be used on high speed roadways (Nielsen 2006).

The Netherlands began their use of OGFC in 1980 and have experienced much success since that introduction. In fact, by 1990 the Netherlands mandated that their entire highway system be surfaced with OGFC. It has been reported that their OGFC pavements in the Netherlands typically last between 10-12 years at which point they must be replaced due to raveling (Nielsen 2006).

The use of OGFC within the United States has been met with varying degrees of success. In 1998, NCAT, the National Center for Asphalt Technology, conducted a survey to gain a better understanding of OGFC usage around the United States. The survey was designed to investigate usage and performance as well as design and construction methodologies. The survey found that only 8% of states had never used an OGFC while 38% of states had discontinued their use of OGFCs. The survey found that agencies reported the expected lifespan of an OGFC pavement to be from 8-12 years. Most states reported that they had an OGFC mix design while some states utilized a recipe. Additives used included a variety of fiber types, silicone, rubber, hydrated lime, and liquid anti-stripping additives (Kandhal et al. 1998). Meanwhile, the survey showed that three different methods were used to determine the optimum binder content. States either utilized the FHWA test (oil absorption capacity of aggregates), visual inspection of draindown, the standard viscosity charts, or property and performance specifications developed by NCAT or NAPA. The property and performance specifications require compacted sample testing (permeability, draindown, and Cantabro abrasion) and subsequent binder content adjustment. Currently, the visual methods similar to those followed by Florida, South Carolina, and others, although subjective, are thought to be the most definitive for selecting the optimum binder content of OGFC mixtures (Kline and Putman 2011)

Benefits of OGFC

OGFC pavements have numerous benefits that make them a desirable pavement type and a few drawbacks to be addressed. The characteristic high air void content of OGFCs makes them very beneficial for use on interstate highways. The high porosity provides the pavement structure with a network of interconnected void spaces that allows water to drain easily through the pavement structure. This system drains water off highway surfaces immediately during a rain event , thus reducing splash and spray, minimizing the risk of hydroplaning, and reducing the glare reflected from the water covering pavement surfaces during a rain event. In fact, a study in England found that the use of OGFCs cuts splash and spray by 95% for a vehicle following a truck at a distance of 10 feet (Nicholls 1997). Another study showed that even during a severe storm event where the OGFC pavement structure remains wet an OGFC outperformed a typical HMA pavement. Because of the air void structure of the OGFC, the pavement surface better transferred the tire loads from the vehicle than a normal HMA pavement did providing drivers with superior tire-pavement interaction in extreme weather (Kandhal 2002). OGFC also provides drivers with better surface friction and better visibility in extreme weather events. Since OGFCs are usually placed in thin layers, high quality aggregates are conserved with the use of OGFCs.

Due to the interconnected void structure of OGFC pavements, OGFCs demonstrate superior ability to absorb road noise from tire/pavement interaction. This open void structure provided by the coarse graded aggregate has been shown to reduce the tire/pavement noise generated from a roadway. One study performed in Colorado compared pavement types with respect to noise reduction finding that OGFC was the best at absorbing road noise from 19 different sites. The study found an indirect linear correlation between road noise and air voids within a pavement (Hanson et al. 2004). In some nations, OGFCs are considered a viable substitute for sound barriers as they decrease sound even for tall structures and are much cheaper to install (Kandhal 2002).

Several studies have been performed to show the improved friction and skid resistance of OGFC layers. Friction is an important property of roadways as low friction roads are known to have more accidents, especially in wet weather. A study performed in Pennsylvania in 1976 compared friction numbers of OGFC surface layers with dense graded HMA surface layers made using the same aggregate sources Table 2.2 (Brunner 1975). Another study in Virginia reported friction values for OGFC between 51 and 72 (Maupin 1976). Meanwhile, a study conducted in France examined a roadway where 52 accidents occurred between 1979 and 1985. After OGFC pavement was placed in this location in 1985, zero accidents occurred on this same stretch of road from 1985 to 1989 (Chaignon 1993).

Table 2.2 – OGFC Pavement Friction Data (Obtained by the Pennsylvania DOT) (Brunner 1975)

Pavement Type	Friction Number 30 mph	Friction Number 40 mph
OGFC with gravel	74	73
OGFC with dolomite	71	70
Dense graded HMA with gravel	68	60
Dense graded HMA with dolomite	65	57

In addition to the safety benefits of the high permeability of OGFCs, the void structure also works as a filter for water born pollutants. This was shown in a study performed by Barrett et al. where an OGFC was placed over a regular HMA pavement typical for OGFC usage. The runoff water was collected from the pavement and found that there was a significant reduction in pollutants (Barrett et al. 2006). The individual reductions of the various pollutants can be seen in Table 2.3.

Table 2.3 – Reduction in Stormwater Pollutants (Barrett et al. 2006)

Pollutant	Reduction (%)
Total Suspended Solids	91
Total Kjeldahl Nitrogen	2
Total Phosphorus	35
Total Copper	47
Total Lead	90
Total Zinc	75
Dissolved Zinc	30

High quality, polish resistant aggregates with good angularity must be used in OGFC applications. This will ensure the OGFC layer with the highest possible interlock, adhesion, and subsequent wear resistance. Since OGFC pavements are placed in such thin lift thicknesses (1-2 inches) and have such an open void structure, they are susceptible to early aging and subsequent deterioration such as raveling. OGFCs also receive the majority of the wear on a pavement structure since these layers are the wearing course in the pavement system. Using the highest quality ingredients in an OGFC mix will ensure the longest service life possible for the pavement layer. Although OGFC is not considered a structural enhancement to a pavement, it does absorb the wear and tear of the roadway and protect the underlying pavement layers. By constructing OGFC layers in thin lifts, OGFC pavements limit the amount of high quality aggregates and other materials needed to produce these pavements.

Drawbacks of OGFC

Some common problems with OGFCs are raveling, pore clogging, and winter maintenance (Kandhal et al. 1998). Because of the recurring nature of these issues the NCAT conducted a survey to determine which problems agencies most commonly faced with the use of OGFCs. Table 2.4 shows the results of that survey (Kandhal et al. 1998; Nielsen 2006).

Table 2.4 – Problems Encountered with Porous Friction Courses (Kandhal et al. 1998; Nielsen 2006)

Agency		Typical Problems Encountered
Europe	Austria	Raveling
	France	Raveling
	Germany	Raveling
	The Netherlands	Raveling & Rapid Aging
	Spain	Raveling & Pore Clogging
	United Kingdom	Pore Clogging & Rapid Aging
United States	Alaska	Ice Removal
	Colorado	Stripping
	Hawaii	Raveling
	Idaho	Pore Clogging
	Iowa	Ice Removal
	Kansas	Ice Removal
	Louisiana	Raveling
	Maine	Ice Removal
	Maryland	Raveling
	Minnesota	Raveling & Pore Clogging
	Rhode Island	Raveling
	South Dakota	Pore Clogging
	Tennessee	Stripping & Ice Removal
	Virginia	Stripping

Winter maintenance is one issue that states should consider carefully before placing OGFC as evidenced by this survey. Because of the interconnected void structure, OGFC pavements can be cooler than their dense graded counterparts in cold weather. Many agencies have noted that snow and ice form on OGFC differently and more quickly than on other pavement surfaces. Snow and ice also thaw off OGFC surfaces more slowly (Yildirim et al. 2006). This calls into question how to handle the winter maintenance for OGFC pavements. In all cases, the uses of sands must be prohibited as sand material will easily clog the pores of the OGFC greatly reducing the pavements permeability. Salt can be used but must be spread as finer grains which can make the need for salt treatments more frequent. Greater frequency in treating an OGFC is often necessary with any treatment method as chemical deicers will tend to infiltrate into the pavement structure diminishing the amount left on the surface for the intended purpose of the winter maintenance treatment. Plowing is another task that is made increasingly difficult with the use of OGFC pavements. OGFCs provide less resistance to a snow plow making them more vulnerable to degradation from the plow than other pavement types (Cooley et al. 2009).

Pore clogging is another troublesome problem for OGFC pavements. Because of the open void structure, any number of materials can penetrate into the void structure and clog the pavement. Clogging is the primary reason why OGFC pavements are best utilized for interstate or other high speed applications. To prevent sands, clays, and other pore clogging materials from entering the pavement structure, high traffic speeds, significant curbing, or erosion control measures are needed. Maintenance can be performed on a clogged porous pavement and has been successful in a number of studies at restoring or partially restoring permeability. One study found that even though a pavement was clogged, as long as the pavement had an initial permeability of 100 m/day, it could function well even after significant clogging (Suresha et al. 2008).

As seen from this survey, raveling is the most commonly fought problem among agencies with experience using OGFC. Raveling is the breaking away of individual aggregate particles from the pavement surface. Once an OGFC layer begins to exhibit raveling, more raveling will follow quickly as this type of deformation builds upon itself. Due to the open and interconnected void structure of this pavement type, water and air are able to pass through the pavement structure unlike common dense graded HMA which limits air/pavement interaction to the surface. This air/pavement interaction within OGFC promotes early aging (oxidation) of the binder, making the binder stiffer and more brittle. Aside from construction related issues early aging is the root problem of OGFC layers since this exact phenomenon exacerbates raveling (Kandhal et al. 1998).

One study performed in the Netherlands indicated that there are two types of raveling failures, cohesive and adhesive. Cohesive is typically involved in hot weather conditions while adhesive failure is usually seen in cold weather conditions. The study asserts that aging somewhat improves a porous pavement resistance to cohesive (warm weather) raveling but dramatically reduces the ability of a porous asphalt to resist adhesive (cold weather) raveling (Mo et al. 2009). These researchers suggest that a flexible binder with the ability to relax and resist permanent deformation is the best at resisting raveling (Mo et al. 2010).

Warm Mix Asphalt – Background

The term warm mix asphalt (WMA) refers to the variety of asphalt technologies which significantly reduce the mixing and compaction temperature of asphalt mixes. From reduced fuel consumption to reduced plant and job site emissions, there are a variety of benefits to using WMA technologies. Projects can have longer haul distances, be paved in cooler weather, and newly constructed pavements can be opened to traffic sooner (Hurley and Prowell 2005). Workers also find that WMA provides them a better work environment (cooler and less emissions) and a mix with better workability and therefore easier compaction. Studies so far have shown that WMA technologies provide reduced aging of the binder limiting pavement cracking (Prowell and Hurley 2007).

Warm mix asphalt can be manipulated to provide desired benefits based upon the needs of a specific project. While warm mix asphalt can undoubtedly lower the temperature of an asphalt mix considerably, the mixing temperature can be dropped a moderate amount instead of the full limit to improve workability at compaction. This can allow for the asphalt pavement to be compacted more densely than usual which in turn can lower the optimum binder content. For a specific project, decreased optimum binder content may be of greater benefit than reduced energy and subsequent fuel consumption (Estakhri et al. 2010).

Undoubtedly, the foremost environmental benefit provided by WMA technologies is the reduction of emissions. This reduction is twofold as less energy is needed in the production of WMA compared to HMA, and less emissions are created by asphalt produced at lower temperatures. With decreased fuel requirements of over 40%, obviously fewer emissions are created as less fuel is burned (Vaitkus et al. 2009). However, asphalt binders emit less vapors at lower temperatures meaning the WMA has the capacity to drastically cut asphalt emissions. The following figures show the expected decrease in each type of emissions for WMA compared to HMA: reduction of CO_2 by 30-40%, reduction of SO_2 by 35%, reduction of volatile organic compounds by 50%, reduction of CO by 10-30%, reduction of NO_2 by 60-70%, and reduction of dust by 20-25% (Vaitkus et al. 2009).

North American HMA is typically produced at temperatures ranging from 300°F to 350°F. With the use of WMA technologies, these same pavements can be produced at temperatures that range between 50 and 100°F lower than HMA while maintaining the desired workability and performance. Clearly, this temperature reduction provides a benefit to the contractor as the reduction in energy cost can exceed 30%. The contractors also benefit from the reduced emissions as much of their efforts in emissions reduction are unnecessary (Hurley and Prowell 2005).

There are four basic types of WMA technologies, chemical, zeolite, wax, and water-injection. Of the four, two (chemical and water-injection) were examined in this research study. Although some WMA technologies have been used in field and research studies, others are new or newly improved as WMA technology develops making them much less researched. Many currently have little to no comprehensive data on actual performance (Vaitkus et al. 2009).

The origins of warm mix asphalt go back to the 1950’s when Prof. Ladis Csanyi, of Iowa State University performed the very first investigations into the possibility of foaming bituminous products to use as a soil stabilization method. After these initial investigations, numerous countries have successfully used foamed binder in paving applications by injecting steam into the asphalt binder. It was not until 1968 that Mobil Oil Australia first added cold water into asphalt binder. This process would eventually replace the steam injections (Button et al. 2007). In the mid 1990's, todays first chemical WMA technologies began to be produced in Europe. The first field trials soon followed before the turn of the century. Not until 2004, did US research commence on WMA technologies (Prowell and Hurley 2007).

Because of the recent development of WMA, most studies conducted have been in the form of case studies which have provided the scientific community with numerous 1-2 year old test sections. While this is a good start in many ways, there is a large gap in knowledge as to what the long term performance of WMA will actually be. This has led to a need to develop reliable test methods for determining accurate predictors for WMA performance. Cutting emissions and contractors' costs and is great for now, but the goal of the scientific community has to be using the newest most efficient WMA technologies to make a better pavement product for users. As technology continues to evolve, engineers can ideally make a product not just comparable to regular HMA but superior to HMA (Diefenderfer and Hearon 2010).

One noteworthy benefit of WMA is the reduced binder aging. Because of the reduced mixing and compaction temperatures, a WMA binder film is softer and less aged than typical HMA binder film. Some WMA products actually chemically affect binder aging; however, this action is product chemistry and temperature dependent making it vary from project to project. This decreased aging is significant as it extends the life of the pavement. Even if a WMA enters its service life with only a one year aging reduction, this one year reduction is one year later that the project must be rehabilitated affording agencies with a significant cost reduction (Diefenderfer and Hearon 2010).

Another benefit of some WMA technologies is that they actually provide a mix with a higher binder film thickness surrounding individual aggregate particles. Between the decreased aging and increased binder film thickness, there is compelling knowledge to suggest that WMA technologies would be perfect to address the raveling concerns facing most agencies currently using OGFC. The majority of concerns agencies seem to have over using WMA technologies is the relatively small knowledge base on the long term effects of the technology (Vaitkus et al. 2009).

Evotherm™

MeadWestvaco's Evotherm™ is one WMA technology that directly affects the chemistry of the mix. The additive is a type of sophisticated asphalt emulsion allowing for better aggregate coating at much lower temperatures. Evotherm™ is a chemical package engineered to improve workability by changing a binder's viscoelastic properties by employing adhesion promoting and asphalt emulsifying chemicals. Evotherm™ is one of the only warm mix technologies that claims a mixing temperature reduction of 100°F. Evotherm™ is stored in a tank and pumped directly into an asphalt binder using heated valves at an asphalt plant. With 70% of the chemical package as asphalt residue adjusting the mix to be proportional is necessary. Using the latest MeadWestvaco product

Evotherm™ 3G, contractors must simply add the product at a rate 0.5% by weight of asphalt binder. Evotherm™ 3G can be stored in a tank and mixed at a plant or mixed with binder at a terminal and supplied premixed to the asphalt plant (Estakhri et al. 2010).

Conventionally, the way Evotherm™ works is that as the chemical package is added to the binder, the water in the emulsifier turns to steam creating WMA (Hurley and Prowell 2006). While this Evotherm™ behaves much like emulsifiers a few distinct characteristics differentiate it. The chemical formula allows for complete coating of the aggregate at 60°C (140°F) and without high water dosages or chemical loadings. Evotherm™ also provides desirable workability and subsequent compaction at these reduced temperatures without sacrificing desired density and cure rate. Evotherm WMA technologies also include a chemical anti-stripping additive meaning the package can be used without the inclusion of the typical anti-stripping additives, including hydrated lime (Prowell et al. 2007).

Evotherm™ can be supplied in three different forms. Evotherm™ ET (Emulsion Technology) is similar to a traditional asphalt emulsion and can simply be substituted in plant for asphalt binder. Evotherm™ DAT (Dispersed Asphalt Technology) is a chemical package in the form of a concentrated solution than uses in-line injection to be added to the asphalt binder at a plant. This version of Evotherm™ is convenient for manufactures by allowing a quick switch between WMA and HMA. Evotherm™ 3G (Third Generation) is the latest product and it is the most advanced. The manufacturer states that Evotherm™ 3G provides temperature reductions of 100°F (Gandhi and Amirkhanian).This product can be added directly to binder at a plant or at an asphalt terminal. All three additives come from a similar chemical composition (Estakhri et al. 2010).

Several research studies have been performed using Evotherm™ warm mix technologies. In one such study, 200 feet of the NCAT test track in Auburn, Alabama was utilized to compare field tests with laboratory tests. This test section was loaded specifically with trailers to provide 10 million ESALs in 2 years. The test compared rutting resistance in the field to that of a laboratory Asphalt Pavement Analyzer (APA) and found them very similar. The study also noted that the WMA section performed very well over the 2 year period. Other findings from the study included that Evotherm™ warm mixes could be stored in a silo for 17 hours with no problem and opened to traffic as soon as 1.75 hours after paving (Prowell et al. 2007).

In Alabama, a warm mix demonstration was held where a field section was compared to a number of laboratory tests including APA rut tests, indirect tensile strength, wheel tracking, dynamic modulus, and creep compliance. The WMA pavement in this study required more binder than the HMA counterpart which may have adversely affected the results of the study since WMA was found to be more susceptible to rutting and had lower tensile strength. The creep test showed that the WMA was more susceptible to load induced damage and dynamic modulus showed that regular HMA was stiffer. However, the field tested cores exhibited tensile strengths much closer to the regular HMA. These results may be evidence that WMA experiences a type of field curing where it gains strength with exposure suggesting that actual WMA field sections may be more similar to regular HMA than lab tests indicate (Kvasnak 2010).

Other studies within the United States have been performed indicating promise for the use of Evotherm™ WMA. In Texas, DOT research found that Evotherm™ could be placed and compacted uniformly in as large as 14 inch sections (Wielinski et al. 2009). The Virginia DOT placed a test section of Evotherm™ WMA and has found no visible distresses after 2 years of observation. Monitoring on this section will continue throughout the life of the pavement (Diefenderfer and Hearon 2010).

Although few studies have been conducted on MWV's Evotherm™, one study was performed in China to determine the relevancy of using Evotherm™ warm mix on ultra-thin pavement sections. Since the researchers used ultra-thin surface, this study is somewhat similar to Evotherm™ applied to OGFC. The study primarily focused on the workability of the Evotherm™ warm mix asphalt as the researchers performed dynamic viscosity testing on hot mix and Evotherm™ warm mix to develop mixing and compaction temperature curves. The paving was performed at a low ambient temperature, and temperature versus time curves were developed to guide future compaction. In the end, Evotherm™ warm mix performed well with the low air temperature on the ultra-thin surface layer (Tao et al. 2009).

Additional testing was conducted by NCAT to observe the field behavior of several warm mix pavements. Evotherm™ was incorporated into these mixes, and researchers found that the densities of the pavements employing warm mix (compacted 8-42 °C below hot mix compaction temperatures) were equivalent or better. The pavements exhibited good rutting resistance, but laboratory samples showed an increase in moisture susceptibility (Prowell et al. 2007).

Foaming Injection Method

Currently, there are three asphalt plant manufacturers with foaming WMA technologies including, Terex Corporation, Gencor Industries, Inc., and Astec, Inc. This type of WMA technology is referred to commonly as foamed asphalt or sometimes free-water systems. In each of these systems, water is added in small dosages (1-2% by weight of the binder) to hot asphalt binder where the water is converted to steam. This process expands the asphalt binder leaving a bituminous product with a lower viscosity than normal asphalt binder. This creates the WMA by allowing the aggregate to be coated thoroughly at much lower temperatures than typical HMA (Wielinski et al. 2009). The cool water can be directly injected into the asphalt binder and requires no chemical additives like the majority of WMA technologies (Astec Industries 2010). This lack of additives makes a WMA project simpler and less expensive for contractors.

Of the three manufacturers, the Double Barrel Green System developed by Astec, Inc. is the most commonly used. In fact, when a company purchases an asphalt plant from Astec, Inc. it automatically includes a Double Barrel Green System in the package. This has led to the increased popularity of the of the foamed WMA technology since plants now come equipped for making this WMA, or existing plants have to make a simple one time investment to add the foaming capability. Terex Corporation's technology uses a system very similar to Astec's Double Barrel Breen System (Wielinski et al. 2009).

Because foamed WMA technology is readily available and requires little investment from contractors, foaming is the most commonly used WMA technology across the United States. This raises problems because the ability to replicate this foaming technology in the lab setting is extremely limited. Currently, on foaming WMA projects the mix must be designed without foam and then adjusted during the trial batch to arrive at the job mix formula (Estakhri et al. 2010). However, a machine, “The Foamer”, capable of producing foamed asphalt binder has been developed for laboratory use in conjunction with foaming WMA projects and for conducting research on this WMA technology.

In California, a demonstration was held using the foaming WMA technology and the conventional (Hveem) mix design method. The researchers found that the foamed asphalt had a lower initial binder stiffness and a higher rutting potential; however, the foaming technology was found to be compatible with the state’s conventional mix design as the WMA pavement met the required in-place density and mechanical properties. The lower stiffness and higher rutting potential was attributed to the lower binder temperatures having a reduced aging effect on the asphalt binder. From the results, the study concluded that this type of WMA technology could be used in place of regular HMA. The test section is still being monitored for long term performance (Wielinski et al. 2009).

WMA and OGFC

Few studies have been performed that combine OGFC and warm mix technology, but one such study was undertaken by Caltrans in May of 2008. In Barros et al. 2008 Caltrans explained how the variety of climate types in California validated exploration of any technology that could help offset the effects of cool weather especially in the northern

California with coastal climates and longer haul times due to distance and traffic. Moreover, the agency wished to determine if warm mix technology could help them expand RAP and OGFC usage across there state.

With these ideas at the forefront, Caltrans selected a test section on Highway 1 in Morro Bay, California. The temperature was 57°F in the afternoon when the test section was placed using a PG 58-34 binder and had a haul distance of 30-45 minutes. These were not ideal paving conditions for OGFC. Caltrans put on an expo for local contractors and material suppliers to observe the operation, and chose to pave a control section of ½ mile and three warm mix experimental sections of the same length using three separate technologies. These three technologies were Advera® WMA (PQ Corporation), Evotherm™ (MeadWestvaco), and Sasobit® (Sasol Wax, USA).

For the paving operation, some additives had trouble meeting the maximum draindown requirement, so the production temperature was lowered for this requirement to be met. The weather conditions varied on the paving days making comparison of the various additives difficult due to this uneven playing field. With this in mind, some of the conclusions from the project were that the production temperature was lowered by 50°F and the compaction temperatures by a minimum of 30°F. Workers noticed a much improved workability and a reduced "stickiness" evidenced by equipment and hauling trucks. This decreased stickiness contrasted sharply with the typical characteristics of the polymer modified binder used. Difficulties experienced in the project were mostly centered on production as plants had trouble with consistency on small batches and learning to use some of the additives affectively (Barros et al. 2008).

Recently, a study was performed at Rutgers University for the New Jersey DOT on stone matrix asphalt (SMA) using Evotherm™ (Bennert 2011). The primary objective of this research was to determine if the fibers included in the mix design could be eliminated without compromising mix quality by employing Evotherm™. The researchers found that the draindown was unaffected by the change in mix design. Moreover, the study showed that the Evotherm™ mix without fiber had a fatigue life 900% greater than the SMA, HMA mix. This dramatic increase in fatigue life is attributed to the decreased binder oxidation aging/stiffening and lower binder absorption provided by the Evotherm™.

Warm mix asphalt technologies have shown their relevancy in research and in field operations through numerous studies and actual projects. The major reason warm mix technologies are being studied, promoted, and adopted in construction is because of the numerous benefits these technologies afford. Some of the most commonly heralded advantages when using warm mix are the reduction in emissions and energy usage. Because of this, WMA has decided environmental advantages over conventional hot mix asphalt. However, this advantage does not typically save paving contractors enough money to warrant them using the warm mix technology. Where then does the true incentive come to use warm mix technology? The real power that will drive the warm mix technology to the forefront is the decreased binder viscosity of warm mix asphalt. This lower viscosity diminishes cool weather compaction problems, reduces the amount of equipment needed at the job site, and reduces the compaction risks associated with stiff mixes (Kristjánsdóttir et al. 2007). Basically, contractors like to see WMA technologies bettering their products instead of complicating them. In the case of OGFC warm mix asphalt has the potential of making the product more durable and more economical. These advantages are much more tangible and easily identifiable by contractors. With contractors and agencies able to see the practical benefits of employing warm mix technology, the market for such technologies is sure to grow (Kristjánsdóttir et al. 2007).

CHAPTER THREE

EXPERIMENTAL MATERIALS AND METHODS

To realize the objectives of this study, the research was divided into two phases including 10 different mix designs (4 HMA, 4 Evotherm™ WMA, and 2 foaming WMA). The primary components of each mix design that were varied were the binder performance grade (PG 76-22 and PG 64-22) and fibers. Initial testing was completed to characterize the mixes based on binder draindown as draindown curves were developed for each mixture. Following the draindown evaluation, the optimum binder content of each mix was determined and samples were made to test the performance properties of each mix, specifically permeability and abrasion resistance.

Materials – Aggregate

For this study, one crushed aggregate source which is typical of the aggregate specified for OGFC mixes across the US was used. The aggregate was a crushed granite with the properties summarized in Table 3.1.

Table 3.1 – Aggregate Properties

Property	Value
Bulk Specific Gravity	2.615
Bulk Specific Gravity (SSD)	2.628
Apparent Specific Gravity	2.650
Absorption	0.5%
LA Abrasion Loss (C grading)	28%
Sulfate Soundness	4.1% max

In the state of South Carolina, crushed granite is the most commonly available aggregate source for asphalt. The stone used for this study has very good abrasion resistance that would pass all state agencies' specifications for HMA production. The absorption value is below 1% which is also recommended for asphalt mixes.

The aggregate gradation was designed to meet the SCDOT requirements for OGFC (SCDOT 2007). This specific gradation has been used for OGFC within the state of South Carolina and is typical for OGFC gradations found around the nation. It combines a No. 7 stone and a No. 89 stone with 1% hydrated lime to reach the specified requirements. The gradation is listed in Table 3.2.

Table 3.2 – Project Gradation and SCDOT specification (SCDOT 2007)

Sieve	Research Gradation (% Passing)	SCDOT OGFC Gradation Specs. (% Passing)
¾-inch (19.0 mm)	100	100
½-inch (12.5 mm)	93	85 – 100
⅜-inch (9.5 mm)	68	55 – 75
No. 4 (4.75 mm)	20	15 – 25
No. 8 (2.36 mm)	7	5 – 10
No. 200 (0.075 mm)	2	0 – 4

Materials - Binder

Two different binder grades were used in this project. The first was a PG 64-22 which is used for most non-interstate HMA paving in South Carolina as well as many other states. The second binder type was a PG 76-22 polymer modified binder which is commonly used in OGFC applications across the nation since it resists deformation better than the PG 64-22 and it also reduces draindown. The polymer modified binder (PG 76-

22) utilized a SBS polymer modifier. The properties of these binders as well as the mixing and compaction temperatures are summarized in Table 3.3.

Table 3.3 – Binder Properties

	Property	PG 64-22	PG 76-22
Original Binder	Viscosity @ 135°C (Pa·s)	0.450	1.642
	Viscosity @ 165°C (Pa·s)	n/a	0.415
	G*/sin @ 64°C (kPa)	1.23	n/a
	G*/sin @ 76°C (kPa)	n/a	1.44
RTFO Aged Binder	G*/sin @64°C (kPa)	3.70	n/a
	G*/sin @ 76°C (kPa)	n/a	2.94
PAV Aged Binder	G*sin @25°C (kPa)	4438	n/a
	G*sin @ 31°C (kPa)	n/a	1070
	Creep stiffness (60s) @ -12°C (MPa)	179	132
	m-value (60s) @ -12°C	0.306	0.366
	Mixing Temperature (°C)	159-166	164-171
	Compaction Temperature (°C)	147-152	151-157

Materials - Additives

Two specific additives were used in this study, hydrated lime and cellulose fibers. Cellulose fibers add stability to the mix and help absorb excess binder which allows the binder content of the mixes to be artificially increased. Fibers were added at a rate of 0.3% by weight of the entire mix. Hydrated lime is an anti-stripping additive added at 1% by weight of the aggregate for each mix. In this project, the Evotherm™ 3G WMA technology already contains a liquid anti-stripping additive; however, the hydrated lime was still used in all mixes within this project to maintain consistent parameters.

Materials – WMA Technologies

In this study two WMA technologies were evaluated: Evotherm™ and foaming. When the Evotherm™ was added to the asphalt binder, the binder was first heated to the target mixing temperature of 141°C (286°F) for the PG 76-22 binder and 135°C (275°F) for the PG 64-22 binder. The Evotherm™ 3G additive was then added to the binder at a rate of 0.5% by weight. The WMA binder was then stirred for 1-2 minutes before being placed back in the oven at the mixing temperature for 30 minutes. Once mixed, the binder was added to the heated aggregate and mixed in a mechanical bucket mixer in the same manner as the regular HMA samples.

For the foaming WMA technology, water was injected into the hot asphalt binder at 2% by weight of the asphalt binder by "The Foamer." The binder used for the foaming WMA mix designs was heated and inserted into "The Foamer" at HMA mix temperatures (171°C for PG 76-22 and 163°C for PG 64-22) before water was injected into the binder and the WMA binder was emitted and mixed with the hot aggregate at WMA mix temperatures (141°C for PG 76-22 and 133°C for PG 64-22). This mixing of the water instigated the foaming action creating the WMA. This foamed WMA binder was then added to the heated aggregate and mixed in a mechanical bucket mixer in the same manner as the regular HMA samples.

Experimental Procedures

Draindown testing was performed for all the mixes in accordance with AASHTO T305 (2005) with the exception that only the mixing temperature was evaluated (Table

3.4). This testing consisted of measuring the binder lost from the mix placed in a draindown basket (No. 4 mesh) and conditioned at the mixing temperature for 1 hour. Two draindown samples were tested per binder content over a binder content range from 4.0 to 7.5%. This testing provided the rate of binder draindown relative to the binder content of the mix. This test has been shown to be effective in determining the stabilizing capacity of fibers in draindown prone mixes like OGFC (Putman and Amirkhanian 2003). Equation 3.1 was used to calculate the draindown.

Table 3.4 – Temperatures for Draindown Testing

Mixture		Binder	Fiber	Test Temperature
76-22 Control F	HMA	PG 76-22	Yes	171°C (340°F)
76-22 Control NF			No	171°C (340°F)
64-22 Control F		PG 64-22	Yes	163°C (325°F)
64-22 Control NF			No	163°C (325°F)
76-22 Evo F	Evotherm™ WMA	PG 76-22	Yes	141°C (286°F)
76-22 Evo NF			No	141°C (286°F)
64-22 Evo F		PG 64-22	Yes	133°C (271°F)
64-22 Evo NF			No	133°C (271°F)
76-22 Foam NF	Foaming WMA	PG 76-22	No	141°C (286°F)
64-22 Foam NF		PG 64-22	No	133°C (271°F)

$$Draindown\ (\%) = \frac{P_i - P_f}{M_t} \times 100\% \qquad \text{Equation 3.1}$$

Where:
Pi – Mass of plate before draindown test
Pf – Mass of plate after draindown test
Mt – Total mass of specimen (asphalt mixture)

Following the draindown testing, the optimum binder content (OBC) of each mix was determined in accordance with the SCDOT procedure for designing OGFC mixtures, SC-T-91 (SCDOT 2010). SCDOT specifies a visual OBC determination method which research suggests is more definitive than other methods (Kline and Putman 2011).

Once the optimum binder contents for each mix had been determined, the moisture susceptibility of each mix was evaluated. The SC-T-69 (SCDOT 2010) procedure was used to test the moisture susceptibility of each mix design at the OBC. This test procedure consists of placing a loose asphalt sample (300g) into a beaker of boiling water for 10 minutes before removing the sample and visually determining the percent stripping. Two samples were tested at the optimum binder content for each mix design.

The temperature reduction for Evotherm™ as recommended by the manufacturer was 30°C. This reduction was applied to the draindown test temperature as well as the mixing and compaction temperature ranges for making the other specimens. The 30°C reduction was used for both WMA technologies (Evotherm™ 3G and foaming) to maintain consistent and comparable research parameters. The mixing and compaction temperature ranges for making samples are listed in Table 3.5.

Table 3.5 – Mixing and Compaction Temperatures

Mixture		Binder	Fiber	Mixing Temperature (°C)	Compaction Temperature (°C)
76-22 Control F	HMA	PG 76-22	Yes	164-171	151-157
76-22 Control NF			No	164-171	151-157
64-22 Control F		PG 64-22	Yes	159-166	147-152
64-22 Control NF			No	159-166	147-152
76-22 Evo F	Evotherm™ WMA	PG 76-22	Yes	134-141	121-127
76-22 Evo NF			No	134-141	121-127
64-22 Evo F		PG 64-22	Yes	129-136	117-122
64-22 Evo NF			No	129-136	117-122
76-22 Foam NF	Foaming WMA	PG 76-22	No	134-141	121-127
64-22 Foam NF		PG 64-22	No	129-136	117-122

A series of specimens were made in this study to realize the objective of the project. The following 5 different types of asphalt specimens were made for testing (4 uncompacted and 1 compacted): draindown (1200g uncompacted), OBC determination (1000g uncompacted), moisture susceptibility (300g uncompacted), maximum specific gravity (1500g uncompacted), and permeability and abrasion testing (3800g compacted). At least 9 compacted samples were made for each mix design at the OBC, while 9 additional samples were made at 0.5% above the OBC for the WMA mixes without fibers to determine the effect of increased binder contents on permeability and abrasion.

The compacted samples (150 mm diameter by 115±5 mm tall) were compacted using a Superpave gyratory compactor at 50 gyrations per sample. Once compacted, the samples were allowed to remain in the mold to cool in front of a fan for approximately 15 minutes. This cooling period prevented the samples from falling apart or becoming distorted due to gravity. After a sample was removed from a mold, it was removed from the compaction area and moved to the cooling station.

All of the compacted samples made per mix design were tested for specific gravity, and porosity and the volumetrics (air voids, VMA, VFA) were calculated for all samples. Once this initial testing was completed, the 9 samples for each mix design were divided into 3 groups of 3 specimens per group for the next phase of testing (3 for permeability, 3 for unaged Cantabro abrasion, and 3 for aged Cantabro abrasion). The porosity data was used to group the samples to ensure that each sample group was representative of the overall mix design properties. Lastly, to verify that the 3 test groups were similar with respect to porosity, an analysis of variance (ANOVA) was performed using $\alpha = 0.05$.

After completing the volumetric testing, 6 of the 9 samples were tested for Cantabro abrasion (3 unaged and 3 aged for 7 days) and the remaining 3 samples were tested for permeability. However, once the permeability samples were tested for initial permeability, the samples were then aged and retested for 4 aging cycles. This means that the samples were tested for initial unaged permeability, then again after 3 days of aging, 6 days of aging, 9 days of aging, and 14 days of aging. All aging for permeability and Cantabro abrasion was conducted in a temperature controlled chamber at 60°C (140°F). The standard procedures for testing can be seen in Table 3.6.

Table 3.6 –Testing Procedures

Procedure/Test	Standard
Maximum Specific Gravity (MSG)	ASTM D2041
Draindown	AASHTO T305
Moisture Susceptibility	SC-T-69
Visual Determination of Draindown (OBC)	SC-T-91
Specimen Compaction	ASTM D6925
Specific Gravity & Porosity	ASTM D7063
Cantabro Abrasion	ASTM D7064

The test procedure used in this study for permeability testing was a falling head test procedure. The experimental setup for this procedure included a 150 mm inside diameter stand pipe, reducers with valve, and u-shaped fitting. Other items required for the test include plumbers putty, plastic wrap, petroleum jelly, and a stopwatch. The outlet was located at the same elevation as the top of the sample. A photo of the apparatus can be seen in Figure 3.1.

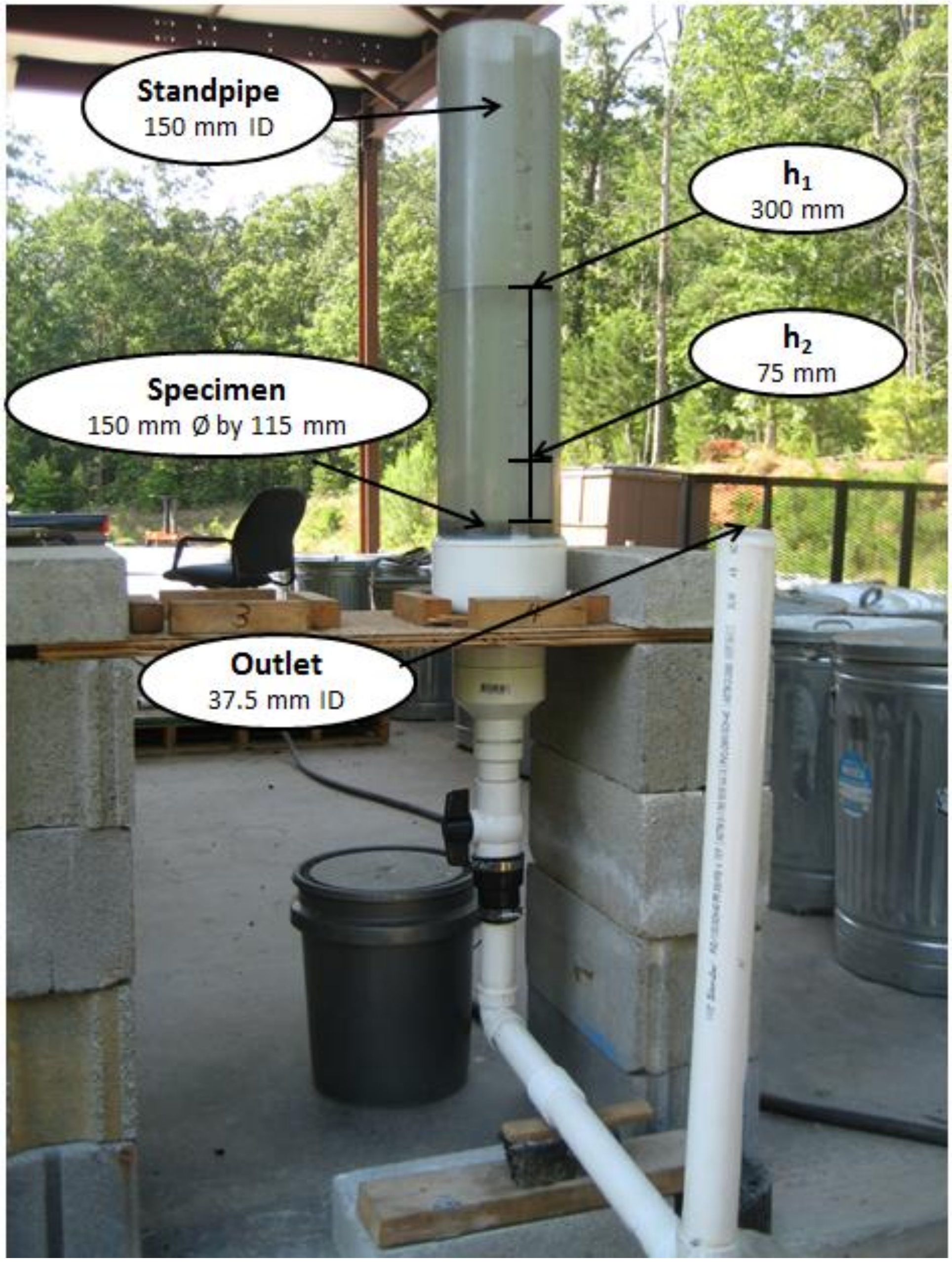


Figure 3.1 – Permeability Testing Setup

In this procedure, the samples were first prepared then placed in the stand pipe for the test. To prepare the samples, they were wrapped in plastic wrap to seal the sides of the sample forcing the water to exit the bottom of the sample. Before placing the samples in the stand pipe, the wrapped sides of the samples were lightly coated in petroleum jelly to lubricate the sample and allow for easy insertion and extraction from the stand pipe. Once placed in the bottom of the stand pipe, plumbers putty was placed on the outer edge of the specimen to prevent any leakage between the stand pipe and the sample. These three steps completed the preparation for this test. The setup progression can be seen in Figure 3.2.

(a) (b) (c)

Figure 3.2 – Sample Preparation Steps: (a) specimen wrapped with plastic wrap, (b) specimen being inserted into the standpipe, and (c) specimen sealed in the stand pipe with plumbers putty.

After a sample was prepared and placed in the stand pipe, the permeability test was run using a falling a head procedure. Before testing, the sample was initially saturated with water by filling the outlet pipe with water. Since the outlet location was level with the top of the sample, the equal head was used to pre-wet the sample for testing. Next, the stand pipe was filled with enough water to create a 30.5 cm (12 inch) head (h_1) above the sample, and the valve at the bottom of the sample was opened to allow the head to be reduced to 7.6 cm (3 inch) (h_2) allowing 4170 cm^3 of water to pass through the sample. The time required for the water to fall from h_1 to h_2 was recorded, and this step was repeated 3 times. The average time was used to calculate the permeability of the sample using Equation 3.2.

$$Permeability = \frac{aL}{At}\ln\left(\frac{h_1}{h_2}\right) \qquad \text{Equation 3.2}$$

Where:
a– area of the stand pipe
L – height of the sample
A – cross-sectional area of the sample
t – time required for water for fall from h_1 to h_2
h_1 – water head at the beginning of the test (30.5 cm)
h_2 – water head at the end of the test (7.6 cm)

The Cantrabro abrasion test was used for abrasion testing in this study. Six samples of the 9 for each mix design were tested for abrasion resistance using the Cantabro test described in ASTM D7064 (3 aged and 3 unaged). This test is conducted by placing a sample in the Los Angeles abrasion apparatus for 300 revolutions with no charges. Once the 300 revolutions are completed, the sample is removed, and the percent mass loss is measured.

Statistical Analysis

A statistical analysis was completed on the experimental data to determine the statistical differences between the volumetric and performance properties in this study. The results of this analysis are presented in tabular form. Within these tables, the letters indicate similarities between the various mix designs within a specific property and were determined using Fisher's test for least significant difference (LSD). Mix designs that have the same letter indicate similarity for a particular property. Some mix designs have more than one letter indicating similarity with more than one other mix design group. All of the analyses were conducted with a 95% level of significance ($\alpha = 0.05$).

CHAPTER FOUR

RESULTS AND DISCUSSION

The OGFC mix designs completed and tested in this study included 10 different mix designs (4 HMA, 4 Evotherm™ WMA, and 2 foaming WMA). Two primary components, binder grade and fibers, were varied and combined to create the 10 mix designs evaluated in this study. First, uncompacted samples were tested for maximum specific gravity, draindown, and optimum binder content (OBC) determination. Then compacted samples were produced for specific gravity, porosity, permeability, and Cantabro abrasion testing. These results were then analyzed to determine the effect of fibers, binder grade, and warm mix on the mix properties.

Draindown Testing

Uncompacted samples were tested for draindown for each of the 10 mix designs in accordance with AASHTO T305. For the majority of agencies, the most commonly accepted maximum limit for binder draindown is 0.3%. The draindown curves produced in this study can be seen in Figures 4.1-4.4, and the complete data set used to develop these curves can be seen in Appendix A. The initial hypothesis of the study was that the WMA technologies might alleviate excessive draindown and, therefore, eliminate the need for fibers. This hypothesis is supported by the data produced by this study. While the draindown curves of the HMA and WMA mixtures including fiber were fairly similar (Figures 4.1 and 4.3), the most significant reduction in draindown using the WMA technologies can be seen in the mixtures that do not contain fibers (Figures 4.2 and 4.4).

In these mixes, the Evotherm™ and foaming mixes performed similarly to each other and only exhibited draindown above the 0.3% limit at two binder contents (6.5% for PG 64-22 Evotherm™ and Foaming and 7.5% for PG 76-22 Evotherm™ and Foaming). It should be noted that these binder contents are at the high end of typical HMA OGFC mixtures containing fibers. In contrast, several of the HMA mixes without fibers exhibited draindown above the 0.3% limit. Such a reduction in draindown in WMA mixes without fibers could potentially lead to the elimination of fibers in OGFC mixes as the primary purpose of including fibers in these mixes is to limit draindown. Additionally, it should be noted that different test temperatures were used in the determination of draindown for the HMA mixtures compared to the WMA mixtures. While the test temperatures differed by 30°C for the WMA mixtures compared to the HMA mixtures, the comparison is valid because the WMA mixtures will be produced at a mixing temperature that is 30°C lower than that of the HMA.

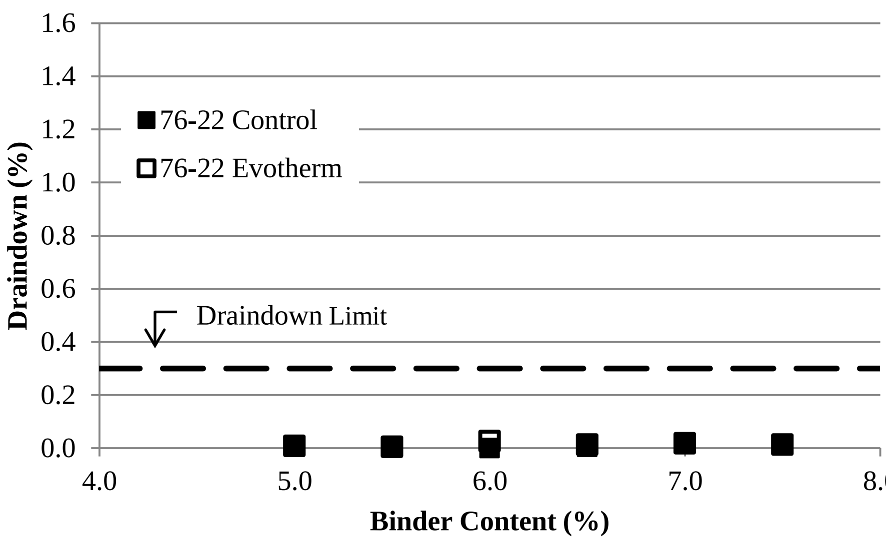


Figure 4.1 – Draindown Results for HMA OGFC and Evotherm™ WMA OGFC Containing PG 76-22 Binder and Cellulose Fibers.

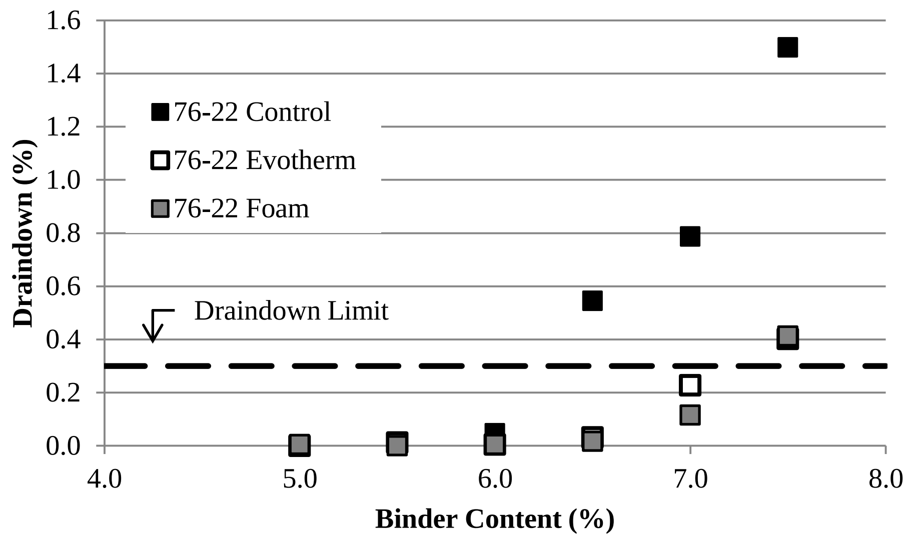


Figure 4.2 – Draindown Results for HMA OGFC and Evotherm™ WMA OGFC Containing PG 76-22 Binder without Cellulose Fibers.

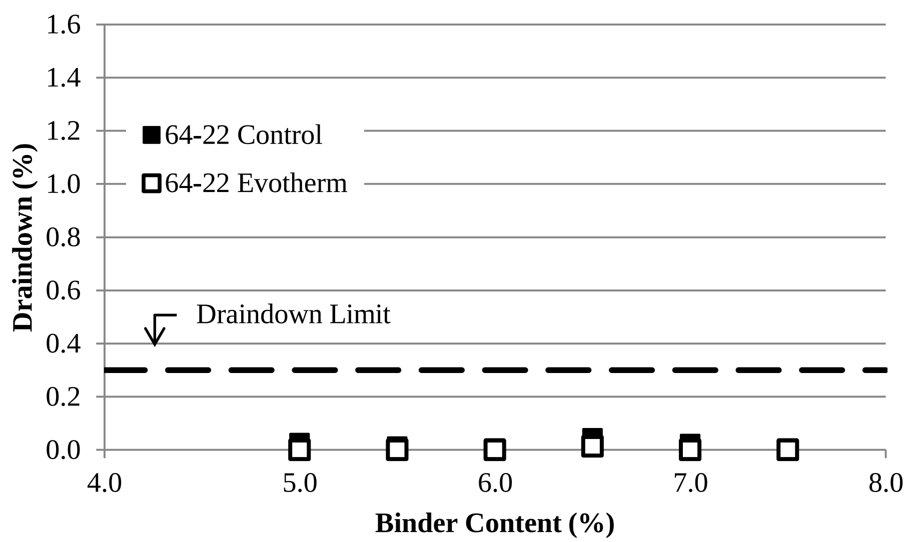


Figure 4.3 – Draindown Results for HMA OGFC and Evotherm™ WMA OGFC Containing PG 64-22 Binder and Cellulose Fibers.

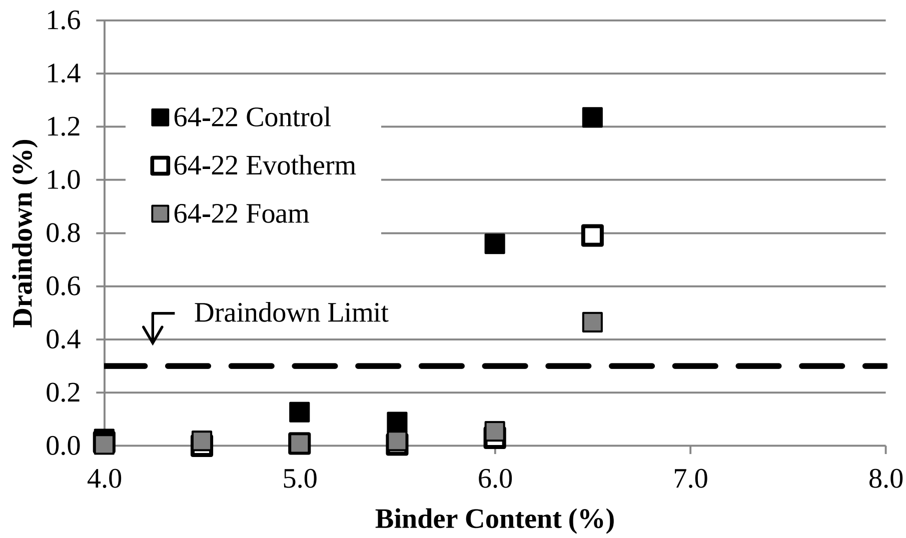


Figure 4.4 – Draindown Results for HMA OGFC and Evotherm™ WMA OGFC Containing PG 64-22 Binder without Cellulose Fibers.

Optimum Binder Content Determination

To determine the optimum binder content of the 10 mix designs, the visual draindown method was used in accordance with SC-T-91 (SCDOT 2010). The photos used to evaluate the visual draindown specimens to determine the OBC for each mix design can be seen in Appendix B. The OBCs of all the mix designs ranged from 5.0% to 7.5% and can be seen in and in Figure 4.5. However, for the mixes without fibers all the OBCs were between 5.0% and 6.0%. It can be noted from Figure 4.5, that the OBCs for the WMA mixes were the same or greater than the equivalent HMA mixture.

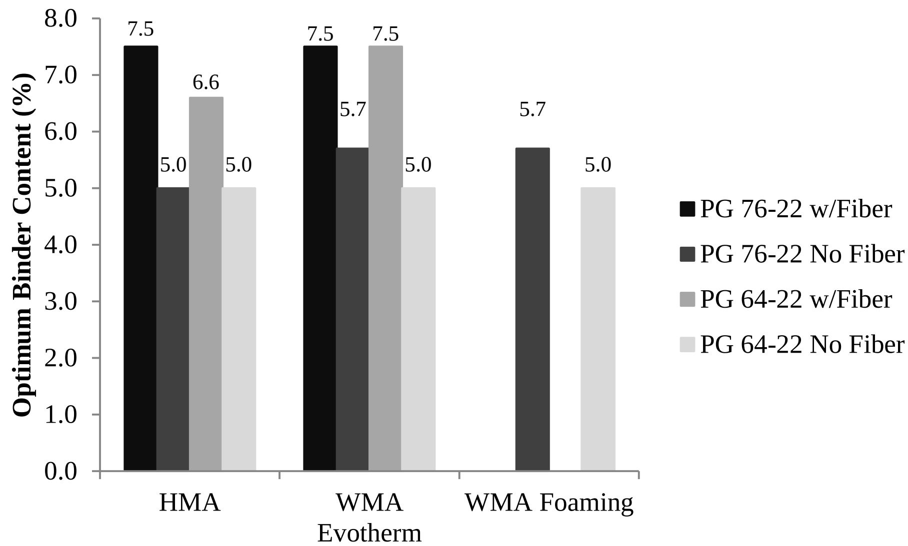


Figure 4.5 – Optimum Binder Contents for HMA OGFC, Evotherm™ WMA OGFC, and Foaming WMA OGFC.

Additionally, the WMA technologies increase the OBCs, which indicates a thicker binder film compared to the HMA mixes. Asphalt producers typically have increased the binder content and film thickness of OGFC mixes by adding additives such as polymers to the binder and fibers in the mix design. However, as evidenced by this study, WMA technologies have the ability provide this same benefit without the expense of additives and without increasing binder draindown.

As seen previously in the binder draindown curves (Figures 4.1-4.4), none of the mix designs exhibit significant draindown at the respective OBC. These curves suggest that the binder contents of WMA mixes could be increased 0.5% without causing excessive draindown. By increasing the binder contents, the WMA mixes without fibers would then have nearly the same amount of binder as typical HMA OGFC mixes with fibers. This advantage would then most likely be realized in an increase in the durability of the mixtures.

Moisture Susceptibility Testing

Uncompacted samples were tested for moisture sensitivity using the boil test outlined in SC-T-69 (SCDOT 2010). Although moisture susceptibility is thought to possibly be a weakness for some WMA technologies, all mixes in this study performed well under this test. This result was expected as the aggregate source used in this study historically performs well with regard to stripping and hydrated lime was also added as an anti-stripping additive to each mix at a rate of 1%.

Volumetric Properties

The volumetric properties of the samples were calculated using the maximum specific gravity and bulk specific gravity testing data. Table 4.1 summarizes the volumetric properties calculated including the air voids, porosity, voids filled with asphalt (VFA), and voids in mineral aggregate (VMA). Air voids and porosity are important properties of any OGFC mix design, as these properties are indicative of the permeability of a mix.

Table 4.1 – Volumetric Properties

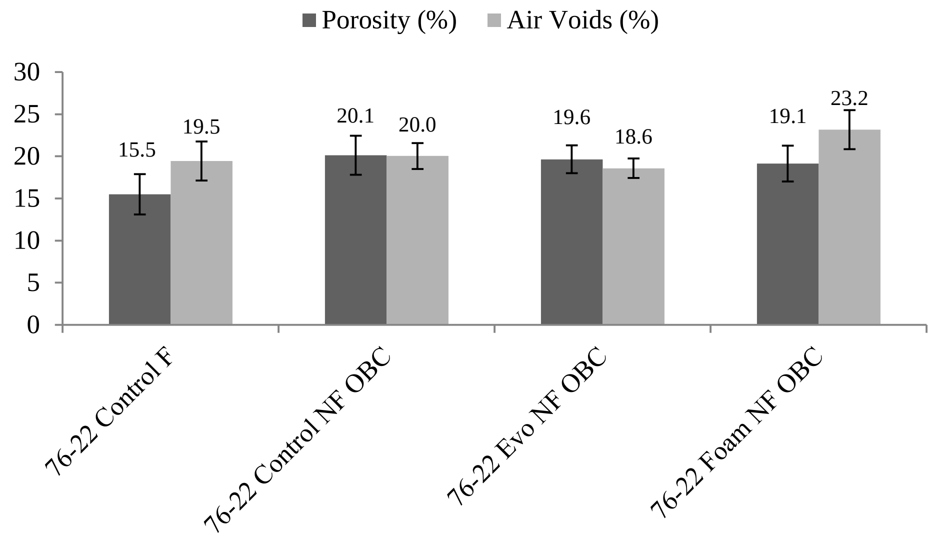
Mix ID	BC (%)	BSG	MSG	Air Voids (%)	Porosity (%)	VMA (%)	VFA (%)
76-22 Control F	7.5	1.929	2.430	19.5	15.5	34.6	40.6
76-22 Control NF OBC	5.0	1.891	2.372	20.0	20.1	29.4	31.2
76-22 Control NF +0.5%	5.5	1.916	2.356	18.6	20.3	28.9	35.4
76-22 Evo NF OBC	5.7	1.909	2.408	20.4	19.6	31.3	33.7
76-22 Evo NF +0.5%	6.2	1.890	2.391	20.5	19.6	32.3	35.3
76-22 Foam NF OBC	5.7	1.902	2.446	23.2	19.1	32.9	32.0
76-22 Foam NF +0.5%	6.2	1.924	2.429	22.2	18.2	32.5	35.5
64-22 Control F	6.6	1.942	2.394	19.2	17.6	31.3	39.7
64-22 Control NF OBC	5.0	1.923	2.353	18.2	19.6	27.6	33.8
64-22 Control NF +0.5%	5.5	1.910	2.337	18.1	20.4	28.4	35.8
64-22 Evo NF OBC	5.0	1.936	2.391	20.7	19.9	29.6	31.2
64-22 Evo NF +0.5%	5.5	1.931	2.374	18.7	19.9	29.2	35.2
64-22 Foam NF OBC	5.0	1.898	2.445	20.9	19.4	30.2	31.1
64-22 Foam NF +0.5%	5.5	1.919	2.427	20.4	19.3	30.7	33.5

Note: OBC indicates mixes prepared at optimum binder content; +0.5% indicates mixes prepared at 0.5% above the optimum binder content

The specific gravity and porosity testing was completed in accordance with ASTM D7063 and was the initial testing performed on compacted samples in this study. The average bulk specific gravity (BSG) and porosity values for each mix design can be seen in Table 4.1 and the porosity data is displayed in Figures 4.6 and 4.7. Table 4.2 displays the statistical analysis used to compare the volumetric properties discussed in this section, and the complete data set can be seen in Appendix C. The BSG values varied minimally between mix designs as expected since the binder contents were varied minimally in this study.

Figures 4.6 and 4.7, show similar porosity values for each mix design except for the mix designs with fibers (PG 76-22 Control F and PG 64-22 Control F). These two data sets exhibited porosity values significantly lower than the mix designs having the same binder grade, but not containing fibers. Since these mixes are representative of OGFC mix designs used by agencies, this is a noteworthy difference which should be expected as two contributing effects of adding cellulose fibers to a mix are reduced air voids and increased binder content

Meanwhile, the similarity in the data is due to the fact that all mix designs had the same aggregate gradation and were tested at OBC or near OBC (OBC and 0.5% above for non-fiber mixes). With each mix, the 0.5% increase in binder content was not large enough to significantly alter the porosity of the mix designs.



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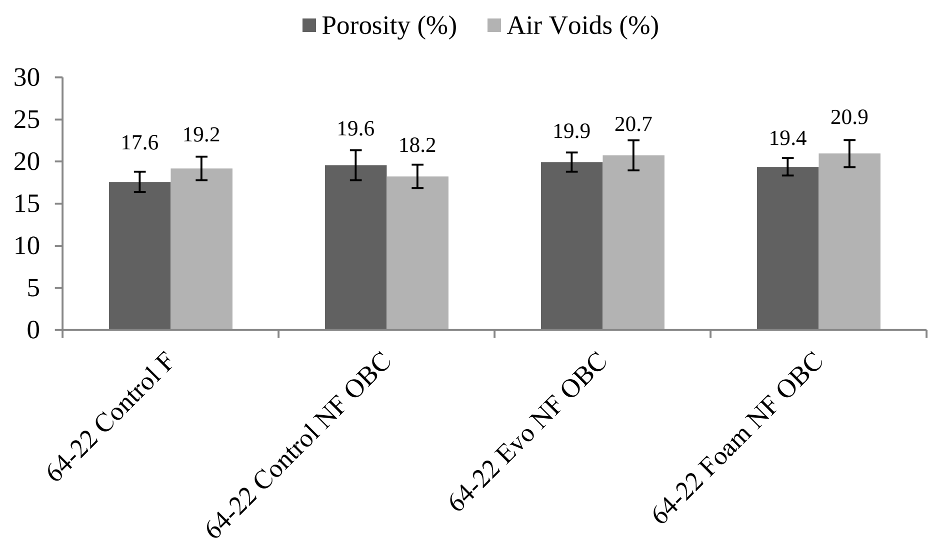
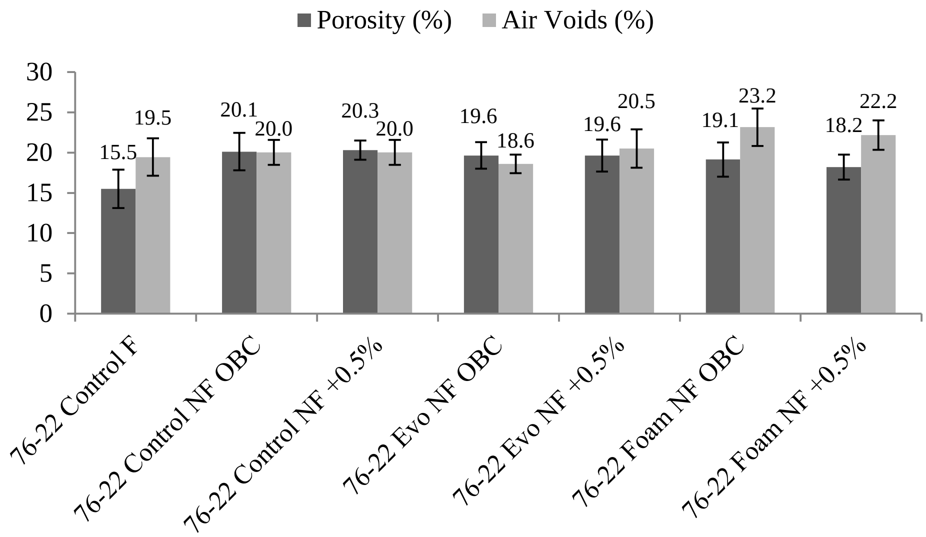


(b)

Figure 4.6 – Average Prosity Results for the Mix Designs Tested with (a) PG 76-22 and (b) PG 64-22 Binder at OBC.



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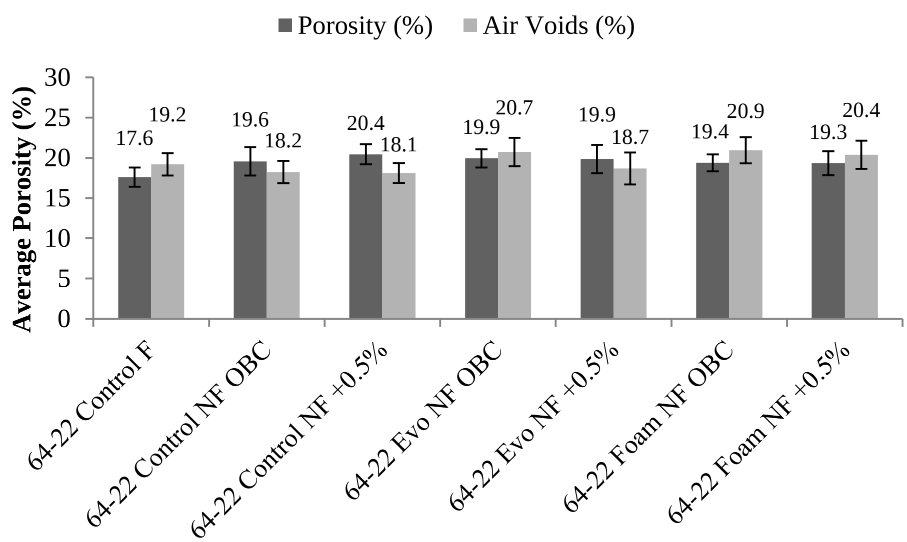


(b)

Figure 4.7 – Average Prosity Results for the Mix Designs Tested with (a) PG 76-22 and (b) PG 64-22 Binder at OBC and 0.5% above the OBC.

As evidenced by the Figures 4.6 and 4.7, the air voids decreased when the binder content for each mix design was increased in like manner to the porosity. This data also shows that the inclusion of fibers in the mix design lowers the air voids. With the inclusion of fibers, the air voids decreases and VFA increases as fibers increase the binder content of the mix and fill the voids. Figure 4.8 displays the relationship between air voids and porosity and displays the consistency in the testing for this study.

Table 4.2 – Statistical Analysis of Volumetric Properties (α = 0.05)

Mix ID	Air Voids	Porosity	VMA	VFA
76-22 Control F	B	D	A	A
76-22 Control NF OBC	BC	A	GF	F
76-22 Control NF +0.5%	D	A	G	BCD
76-22 Evo NF OBC	B	A	CD	CDE
76-22 Evo NF +0.5%	B	A	BC	BCD
76-22 Foam NF OBC	A	AB	B	EF
76-22 Foam NF +0.5%	AB	BC	B	BC
64-22 Control F	CD	C	CD	A
64-22 Control NF OBC	D	AB	H	CDE
64-22 Control NF +0.5%	D	A	GH	B
64-22 Evo NF OBC	B	A	EFG	F
64-22 Evo NF +0.5%	CD	A	FG	BCD
64-22 Foam NF OBC	B	AB	DEF	F
64-22 Foam NF +0.5%	B	AB	DE	DE

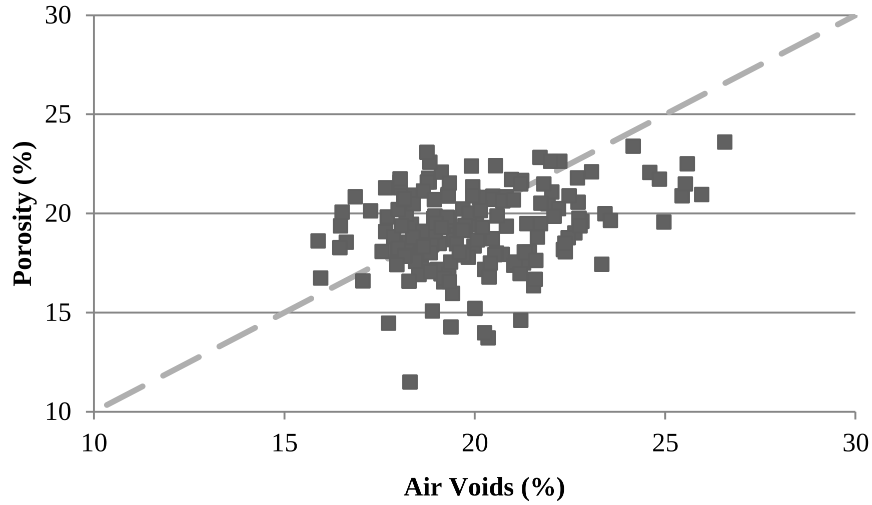


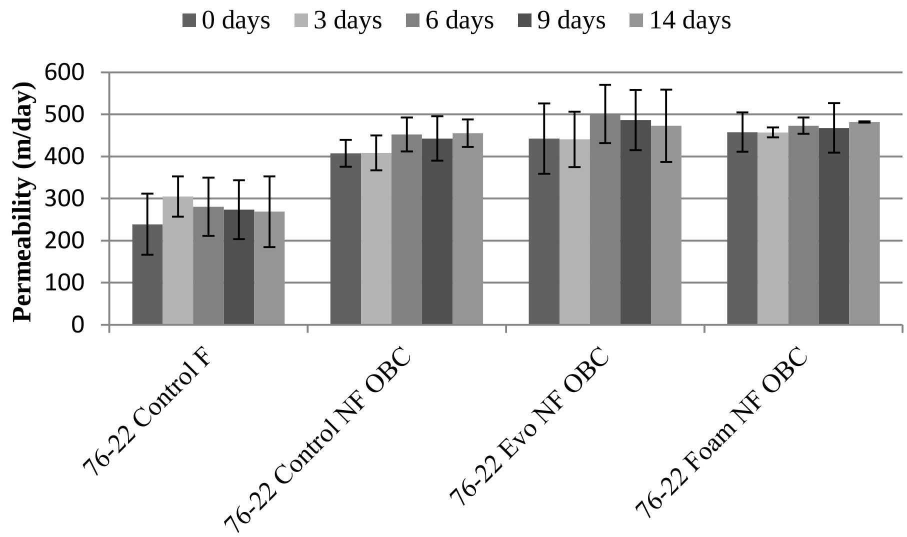
Figure 4.8 – Relationship between Porosity and Air Voids of All Samples.

Performance Properties – Permeability

Permeability testing was performed using the falling head test outlined in Chapter 3. The permeability values for each mix design at the OBC can be seen in Figure 4.10 while the permeability data comparison between the OBC samples and the 0.5% increased binder content samples can be seen in Figure 4.11. The permeability samples were tested for initial permeability and then aged (3, 6, 9, and 14 days) and retested to determine the effect of aging on OGFC permeability. This aged permeability testing was performed because there has been some concern that binder draindown in a pavement over time could lead to reduction in permeability. However, aging the samples did not decrease the permeability of any of the mix designs as the test specimens maintained nearly constant or slightly increased permeability throughout the aging process. In fact, most mix designs exhibited slightly higher permeability readings as the specimens aged;

however this increase was not statistically significant as evidenced in Table 4.3. This slight increase was attributed to binder shrinking due to oxidation during the aging process. Samples were tested for porosity after the aged permeability testing conducted and found to have slightly higher porosity as evidenced in Table 4.4, but the increase was not significant.

Meanwhile, the 0.5% increase in binder content did not significantly alter the permeability; however, the inclusion of fibers was the only distinguishable factor that significantly altered the permeability. Both the mix designs with fibers displayed significantly lower permeability than the other control and WMA mix designs without fiber as evidenced in Table 4.5. This is expected since adding fibers to a mix design significantly increases the binder content and reduces the void content and porosity, subsequently decreasing the permeability. The complete permeability test data can be seen in Appendix D.



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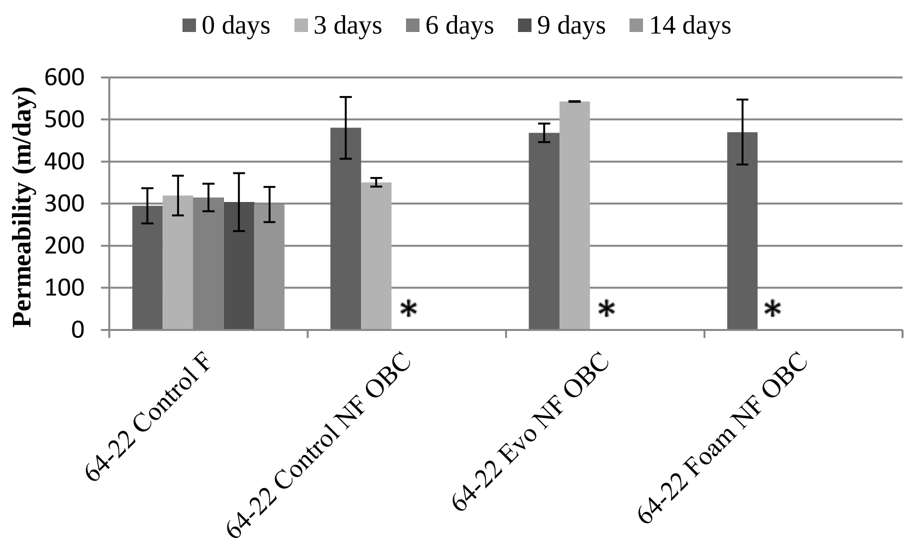
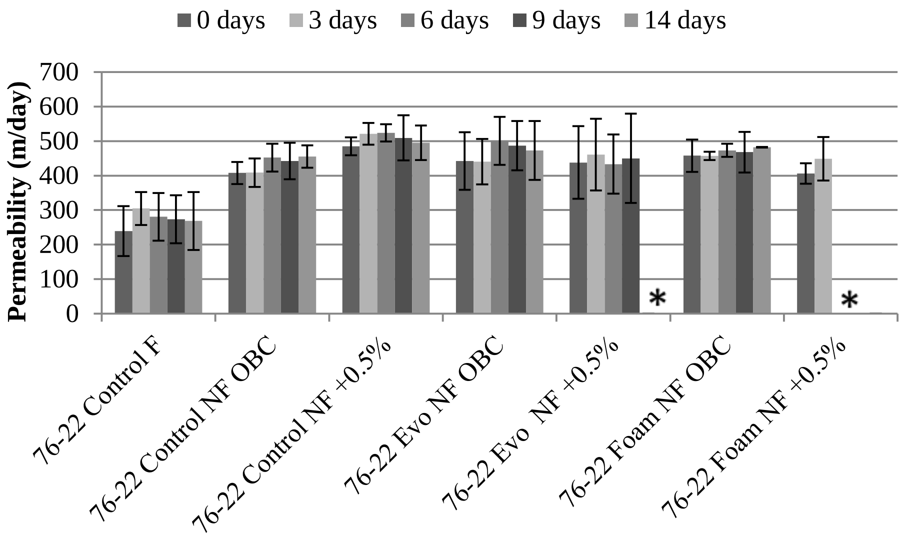


(b)

Figure 4.9 – Permeability Testing Results for Each Mix Design Tested with (a) PG 76-22 and (b) PG 64-22 Binder at OBC, Aged and Tested Incrementally (0, 3, 6, 9, and 14 Days). Note: * denotes that sample collapsed or deformed during aging.



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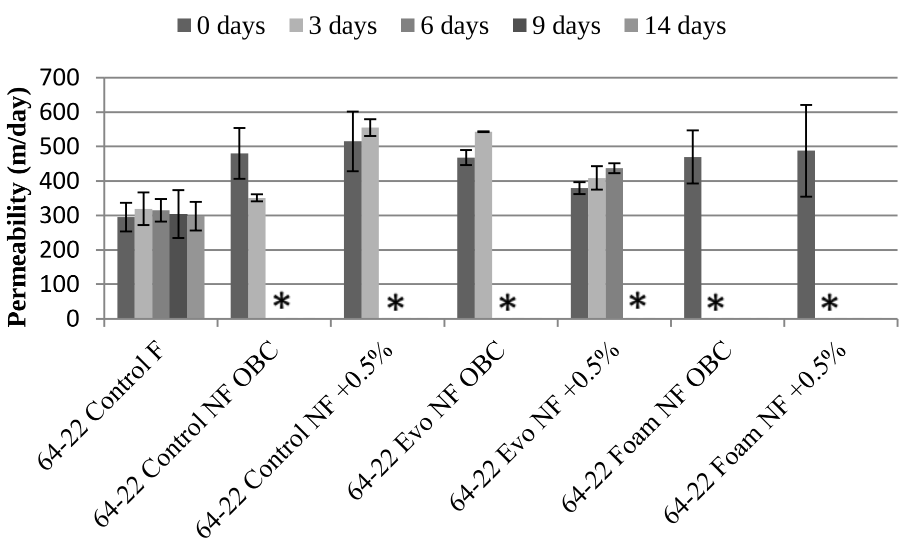


(b)

Figure 4.10 –Permeability Testing Results for Each Mix Design Tested with (a) PG 76-22 and (b) PG 64-22 Binder at OBC and 0.5% Above the OBC, Aged and Tested Incrementally (0, 3, 6, 9, and 14 Days). Note: * denotes that sample collapsed or deformed during aging.

Table 4.3 – Statistical Analysis of Permeability Aging Data (α = 0.05)

Mix ID	Permeability				
	0 day	3 day	6 day	9 day	14 day
76-22 Control F	A	A	A	A	A
76-22 Control NF OBC	A	A	A	A	A
76-22 Control NF +0.5%	A	A	A	A	A
76-22 Evo NF OBC	A	A	A	A	A
76-22 Evo NF +0.5%	A	A	A	A	*
76-22 Foam NF OBC	A	A	A	A	A
76-22 Foam NF +0.5%	A	A	*	*	*
64-22 Control F	A	A	A	A	A
64-22 Control NF OBC	A	A	*	*	*
64-22 Control NF +0.5%	A	A	*	*	*
64-22 Evo NF OBC	A	B	*	*	*
64-22 Evo NF +0.5%	A	AB	B	*	*
64-22 Foam NF OBC	*	*	*	*	*
64-22 Foam NF +0.5%	*	*	*	*	*

Note: * denotes that sample collapsed or deformed during aging.

Table 4.4 – Comparison of Initial vs. Aged Porosity

Mix ID	Porosity Initial (0 days) (%)	Porosity Aged (14 days) (%)
76-22 Control F	15.6	16.1
76-22 Control NF OBC	20.2	20.5
76-22 Control NF +0.5%	20.3	21.6
76-22 Evo NF OBC	19.9	23.3
76-22 Evo NF +0.5%	18.2	17.6
64-22 Control F	16.6	19.0

Note: all mix designs are not displayed since some samples collapsed or deformed during aging.

Table 4.5 – Statistical Analysis of Permeability Mix Design Data (α = 0.05)

	Permeability				
Mix ID	**0 day**	**3 day**	**6 day**	**9 day**	**14 day**
76-22 Control F	D	G	B	C	B
76-22 Control NF OBC	ABC	DEF	A	AB	A
76-22 Control NF +0.5%	AB	ABC	A	A	A
76-22 Evo NF OBC	AB	CDE	A	A	A
76-22 Evo NF +0.5%	AB	BCD	A	A	*
76-22 Foam NF OBC	AB	BCD	A	A	A
76-22 Foam NF +0.5%	ABC	CD	*	*	*
64-22 Control F	CD	FG	B	BC	B
64-22 Control NF OBC	AB	EFG	*	*	*
64-22 Control NF +0.5%	A	A	*	*	*
64-22 Evo NF OBC	AB	AB	*	*	*
64-22 Evo NF +0.5%	BC	DEF	A	*	*
64-22 Foam NF OBC	AB	*	*	*	*
64-22 Foam NF +0.5%	AB	*	*	*	*

Note: * denotes that sample collapsed or deformed during aging.

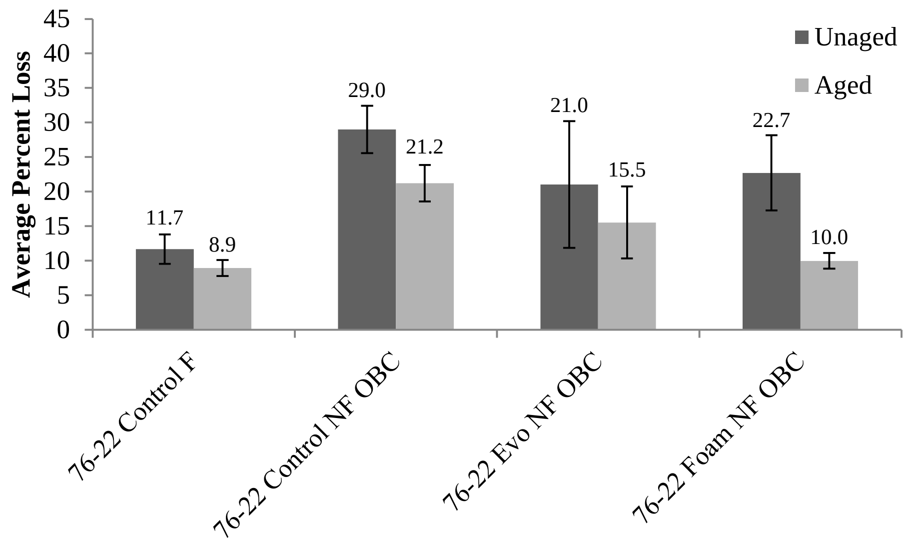
Performance Properties – Abrasion Resistance

The test used to analyze the abrasion resistance of the mix designs was the Cantabro abrasion test. Although not as popular in the United States, this test is commonly used in Europe and was performed in this study in accordance with ASTM D7064. Both the unaged and aged data can be seen in Figure 4.11. The effect of binder content on the abrasion resistance is illustrated clearly in Figure 4.12, which displays the comparison between the samples at OBC and the samples that were tested at 0.5% above the OBC. The complete testing data for the Cantabro abrasion resistance as well as the photos of the tested samples can be seen in Appendix E.

In nearly every mix design, the aged samples outperformed the unaged samples. This trend has been seen before in a similar research study (Kline and Putman 2010), but was somewhat unexpected since the binder oxidizes during aging becoming stiffer and more brittle. This stiffening was the characteristic of the binder aging that affected the test the most, having a much larger impact than the increased brittleness of the binder. This concept has been seen in a study performed by Mo et al. 2009, examining abrasion resistance. Researchers found that oxidation of binder actually improved the abrasion resistance of a sample during warm weather conditions but dramatically decreased the abrasion resistance of a sample in cold weather as the elasticity of the binder is compromised.

The figures can also be used to compare the affect of fibers on the durability of OGFC. For the unaged samples, the mix designs with fibers significantly outperformed the mix designs without fibers. However, after the samples were aged, the WMA mix designs without fibers satisfied the specifications set by states that use abrasion loss in their mix evaluation (Kline 2010).

The expected trend of these results was that as binder content increases, the percent loss during the Cantabro test decreases indicating a higher durability mix design. However, as indicated in Table 4.6, there was no significant difference between the unaged abrasion loss for the mixes made at the OBC and mixes made at 0.5% higher binder contents for the same mix. This could be due to the fact that the binder contents evaluated were at or above the OBC. If the abrasion loss was measured at a binder content 0.5% below the OBC, the durability would likely decrease as seen in other research (Kline 2010). The only exception was the PG 64-22 Control NF mix. The same trend was true for the aged abrasion loss for all mixes.



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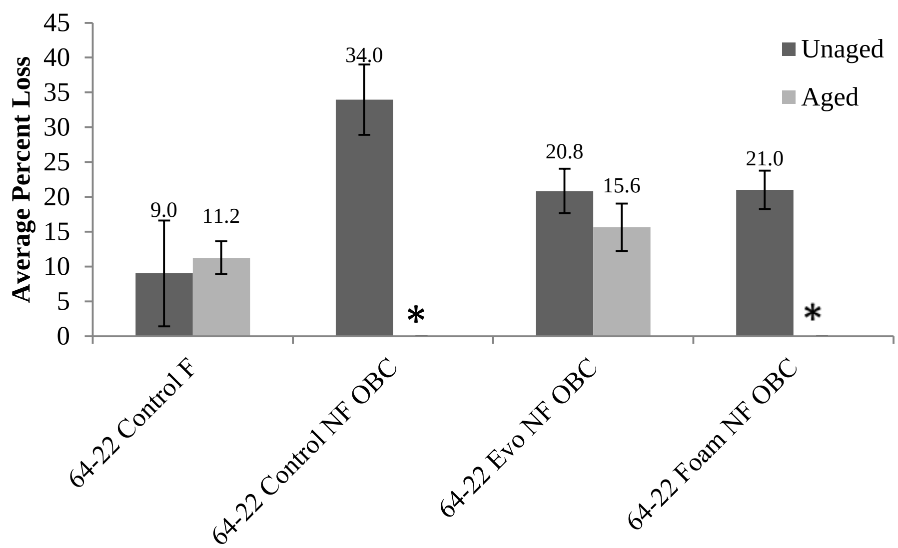
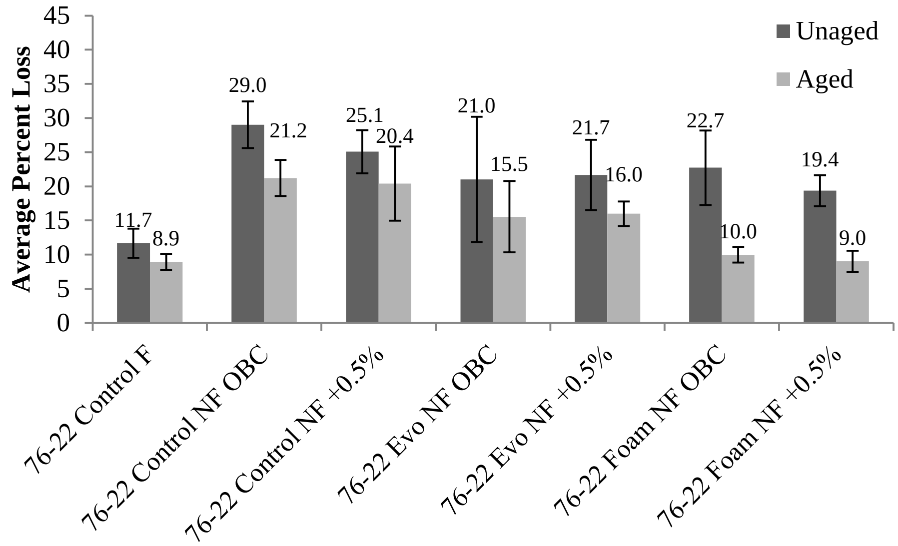


(b)

Figure 4.11 – Cantabro Abrasion Testing Results for Each Mix Design Tested with (a) PG 76-22 and (b) PG 64-22 binder at OBC. Note: * denotes that sample collapsed or deformed during aging.



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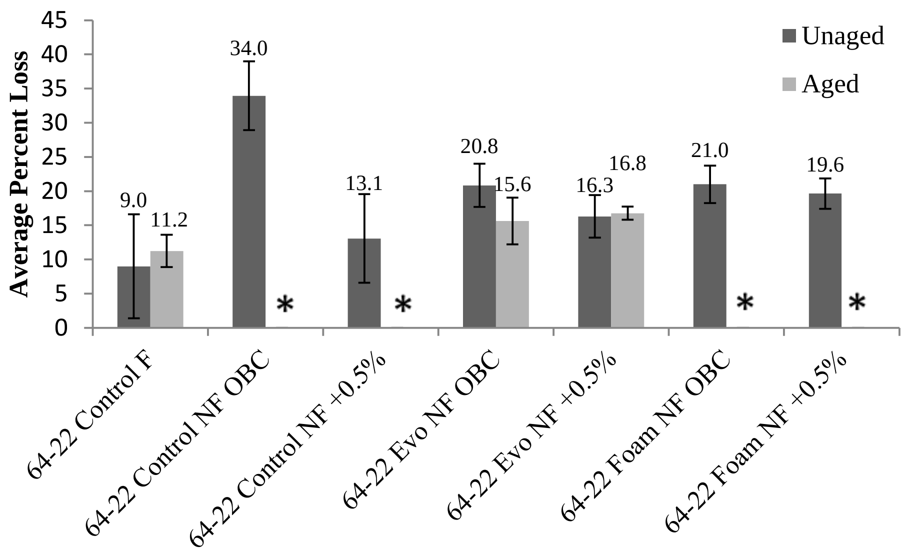

(b)

Figure 4.12 – Cantabro Abrasion Testing Results for Each Mix Design Tested with (a) PG 76-22 and (b) PG 64-22 binder at OBC and 0.5% above the OBC. Note: * denotes that sample collapsed or deformed during aging.

Table 4.6– Statistical Analysis of Cantabro Abrasion Data (α = 0.05)

Mix ID	Cantabro (Unaged)	Cantabro (Aged)	Significant Difference (Unaged vs. Aged)
76-22 Control F	G	D	No
76-22 Control NF OBC	AB	A	Yes
76-22 Control NF +0.5%	BC	AB	No
76-22 Evo NF OBC	EFG	BC	No
76-22 Evo NF +0.5%	CDE	ABC	No
76-22 Foam NF OBC	BCD	D	Yes
76-22 Foam NF +0.5%	CDEF	D	Yes
64-22 Control F	G	CD	No
64-22 Control NF OBC	A	*	*
64-22 Control NF +0.5%	FG	*	*
64-22 Evo NF OBC	CDE	BC	No
64-22 Evo NF +0.5%	DEFG	AB	No
64-22 Foam NF OBC	CDE	*	*
64-22 Foam NF +0.5%	CDEF	*	*

Note: * denotes that sample collapsed or deformed during aging.

Sample Loss

The loss of some samples during the aging process could be cause for concern in this study. The large majority of these samples were of PG 64-22 mix designs illustrating the effect polymer that modification had on the samples. Although a number of samples collapsed or became deformed during the aging process, this is not necessarily indicative of field performance. In the field, porous pavements are placed with some form of edge confinement or in thin layers as is the case in OGFC (1-2 inches). The only case where the behavior exhibited in this study could be problematic would be at an unconfined edge of a porous pavement having a relatively large lift thickness. In this scenario, the porous pavement layer could exhibit edge cracking.

CHAPTER FIVE

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The goal of this study was to evaluate Evotherm™ (a chemical package) and foaming (a water-injection method) WMA technologies to determine their effectiveness in producing high quality OGFC mixes. Specifically, this study focused on the effect of the removal of stabilizing additives (fibers and polymers) on the optimum binder content and performance of WMA OGFC mixtures. This evaluation was based on the comparison of Evotherm™ WMA and foaming WMA mixes with traditional HMA OGFC using four main criteria: draindown, moisture susceptibility, permeability, and abrasion resistance.

Overall, 10 different mix designs were tested and evaluated for use in OGFC pavements. Both volumetric and performance properties were analyzed to assess the performance of each mix design. The results suggested that there is a high potential for the use of warm mix in OGFC and that further research should be conducted on this topic.

Conclusions

Based on the results of this study, WMA technologies can be used to successfully produce high quality OGFC pavements. WMA technologies have the ability to improve the properties of OGFC and simplify mix production. While adding fibers to a typical

OGCF mix decreases draindown and improves mix stability, fibers are difficult to control during production and can create inconsistencies in a mix. By decreasing binder draindown, WMA technologies allow for the removal of fibers without significantly increasing binder draindown. Also, due to the fiber removal, the OBC of the WMA OGFC mixes is significantly lower than typical fiber stabilized HMA OGFC mixes. However, the OBC of WMA OGFC mixtures without fibers is greater than similar HMA mixtures without fibers, therefore, the binder film is thicker thus potentially improving the durability. These benefits of using WMA technologies in OGFC provide cost saving measures for contractors and eliminate a troublesome piece of OGFC production. The following conclusions regarding WMA OGFC mix designs from this study were made:

- WMA technologies significantly reduced draindown compared to HMA when fibers were removed from a mix while draindown was negligible for either HMA or WMA mix designs when fiber was included at 0.3%. This reduction in draindown allows for the removal of fibers in WMA OGFC.
- Also, the removal of polymers (PG 76-22 to PG 64-22) served to shift the draindown curve approximately 1% for both WMA and HMA mix designs. This shift indicates the draindown reducing capacity of polymers independent of mix type (WMA or HMA).
- The OBCs of the WMA, OGFC mix designs were greater than or equal to the OBCs of the HMA OGFC mix designs, indicating a thicker binder film for the WMA mix designs. None of the WMA, OGFC mix designs exhibited significant draindown at the OBC or 0.5% above the OBC.

- Moisture susceptibility was not a concern with the warm mix technologies evaluated in this study (Evotherm™ and foaming). It should be noted that hydrated lime was included in all mixtures.
- The removal of fiber in OGFCs significantly increases the porosity and subsequently the permeability of a mix. When the binder content was raised by 0.5% in OGFC mix designs, the permeability was not significantly affected. Meanwhile, the permeability of OGFCs is not decreased due to binder draindown occurring from long-term aging for the OGFC mix designs evaluated in this study. This indicates that if a mix is properly designed, clogging occurring in porous asphalt pavements is exclusively caused by particles entering the interconnected void space not by binder draindown due to aging.
- WMA, OGFC mix designs without fiber outperformed HMA mixtures without fiber with respect to abrasion resistance, and all of the WMA, OGFC mix designs met typical Cantabro abrasion requirements in the aged condition.

Recommendations

After evaluating the results and conclusions of this research, there are several recommendations that have been made for both the practical application of the results and for future research.

Application of Research Findings

- WMA technologies can be used to limit draindown and meet specifications. This indicates that WMA technologies can be used to produce high quality OGFC. Removing fibers is an especially valuable finding since fiber removal will reduce contractor cost and remove an inconsistent and troublesome part of OGFC production.
- The use of draindown curves is helpful in combination with the visual method for determining the OBC and adjusting the binder content of an OGFC mix.
- Porous pavements should be placed in thin lifts (OGFC) or combined with some form of curbing to prevent edge cracking.

Future Research

- Evaluate the aging procedure of the Cantabro abrasion test and evaluate various test methods to determine the abrasion performance test that best indicates field raveling potential.
- Further evaluate WMA, OGFC performance properties in field performance trials.
- Evaluate other WMA technologies for use in OGFCs.

APPENDICES

Appendix A

Draindown Data

Table A.1 – Draindown Data for PG 76-22 Binder

Mix ID	BC	Draindown 1 (%)	Draindown 2 (%)	Average Draindown (%)
76-22 Control F	5.0	0.00	0.01	0.00
76-22 Control F	5.5	0.01	0.01	0.01
76-22 Control F	6.0	0.00	0.00	0.00
76-22 Control F	6.5	0.00	0.01	0.00
76-22 Control F	7.0	0.02	0.02	0.02
76-22 Control F	7.5	0.00	0.03	0.01
76-22 Control NF	5.0	0.00	0.01	0.00
76-22 Control NF	5.5	0.01	0.00	0.00
76-22 Control NF	6.0	0.04	0.05	0.05
76-22 Control NF	6.5	0.49	0.60	0.55
76-22 Control NF	7.0	0.75	0.82	0.79
76-22 Control NF	7.5	1.42	1.57	1.50
76-22 Evo F	5.0	0.02	0.00	0.01
76-22 Evo F	5.5	0.00	0.01	0.00
76-22 Evo F	6.0	0.02	0.03	0.03
76-22 Evo F	6.5	0.02	0.01	0.01
76-22 Evo F	7.0	0.01	0.03	0.02
76-22 Evo F	7.5	0.01	0.02	0.01
76-22 Evo NF	5.0	0.00	0.00	0.00
76-22 Evo NF	5.5	0.01	0.02	0.01
76-22 Evo NF	6.0	0.00	0.01	0.00
76-22 Evo NF	6.5	0.02	0.04	0.03
76-22 Evo NF	7.0	0.18	0.28	0.23
76-22 Evo NF	7.5	0.33	0.48	0.40
76-22 Foam NF	5.0	0.01	0.00	0.00
76-22 Foam NF	5.5	0.00	0.00	0.00
76-22 Foam NF	6.0	0.01	0.00	0.00
76-22 Foam NF	6.5	0.00	0.03	0.02
76-22 Foam NF	7.0	0.11	0.12	0.12
76-22 Foam NF	7.5	0.42	0.40	0.41

Table A.2 – Draindown Data for PG 64-22 Binder

Mix ID	BC	Draindown 1 (%)	Draindown 2 (%)	Average Draindown (%)
64-22 Control F	5.0	0.04	0.01	0.03
64-22 Control F	5.5	0.01	0.02	0.01
64-22 Control F	6.0	0.01	0.00	0.00
64-22 Control F	6.5	0.04	0.05	0.04
64-22 Control F	7.0	0.04	0.00	0.02
64-22 Control F	7.5	0.00	0.01	0.00
64-22 Control NF	4.0	0.00	0.05	0.02
64-22 Control NF	4.5	0.03	0.01	0.02
64-22 Control NF	5.0	0.04	0.21	0.13
64-22 Control NF	5.5	0.04	0.14	0.09
64-22 Control NF	6.0	0.86	0.66	0.76
64-22 Control NF	6.5	1.13	1.34	1.23
64-22 Evo F	5.0	0.00	0.00	0.00
64-22 Evo F	5.5	0.00	0.00	0.00
64-22 Evo F	6.0	0.00	0.00	0.00
64-22 Evo F	6.5	0.00	0.03	0.01
64-22 Evo F	7.0	0.00	0.00	0.00
64-22 Evo F	7.5	0.00	0.00	0.00
64-22 Evo NF	4.0	0.03	0.00	0.01
64-22 Evo NF	4.5	0.00	0.00	0.00
64-22 Evo NF	5.0	0.00	0.02	0.01
64-22 Evo NF	5.5	0.01	0.00	0.00
64-22 Evo NF	6.0	0.04	0.02	0.03
64-22 Evo NF	6.5	0.71	0.87	0.79
64-22 Foam NF	4.0	0.01	0.00	0.00
64-22 Foam NF	4.5	0.02	0.02	0.02
64-22 Foam NF	5.0	0.01	0.01	0.01
64-22 Foam NF	5.5	0.02	0.02	0.02
64-22 Foam NF	6.0	0.07	0.04	0.05
64-22 Foam NF	6.5	0.52	0.41	0.46

<u>Appendix B</u>

<u>OBC Determination Photos</u>

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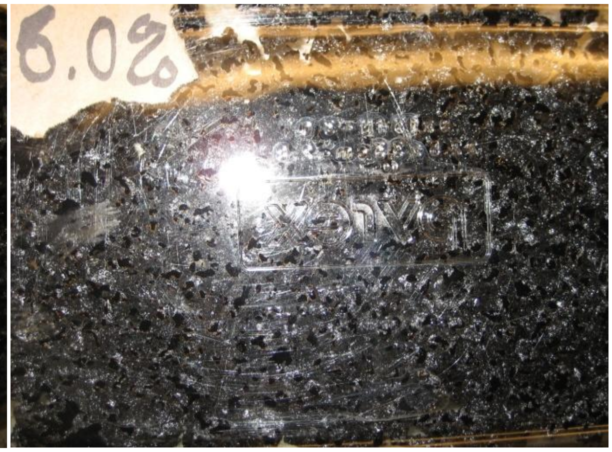

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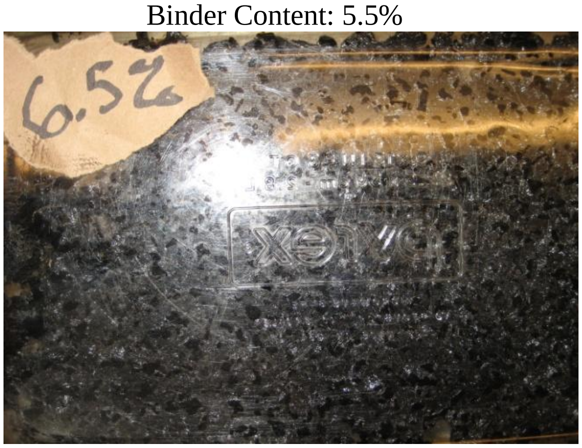

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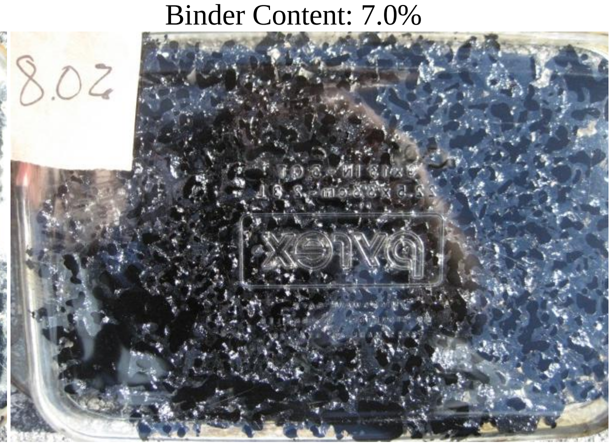

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Figure B.1: OBC Determination for PG 76-22 F

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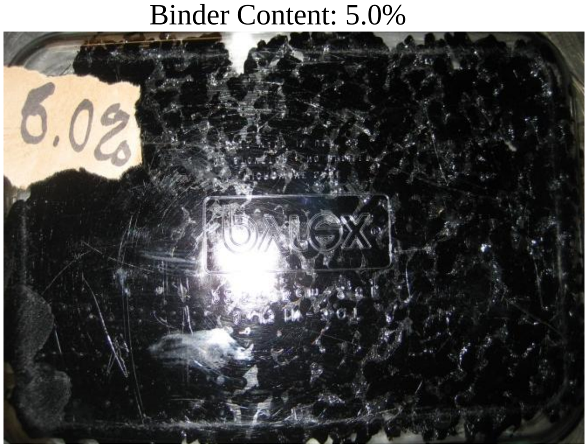

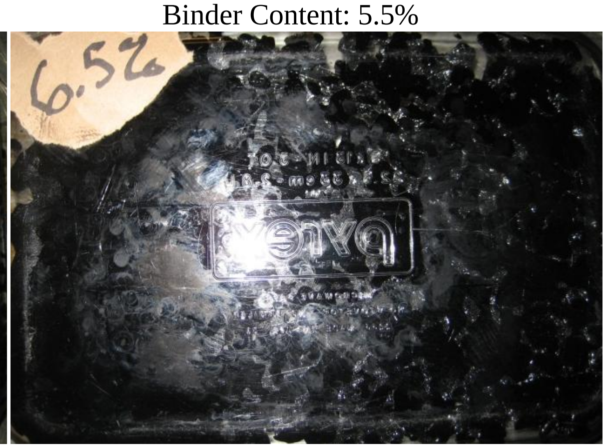

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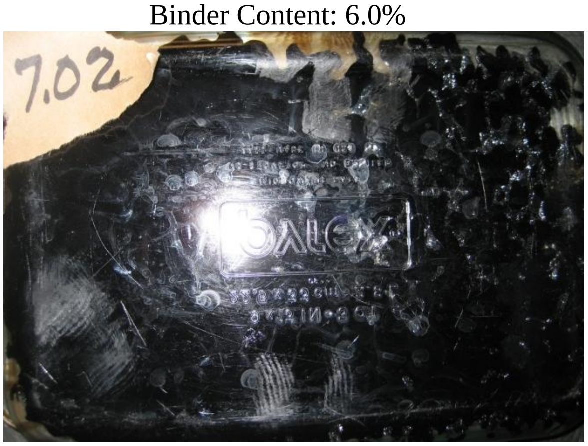

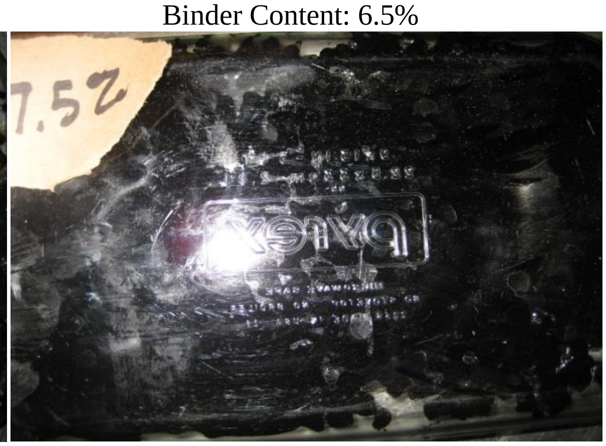

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Figure B.2: OBC Determination for PG 76-22 NF

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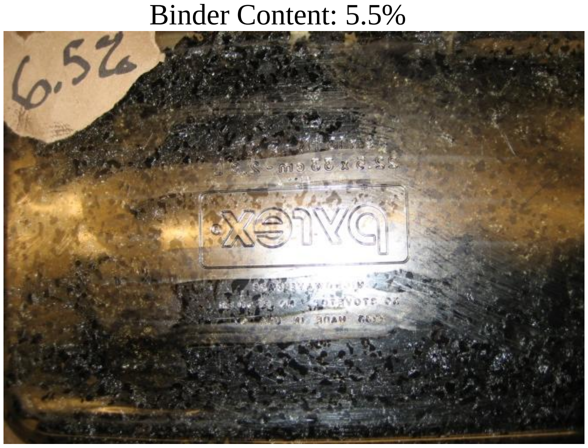

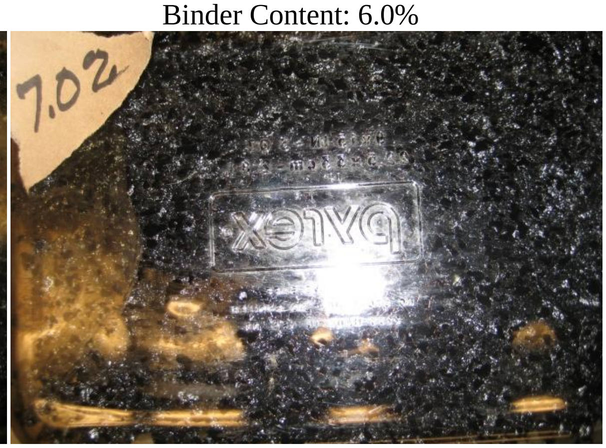

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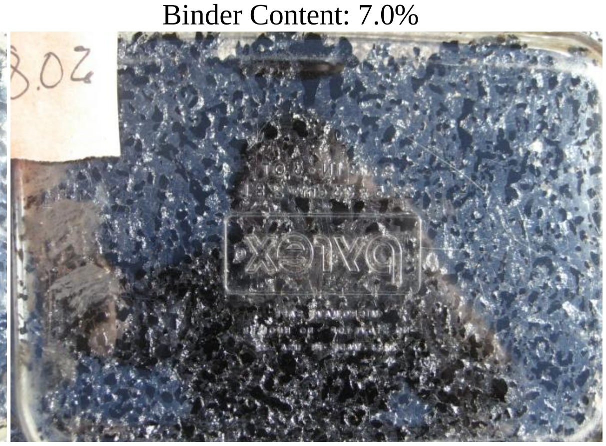

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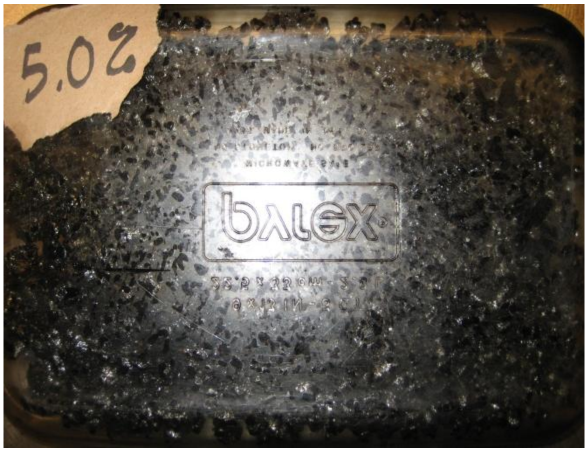
Figure B.3: OBC Determination for PG 76-22 Evo F



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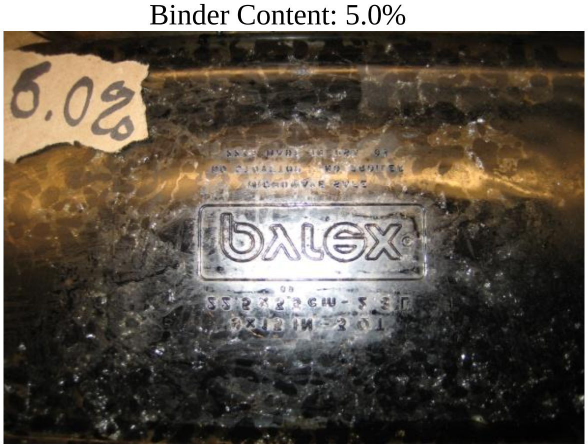

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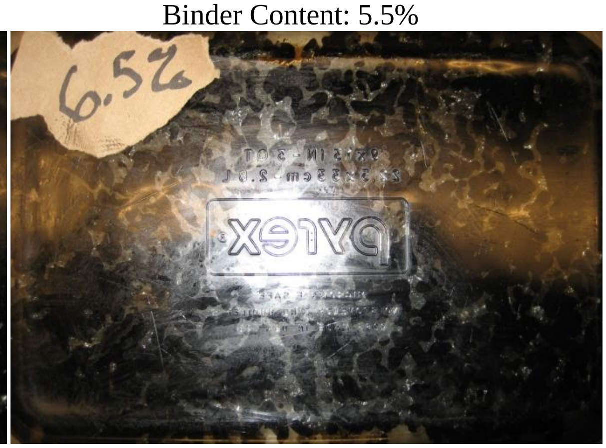

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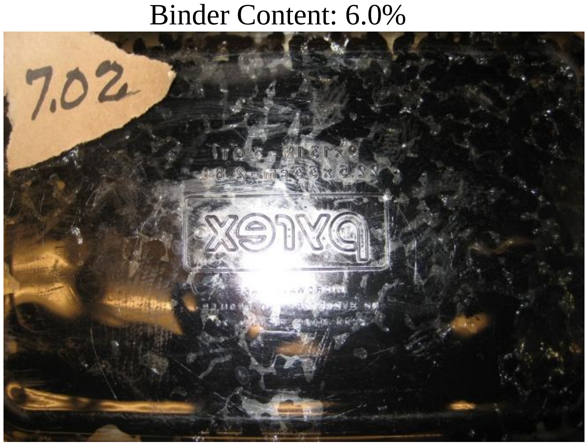

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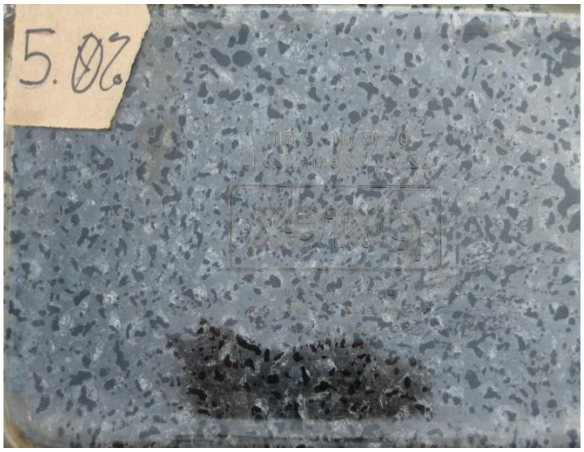
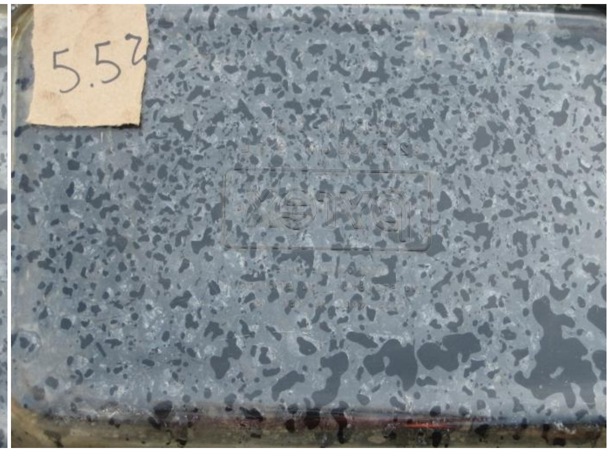
Figure B.4: OBC Determination for PG 76-22 Evo NF





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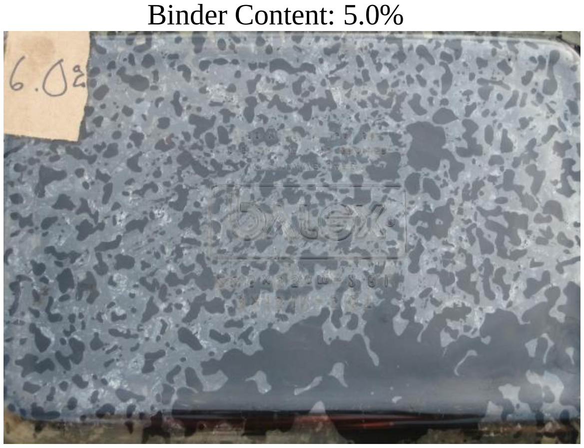

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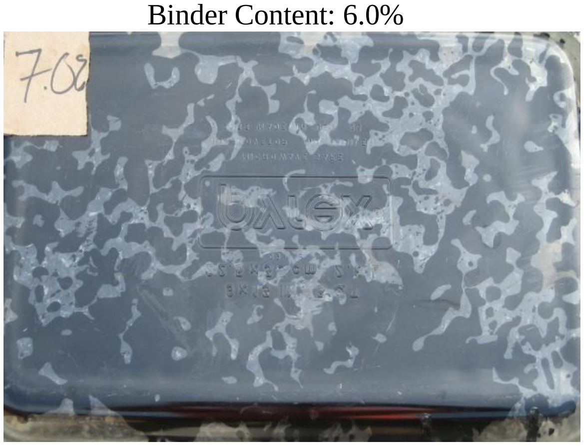

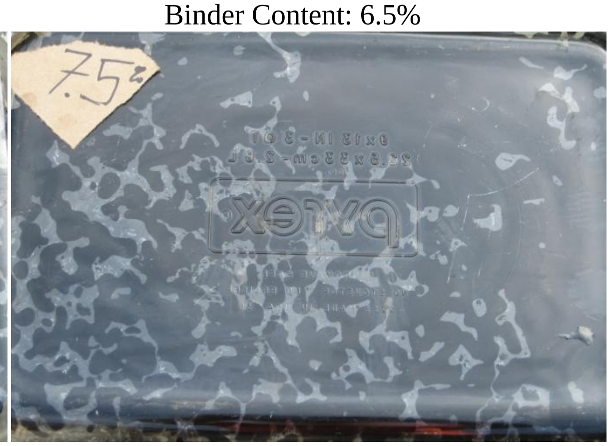

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Figure B.5: OBC Determination for PG 76-22 Foam NF

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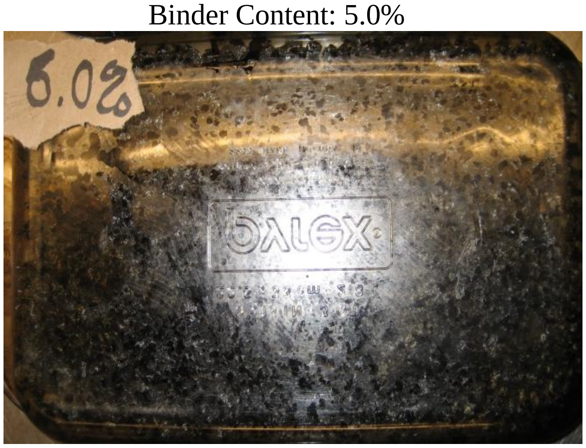

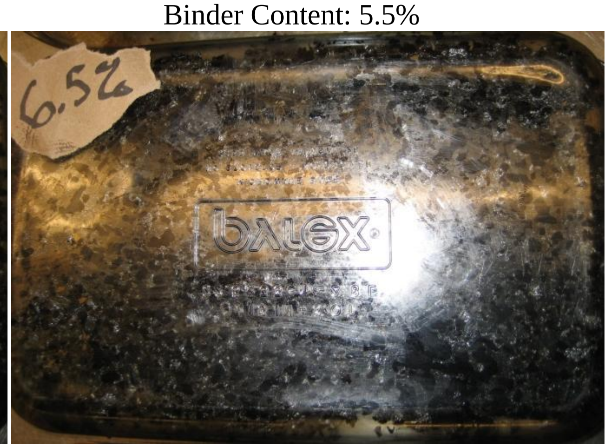

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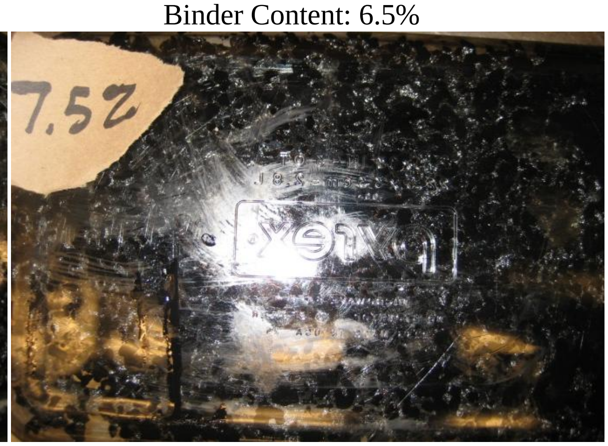

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Figure B.6: OBC Determination for PG 64-22 F

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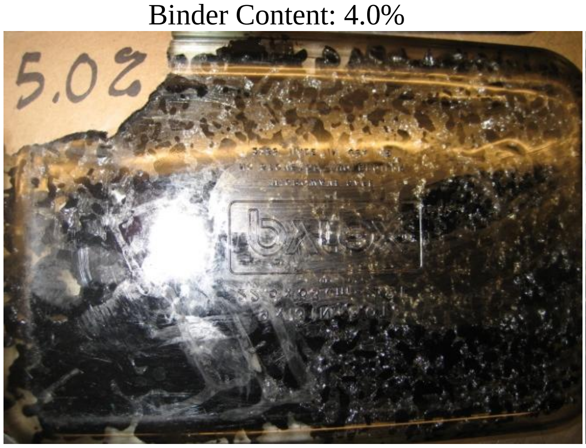

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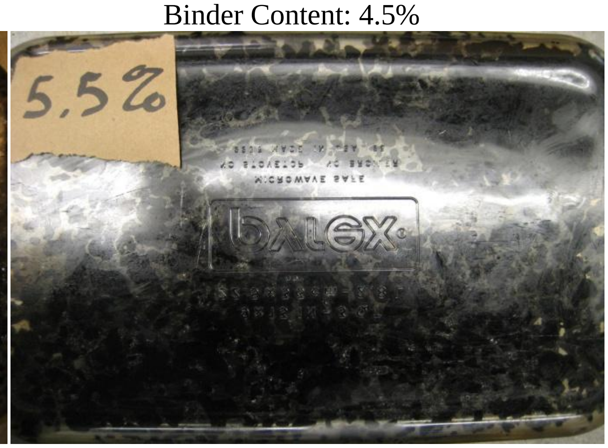

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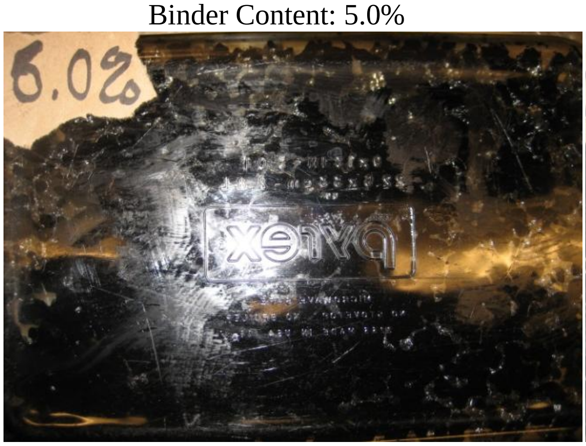

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Figure B.7: OBC Determination for PG 64-22 NF

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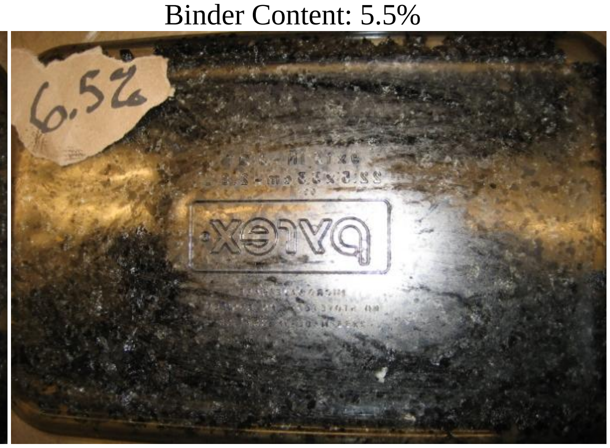

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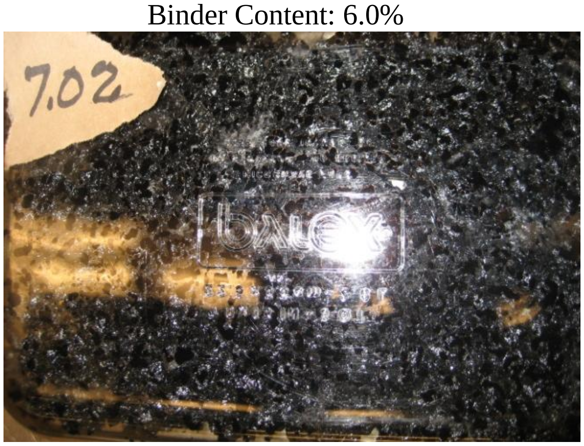

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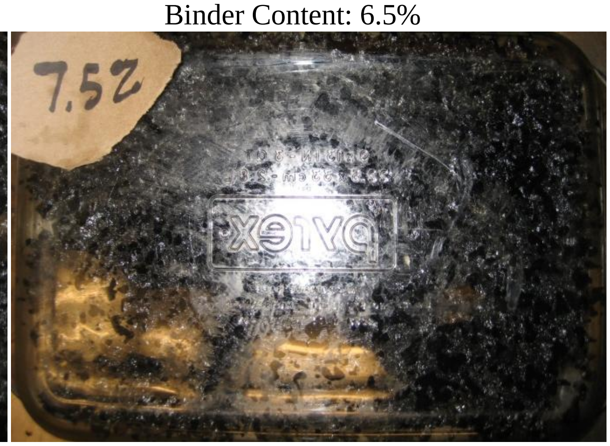

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Figure B.8: OBC Determination for PG 64-22 Evo F

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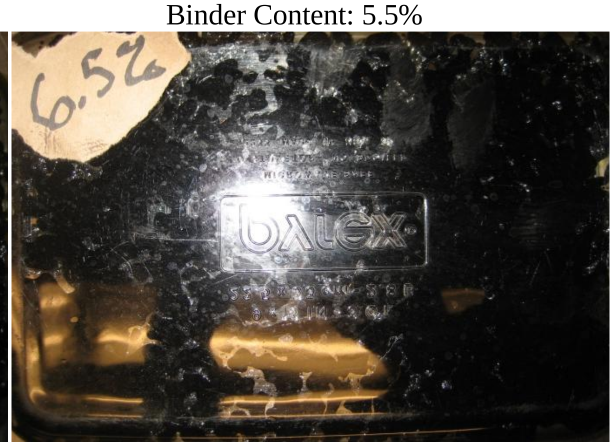

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Figure B.9: OBC Determination for PG 64-22 Evo NF

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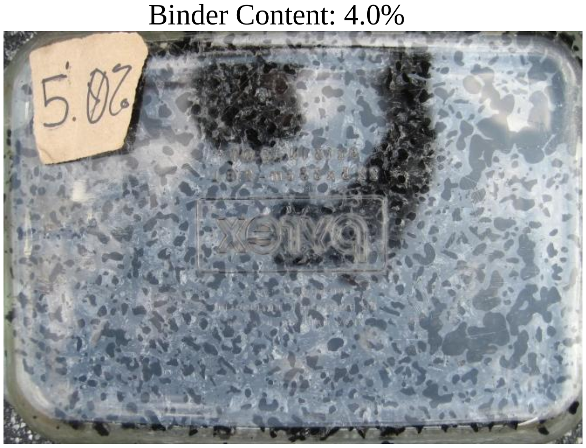

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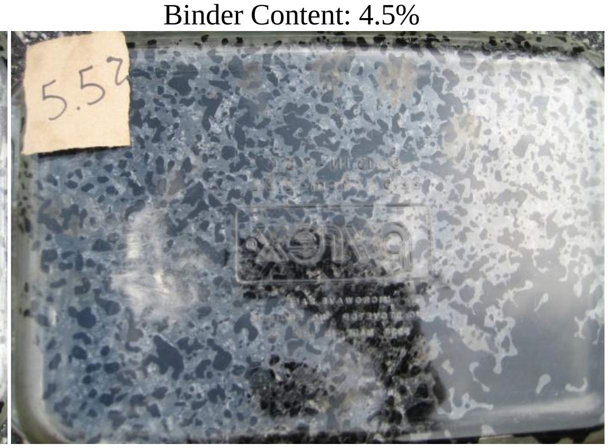

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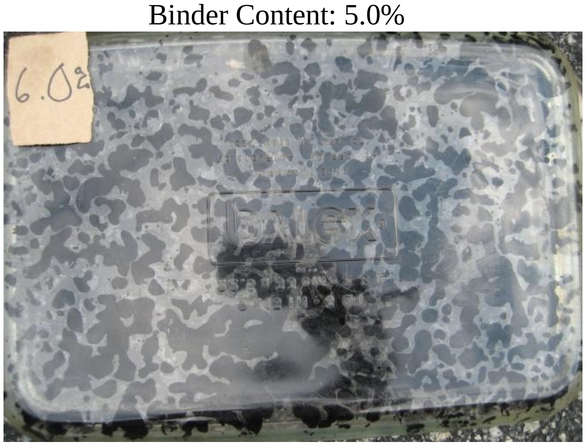

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Figure B.10: OBC Determination for PG 64-22 Foam NF

Appendix C

Volumetrics Data

Table C.1a: Volumetric Data Set 1

Mix ID	BSG	BSG Average	ASG	ASG Average	Porosity (%)	Porosity Average (%)
76-22 Control F	1.915	1.929	2.242	2.282	14.6	15.5
76-22 Control F	1.971		2.321		15.1	
76-22 Control F	1.999		2.337		14.5	
76-22 Control F	1.935		2.243		13.7	
76-22 Control F	1.959		2.285		14.3	
76-22 Control F	1.966		2.367		16.9	
76-22 Control F	1.863		2.256		17.4	
76-22 Control F	1.906		2.279		16.3	
76-22 Control F	1.799		2.276		21.0	
76-22 Control F	1.906		2.287		16.7	
76-22 Control F	1.985		2.243		11.5	
76-22 Control F	1.938		2.253		14.0	
76-22 Control NF OBC	1.926	1.891	2.456	2.369	21.6	20.1
76-22 Control NF OBC	1.893		2.342		19.2	
76-22 Control NF OBC	1.928		2.326		17.1	
76-22 Control NF OBC	1.878		2.328		19.3	
76-22 Control NF OBC	1.857		2.406		22.8	
76-22 Control NF OBC	1.900		2.447		22.4	
76-22 Control NF OBC	1.917		2.297		16.5	
76-22 Control NF OBC	1.930		2.385		19.1	
76-22 Control NF OBC	1.922		2.318		17.1	
76-22 Control NF OBC	1.825		2.342		22.1	
76-22 Control NF OBC	1.885		2.429		22.4	
76-22 Control NF OBC	1.834		2.345		21.8	

Table C.1b: Volumetric Data Set 1 (Continued)

Mix ID	BSG	BSG Average	ASG	ASG Average	Porosity (%)	Porosity Average (%)
76-22 Control NF +0.5%	1.926	1.916	2.364	2.405	18.5	20.3
76-22 Control NF +0.5%	1.923		2.432		20.9	
76-22 Control NF +0.5%	1.884		2.338		19.4	
76-22 Control NF +0.5%	1.896		2.346		19.2	
76-22 Control NF +0.5%	1.968		2.440		19.4	
76-22 Control NF +0.5%	1.913		2.446		21.8	
76-22 Control NF +0.5%	1.906		2.445		22.1	
76-22 Control NF +0.5%	1.949		2.440		20.1	
76-22 Control NF +0.5%	1.873		2.368		20.9	
76-22 Control NF +0.5%	1.940		2.397		19.1	
76-22 Control NF +0.5%	1.901		2.403		20.9	
76-22 Control NF +0.5%	1.914		2.441		21.6	
76-22 Evo NF OBC	1.909	1.909	2.326	2.376	17.9	19.6
76-22 Evo NF OBC	1.934		2.424		20.2	
76-22 Evo NF OBC	1.916		2.416		20.7	
76-22 Evo NF OBC	1.920		2.318		17.2	
76-22 Evo NF OBC	1.897		2.421		21.7	
76-22 Evo NF OBC	1.923		2.413		20.3	
76-22 Evo NF OBC	1.861		2.343		20.6	
76-22 Evo NF OBC	1.903		2.431		21.7	
76-22 Evo NF OBC	1.913		2.332		18.0	
76-22 Evo NF OBC	1.924		2.429		20.8	
76-22 Evo NF OBC	1.859		2.311		19.6	
76-22 Evo NF OBC	1.950		2.354		17.2	

Table C.1c: Volumetric Data Set 1 (Continued)

Mix ID	BSG	BSG Average	ASG	ASG Average	Porosity (%)	Porosity Average (%)
76-22 Evo NF +0.5%	1.872	1.890	2.324	2.352	19.5	19.6
76-22 Evo NF +0.5%	1.914		2.433		21.3	
76-22 Evo NF +0.5%	1.780		2.296		22.5	
76-22 Evo NF +0.5%	1.929		2.322		16.9	
76-22 Evo NF +0.5%	1.964		2.419		18.8	
76-22 Evo NF +0.5%	1.947		2.406		19.1	
76-22 Evo NF +0.5%	1.913		2.343		18.4	
76-22 Evo NF +0.5%	1.928		2.338		17.5	
76-22 Evo NF +0.5%	1.860		2.403		22.6	
76-22 Evo NF +0.5%	1.911		2.349		18.6	
76-22 Evo NF +0.5%	1.857		2.270		18.2	
76-22 Evo NF +0.5%	1.803		2.313		22.1	
76-22 Foam NF OBC	1.824	1.898	2.305	2.348	20.9	19.1
76-22 Foam NF OBC	1.796		2.351		23.6	
76-22 Foam NF OBC	1.967		2.400		18.0	
76-22 Foam NF OBC	1.971		2.346		16.0	
76-22 Foam NF OBC	1.822		2.320		21.5	
76-22 Foam NF OBC	1.899		2.317		18.1	
76-22 Foam NF OBC	1.925		2.334		17.5	
76-22 Foam NF OBC	1.899		2.330		18.5	
76-22 Foam NF OBC	1.931		2.342		17.5	
76-22 Foam NF OBC	1.932		2.436		20.7	
76-22 Foam NF OBC	1.925		2.349		18.1	
76-22 Foam NF OBC	1.889		2.343		19.4	

Table C.1d: Volumetric Data Set 1 (Continued)

Mix ID	BSG	BSG Average	ASG	ASG Average	Porosity (%)	Porosity Average (%)
76-22 Foam NF +0.5%	1.825	1.919	2.332	2.346	21.7	18.2
76-22 Foam NF +0.5%	1.910		2.330		18.0	
76-22 Foam NF +0.5%	1.856		2.310		19.6	
76-22 Foam NF +0.5%	1.903		2.343		18.8	
76-22 Foam NF +0.5%	1.933		2.342		17.5	
76-22 Foam NF +0.5%	1.914		2.305		17.0	
76-22 Foam NF +0.5%	1.952		2.414		19.1	
76-22 Foam NF +0.5%	1.959		2.347		16.5	
76-22 Foam NF +0.5%	1.985		2.379		16.6	
76-22 Foam NF +0.5%	1.934		2.324		16.8	
76-22 Foam NF +0.5%	1.904		2.311		17.6	
76-22 Foam NF +0.5%	1.951		2.412		19.1	
64-22 Control F	1.915	1.942	2.258	2.357	15.2	17.6
64-22 Control F	1.852		2.287		19.0	
64-22 Control F	1.958		2.390		18.1	
64-22 Control F	1.985		2.380		16.6	
64-22 Control F	1.950		2.347		16.9	
64-22 Control F	1.949		2.374		17.9	
64-22 Control F	1.941		2.418		19.7	
64-22 Control F	1.943		2.342		17.0	
64-22 Control F	1.934		2.323		16.7	
64-22 Control F	1.963		2.399		18.1	
64-22 Control F	1.963		2.401		18.2	
64-22 Control F	1.952		2.369		17.6	

Table C.1e: Volumetric Data Set 1 (Continued)

Mix ID	BSG	BSG Average	ASG	ASG Average	Porosity (%)	Porosity Average (%)
64-22 Control NF OBC	1.928	1.923	2.449	2.391	21.3	19.6
64-22 Control NF OBC	1.928		2.458		21.6	
64-22 Control NF OBC	1.925		2.344		17.9	
64-22 Control NF OBC	1.926		2.343		17.8	
64-22 Control NF OBC	1.904		2.336		18.5	
64-22 Control NF OBC	1.930		2.337		17.4	
64-22 Control NF OBC	1.956		2.471		20.8	
64-22 Control NF OBC	1.910		2.467		22.6	
64-22 Control NF OBC	1.965		2.405		18.3	
64-22 Control NF OBC	1.939		2.367		18.1	
64-22 Control NF OBC	1.833		2.287		19.8	
64-22 Control NF OBC	1.926		2.428		20.7	
64-22 Control NF +0.5%	1.907	1.910	2.349	2.400	18.8	20.4
64-22 Control NF +0.5%	1.894		2.389		20.7	
64-22 Control NF +0.5%	1.951		2.441		20.1	
64-22 Control NF +0.5%	1.966		2.415		18.6	
64-22 Control NF +0.5%	1.894		2.363		19.9	
64-22 Control NF +0.5%	1.871		2.365		20.9	
64-22 Control NF +0.5%	1.899		2.468		23.1	
64-22 Control NF +0.5%	1.914		2.374		19.4	
64-22 Control NF +0.5%	1.913		2.413		20.7	
64-22 Control NF +0.5%	1.866		2.337		20.1	
64-22 Control NF +0.5%	1.924		2.444		21.3	
64-22 Control NF +0.5%	1.915		2.447		21.7	

Table C.1f: Volumetric Data Set 1 (Continued)

Mix ID	BSG	BSG Average	ASG	ASG Average	Porosity (%)	Porosity Average (%)
64-22 Evo NF OBC	1.900	1.902	2.315	2.376	17.9	19.9
64-22 Evo NF OBC	1.916		2.396		20.0	
64-22 Evo NF OBC	1.880		2.335		19.5	
64-22 Evo NF OBC	1.926		2.368		18.7	
64-22 Evo NF OBC	1.884		2.399		21.5	
64-22 Evo NF OBC	1.867		2.348		20.5	
64-22 Evo NF OBC	1.854		2.343		20.9	
64-22 Evo NF OBC	1.994		2.447		18.5	
64-22 Evo NF OBC	1.930		2.441		20.9	
64-22 Evo NF OBC	1.865		2.362		21.1	
64-22 Evo NF OBC	1.953		2.424		19.5	
64-22 Evo NF OBC	1.860		2.332		20.2	
64-22 Evo NF +0.5%	1.942	1.924	2.426	2.401	19.9	19.9
64-22 Evo NF +0.5%	1.885		2.353		19.9	
64-22 Evo NF +0.5%	1.954		2.437		19.8	
64-22 Evo NF +0.5%	1.938		2.436		20.5	
64-22 Evo NF +0.5%	1.932		2.388		19.1	
64-22 Evo NF +0.5%	1.933		2.349		17.7	
64-22 Evo NF +0.5%	1.947		2.439		20.2	
64-22 Evo NF +0.5%	1.911		2.343		18.5	
64-22 Evo NF +0.5%	1.915		2.441		21.5	
64-22 Evo NF +0.5%	1.995		2.396		16.7	
64-22 Evo NF +0.5%	1.800		2.350		23.4	
64-22 Evo NF +0.5%	1.931		2.449		21.1	

Table C.1g: Volumetric Data Set 1 (Continued)

Mix ID	BSG	BSG Average	ASG	ASG Average	Porosity (%)	Porosity Average (%)
64-22 Foam NF OBC	1.872	1.936	2.339	2.402	20.0	19.4
64-22 Foam NF OBC	1.921		2.343		18.0	
64-22 Foam NF OBC	1.960		2.384		17.8	
64-22 Foam NF OBC	1.972		2.452		19.6	
64-22 Foam NF OBC	1.983		2.431		18.4	
64-22 Foam NF OBC	1.889		2.354		19.8	
64-22 Foam NF OBC	1.913		2.407		20.5	
64-22 Foam NF OBC	1.981		2.447		19.0	
64-22 Foam NF OBC	1.911		2.434		21.5	
64-22 Foam NF OBC	1.896		2.334		18.8	
64-22 Foam NF OBC	1.962		2.433		19.4	
64-22 Foam NF OBC	1.973		2.461		19.8	
64-22 Foam NF +0.5%	1.917	1.931	2.320	2.394	17.4	19.3
64-22 Foam NF +0.5%	1.949		2.373		17.9	
64-22 Foam NF +0.5%	1.931		2.375		18.7	
64-22 Foam NF +0.5%	1.937		2.399		19.3	
64-22 Foam NF +0.5%	1.970		2.403		18.0	
64-22 Foam NF +0.5%	1.894		2.447		22.6	
64-22 Foam NF +0.5%	1.974		2.417		18.3	
64-22 Foam NF +0.5%	1.967		2.443		19.5	
64-22 Foam NF +0.5%	1.821		2.264		19.6	
64-22 Foam NF +0.5%	1.963		2.432		19.3	
64-22 Foam NF +0.5%	1.922		2.427		20.8	
64-22 Foam NF +0.5%	1.924		2.424		20.6	

Table C.2a: Volumetric Data Set 2

Mix ID	Air Voids (%)	Air Voids Average (%)	VMA (%)	VMA Average (%)	VFA (%)	VFA Average (%)
76-22 Control F	21.2	19.5	35.1	34.6	39.6	40.6
76-22 Control F	18.9		33.1		43.1	
76-22 Control F	17.7		32.2		45.0	
76-22 Control F	20.4		34.4		40.8	
76-22 Control F	19.4		33.6		42.3	
76-22 Control F	19.1		33.4		42.7	
76-22 Control F	23.3		36.9		36.7	
76-22 Control F	21.6		35.4		39.1	
76-22 Control F	26.0		39.0		33.4	
76-22 Control F	21.6		35.4		39.0	
76-22 Control F	18.3		32.7		44.0	
76-22 Control F	20.3		34.3		41.0	
76-22 Control NF OBC	18.8	20.0	28.1	29.4	33.1	31.2
76-22 Control NF OBC	20.2		29.4		31.2	
76-22 Control NF OBC	18.7		28.1		33.2	
76-22 Control NF OBC	20.8		29.9		30.4	
76-22 Control NF OBC	21.7		30.7		29.3	
76-22 Control NF OBC	19.9		29.1		31.6	
76-22 Control NF OBC	19.2		28.5		32.6	
76-22 Control NF OBC	18.6		28.0		33.4	
76-22 Control NF OBC	19.0		28.3		32.8	
76-22 Control NF OBC	23.1		31.9		27.7	
76-22 Control NF OBC	20.5		29.7		30.7	
76-22 Control NF OBC	22.7		31.6		28.1	

Table C.2b: Volumetric Data Set 2 (Continued)

Mix ID	Air Voids (%)	Air Voids Average (%)	VMA (%)	VMA Average (%)	VFA (%)	VFA Average (%)
76-22 Control NF +0.5%	18.3	18.6	28.5	28.9	35.9	35.4
76-22 Control NF +0.5%	18.4		28.6		35.8	
76-22 Control NF +0.5%	20.1		30.1		33.3	
76-22 Control NF +0.5%	19.5		29.6		34.1	
76-22 Control NF +0.5%	16.5		27.0		38.8	
76-22 Control NF +0.5%	18.8		29.0		35.1	
76-22 Control NF +0.5%	19.1		29.3		34.6	
76-22 Control NF +0.5%	17.3		27.6		37.5	
76-22 Control NF +0.5%	20.5		30.5		32.7	
76-22 Control NF +0.5%	17.7		28.0		36.9	
76-22 Control NF +0.5%	19.3		29.4		34.4	
76-22 Control NF +0.5%	18.8		28.9		35.2	
76-22 Evo NF OBC	20.7	20.4	31.3	31.3	33.7	33.7
76-22 Evo NF OBC	19.7		30.4		35.1	
76-22 Evo NF OBC	20.4		31.0		34.1	
76-22 Evo NF OBC	20.3		30.9		34.3	
76-22 Evo NF OBC	21.2		31.7		33.0	
76-22 Evo NF OBC	20.1		30.8		34.5	
76-22 Evo NF OBC	22.7		33.0		31.1	
76-22 Evo NF OBC	21.0		31.5		33.3	
76-22 Evo NF OBC	20.6		31.1		33.9	
76-22 Evo NF OBC	20.1		30.7		34.5	
76-22 Evo NF OBC	22.8		33.1		31.0	
76-22 Evo NF OBC	19.0		29.8		36.1	

Table C.2c: Volumetric Data Set 2 (Continued)

Mix ID	Air Voids (%)	Air Voids Average (%)	VMA (%)	VMA Average (%)	VFA (%)	VFA Average (%)
76-22 Evo NF +0.5%	21.7	20.5	32.9	32.3	34.1	35.3
76-22 Evo NF +0.5%	20.0		31.4		36.5	
76-22 Evo NF +0.5%	25.6		36.3		29.4	
76-22 Evo NF +0.5%	19.3		30.9		37.5	
76-22 Evo NF +0.5%	17.9		29.7		39.7	
76-22 Evo NF +0.5%	18.6		30.3		38.6	
76-22 Evo NF +0.5%	20.0		31.5		36.5	
76-22 Evo NF +0.5%	19.4		30.9		37.4	
76-22 Evo NF +0.5%	22.2		33.4		33.4	
76-22 Evo NF +0.5%	20.1		31.5		36.3	
76-22 Evo NF +0.5%	22.3		33.5		33.3	
76-22 Evo NF +0.5%	24.6		35.4		30.5	
76-22 Foam NF OBC	25.5	23.2	35.5	32.9	28.3	32.0
76-22 Foam NF OBC	26.6		36.5		27.2	
76-22 Foam NF OBC	19.6		30.4		35.6	
76-22 Foam NF OBC	19.4		30.3		35.9	
76-22 Foam NF OBC	25.5		35.6		28.2	
76-22 Foam NF OBC	22.4		32.9		31.9	
76-22 Foam NF OBC	21.3		31.9		33.3	
76-22 Foam NF OBC	22.4		32.8		31.9	
76-22 Foam NF OBC	21.1		31.7		33.6	
76-22 Foam NF OBC	21.0		31.7		33.6	
76-22 Foam NF OBC	21.3		31.9		33.3	
76-22 Foam NF OBC	22.8		33.2		31.4	

Table C.2d: Volumetric Data Set 2 (Continued)

Mix ID	Air Voids (%)	Air Voids Average (%)	VMA (%)	VMA Average (%)	VFA (%)	VFA Average (%)
76-22 Foam NF +0.5%	24.9	22.2	35.8	32.5	30.6	35.5
76-22 Foam NF +0.5%	21.3		32.8		34.9	
76-22 Foam NF +0.5%	23.6		34.7		32.1	
76-22 Foam NF +0.5%	21.6		33.1		34.5	
76-22 Foam NF +0.5%	20.4		32.0		36.2	
76-22 Foam NF +0.5%	21.2		32.7		35.1	
76-22 Foam NF +0.5%	19.6		31.3		37.4	
76-22 Foam NF +0.5%	19.3		31.1		37.8	
76-22 Foam NF +0.5%	18.3		30.2		39.4	
76-22 Foam NF +0.5%	20.4		32.0		36.3	
76-22 Foam NF +0.5%	21.6		33.0		34.6	
76-22 Foam NF +0.5%	19.7		31.4		37.3	
64-22 Control F	20.0	19.2	32.2	31.3	37.9	39.7
64-22 Control F	22.6		34.5		34.3	
64-22 Control F	18.2		30.7		40.7	
64-22 Control F	17.1		29.7		42.6	
64-22 Control F	18.5		31.0		40.2	
64-22 Control F	18.6		31.0		40.1	
64-22 Control F	18.9		31.3		39.6	
64-22 Control F	18.8		31.2		39.7	
64-22 Control F	19.2		31.5		39.1	
64-22 Control F	18.0		30.5		41.1	
64-22 Control F	18.0		30.5		41.0	
64-22 Control F	18.4		30.9		40.3	

Table C.2e: Volumetric Data Set 2 (Continued)

Mix ID	Air Voids (%)	Air Voids Average (%)	VMA (%)	VMA Average (%)	VFA (%)	VFA Average (%)
64-22 Control NF OBC	18.1	18.2	27.4	27.6	34.1	33.8
64-22 Control NF OBC	18.0		27.4		34.1	
64-22 Control NF OBC	18.2		27.5		33.9	
64-22 Control NF OBC	18.2		27.5		33.9	
64-22 Control NF OBC	19.1		28.3		32.6	
64-22 Control NF OBC	18.0		27.3		34.2	
64-22 Control NF OBC	16.9		26.3		35.9	
64-22 Control NF OBC	18.8		28.1		32.9	
64-22 Control NF OBC	16.5		26.0		36.6	
64-22 Control NF OBC	17.6		27.0		34.8	
64-22 Control NF OBC	22.1		31.0		28.6	
64-22 Control NF OBC	18.1		27.5		33.9	
64-22 Control NF +0.5%	18.4	18.1	28.5	28.4	35.6	35.8
64-22 Control NF +0.5%	18.9		29.0		34.7	
64-22 Control NF +0.5%	16.5		26.9		38.6	
64-22 Control NF +0.5%	15.9		26.4		39.7	
64-22 Control NF +0.5%	19.0		29.0		34.7	
64-22 Control NF +0.5%	19.9		29.9		33.3	
64-22 Control NF +0.5%	18.7		28.9		35.0	
64-22 Control NF +0.5%	18.1		28.3		36.0	
64-22 Control NF +0.5%	18.2		28.3		35.9	
64-22 Control NF +0.5%	20.2		30.1		33.0	
64-22 Control NF +0.5%	17.7		27.9		36.7	
64-22 Control NF +0.5%	18.0		28.2		36.1	

Table C.2f: Volumetric Data Set 2 (Continued)

Mix ID	Air Voids (%)	Air Voids Average (%)	VMA (%)	VMA Average (%)	VFA (%)	VFA Average (%)
64-22 Evo NF OBC	20.5	20.7	29.7	29.6	30.9	31.2
64-22 Evo NF OBC	19.9		29.1		31.8	
64-22 Evo NF OBC	21.4		30.5		29.8	
64-22 Evo NF OBC	19.4		28.8		32.4	
64-22 Evo NF OBC	21.2		30.3		30.0	
64-22 Evo NF OBC	21.9		31.0		29.2	
64-22 Evo NF OBC	22.5		31.5		28.5	
64-22 Evo NF OBC	16.6		26.3		36.7	
64-22 Evo NF OBC	19.3		28.6		32.6	
64-22 Evo NF OBC	22.0		31.0		29.0	
64-22 Evo NF OBC	18.3		27.8		34.0	
64-22 Evo NF OBC	22.2		31.2		28.8	
64-22 Evo NF +0.5%	18.2	18.7	28.5	29.2	36.2	35.2
64-22 Evo NF +0.5%	20.6		30.6		32.8	
64-22 Evo NF +0.5%	17.7		28.1		37.0	
64-22 Evo NF +0.5%	18.4		28.7		35.9	
64-22 Evo NF +0.5%	18.6		28.9		35.5	
64-22 Evo NF +0.5%	18.6		28.9		35.6	
64-22 Evo NF +0.5%	18.0		28.4		36.5	
64-22 Evo NF +0.5%	19.5		29.7		34.2	
64-22 Evo NF +0.5%	19.3		29.5		34.5	
64-22 Evo NF +0.5%	16.0		26.6		39.9	
64-22 Evo NF +0.5%	24.2		33.7		28.4	
64-22 Evo NF +0.5%	18.7		28.9		35.5	

Table C.2g: Volumetric Data Set 2 (Continued)

Mix ID	Air Voids (%)	Air Voids Average (%)	VMA (%)	VMA Average (%)	VFA (%)	VFA Average (%)
64-22 Foam NF OBC	23.4	20.9	32.5	30.2	27.9	31.1
64-22 Foam NF OBC	21.4		30.7		30.2	
64-22 Foam NF OBC	19.8		29.3		32.3	
64-22 Foam NF OBC	19.3		28.9		33.0	
64-22 Foam NF OBC	18.9		28.5		33.7	
64-22 Foam NF OBC	22.7		31.9		28.7	
64-22 Foam NF OBC	21.7		31.0		29.8	
64-22 Foam NF OBC	19.0		28.6		33.5	
64-22 Foam NF OBC	21.8		31.1		29.8	
64-22 Foam NF OBC	22.5		31.6		29.0	
64-22 Foam NF OBC	19.8		29.2		32.4	
64-22 Foam NF OBC	19.3		28.8		33.1	
64-22 Foam NF +0.5%	21.0	20.4	31.2	30.7	32.7	33.5
64-22 Foam NF +0.5%	19.7		30.1		34.5	
64-22 Foam NF +0.5%	20.5		30.7		33.4	
64-22 Foam NF +0.5%	20.2		30.5		33.8	
64-22 Foam NF +0.5%	18.8		29.3		35.8	
64-22 Foam NF +0.5%	22.0		32.1		31.4	
64-22 Foam NF +0.5%	18.7		29.2		36.0	
64-22 Foam NF +0.5%	19.0		29.4		35.5	
64-22 Foam NF +0.5%	25.0		34.7		27.9	
64-22 Foam NF +0.5%	19.1		29.6		35.3	
64-22 Foam NF +0.5%	20.8		31.1		32.9	
64-22 Foam NF +0.5%	20.7		31.0		33.0	

Appendix D

Permeability Data

Table D.1a: Permeability Data at 0-Days Aging

Mix ID	Permeability (m/day)	Average Permeability (m/day)	Std. Dev. (m/day)	C.V. (%)
76-22 Control F	165	239	72.5	30.3
76-22 Control F	243			
76-22 Control F	309			
76-22 Control NF OBC	408	408	32.1	7.9
76-22 Control NF OBC	440			
76-22 Control NF OBC	376			
76-22 Control NF +0.5%	457	485	25.9	5.3
76-22 Control NF +0.5%	489			
76-22 Control NF +0.5%	508			
76-22 Evo NF OBC	371	443	83.5	18.9
76-22 Evo NF OBC	423			
76-22 Evo NF OBC	534			
76-22 Evo NF +0.5%	467	438	104.9	23.9
76-22 Evo NF +0.5%	322			
76-22 Evo NF +0.5%	525			
76-22 Foam NF OBC	457	458	46.7	10.2
76-22 Foam NF OBC	411			
76-22 Foam NF OBC	505			
76-22 Foam NF +0.5%	432	406	29.8	7.3
76-22 Foam NF +0.5%	374			
76-22 Foam NF +0.5%	412			

Table D.1b: Permeability Data at 0-Days Aging

Mix ID	Permeability (m/day)	Average Permeability (m/day)	Std. Dev. (m/day)	C.V. (%)
64-22 Control F	253	295	41.9	14.2
64-22 Control F	337			
64-22 Control F	296			
64-22 Control NF OBC	424	480	73.6	15.3
64-22 Control NF OBC	453			
64-22 Control NF OBC	564			
64-22 Control NF +0.5%	429	515	86.9	16.9
64-22 Control NF +0.5%	513			
64-22 Control NF +0.5%	602			
64-22 Evo NF OBC	471	468	21.8	4.7
64-22 Evo NF OBC	489			
64-22 Evo NF OBC	445			
64-22 Evo NF +0.5%	360	380	17.1	4.5
64-22 Evo NF +0.5%	391			
64-22 Evo NF +0.5%	388			
64-22 Foam NF OBC	462	470	77.0	16.4
64-22 Foam NF OBC	397			
64-22 Foam NF OBC	551			
64-22 Foam NF +0.5%	641	488	133.1	27.3
64-22 Foam NF +0.5%	423			
64-22 Foam NF +0.5%	400			

Table D.2a: Permeability Data at 3-Days Aging

Mix ID	Permeability (m/day)	Average Permeability (m/day)	Std. Dev. (m/day)	C.V. (%)
76-22 Control F	250	305	47.8	15.7
76-22 Control F	334			
76-22 Control F	331			
76-22 Control NF OBC	408	409	41.2	10.1
76-22 Control NF OBC	450			
76-22 Control NF OBC	368			
76-22 Control NF +0.5%	497	521	31.4	6.0
76-22 Control NF +0.5%	511			
76-22 Control NF +0.5%	557			
76-22 Evo NF OBC	378	441	65.8	14.9
76-22 Evo NF OBC	435			
76-22 Evo NF OBC	509			
76-22 Evo NF +0.5%	484	461	103.7	22.5
76-22 Evo NF +0.5%	348			
76-22 Evo NF +0.5%	551			
76-22 Foam NF OBC	449	457	11.8	2.6
76-22 Foam NF OBC	466			
76-22 Foam NF OBC	*			
76-22 Foam NF +0.5%	490	449	63.4	14.1
76-22 Foam NF +0.5%	376			
76-22 Foam NF +0.5%	480			

Note: * denotes that sample collapsed or deformed during aging.

Table D.2b: Permeability Data at 3-Days Aging

Mix ID	Permeability (m/day)	Average Permeability (m/day)	Std. Dev. (m/day)	C.V. (%)
64-22 Control F	266	319	47.0	14.7
64-22 Control F	356			
64-22 Control F	335			
64-22 Control NF OBC	358	351	10.3	2.9
64-22 Control NF OBC	344			
64-22 Control NF OBC	*			
64-22 Control NF +0.5%	578	555	23.9	4.3
64-22 Control NF +0.5%	531			
64-22 Control NF +0.5%	556			
64-22 Evo NF OBC	*	543	1.0	0.2
64-22 Evo NF OBC	543			
64-22 Evo NF OBC	542			
64-22 Evo NF +0.5%	442	409	33.9	8.3
64-22 Evo NF +0.5%	374			
64-22 Evo NF +0.5%	410			
64-22 Foam NF OBC	*	*	*	*
64-22 Foam NF OBC	*			
64-22 Foam NF OBC	*			
64-22 Foam NF +0.5%	*	*	*	*
64-22 Foam NF +0.5%	*			
64-22 Foam NF +0.5%	455			

Note: * denotes that sample collapsed or deformed during aging.

Table D.3a: Permeability Data at 6-Days Aging

Mix ID	Permeability (m/day)	Average Permeability (m/day)	Std. Dev. (m/day)	C.V. (%)
76-22 Control F	203	281	69.3	24.7
76-22 Control F	303			
76-22 Control F	336			
76-22 Control NF OBC	406	452	40.3	8.9
76-22 Control NF OBC	481			
76-22 Control NF OBC	470			
76-22 Control NF +0.5%	502	524	24.8	4.7
76-22 Control NF +0.5%	518			
76-22 Control NF +0.5%	551			
76-22 Evo NF OBC	428	501	69.4	13.9
76-22 Evo NF OBC	510			
76-22 Evo NF OBC	565			
76-22 Evo NF +0.5%	469	433	86.0	19.8
76-22 Evo NF +0.5%	335			
76-22 Evo NF +0.5%	496			
76-22 Foam NF OBC	487	473	19.2	4.0
76-22 Foam NF OBC	460			
76-22 Foam NF OBC	*			
76-22 Foam NF +0.5%	*	*	*	*
76-22 Foam NF +0.5%	*			
76-22 Foam NF +0.5%	*			

Note: * denotes that sample collapsed or deformed during aging.

Table D.3b: Permeability Data at 6-Days Aging

Mix ID	Permeability (m/day)	Average Permeability (m/day)	Std. Dev. (m/day)	C.V. (%)
64-22 Control F	277	315	32.8	10.4
64-22 Control F	337			
64-22 Control F	330			
64-22 Control NF OBC	*	*	*	*
64-22 Control NF OBC	375			
64-22 Control NF OBC	*			
64-22 Control NF +0.5%	638	*	*	*
64-22 Control NF +0.5%	*			
64-22 Control NF +0.5%	*			
64-22 Evo NF OBC	*	*	*	*
64-22 Evo NF OBC	*			
64-22 Evo NF OBC	480			
64-22 Evo NF +0.5%	*	437	14.3	3.3
64-22 Evo NF +0.5%	447			
64-22 Evo NF +0.5%	427			
64-22 Foam NF OBC	*	*	*	*
64-22 Foam NF OBC	*			
64-22 Foam NF OBC	*			
64-22 Foam NF +0.5%	*	*	*	*
64-22 Foam NF +0.5%	*			
64-22 Foam NF +0.5%	476			

Note: * denotes that sample collapsed or deformed during aging.

Table D.4a: Permeability Data at 9-Days Aging

Mix ID	Permeability (m/day)	Average Permeability (m/day)	Std. Dev. (m/day)	C.V. (%)
76-22 Control F	195	274	69.8	25.5
76-22 Control F	299			
76-22 Control F	327			
76-22 Control NF OBC	418	443	52.8	11.9
76-22 Control NF OBC	503			
76-22 Control NF OBC	406			
76-22 Control NF +0.5%	506	509	65.7	12.9
76-22 Control NF +0.5%	446			
76-22 Control NF +0.5%	577			
76-22 Evo NF OBC	425	486	71.4	14.7
76-22 Evo NF OBC	469			
76-22 Evo NF OBC	565			
76-22 Evo NF +0.5%	475	450	129.2	28.7
76-22 Evo NF +0.5%	310			
76-22 Evo NF +0.5%	565			
76-22 Foam NF OBC	510	468	59.1	12.6
76-22 Foam NF OBC	426			
76-22 Foam NF OBC	*			
76-22 Foam NF +0.5%	*	*	*	*
76-22 Foam NF +0.5%	*			
76-22 Foam NF +0.5%	*			

Note: * denotes that sample collapsed or deformed during aging.

Table D.4b: Permeability Data at 9-Days Aging

Mix ID	Permeability (m/day)	Average Permeability (m/day)	Std. Dev. (m/day)	C.V. (%)
64-22 Control F	225	304	68.9	22.7
64-22 Control F	350			
64-22 Control F	337			
64-22 Control NF OBC	*	*	*	*
64-22 Control NF OBC	375			
64-22 Control NF OBC	*			
64-22 Control NF +0.5%	*	*	*	*
64-22 Control NF +0.5%	*			
64-22 Control NF +0.5%	*			
64-22 Evo NF OBC	*	*	*	*
64-22 Evo NF OBC	*			
64-22 Evo NF OBC	390			
64-22 Evo NF +0.5%	*	*	*	*
64-22 Evo NF +0.5%	*			
64-22 Evo NF +0.5%	*			
64-22 Foam NF OBC	*	*	*	*
64-22 Foam NF OBC	*			
64-22 Foam NF OBC	*			
64-22 Foam NF +0.5%	*	*	*	*
64-22 Foam NF +0.5%	*			
64-22 Foam NF +0.5%	510			

Note: * denotes that sample collapsed or deformed during aging.

Table D.5a: Permeability Data at 14-Days Aging

Mix ID	Permeability (m/day)	Average Permeability (m/day)	Std. Dev. (m/day)	C.V. (%)
76-22 Control F	173	269	83.9	31.2
76-22 Control F	326			
76-22 Control F	308			
76-22 Control NF OBC	447	455	32.7	7.2
76-22 Control NF OBC	491			
76-22 Control NF OBC	428			
76-22 Control NF +0.5%	489	495	50.0	10.1
76-22 Control NF +0.5%	448			
76-22 Control NF +0.5%	548			
76-22 Evo NF OBC	408	473	85.6	18.1
76-22 Evo NF OBC	441			
76-22 Evo NF OBC	570			
76-22 Evo NF +0.5%	*	*	*	*
76-22 Evo NF +0.5%	363			
76-22 Evo NF +0.5%	*			
76-22 Foam NF OBC	485	486	1.2	0.2
76-22 Foam NF OBC	487			
76-22 Foam NF OBC	*			
76-22 Foam NF +0.5%	*	*	*	*
76-22 Foam NF +0.5%	*			
76-22 Foam NF +0.5%	*			

Note: * denotes that sample collapsed or deformed during aging.

Table D.5b: Permeability Data at 14-Days Aging

Mix ID	Permeability (m/day)	Average Permeability (m/day)	Std. Dev. (m/day)	C.V. (%)
64-22 Control F	249			
64-22 Control F	322	298	42.1	14.1
64-22 Control F	323			
64-22 Control NF OBC	*			
64-22 Control NF OBC	385	*	*	*
64-22 Control NF OBC	*			
64-22 Control NF +0.5%	*			
64-22 Control NF +0.5%	*	*	*	*
64-22 Control NF +0.5%	*			
64-22 Evo NF OBC	*			
64-22 Evo NF OBC	*	*	*	*
64-22 Evo NF OBC	353			
64-22 Evo NF +0.5%	*			
64-22 Evo NF +0.5%	*	*	*	*
64-22 Evo NF +0.5%	*			
64-22 Foam NF OBC	*			
64-22 Foam NF OBC	*	*	*	*
64-22 Foam NF OBC	*			
64-22 Foam NF +0.5%	*			
64-22 Foam NF +0.5%	*	*	*	*
64-22 Foam NF +0.5%	*			

Note: * denotes that sample collapsed or deformed during aging.

Appendix E

Cantabro Abrasion Resistance Data and Photos

Table E.1a: Cantabro Abrasion Resistance Data

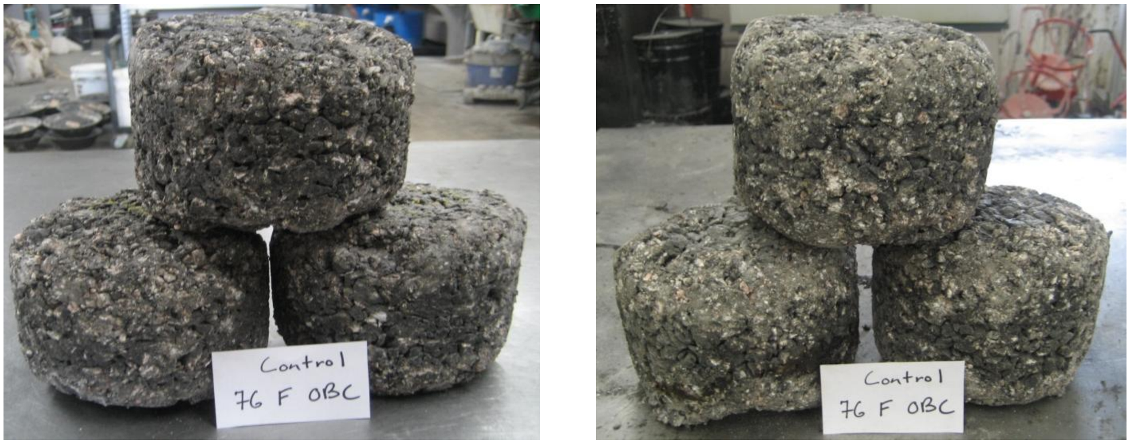
Mix ID	Unaged Loss (%)	Unaged Average Loss (%)	Aged Loss (%)	Aged Average Loss (%)
76-22 Control F	10.2	11.7	7.9	8.9
76-22 Control F	10.8		10.2	
76-22 Control F	14.1		8.7	
76-22 Control NF OBC	28.9	29.0	19.3	21.2
76-22 Control NF OBC	25.7		24.2	
76-22 Control NF OBC	32.5		20.1	
76-22 Control NF +0.5%	26.4	25.1	22.0	20.4
76-22 Control NF +0.5%	21.5		24.9	
76-22 Control NF +0.5%	27.3		14.4	
76-22 Evo NF OBC	39.1	21.0	*	15.5
76-22 Evo NF OBC	23.7		*	
76-22 Evo NF OBC	16.7		*	
76-22 Evo NF OBC	16.1		11.9	
76-22 Evo NF OBC	9.5		19.2	
76-22 Evo NF +0.5%	26.4	17.3	17.3	16.0
76-22 Evo NF +0.5%	16.2		14.7	
76-22 Evo NF +0.5%	22.5		*	
76-22 Foam NF OBC	29.0	22.7	9.8	10.0
76-22 Foam NF OBC	19.6		9.0	
76-22 Foam NF OBC	19.6		11.2	
76-22 Foam NF +0.5%	19.7	19.4	9.9	9.0
76-22 Foam NF +0.5%	21.4		7.2	
76-22 Foam NF +0.5%	16.9		10.0	

Note: * denotes that sample collapsed or deformed during aging.

Table E.1b: Cantabro Abrasion Resistance Data

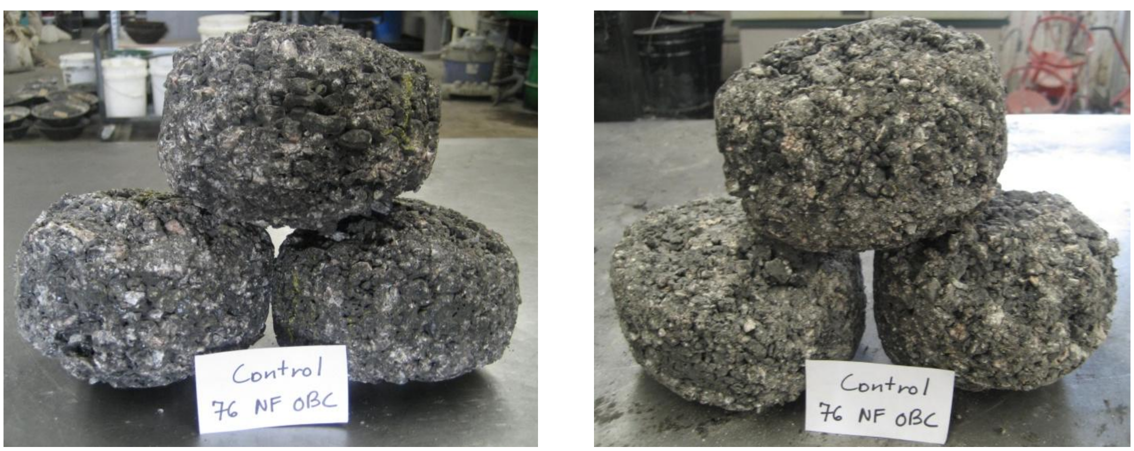
Mix ID	Unaged Loss (%)	Unaged Average Loss (%)	Aged Loss (%)	Aged Average Loss (%)
64-22 Control F	4.5	9.0	13.8	11.2
64-22 Control F	4.8		9.1	
64-22 Control F	17.8		10.8	
64-22 Control NF OBC	34.9	34.0	*	*
64-22 Control NF OBC	38.5		*	
64-22 Control NF OBC	28.5		*	
64-22 Control NF +0.5%	19.8	13.1	*	*
64-22 Control NF +0.5%	12.4		*	
64-22 Control NF +0.5%	6.9		*	
64-22 Evo NF OBC	17.7	20.8	15.3	15.6
64-22 Evo NF OBC	24.0		19.2	
64-22 Evo NF OBC	20.8		12.4	
64-22 Evo NF +0.5%	13.5	16.3	16.1	16.8
64-22 Evo NF +0.5%	19.7		17.5	
64-22 Evo NF +0.5%	15.8		*	
64-22 Foam NF OBC	19.3	21.0	*	*
64-22 Foam NF OBC	19.6		*	
64-22 Foam NF OBC	24.2		*	
64-22 Foam NF +0.5%	20.6	19.6	*	*
64-22 Foam NF +0.5%	21.3		*	
64-22 Foam NF +0.5%	17.1		*	

Note: * denotes that sample collapsed or deformed during aging.



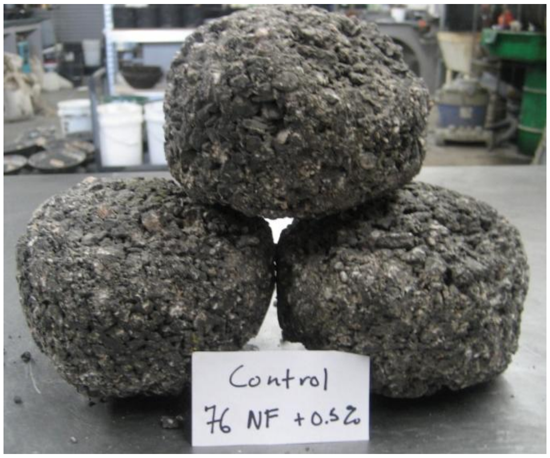
Unaged Aged

Figure E.1: Unaged vs. Aged of PG 76-22 Control F OBC



Unaged Aged

Figure E.2: Unaged vs. Aged of PG 76-22 Control NF OBC



Unaged Aged

Figure E.3: Unaged vs. Aged of PG 76-22 Control NF +0.5%

Unaged Aged

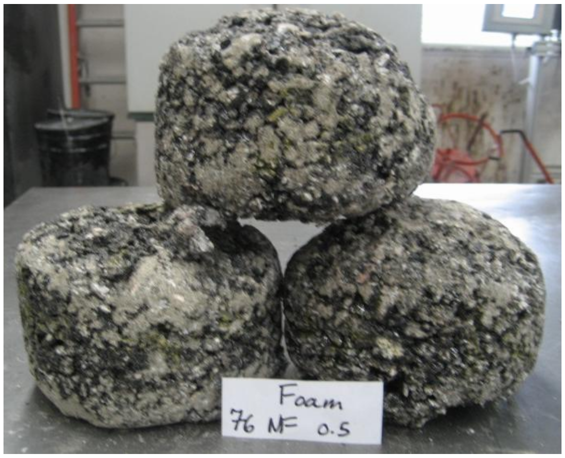
Figure E.4: Unaged vs. Aged of PG 76-22 Evo NF OBC

Unaged Aged

Figure E.5: Unaged vs. Aged of PG 76-22 Evo NF +0.5%

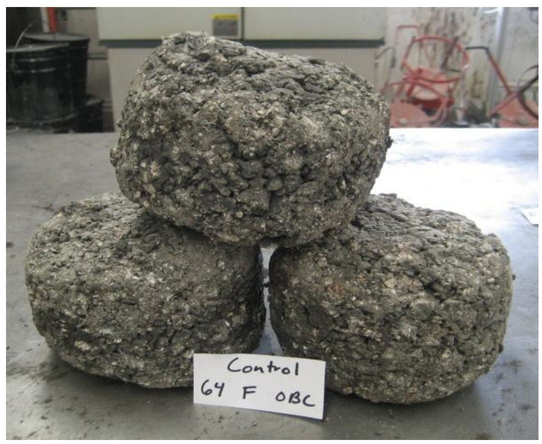
Unaged Aged

Figure E.6: Unaged vs. Aged of Foam 76 NF OBC



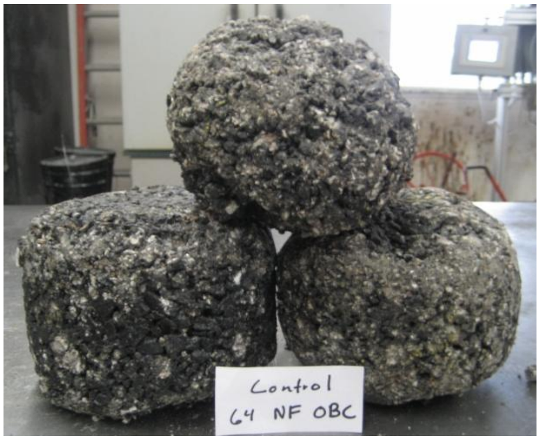
Unaged Aged

Figure E.7: Unaged vs. Aged of Foam 76 NF +0.5%



Unaged Aged

Figure E.8: Unaged vs. Aged of PG 64-22 Control F OBC

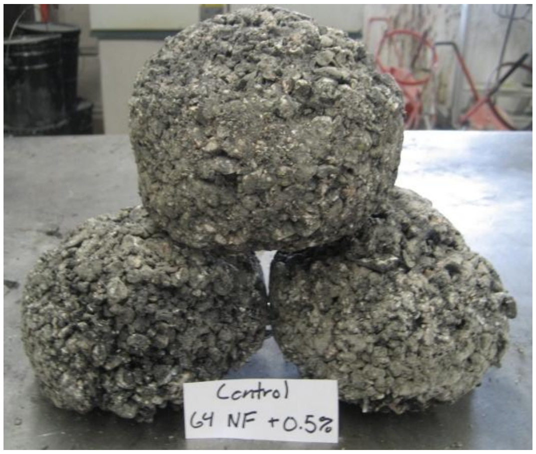


*

Unaged Aged

Figure E.9: Unaged vs. Aged of PG 64-22 Control NF OBC

Note: * denotes that sample collapsed or deformed during aging.

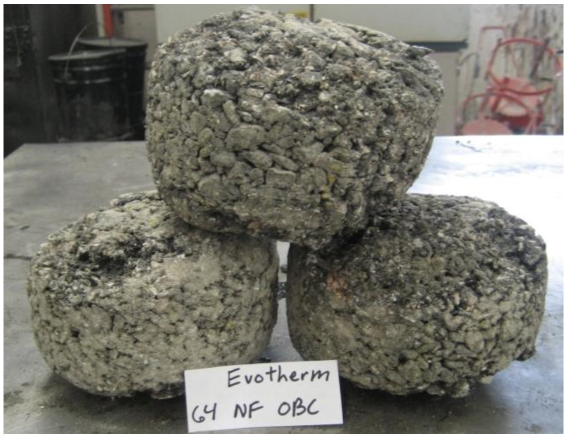


*

Unaged Aged

Figure E.10: Unaged vs. Aged of PG 64-22 Control NF +0.5%

Note: * denotes that sample collapsed or deformed during aging.

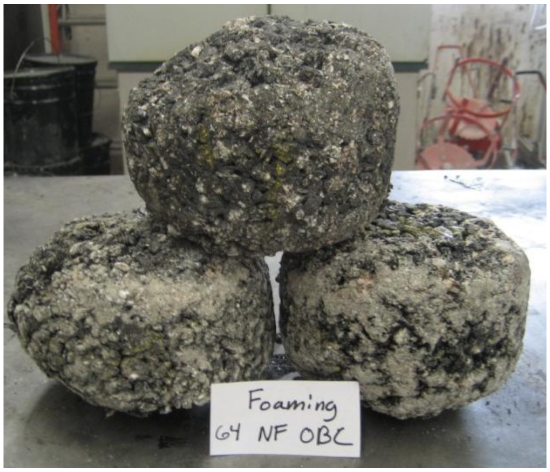


Unaged Aged

Figure E.11: Unaged vs. Aged of PG 64-22 Evo NF OBC

Unaged Aged

Figure E.12: Unaged vs. Aged of PG 64-22 Evo NF +0.5%



*

Unaged Aged

Figure E.13: Unaged vs. Aged of PG 64-22 Foam NF OBC

Note: * denotes that sample collapsed or deformed during aging.

*

Unaged Aged

Figure E.14: Unaged vs. PG 64-22 Foam NF +0.5%

Note: * denotes that sample collapsed or deformed during aging.

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