Final Report

Evaluation of Open Graded Friction Courses: Construction, Maintenance, and Performance Phase II

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Principal Investigator:
Bradley J. Putman

Co-Authors:
Behrooz Danish, Kimberly R. Lyons,
Haripriya Nekkanti, & Thomas S. Repik

Glenn Department of Civil Engineering
Clemson University

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16. Abstract

This study investigated multiple factors that influence the performance of open graded friction courses (OGFC) in South Carolina with the ultimate goal of improving the long-term durability and performance of OGFCs. The research included laboratory studies to evaluate the influence of aggregate Los Angeles (LA) Abrasion and breakdown, aggregate gradation, compaction temperature, binder content, and tack coats using performance measures such as porosity, mean texture depth, Cantabro abrasion, indirect tensile strength (ITS), direct shear strength, and a newly developed surface abrasion test. Limited field evaluations were also conducted to assess the in-situ performance of OGFC. The results informed specification changes that the SCDOT had implemented throughout the duration of this study, including the addition of a 9.5 mm nominal maximum aggregate size (NMAS) OGFC mix, adjustment of the gradation of the 12.5 mm NMAS OGFC mix, and tack coat specifications for OGFC. Additional recommendations were also suggested for consideration based on the results of this study.

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Executive Summary

The overarching goal of this research was to determine how to improve the long-term durability and performance of Open Graded Friction Course (OGFC) mixtures in South Carolina. To accomplish this goal, the research team investigated the root causes of premature raveling of OGFC mixtures and developed recommendations to address this widespread performance issue. The research team also investigated the influence of key variables associated with each cause on the performance of OGFC, which are detailed below.

Evaluation of Aggregate Los Angeles (LA) Abrasion and Breakdown in OGFC Mixtures

Aggregates from 11 quarries around South Carolina varying in LA Abrasion values from 20-54 were evaluated to determine the influence of LA Abrasion on OGFC mixture performance in the laboratory as well as the degree to which aggregates breakdown, thus altering the mix gradation due to mixing and compaction. The results indicated that mixes made with higher LA Abrasion aggregate generally outperformed those made with lower LA aggregates. This unexpected result was linked to aggregate breakdown during mixing and compacting that altered the gradation to allow for greater packing density and reduced the porosity. The change in gradation was quantified using the uniformity coefficient (C_u) to compare the original gradation to the gradation after mixing and compaction that was also validated in a field trial.

Evaluation of Aggregate Gradation in OGFC Mixtures

OGFC mixtures having a nominal maximum aggregate size (NMAS) of 9.5 mm and 12.5 mm were evaluated to determine the effects of varying the percent of material passing the No. 4 sieve and the percent passing the No. 200 sieve on the laboratory performance properties. The results of this study supported the specification revisions that the South Carolina Department of Transportation (SCDOT) made to the OGFC gradation by increasing the allowable percent passing the No. 4 sieve from 15-25% to 15-30%. Additionally, increasing the filler content of OGFC mixes, within reason, has the potential to result in positive effects on the durability while still maintaining adequate permeability for drainage performance. Finally, the use of the 9.5 mm NMAS gradation for mainline OGFC paving could also yield performance benefits.

Evaluation of Compaction Temperature of OGFC

Pavement mat temperature data obtained from OGFC paving projects was analyzed to determine the impacts of paver stops on the occurrence of thermal segregation and the influence of compaction temperature on OGFC mixture properties. The study showed that paver stops often result in areas of thermal segregation, which could have longer-term effects on the pavement durability. Additionally, lab tests indicated that OGFC made with a warm mix additive like Evotherm® may be less sensitive to changes in the compaction temperature than conventional hot mix OGFC.

Evaluation of OGFC Durability Test Methods and Variables

Multiple test methods were evaluated to assess the durability performance of OGFC mixtures and the influence of different variables including binder content and long-term aging. Results showed that increasing the binder content of the OGFC mix from 5-6%, and then from 6-7% increased the performance in all test procedures evaluated in this study, however, it also resulted in a porosity reduction, which needs to be monitored to ensure sufficient permeability. When the OGFC specimens were subjected to aging at 60°C, the stiffness of the binder increased due to oxidation which was reflected in the durability performance tests.

Evaluation of Bonding of OGFC Layers

Bond performance between OGFC and a Surface Type A layer was evaluated to determine the influence of tack coat material, tack coat application rate, OGFC gradation, and OGFC compaction effort. The results of this study indicated that the non-tracking tack coat product, UltraTack® and UltraFuse®, yielded the highest interlayer shear strength (ISS) results compared to the other traditional tack coat materials (i.e., PG 64-22, CRS-2, and HFMS-1H). The emulsion products exhibited the highest ISS at the lowest application rate of 0.033 gal/yd^2 residual and additional material resulted in a decrease in strength. However, for the hot applied binder products, the ISS performance generally increased with increased application rate. In all cases, the mechanical bond and adhesive bond (i.e., aggregate embedment and tack coat, respectively) at the interface between layers was stronger than the OGFC mix itself. The ISS increased with the increase in percent passing No. 4 sieve for the composite specimens with a NMAS of 12.5 mm. Finally, the ISS increased with an increase in compaction effort to a point where it leveled off.

Field Performance of OGFC

Select OGFC pavements were analyzed to assess the in-situ performance. The results of this portion of the study confirmed findings from previous studies including that the infiltration of OGFC layers is typically higher closer to a transverse joint, then decreases until leveling out approximately 100 ft beyond the joint. OGFC pavements can become clogged, thus reducing the infiltration of the surface and the ability of the layer to drain water. This was seen in a pavement section that, despite cores having porosity values ranging from 13-21%, exhibited low to no surface infiltration. The majority of localized areas of raveling occur at either transverse joints or bridge departures. WMA OGFC mixes generally exhibited better field performance (i.e., durability) than HMA OGFC mixes, but data was limited.

Recommendations and Benefits

The results of this comprehensive study informed a series of recommendations to be considered for implementation by the SCDOT that could potentially enhance the safety, durability, and life-cycle costs of OGFC pavements, thus supporting the SCDOT's Strategic Plan—specifically Goals 1 and 2.

Goal 1: Improve safety programs and outcomes in our high-risk areas.
Goal 2: Maintain and preserve our existing transportation infrastructure.

These recommendations included specification modifications related to increasing aggregate LA Abrasion max to 55; adjusting percent passing the No. 4 and 200 sieves on the gradation specifications; adding a 9.5 mm NMAS mixture; limiting paver stops; additional rolling at transverse joints; ensure smooth transitions at transverse joints and bridges; tack coat materials and application rates; and pavement testing as part of the acceptance process. Some of these recommendations were implemented throughout the duration of this project.

Steering and Implementation Committee Members

Mr. Cliff Selkinghaus, SCDOT (committee chair, August 2019-June 2021) | Mr. Chad Hawkins, SCDOT (committee chair, November 2015-August 2019) | Mr. Dennis Garber, SCDOT | Mr. James Garling, FHWA | Mr. Rickele Gennie, FHWA | Mr. Jason Johnston, SCDOT | Mr. Kevin Paxton, SCDOT | Mr. Todd Steagall, SCDOT

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1. Introduction

Problem Statement

Open graded friction course (OGFC) is a very effective mix for reducing overspray and increasing friction resistance during wet conditions and thereby providing a safer driving surface on interstates as compared to dense graded mixes. The open void structure of OGFC mixtures has also been shown to provide additional benefits including highway noise reduction and improved stormwater runoff quality. With all of the positive attributes of OGFC mixtures, there are two common problems that have caused inconsistency in OGFC performance: raveling and binder draindown (Cooley et al. 2009; Kandhal 2002; Alvarez et al. 2010). Previous studies have identified four primary potential causes of raveling in OGFC (Putman 2012; Watson et al. 2015):

1. Mix materials and composition
2. Layer thickness
3. Bond with the underlying pavement layer
4. Field compaction effort

An OGFC mix must be constructed using durable aggregate that can withstand the high traffic loads while maintaining an open texture to allow water to drain through the structure. The SCDOT specifications for OGFC require an aggregate that has a Los Angeles (LA) Abrasion loss (AASHTO T96) that is less than 52% to ensure a highly durable mix. In addition to LA Abrasion, several other factors affect the durability of OGFC (Putman et al. 2015; Watson et al. 2015) and should be considered when determining mix design properties for OGFC and should include durability test methods, addition/deletion of fibers and methods for determining optimal binder content. These topics as well as others including construction and maintenance related topics should be researched to ultimately increase the overall durability for OGFC mixes, thus increasing the life-cycle of OGFC.

Background

In 2012, the final report for SPR 687 *Evaluation of Open-Graded Friction Courses: Construction, Maintenance, and Performance* was published detailing the findings and recommendations from what will be considered Phase I of the work related to OGFC in South Carolina (Putman 2012). The primary objective of the Phase I study was to identify methods to improve the design, performance, construction, and maintenance of OGFC in South Carolina. To accomplish this objective, several tasks were completed to gain as much information about OGFCs as possible and recommendations were made for the South Carolina Department of Transportation's (SCDOT) consideration. Following that report, the SCDOT continues to implement several of the recommendations from that study including the following:

Mix Design

- Continue the use of SC-T-91 *Method of Determining the Optimum Binder Content in an Uncompacted Bituminous Mixture*, but add mixture performance evaluation procedures to measure porosity and raveling susceptibility.
- Consider 9.5 mm nominal maximum aggregate size (NMAS) gradations for OGFC as they exhibited better all-around performance than other gradations evaluated.
- Consider alternatives to fibers to mitigate mixture draindown.

Thickness Design

- Consider minimum OGFC layer thicknesses of 1¼ inches and no less than two times the maximum aggregate size of the OGFC mixture.

Construction

- Follow recommended guidelines to potentially reduce the risk of localized mix raveling at transverse joints.
- Ensure adequate tack coat application to promote adhesion of the OGFC layer to the underlying layer. Study the effect of tack coat variables (e.g., type of material, application rate, surface preparation) on the raveling potential of OGFC mixes.

Further Study

1. Construct and evaluate OGFC test sections made with the use of alternatives to stabilizing fibers (e.g., ground tire rubber modified binders, warm mix asphalt technologies, mineral filler stabilizers, gradation modifications, or lower production temperatures, among others).
2. Compare the performance of current 12.5 mm OGFC gradation specified by SCDOT to alternative 9.5 mm gradations to determine if gradation specifications should be modified to improve field performance.
3. Further study the causes of localized raveling near transverse joints and develop solutions to minimize this performance issue.

Study Objectives & Deliverables

The overarching goal of this research was to determine how to improve the long-term durability and performance of OGFC mixtures in South Carolina. To accomplish this goal, the research team investigated the root causes of premature raveling of OGFC mixtures and developed recommendations to address this widespread performance issue. The research team also investigated the influence of key variables associated with each cause on the performance of OGFC. Specifically, this included the following:

- Evaluating laboratory test methods to assess the durability of OGFC mixtures
- Assessing the influence of mixture composition including aggregate type, properties, and gradation as well as binder content on the performance of OGFC mixtures
- Investigating the impacts of OGFC layer bond on pavement performance
- Studying the long-term durability and functional performance of OGFC mixtures in the field

This project was carried out in multiple studies that are summarized in individual chapters as follows.

Evaluation of Aggregate LA Abrasion and Breakdown in OGFC Mixtures (Chapter 5)

Aggregates from 11 quarries around South Carolina varying in LA Abrasion values from 20-54 were evaluated to determine the influence of LA Abrasion on OGFC mixture performance in the laboratory as well as the degree to which aggregates breakdown, thus altering the mix gradation due to mixing and compaction.

Evaluation of Aggregate Gradation in OGFC Mixtures (Chapter 6)

OGFC mixtures having NMAS of 9.5 mm and 12.5 mm were evaluated to determine the effects of varying the percent of material passing the No. 4 sieve and the percent passing the No. 200 sieve on the laboratory performance properties.

Evaluation of Compaction Temperature of OGFC (Chapter 7)

Pavement mat temperature data obtained from OGFC paving projects was analyzed to determine the impacts of paver stops on the occurrence of thermal segregation and the influence of compaction temperature on OGFC mixture properties was evaluated in the lab.

Evaluation of OGFC Durability Test Methods and Variables (Chapter 8)

Multiple test methods were evaluated to assess the durability performance of OGFC mixtures and the influence of different variables including binder content and long-term aging.

Evaluation of Bonding of OGFC Layers (Chapter 9)

Bond performance between OGFC and Surface Type A layers was evaluated to determine the influence of tack coat material, tack coat application rate, OGFC gradation, and OGFC compaction effort. Surface Type A was selected as it is the standard surface mixture on interstate routes prior to the application of an OGFC layer.

Field Performance of OGFC (Chapter 10)

Select OGFC pavements were analyzed to assess the in-situ performance.

2. Literature Review

Overview of Open Graded Friction Courses

Porous asphalt is a type of asphalt that permits stormwater to infiltrate through the asphalt into the natural soil bed (Figure 2.1-a). An OGFC is a type of asphalt mix that is ordinarily used as a wearing course commonly having a thickness of 1.5 inches or less. Traditional OGFC is used as an overlay on the top of a dense-graded surface course on heavy traffic roadways. This permeable wearing course is utilized to enhance the skid resistance of pavements and limit the hydroplaning on roadways (Fig 2.1-b).

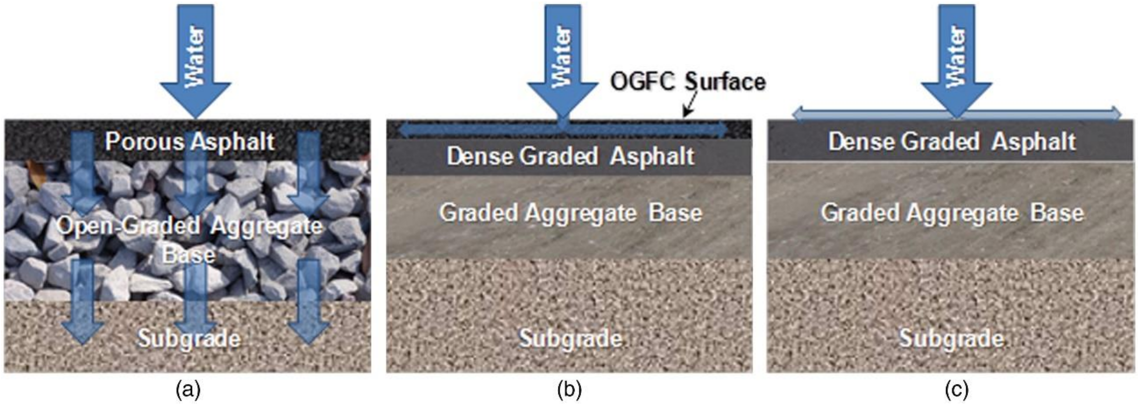


Figure 2.1. Typical Asphalt Pavement Sections (a) permeable asphalt pavement, (b) asphalt pavement with OGFC surface, and (c) conventional asphalt pavement (Putman and Kline 2012)

Benefits

Safety

Approximately 6,000 individuals are killed, and more than 445,000 individuals are injured in weather-related crashes in the U.S. every year. By far, most weather-related accidents (73%) occur on wet pavements (Hamilton, 2016). An investigative study by the National Highway Traffic Safety Administration found that the lifetime monetary cost for every casualty was determined to be $1.4 million. Hence, any reduction in traffic fatalities can have a dramatic impact on our society as a whole (NHTSA, 2014).

The Bureau of Transportation Statistics reported 5.81 million vehicle crashes in 2008 resulting in over 37,000 fatalities. Approximately 42% of these fatal accidents occurred on state or US highways in high-speed zones with the majority of these being considered rainy/cloudy conditions (Guarino and Champaneri 2010).

OGFC and porous friction courses (PFC) have been widely used in many parts of the world, especially on highways to improve roadway safety in wet conditions. While these names are often used interchangeably, PFCs are generally designed to have at least 18% air voids, while conventional OGFC mixtures typically contain between 10 and 15% air voids (Cooley et al. 2009). These mixes are applied on top of a conventional impervious pavement layer in areas that experience high traffic volumes and moderate to heavy rainfall (Caltrans 2006). Due to the high void content, and porosity, resulting from an open aggregate gradation, these mixes facilitate rapid drainage of run-off during rainfall, which improves visibility by reducing splash and spray, reduces hydroplaning, and increases the resistance to skidding in wet conditions (Kandhal 2002; Shaowen and Shanshan 2011), generally making it safer for drivers during wet conditions (Poulikakos and Partl 2009). In addition to safety benefits, the macrotexture of OGFC has also been reported to increase fuel economy and reduce tire wear (Khalid and Perez 1996).

The Louisiana Department of Transportation also performed a traffic safety analysis on three separate highway sections that were newly paved with OGFC surface layers (Putman 2007). It was found on an I-20 OGFC section that wet weather accidents were reduced by 76% over the first five years after placement. Vehicular fatalities were eliminated on the road during this time. The second section on US 71 eliminated all wet weather accidents and fatalities over the same 5-year span. The last OGFC test section, US 171, reduced the overall wet weather traffic accidents by 57%. The Louisiana DOT reported that 13.5% of fatal accidents and 18.8% of all accidents occur under wet weather conditions and can be greatly reduced with OGFC application.

Shimeno and Tanaka conducted a study of expressways in Japan before 1991 and after 2002 that showed that the fatality rate at the same sites decreased by about two thirds after introducing OGFC as a surface course. The better visibility and high skid resistance of the porous asphalt surface was attributed to this positive impact (Shimeno and Tanaka 2010). Similarly, the SCDOT conducted a study of the safety performance of OGFC in 2008 that showed a 26% reduction in wet weather crashes per year at interstate locations after adding OGFC (Werts 2008).

The Federal Highway Administration (FHWA) studied pavement safety performance to evaluate the effects of various low-cost pavement treatments on roadway safety. In this study the researchers analyzed crash data before and after treatments were installed. Different pavement treatments were compared using two tangible measures: the crash modification factor (CMF) and benefit-cost (BC) ratios. It was reported that after OGFC treatment on multilane roadways, or freeways, there was a significant decrease in total crashes in the state of North Carolina. The study also reported that for freeways, the CMF decreased (i.e., increasing benefit) as the pavement age increased for the first four years. For two-lane roads, however, the trend was the opposite, and the benefits declined as the pavement aged. It was also found that the overall BC ratio was 2.1 for OGFC for all the states that participated in this study and as high as 9.15 for the state of North Carolina (Merritt et al. 2015).

Challenges

While there are many benefits to using OGFC mixes, these mixes are prone to both functional and durability performance related issues and there are often tradeoffs between the two. From a functional performance perspective, permeability is perhaps the most important property as it enables water drainage. In service, the permeability or infiltration of OGFC pavement layers can be reduced by sediment clogging the surface voids or by binder settling into the internal voids due to long-term draindown over time (Rogge and Hunt 1999; Putman and Lyons 2015).

Raveling

The main durability related issue for OGFC is surface raveling, which can progress over large areas resulting in ride quality concerns (Huber 2000; Cooley et al. 2009). Raveling occurs on the surface as a result of the dislodgement of aggregate particles; it is a loss of fine and coarse aggregates from the asphalt matrix (Mathaven et al 2014). Raveling typically occurs as the result of either loss of bond between the asphalt binder and the aggregate particles or the fracture of the asphalt binder between aggregate particles.

In addition to high and low temperatures, there are several factors that contribute to raveling. Raveling can be caused by inadequate compaction during construction, ingress of water, aggregate properties, aggregate gradation, mix design, binder aging, aggregate segregation, and high traffic loads (Mansour and Putman 2013; Mitchell 2014). Short-term raveling occurs on new pavements due to traffic load and tire stresses on an asphalt surface. Potential causes for this can be the ratio of nominal maximum aggregate size to lift thickness and the amount of asphalt binder and air voids in the mix (James et al. 2017).

An asphalt pavement requires high density during construction to develop sufficient cohesion between aggregate particles. Inadequate compaction during construction reduces this cohesion, thus resulting in raveling of the pavement surface. Poor construction practices, such as placing the mix at a cold temperature or not appropriately compacting the mix also prevents the creation of the stone skeleton, which is necessary to maintain the structural integrity of the pavement (James 2016). Mechanical wear by studded tires, snowplow blades, and tracked vehicles can also occur especially in colder regions (Raveling 2009).

Raveling and loss of material eventually leads to potholes which reduces the durability of the pavement (Mitchell et al, 2014). Raveling of an asphalt pavement can result in loose debris on the pavement, roughness of the pavement surface, water collecting in the raveled locations resulting in vehicle hydroplaning and stripping, and loss of friction, which reduces the skid resistance of the pavement. Stripping is the loss of bond between aggregates and asphalt binder due to moisture or poor aggregate-to-asphalt binder chemistry. When stripping begins at the surface and progresses downward, it usually results in raveling (Raveling 2009).

Delamination

Delamination is another durability that has been reported with OGFC mixes. Delamination occurs when the bond between the underlying surface and the OGFC is inadequate and causes a slip plane. Figure 2.2 shows delamination distress in an asphalt concrete pavement section. According to the National Association of Australian State Road Authorities (1987), "*delamination is the loss of a discrete area of the surface layer of the asphalt pavement that shows clear delineation of the surface layer from the layer below*". Generally, delamination distress occurs in the wheel path as shown in Figure 2.2.

Figure 2.2. Delamination Distress in an Asphalt Pavement (National Association of Australian State Road Authorities, 1987).

Aging

Accelerated aging is another issue observed in OGFC pavements that leads to durability issues such as raveling. The high porosity of these mixtures allows increased penetration of oxygen and other elements, aging the asphalt at faster rates than traditional pavements. The decrease in binder thickness around aggregate particles and oxidation of the remaining binder film near the surface of the pavement can lead to an increase in raveling of OGFC.

The aging of asphalt binders primarily occurs due to the volatilization of light oils present in the chemical makeup of the binder and oxidation caused by the air surrounding the asphalt pavement. Oxidation of asphalt binders occurs at a relatively slow rate. Oxidation and loss of light oils leads to an increase in stiffness and a reduction in the flexibility of the binder (Lavin 2003). Aging of the asphalt binder is one of the primary factors behind the deterioration of asphalt pavements.

Lu and Isacsson found that there are two primary effects of aging on the behavior of asphalt binder. The first mechanism is the impact that aging has on the rheological properties of the asphalt binder such as oxidation, loss of volatile components, and migration of oily components from the bitumen into the aggregate. The second mechanism is physical hardening, a reversible process in which the stiffness of the asphalt binder increases at constant low temperatures. In a study on bitumen aging, Lu and Isacsson found that aging influences the chemical and rheological properties of the bituminous binder and that the chemical and rheological changes are generally not consistent (Lu and Isacsson 2002).

Long-Term Draindown

Higher pavement temperatures occurring in summer months can lead to clogging and raveling of OGFC due to long-term gravity induced binder draindown. Long-term draindown is defined as the downward migration of asphalt binder, due to gravitational forces, through the pore structure of an open graded friction course over the service life of the structure. It has been speculated that thick films of unmodified asphalt binder liquefy due to the increase in pavement temperature during hot summer months, then drain down due to gravity. The remaining thin films of asphalt binder coating the aggregates near the surface then age more rapidly, becoming brittle (Huber, 2000). The migration of the binder also results in clogging of pores within the OGFC layer.

In a study conducted by Putman and Lyons (2015), the long-term draindown of OGFC specimens was evaluated by measuring the permeability of mixes every 14 days over a 84-day conditioning period at 140°F (60°C). The study showed a steady decrease in the permeability of the conditioned specimens for the first 56 days of conditioning. This showed evidence of long-term draindown based on the permeability reduction of the specimens over time due to the internal air voids becoming clogged over the conditioning period (Putman and Lyons 2015).

To explain what was happening to the binder internally in the structure of the specimens, Putman and Lyons conducted an additional study on the specimens that were aged for 84-days. Each specimen was sliced into four sections horizontally, and the percent binder content was determined for each slice. The study found that the binder content for the top slice was less than that of the original binder content of the asphalt mix design, where the bottom slice had a higher binder content. This indicated that the binder was draining downward over time (Putman and Lyons 2015).

Other

Areas with intense winter climates witness a low service life for OGFC layers. The pavement's ability to withstand winter conditions is an issue due to the freeze/thaw action within the pores, causing the asphalt to break down and crack. Snowplows and vehicles using tire chains cause distress on the OGFC pavement surface and destroy the aggregate bond. The pores will also clog when sand, salt, or other anti-icing agents are placed on the road, which require regular roadway maintenance. Coastal areas have the same issues with sand transported by wind and vehicles into the asphalt pores. These areas generally avoid OGFC designs due to higher maintenance costs and structural issues over time.

OGFC Materials

Binder

Several techniques can been used to minimize the occurrence of draindown such as the use of modified asphalt binders, addition of cellulose fibers, the use of warm mix asphalt technologies, and the addition of ground tire rubber. The following is a list of the different types of modifiers used for asphalt modification: block copolymers (SBS), SBR latex, Polyolefins, crumb rubber, chemical additives, and engineered binders (Kluttz 2012). Martinez-Boza et al. stated that in order to increase the service life of pavements over a wide range of temperatures, especially higher temperatures, the addition of polymers to bitumen are important. Copolymers such a styrene-butadiene-styrene (SBS) are used to improve bitumen and have proven to be very effective modifiers for bitumen (Martinez-Boza et al. 2001).

Polymer modified binders are less susceptible to higher temperature changes than unmodified asphalt binders which helps to improve the performance of the pavement over its lifetime. Polymer modified asphalt binders are widely used to help withstand increased traffic volumes and loads in higher temperature areas and locations (Yildirim 2007). A study conducted by Mogawer et al. showed that modified asphalt binders had higher elastic recovery and better resistance to fatigue cracking than unmodified binder (Mogawer et al. 2011). The performance of polymer modified binders depends upon the stiffness of the base binder, cross-linking between the base binder and polymer, type of polymer, and the quantity of the polymer (Shirodkar et al. 2012). In a study conducted by Lu and Isacsson, the results indicated that SBS modified bitumen present better rheological properties than equivalent base bitumen, which increases the long-term durability of asphalt pavements (Lu and Isacsson 1998).

Warm mix technology is another modification used to alter the properties of asphalt mixtures. Warm mix asphalt (WMA) is a type of asphalt that is produced using warm mix technologies that allow producers of hot mix asphalt (HMA) to lower production and construction temperatures by 30-120^{o}F. WMA technologies reduce the viscosity of the asphalt binder so that aggregates can be coated at lower temperatures. Reducing the viscosity also makes the mixture easier to manipulate and compact at the lower temperature (Warm Mix Asphalt 2016). The lower production temperatures also reduces the degree of binder oxidation, which can improve the short-term durability.

Aggregates

Gradation

Aggregate gradation plays an important role in the structural and functional performance of OGFC mixes. Aggregates are classified as coarse and fine based on their size and aggregates whose particle size is finer than 75 µm (No. 200 sieve) are referred to as fillers (Zulkati et al. 2011). The coarse aggregate content of the mix should be high as it controls the porosity of the OGFC mix and the fine aggregate content of the mix should be lower to increase stone-on-stone contact, prevent the separation of coarse of aggregate particles, and avoid closing of air voids (Ruiz et al. 1990). The potential for rutting increases when the coarse aggregate particles get separated. Therefore, OGFC mixes should have high content of coarse aggregate with stone-on-stone contact to minimize rutting. When coarse aggregate particles get separated the potential for rutting increases (Mansour and Putman 2013). The porosity in porous asphalt and OGFC is also a function of the gradation and quantity of the coarse aggregate in the mixture**.** By increasing the proportion of coarse aggregate and reducing the amount of fine aggregate in the mix design, the porosity can be increased (Hardiman 2005).

The National Center for Asphalt Technology (NCAT) in Auburn, Alabama conducted a study to determine the effect of OGFC gradation on different performance variables (Kandhal et al. 1999). The FHWA recommended gradation was used for comparison while the experimental gradations increased in coarseness by altering the #4 sieve percent passing from 15-40%. The durability testing was by means of Cantabro abrasion resistance while functional performance was measured using the Florida DOT falling head permeability test.

It was found that the abrasion loss decreased when the gradation contained more fine aggregate. The abrasion values ranged from 8.1% loss with 40% passing the #4 sieve to 14.7% loss with 15% passing the #4 sieve (i.e., a coarser gradation). As expected, the permeability increased with the coarser gradation. The permeability results ranged from 117 m/day for 15% passing the #4 sieve to 21 m/day for 40% passing the #4 sieve. The results did not follow a linear trend as the permeability increased exponentially as the gradation became coarser.

NCAT also noted that the rutting potential increased for coarser gradations after testing. In summary, as the gradation became more coarse, the functional performance improved but structural performance was sacrificed. Finer gradations improved the abrasion resistance and were less susceptible to rutting while sacrificing porosity and infiltration potential.

The performance and characteristics of asphalt mixtures in general, but not specifically OGFC, are also affected by filler content even with its small size. Fillers include, but are not limited to materials such as hydrated lime, fly ash, Portland cement, limestone dust, silt, volcanic ash, and recycled brick powder. According to a recent survey, fillers (i.e., specifically hydrated lime) have contributed to achieving OGFC service lives of more than 12 years (Watson et al. 2018). Filler contents ranging from 0-5% passing the 0.075mm (No. 200) sieve are allowed in OGFC specifications across the US (Watson et al. 2018).

Asphalt mixture performance (e.g., workability, stability, moisture resistance, resilient modulus, and rutting resistance) can be positively affected by the presence of filler (Shurky et al. 2018). When the filler content increases, the indirect tensile strength of asphalt mixtures has been shown to increase as well, which typically increases cracking resistance (Shurky et al. 2018). Additionally, mix cohesion and internal stability increases due to the good packing that is improved by the filler content (Brown et al. 1989). When the asphalt binder and fillers are mixed, an asphalt-filler mastic is formed, which is affected by the filler content (Kandhal 2002). The mixture performance is affected by the mastic since the filler absorbs more asphalt due to the larger surface area compared to other aggregates in the asphalt mixture (Aylor 2007). The mastic, then increases the resilient modulus of the mixture due to the presence of fillers (Anderson 1987; Tayebali et al. 1998). The temperature susceptibility and durability of the asphalt binder also improves with the addition of fillers (Bahia et al. 2011). If too much filler is added relative to the binder content, the coating of the aggregate during mixing and workability of the mix could be negatively affected, which can lead to performance issues (Zulkati et al. 2011).

OGFC mixtures used by the Georgia and South Carolina DOTs generally have the same aggregate type, gradation, binder type, optimum binder content, and fiber content, but there have still been differences in field performance. This prompted Watson et al. to evaluate both mix designs as part of NCHRP Project 01-55 (2018). That study included the investigation of filler content on the Georgia and South Carolina OGFC mixes where baghouse fines (BHF) were added to each mix at a rate of 2% and 4% (Watson et al. 2018). The results showed that while increasing the filler content reduced the void content, the permeability was still acceptable up to a maximum limit, but the raveling resistance was significantly improved. This prompted the authors to recommend the allowance of additional filler in areas where raveling is the primary form of distress as long as the permeability is sufficient (Watson et al. 2018).

The gradations of OGFC mixtures varies across the US based the experiences of each state transportation department. Some states use one gradation while others use two or more gradations. Georgia and North Carolina are the only states which have use three different gradation specifications (Cooley et al. 2009).

LA Abrasion

An important property determining the performance aggregate is its toughness via the LA Abrasion test per ASTM C131. From previous studies, it has been concluded that aggregate with high LA values led to a decrease of void content due to breakdown during mixing, compacting, and serviceability (Putman et al. 2014). Also, the abrasion resistance generally increased with higher aggregate LA values. This was likely due to aggregate breakdown during mixing and compacting, which led to a porosity reduction. When the air voids are worked out of the mix, the pavement structural durability improves but there is a loss in functional performance. Aggregate with lower durability, or higher LA values, cannot efficiently perform under these load conditions and maintain a porous structure.

Many state requirements for the aggregates LA Abrasion values differ based on the region that the local aggregate is mined from. The SCDOT requires all OGFC mixtures to obtain crushed coarse aggregate with an LA value no greater than 52%. This LA requirement is higher than most states due to South Carolina aggregate containing a high percentage of mica. Mining locations around the state have a high variation in LA values due to this, ranging from lower 20's (e.g., Augusta and Rock Hill) near the states fault line, to low/mid 50's (e.g., Greenville and Spartanburg).

Aggregate Breakdown

OGFC mix designs have specific gradation ranges that contractors must meet to avoid penalty. Aggregate accounts for approximately 94% of OGFC mixtures so analyzing degradation after mixing and compacting is critical. Aggregate sizes may change significantly by the time it is placed on the roadway and change the desired pavement properties.

Aggregate must be resistant to abrasion and compressional loads for adequate structural performance. "Often pavement distress, such as stripping and rutting, can be traced directly to aggregates used. Clearly, proper aggregate selection is necessary for attaining desired performance (Wu et al. 1998)." Production, transportation, placement, and compaction are all areas where aggregate has the potential to break down and change from the original design. This is especially important to consider for OGFC mixtures during compaction because of the low stone on stone contact area, which normally would distribute the loading with the addition of finer material. Instead, minimizing fine materials leads to a support reduction within the asphalt structure. The same loading distributed over a smaller area increases the particle stress and leads to fracture.

Degradation during construction can be associated with changes in aggregate structure from lab design to what is observed in the field (Wu et al. 1998). When the pavement reaches its maximum compaction, any further compaction damages the material. This over-compaction could potentially degrade the aggregate, which closes the designed voids reducing the functional performance or water infiltration rate.

Moisture-related issues can also occur due to aggregate degradation during compaction. When aggregate particles fracture, a surface that is not covered with binder is exposed. If water is able to penetrate between the binder film and aggregate particle, stripping of the binder from the aggregate could occur that will result in performance issues (Wu et al. 1998).

Surprisingly, there is a lack of attention toward aggregate degradation for asphalt pavements in the US. Per Wu et al. (1998), 94% of US states have an LA Abrasion requirement in their mix design and only two states have an aggregate degradation requirement in addition to LA Abrasion. Since degradation will alter OGFC pavement performance (Kandhal and Mallick 1999; Watson et al. 2003), a single minimum LA Abrasion requirement for all aggregate sources may not be sufficient.

Commonly, the requirement for LA Abrasion among US states is no more than 40-45% loss. In South Carolina, the maximum permitted loss is 52% due to aggregate availability and geography (SCDOT 2007). This allows a significant potential for breakdown between production and the finished product opening to the public. Agencies must work with local aggregate to reduce shipping costs and improve efficiency. However, more attention needs to be directed to internal structural breakdown of pavements.

The SCDOT Supplemental Specification for OGFC, which has been revised multiple times since the Standard Specifications for Highway Construction was published in 2007, provides recommendations on compaction machinery, weight, and passes to avoid aggregate breakdown. After this it is noted if any breakdown occurs, the appropriate measures should be taken in order to eliminate breakdown (SCDOT 2019). There are no descriptions on methods to do this. Most OGFC contractors understand approaches to eliminate breakdown if it occurs, but without standards there is no guarantee of effective changes and will vary from project and contractor. Further research of prevention measures show this trend among multiple DOT agencies and asphalt information/standard websites. This should be addressed in order to maintain consistency among all OGFC projects.

Previous Research

Another study by Watson et al. analyzed the effect of aggregate breakdown when gyrations were altered using a Superpave Gyratory Compactor (2003). This analysis originated from studying the height change with each compactor gyration. Sample heights continued to decrease with each additional gyration after they believed aggregate particle interlock was achieved. The binder was extracted using the ignition oven method outlined by AASHTO TP 53-97 and a sieve analysis was performed. This test was performed while altering the aggregate types between granite, crushed gravel, and trap rock.

The gyrations applied alternated between 30, 45, and 60. The results of this study showed the aggregate breakdown ranging from 0% for the #200 sieve to 10% on the #4 sieve. It was also noted that breakdown of aggregate for 30 gyrations was very similar to 60 gyrations, which suggests that the initial breakdown rapidly increased at the beginning but began to balance out after. The breakdown increased when the compaction effort increased for crushed gravel and trap rock but varied for granite. Breakdown of mixtures containing granite were not dependent on the number of gyrations, which is the primary aggregate mined in South Carolina.

The breakdown due to binder extraction via the ignition oven method was also analyzed before use. NCAT studied the breakdown of six different aggregate sources containing three high loss aggregate categories: dolomites, basalt, and chlorite (Prowell and Hurley 2005). The conclusion of this study determined that substantial breakdown was not observed and the ignition oven test was accurate for determining binder content and aggregate gradation.

Another study observed, by researchers in Arkansas, complemented these results (Hall and Williams 1998). The range of samples tested contained limestone, crushed gravel, and sand from four asphalt plants. The results showed that the ignition oven extraction method had minimal effect on gradation change. Some of the aggregate particles were noticeably ruptured but did not alter the gradation results. It was concluded that, for these aggregate types, the ignition oven test was adequate.

Performance

Raveling

Raveling is commonly seen in porous asphalt mixtures such as OGFC because of the reduction in fine aggregates. Figure 2.3, shows raveling of OGFC on Interstate-85 in Greenville, SC. If fine particles are missing from the aggregate matrix, then the asphalt binder is only able to bind coarse aggregate particles at relatively few contact points. The fewer the contact points between aggregate particles; the more likely raveling is to occur on the surface of the pavement (Shaowen and Shanshan 2011). The fine aggregate usually wears away first but as the erosion continues, larger particles are broken free from the matrix. Over time, the pavement has a rough and jagged appearance typical of surface erosion (Mathaven 2014). This reduction in surface aggregates leads to a decrease in the ride quality of the pavement and eventually leads to more severe problems.

Figure 2.3. Raveling of OGFC on I-85 in Greenville, SC

Laboratory studies have shown that a better performing OGFC pavement can be achieved by using a finer gradation for OGFC mixes. Mixes with 15% or less of aggregate passing the 4.75 mm sieve are vulnerable to significant binder draindown and it is recommended to provide a suitable stabilizer such as polymer-modified binders or fibers in the mix to prevent excessive drain-down. The use of both polymer-modified binder and fiber can minimize the abrasion loss and thus increase the durability of OGFC (Mallick et al. 2000).

Abrasion resistance of compacted asphalt specimens is commonly measured using the Cantabro abrasion test outlined in ASTM D7064. The test is conducted by recording the initial weight of the specimen, then placing the specimen in the Los Angeles abrasion apparatus for 300 revolutions without the steel charge at room temperature. Once the 300 revolutions are complete, the specimen is removed and the final weight is recorded. The percent mass loss is then calculated by dividing the mass loss by the initial mass of the specimen. For comparative measurements, the Cantabro test is simple, inexpensive, and quick; however, the stress exerted on the specimens (i.e., impact resulting from rotating in a drum) is not representative of the stress caused by traffic (Herrington et al. 2005).

Abrasion loss is used to evaluate the resistance to disintegration of porous asphalt mixes (Hardiman 2005). Hardiman found that polymer modified binder (SBS) mixes were found to be more resistant to disintegration compared to conventional (i.e., penetration grade 60/70) asphalt mixes. The permeability and resistance to abrasion loss decreases when the maximum aggregate sizes in porous asphalt decreases (Hardiman 2005). In a study conducted by Putman, a decrease in the abrasion loss was seen when the binder content of the mix design was increased. As the binder content increases, a thicker and stronger film of binder is holding the aggregate together, thus increasing the abrasion resistance of the pavement structure (Putman 2012).

In a study conducted by Mansour and Putman, the Cantabro abrasion test was used to characterize the durability of the compacted specimens. A maximum loss of 20% is specified for unaged conditioned specimens and 30% for aged specimens (Kandhal 2002). The results indicated that abrasion resistance was influenced by the mixture porosity and air voids. The gradation with the highest porosity exhibited the highest abrasion loss and the mix with the lowest porosity experienced the lowest abrasion loss (Mansour and Putman 2013).

Hamzah et al. found that the abrasion loss for all mixes decreased as the initial conditioning temperature (ICT) and binder content were increased. The specimens were conditioned at a specific temperature for 4 hours. The specimens were placed in the Los Angeles drum and tumbled for 300 rotations without a steel charge. An infrared thermometer was used to determine the temperatures of the specimen skin and the internal walls of the Los Angeles drum during testing. Using the abrasion loss at an ICT of 15^{o}C as the baseline, the abrasion losses of specimens initially conditioned at 20, 25, 30, and 35^{o}C decreased by 16.7%, 39.9%, 57.9%, and 65.0%, respectively (Hamzah 2012).

The ICT had a distinct effect on the abrasion loss of porous asphalt. At lower temperatures, binder becomes brittle and more prone to disintegrate when exposed to external forces. A statistical analysis of the binder types showed that the SBS modified binder resulted in a higher resistance than the conventional binder. This study also showed that the higher binder contents (i.e., 5.0% and 5.5%) and higher initial ICT (i.e., above 30^{o}C) yielded the lowest abrasion loss values (Hamzah 2012).

Construction

To obtain the correct compaction in the field, the temperature of the mixture is a critical factor. Prior to the approval and subsequent widespread use of WMA for OGFC, the SCDOT Highway Construction Specifications required OGFC temperatures to be between $325\text{-}350^{o}$F when discharged from the production plant. These temperatures would vary based on travel time from the plant to job site. The maximum permitted travel time for OGFC was one hour after mixing from the source. The recommended temperature at the time of placement was 320^{o}F to ensure the pavement maintains proper temperatures by the time it is compacted. Compaction temperatures in the field ranged from $300\text{-}320^{o}$F after balance is maintained in the paving system. With the use of WMA, the specifications were updated to reflect the use of WMA additives. Examples of updates include limiting the maximum production temperature to that approved in the job mix formula, limiting the minimum production temperature to 225^{o}F, limiting the duration from loadout-discharge at the plant to placement to 90 minutes, and limiting paver stops during placement (SCDOT 2019).

Before placement of OGFC layers, a tack coat overlay is required for structural bonding. To prevent over compaction, the SCDOT recommends an 8-10 ton tandem steel wheel roller is used at no more than 3 passes. The pavement should be compacted to ensure bonding to the underlying layer but prevent over compaction, which will lead to critically reduced void content and aggregate breakdown. It is not recommended to use a pneumatic rubber tire roller at any point of compaction, as this leads to surface sealing of pores. Since OGFC mixes contain small amounts of fine aggregate, breakdown during compaction is a cause for concern. Per SCDOT Highway Construction Specifications, aggregate breakdown should be monitored throughout construction. If it is observed, proper adjustments should be made to eliminate this behavior.

Bonding

Proper layer bonding during construction of asphalt pavements is critical to the performance of a roadway allowing the structure to act as a monolithic structure transferring stresses from one layer to the layer beneath. Insufficient bonding, on the other hand, may increase stresses and tensile strains in individual pavement layers when subjected to traffic loading (Wang et al. 2017). Poor bonding can frequently prompt greater distresses, such as delamination of the surface course. Research has indicated that even with just a 10-30% loss in bond strength, stresses and strains at the bottom of the asphalt layers can increase resulting in a significant reduction in fatigue life of approximately 50-70%. This can cause premature distresses such as slippage cracking, potholes, raveling, de-bonding, bulging or cracking and, as a result, can decrease the service life of the pavement (Wang et al. 2017; DeBondt and Scarpas 1996; Buchanan and Woods 2004; Johnson 2015). The costs associated with a bonding failure can be significant, potentially even exceeding the original costs of a maintenance overlay.

Inability to bond asphalt layers has been known to bring about slipping and pushing or shoving of surface layers of asphalt. Additionally, a reduction in fatigue life is also a potential result of poor bonding (Johnson 2015). There are two mechanisms that contribute to bonding between asphalt concrete layers: adhesive bond and a mechanical bond. Application of tack coat between asphalt layers creates an adhesive bond, but the mechanical bond results from the surface friction between layers to resist the slippage (Clark et al. 2010). Milling the existing pavement surface is a good example of mechanical bonding or surface friction between asphalt lifts. With milling, the roughly milled surface interlocks with the aggregate from the asphalt overlay in the presence of tack coat to achieve a combined adhesive and mechanical bond.

There have been several studies on the bond strength between dense graded asphalt layers, but few have addressed the OGFC layer bond strength with underlying dense graded asphalt. A study by Chen and Huang (2010) concluded that tack coats were more effective in increasing the interlayer shear strength between dense graded mixtures compared to the interface between open graded and dense graded mixtures. This was attributed to smoother surface (i.e., lower macrotexture depth) of the dense graded mix the higher, which resulted in more contact area, thus increasing the bonding between layers. The open graded mixture had a higher macrotexture depth, thus reducing the contact area and the ultimate bond strength (Chen and Huang 2010).

OGFC mixes also have relatively fewer contact points among aggregate particles compared to conventional mixtures, making it prone to raveling, especially when there is a weak bond between pavement layers and the applied strain exceeds the design limits under cyclic traffic load. Raveling and de-bonding were also reported as the top two OGFC distresses by the state transportation agencies as part of the national survey summarized in Chapter 3. Considering this situation, there is likely a relationship between raveling and de-bonding that needs to be investigated.

Tack Coat

Tack coat is a sprayed application of an asphalt binder or emulsion on an existing asphalt pavement before placement of another layer of fresh asphalt concrete. The tack coat acts as the glue between the layers creating a monolithic material which works as a single unit to distribute the applied stresses instead of unbound, independent, layers (Johnson 2015). Common materials used for tack coats are asphalt emulsions and paving grade binders. The most common tack coat material of choice is emulsions followed by paving grade binders. In a survey conducted as part of this study (Chapter 3), 60% of respondents reported that asphalt emulsions were the preferred tack coat materials and asphalt binder was the second most preferred. Mohammad et al. reported similar preferences (2012).

An asphalt emulsion is produced by combining liquid asphalt cement and water with an emulsifying agent to increase the volume and change the viscosity to achieve better surface coverage. The most common types of emulsions used for tack coat are slow-setting (e.g., SS-1, HFMS-1H, SS-1h, CSS-1, and CSS-1h) and rapid-setting emulsions (e.g., RS-1, RS-2, CRS-1, CRS-2, CRS-2P (polymer-modified), and CRS-2L (i.e., latex-modified)). Asphalt emulsions are divided into three categories: anionic, cationic, and nonionic. An anionic emulsion has a negative electrical charge and a cationic emulsion has a positive electrical charge. If the letter “C” is placed in front of the emulsion grade (e.g., CRS-2), the emulsion type is cationic. If the letter “C” is not shown in front of the emulsion grade, the emulsion type is anionic (e.g., SS-1H). Nonionic emulsions are not generally used for pavement construction. Medium set (MS) emulsions can additionally be classified as “HF” or high-float. In HF emulsions, the emulsifier forms a gel structure in the asphalt residue. The thicker asphalt film allows HF emulsions to perform in a wider temperature range. Further, some emulsions are graded with the letter “H” following the emulsion classification. The “H” means that harder base asphalt has been used in the emulsion (e.g., HFMS-1H) (Mohammad et al. 2021).

To achieve a proper bond between asphalt layers, the tack coat type and application rate are important factors. Many researchers have recommended different tack rates depending on the existing pavement surface conditions (e.g., new, old, milled, etc.). Paul and Scherocman (1998) found that the residual application rates of the emulsions varied between 0.01 and 0.06 gal/yd^2. The residual asphalt contents, as specified in the Hot-Mix Asphalt Paving Handbook (USACE 2000), should range from 0.04 to 0.06 gal/yd^2. In 2012, Mohammad et al. conducted an intensive study on optimization of tack coat under the National Cooperative Highway Research Program (NCHRP) and summarized the findings in regards to tack coat rates and the recommended tack coat application rates are summarized in Table 2.1 (Mohammad et al. 2012). The application rates recommended in South Carolina are summarized in Table 2.2 (SCDOT 2015).

Table 2.1. Recommended Tack Coat Application Rates from NCHRP Report 712 (Mohammad et al. 2012)

	Application Rate (gal/yd^2)		
Pavement Condition	**Residual**	**Undiluted**	**Diluted (1:1)**
New HMA	0.03 – 0.04	0.05 – 0.07	0.10 – 0.13
Oxidized HMA	0.04 – 0.06	0.07 – 0.10	0.13 – 0.20
Milled HMA Surface	0.06 – 0.08	0.10 – 0.13	0.20 – 0.27
Milled PCC Surface	0.06 – 0.08	0.10 – 1.13	0.20 – 0.27
Portland Cement Concrete (PCC)	0.04 – 0.06	0.07 – 0.10	0.13 – 0.20

Table 2.2. Tack Coat Recommendations for South Carolina (SCDOT 2015)

	Application Rate* (gal/yd^2) 130 – 160°F		
Existing Surface	**HFMS-1, HFMS-2**	**CRS-1, CRS-2**	**Non-Tracking**
New Asphalt (hot, placed same day)	0.03	0.02	See manufacturer's recommendations for application rate and temperature
New Asphalt (older than one day)	0.06	0.05	
Oxidized or Milled	0.08	0.07	
Concrete	0.08	0.07	

**Application rate is based on total emulsion*

Before an asphalt emulsion breaks, it is brown in color because it contains both asphalt cement and water. When the emulsion breaks, the water isolates from the binder and the color of the emulsion changes from dark brown to black. When all the water evaporates, the emulsion is said to have "set." Under general conditions, setting occurs in 1 to 2 hours (Mohammad 2012), but the literature generally lacks complete agreement concerning how long a tack coat should remain uncovered before placing the subsequent asphalt layer. In the survey summarized in Chapter 3, nearly 70% of the respondents stated that they require curing (setting) time for tack coat emulsions until it completely breaks. The setting time depends on environmental conditions at the projects and the type of emulsion used.

3. Survey of OGFC in the US

As part of this research project, a survey was designed to gain an understanding of the construction practices and performance of open graded friction courses (OGFC) in other states with particular focus on the bonding of OGFC to the underlying pavement layer. The survey was distributed to US State Departments of Transportation (DOTs), including the District of Columbia, as well as to Canadian provincial transportation agencies for a total of 65 agencies.

Twenty US states and one Canadian province responded to the questionnaire. From the responses, it was found that most northern states are not using OGFC mix due to problems with clogging and ice removal during the winter season. On the contrary, most of the southern and southeastern states use, or have previously used OGFC mix.

Of the respondents, nine states reported that they are currently using OGFC, ten states reported that are not using OGFC mixes (mostly cold climate states), and only one state reported that they used OGFC in the past, but are no longer using it. Other states did not respond to the survey. The results are mapped in (Figure 3.1).

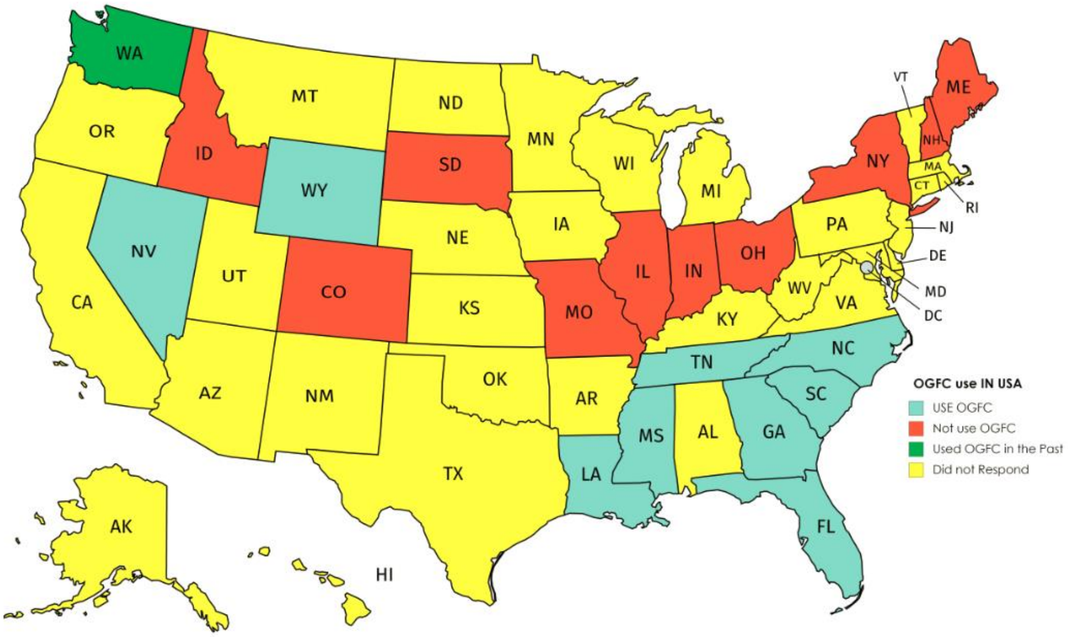


Figure 3.1. Current use of OGFC in the US based on survey respondents

Nearly 63% of respondents reported raveling as a common distress they experienced with OGFC and the second most common distress reported by 38% of respondents was de-bonding and delamination. These survey results confirm the findings of the literature review.

Respondents were asked to rate the performance of OGFC in their states. The question had responses from 20 states and one response from Canada. Questions and answers to the survey are presented in this section.

Performance of OGFC: In the survey, only one state rated the durability performance of OGFC as excellent, five rated it as very good, and four states rated it as good. These responses were all from the states currently using OGFC mix, but the rest of the respondents were not satisfied with the performance of OGFC in their state, or some of the states were unable to answer since they do not use OGFC mix (Figure 3.2).

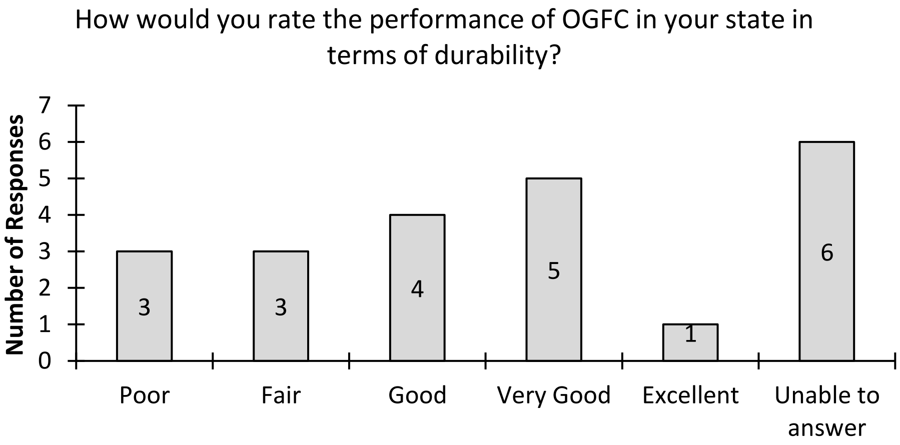


Figure 3.2. Performance of OGFC in the US

Surface friction of OGFC: Respondents were asked to rate the performance of OGFC with respect to surface friction. The question had 21 responses that are summarized in Figure 3.3.

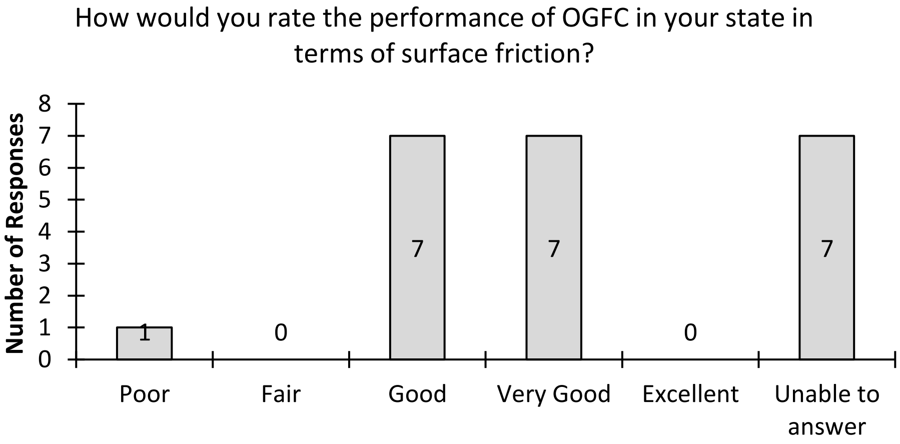


Figure 3.3. Surface friction performance of OGFC in the US

Limitations or common problems of OGFC: Respondents were asked to select the most common distresses with OGFC pavements. As part of the responses, one of the states reported that they experienced studded tire wear distress with OGFC mix during the cold season. One of the states reported that it is expensive to use OGFC and chip seals will provide similar benefits at a lower price. Note that the responses in the "Other" section indicate that they do not use OGFC mix. The responses are summarized in Figure 3.4.

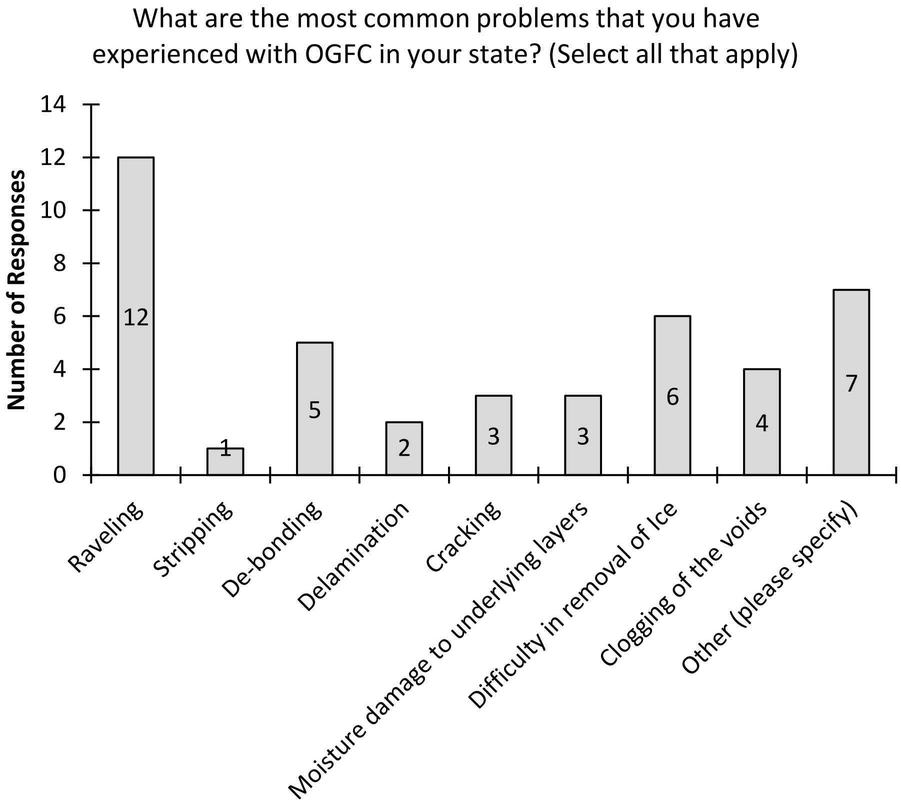


Figure 3.4. Common distresses with the use of OGFC in the US

OGFC binder content by weight: Respondents were asked to select the typical percent binder content (by weight) for the OGFC mixes used in their states. From the responses, it was found that the typical binder content for OGFC mix is between 6.0-6.5% by total weight of the mix (Figure 3.5).

Minimum OGFC placement temperature: Many respondents reported 60°F as the minimum ambient temperature to allow OGFC paving, but there are some states that they allow paving as low as 50°F ambient temperature.

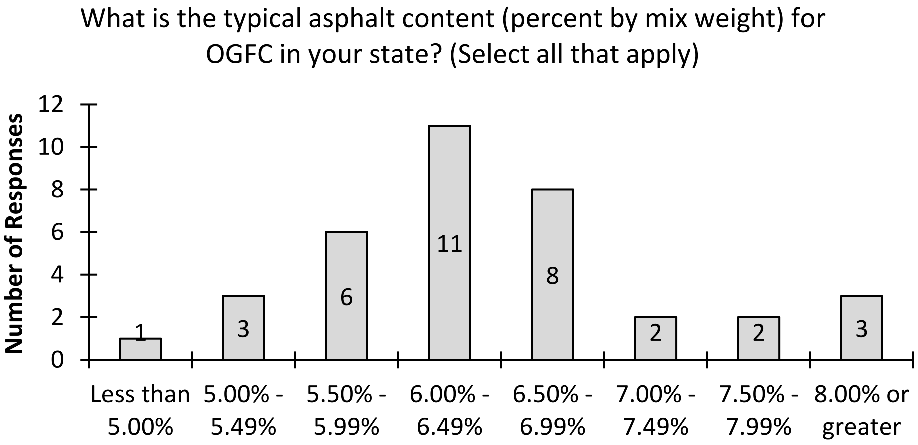


Figure 3.5. Percent binder content in OGFC mix

Tack coat type: In this question, the respondents were asked to select the most common type of tack coat material used for OGFC pavements in their state. Nearly 60% of the respondents selected emulsified asphalt as the most commonly specified material (Figure 3.6). The second most common choice was asphalt cement. In the “Other” response to this question, one state responded that if they use OGFC as wearing course for a porous application then they don’t use any tack coat. Another respondent stated that they had used some trackless products as well as high strength hot applied bond coat (i.e., UltraFuse).

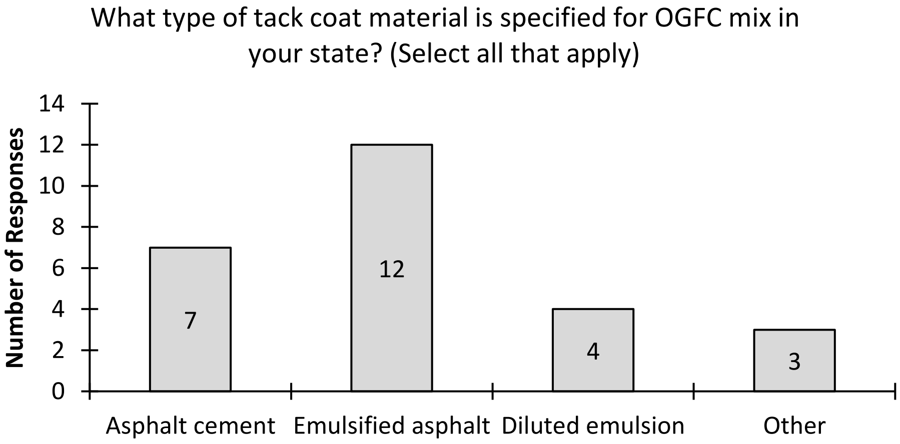


Figure 3.6. Tack coat type for OGFC mix

Tack coat products for OGFC: In this question, the respondents were asked to list the tack coat products they recommend for use with OGFC mix in their state. The responses noted that trackless tack and PG

64-22 were the most common followed by other emulsion products like SS-1, SS-1h, CSS-1, CSS-1h, CRS-2, CRS-2P, CQS-1h, CSS-1h. The choices were varied based on the states and geographical preference or availability of local products.

Tack coat products for night-time paving of OGFC: In this question, the respondents were asked to provide the list of tack coat products that they recommend specifically for night-time construction with OGFC mix if there is any. There was no difference in tack coat specifications between night-time and day-time construction.

Dilution of asphalt emulsion products: This question was regarding allowing the dilution of the asphalt emulsion products for better coverage of the pavement surface. In response to this question, 50% of the respondents stated that dilution of asphalt emulsion products is not allowed, but 25% of the respondents stated that dilution is allowed only at the emulsion producer facility, not at the paving site (Figure 3.7).

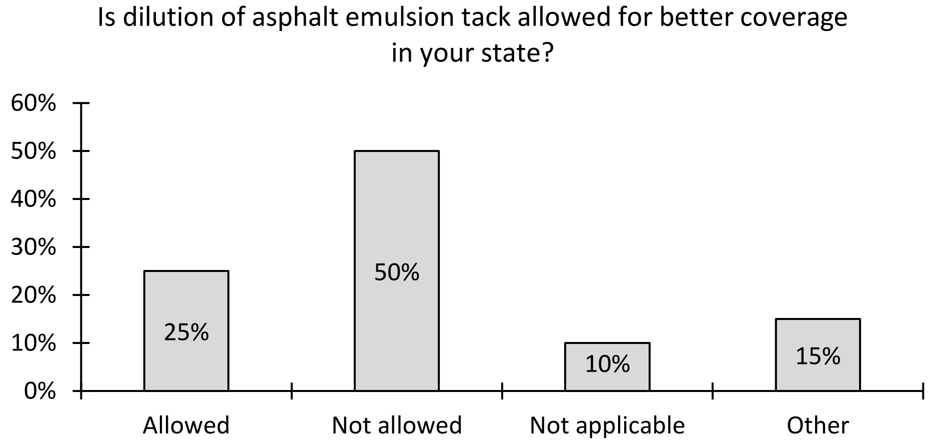


Figure 3.7. Dilution of asphalt emulsion tack coat for OGFC mix

Tack coat rate: The respondents were asked to specify the tack coat rate (gal/yd^2) they specify for OGFC pavements. There were various tack coat rates among state transportation agencies ranging from 0.03 to 0.2 gal/yd^2 (emulsified asphalt rate). Since the tack coat is not a separate pay item in most of the contracts, it was noted that contractors tend to use the minimum specified tack rate. While the minimum tack rate would comply with the current specifications, it might not be adequate for an optimum bond between layers.

Curing time for sprayed tack coat: The respondents were asked if they require any specific curing time for sprayed emulsion tack coats. Most of the respondents stated that they require curing until the emulsion changes color from brown to black (i.e., it breaks), but not a specific time range since the curing time can vary based on site, wind speed, ambient temperature, and other variables.

Best practices to minimize tracking: In this question, the respondents stated what best practices they used to minimize tack coat tracking during construction. Many agencies responded that they prefer to use a trackless tack or material transfer vehicle whenever feasible. The responses are summarized in Figure 3.7. Some of the respondents reported their practices with a comment in response to this question and the comments are summarized as follows:

One respondent stated that they require the tack coat for HMA construction to be fully cured and if pickup occurs, the damaged areas shall be repaired. In another response, it was reported that they use paving grade asphalt if the existing surface is clean to reduce the tracking. Another respondent stated that they apply the tack coat well in advance of the paver and wait for it to set before paving. One state mentioned that they use material transfer vehicles (MTV), but noted that these really do not aid in mitigating the tracking of tack if only one lane is closed. Another one stated that MTVs, can help if staged on the shoulder to keep off the paving surface.

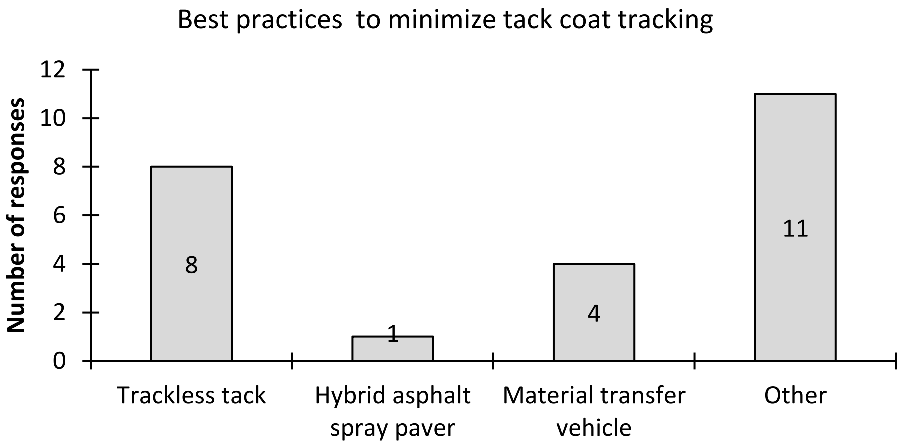


Figure 3.7. Best practices to minimize tack coat tracking

Best practices for cleaning the existing pavement surface: In this question, the respondents stated what best practices they use to clean and prepare the surface before tack coat application. Common practices include air blasting the surface of the old pavement and the surface must also be dry and clean of loose material.

Measuring tack coat performance: Respondents were asked if they have a process in place to measure the bonding performance of tack coats. Many of the respondents stated that they do not have a quality control (QC) process to measure the performance of tack coat. Only 20% of respondents stated that they have some performance measurement testing specs for tack coats, but they commented that it is either for internal QC/QA or information only and not required by specifications. The responses are summarized in Figure 3.8.

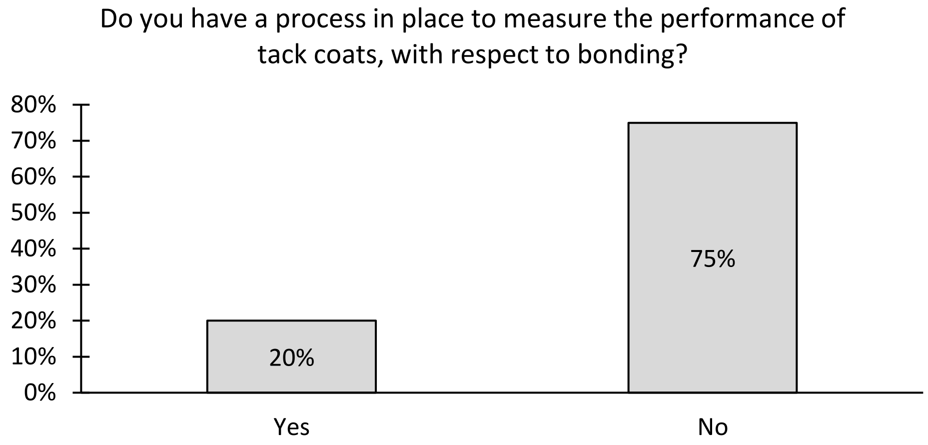


Figure 3.8. Performance measurement processes for tack coats

Survey Summary

This survey was designed to gather the most up-to-date information and best practices regarding OGFC mix production and construction in the United States. As expected, the greater part of the northern states are not utilizing OGFC mixes. On the contrary, many southeastern states utilize OGFC in their high traffic roadways for better safety to reduce hydroplaning. In the southern US, nine states reported that they are currently using OGFC, and ten states reported that are not using OGFC mixes which mostly consist of cold climate states.

Nearly all of the respondents that use OGFC reported raveling as the most common distress that they have experienced and the second highest distress was reported to be de-bonding and delamination. The survey results confirm the most common problems that the literature review also emphasizes regarding OGFC mixes. To address these issues, there was a clear need for an in-depth investigation and experimental studies to improve the performance of OGFC mixes.

4. Methodology

Throughout the course of this project, multiple studies were completed to achieve the overall project objectives. The sub-studies are discussed in separate chapters throughout this report as follows:

CHAPTER 5: Evaluation of Aggregate Breakdown in OGFC Mixtures

CHAPTER 6: Evaluation of Aggregate Gradation in OGFC Mixtures

CHAPTER 7: Evaluation of Compaction Temperature of OGFC

CHAPTER 8: Evaluation of OGFC Durability Test Methods and Variables

CHAPTER 9: Evaluation of Bonding of OGFC Layers

CHAPTER 10: Field Performance of OGFC

This chapter provides descriptions of the experimental methods used to complete the research included in these studies. As some of the methods were used in multiple studies, they are described in this chapter to limit repetition.

Specimen Preparation

Lab Mixing

For lab-mixed specimens, the aggregate batch (including hydrated lime) was prepared and pre-heated to 350°F (177°C) in an oven. The heated aggregate was transferred to a mixing bucket where the appropriate amount of binder, heated to the designated mixing temperature, was added to the aggregate. The mixture was mixed in a bucket mixer for approximately two minutes to ensure thorough coating of all aggregate particles. If an OGFC mix contained cellulose fibers, they were added to the heated aggregate and mixed thoroughly just prior to adding the binder. After mixing, loose material was conditioned in an oven at the designated compaction temperature for two hours prior to compaction.

Plant-Mix Sampling

This project evaluated OGFC mixtures sampled during production at the plant. In these cases, mix was sampled from a haul truck prior to leaving the plant. The sampled mix was either placed in a steel bucket or a coated cardboard box, depending on the quantity needed, then transported to the research lab. Prior to compaction, the material was heated in an oven until it could be manipulated by hand, then transferred to a tray where it was divided into appropriate specimen sizes and heated at the appropriate compaction temperature for two hours prior to compaction.

Specimen Compaction

All test specimens in this research had a diameter of 150 mm (5.9 in) and were compacted using a Superpave Gyratory Compactor with a compaction pressure of 600 kPa (87 psi) per ASTM 6925 (ASTM 2015). The specimen height was 115±5 mm (4.5±0.2 in) for most studies included in this project, with the exception of the OGFC overlays in the tack coat study discussed in Chapter 9. The compaction effort also varied based on the specific study, but was typically 50 gyrations based on typical guidance for OGFC mix design (ASTM 2013; SCDOT 2013; Watson et al. 2003; Watson et al. 2015).

Test Procedures

Aggregate Breakdown (Chapter 5)

To quantify the aggregate breakdown due to mixing and compaction in Chapter 5, compacted specimens were run through the ignition oven to remove the binder per ASTM D6307 (ASTM 2015). The gradation of the remaining aggregate was measured in accordance with ASTM C136 to identify any changes in the gradation resulting from aggregate breakdown due to mixing and compaction (ASTM 2014). The breakdown due to mixing alone was determined following the same procedure for additional OGFC specimens that were mixed, but not compacted.

Porosity (Chapters 5-10)

The porosity of OGFC specimens was measured using the procedure outlined in SC-T-128 (SCDOT 2013a). When specimens were divided into multiple groups for testing, they were grouped in such a way that the average porosity of each group was similar.

Cantabro Abrasion (Chapters 5-8)

The Cantabro method outlined in SC-T-127 was used to determine the resistance to abrasion of OGFC mixtures (SCDOT 2013b). For this, test a single specimen was placed in the LA Abrasion drum without the steel charge and tumbled for 300 revolutions. After the test, the percent mass loss of the specimen was calculated as the difference between the mass of the specimen before the test and the mass of the specimen after the test relative to the initial mass.

Indirect Tensile Strength (Chapters 6-8)

The indirect tensile strength of OGFC specimens was measured in accordance with SC-T-70 (SCDOT 2009). This test was conducted on specimens conditioned in air at 25^{o}C using a loading rate of 2 in/min.

Shear Strength (Chapters 6, 8, 9)

The test procedure outlined in AASHTO TP-114 (AASHTO 2017) was used to measure the interface shear strength (ISS) between two layers of asphalt as detailed in Chapter 9. This procedure was also used to measure the shear strength of OGFC mixes themselves in Chapters 6, 8, and 9. All specimens were tested at room temperature (25°C) using a loading rate of 0.1 in/min.

Mean Texture Depth (Chapters 6, 9)

The surface texture (i.e., mean texture depth) was measured using a variation of the sand patch method outlined in ASTM E965 described by Martin et al. (2014) (ASTM 2015). The perimeter of the top surface of each specimen was wrapped with paper, forming a rim above the surface of the specimen to prevent the loss of glass beads during the test. Glass beads meeting the requirements of ASTM E965 were then spread over the specimen surface using an ice hockey puck. The mass of glass beads required to fill the surface voids of each specimen was recorded (m_{beads}), and the volume of the beads (V_{beads}) was calculated based on m_{beads} and the unit weight of the glass beads. The mean texture depth (MTD) was calculated using Eq. (4.1) (ASTM 2015), where D is the average diameter of the specimen.

$$MTD = \frac{4V_{beads}}{\pi D} \tag{4.1}$$

Permeability (Chapter 9)

The falling head permeability test outlined in FM 5-565 was used to measure the permeability of base and composite specimens in Chapter 9 (FDOT 2015).

Infiltration (Chapter 10)

The infiltration test based on ASTM C1701 and outlined in Appendix B was used to measure the surface infiltration of OGFC pavements.

5. Aggregate LA Abrasion and Breakdown

Objectives and Scope

The primary objective of this portion of the study was to build on previous studies and further investigate the influence of aggregate LA Abrasion value on the performance of OGFC mixtures. To accomplish this objective, the scope of work included two primary tasks.

1. Examine the effects of aggregate LA Abrasion on the durability and porosity of OGFC mixtures. Durability was assessed using the Cantabro abrasion resistance test while porosity was used as a measure of the functional performance of OGFC pavements.
2. Determine the degree of aggregate breakdown (i.e., gradation changes) of OGFC mixtures after mixing and compaction.

Experimental Methods

To accomplish the objective of this study, OGFC mixtures were mixed, compacted, and evaluated in the laboratory using 11 different South Carolina aggregate sources. All aggregates were crushed stone and the properties of each source are summarized in Table 5.1. The LA Abrasion value was the main variable in this study, so aggregate sources were selected to obtain a wide range of LA Abrasion values (low-20s to mid-50s) while also maintaining geographic diversity across the state.

Table 5.1. Properties of Aggregates Included in This Study

Quarry	Rock Type	G_{sb}	Absorption (%)	LA Abrasion(%)
A	Granite	2.61	0.87	54
B	Granite	2.60	0.89	50
C	Granite	2.65	0.51	51
D	Granite	2.62	0.58	36
E	Granite	2.64	0.53	45
F	Granite	2.59	0.69	43
G	Granite	2.62	0.45	30
H	Granite	2.75	0.65	23
I	Granite	2.66	0.72	20
J	Granite	2.59	0.79	35
K	Marble Schist	2.81	0.61	30

All specimens evaluated in this study were prepared using the same mix design meeting the SCDOT OGFC specifications as noted in Table 5.2 (SCDOT 2007). This mix design was selected based on existing OGFC job mix formulas in South Carolina. All specimens had a total aggregate mass of 3800 g, including hydrated lime.

Table 5.2. OGFC Job Mix Formula (JMF) Used for This Study

Aggregate	**Percent Passing**	
Sieve	**JMF**	**SCDOT Spec.**
¾ in (19 mm)	100	100
½ in (12.5 mm)	94.0	85-100
⅜ in (9.5 mm)	69.0	55-75
No. 4 (4.75 mm)	19.0	15-30
No. 8 (2.36 mm)	7.0	5-15
No. 30 (600 μm)	3.5	–
No. 100 (150 μm)	2.0	–
No. 200 (75 μm)	1.0	0-4
Binder	PG 76-22 (SBS)	6.0% by total mix weight
Fiber	Cellulose	0.3% by total mix weight
Anti-Stripping Agent	Hydrated Lime	1.0% by aggregate weight
Mixing Temperature	325°F (163°C)	
Compaction Temperature	315°F (157°C)	

This study was divided into two phases:

1. Performance of compacted OGFC specimens was measured using the Cantabro abrasion and porosity tests.
2. Breakdown of the aggregate due to mixing and compaction.

Phase 1: Performance of Compacted OGFC Specimens

A total of six specimens for each quarry were produced and compacted for the Phase 1 study. The porosity of each specimen was measured, then three of the specimens were tested for durability using the Cantabro abrasion test and the other three were tested for breakdown in Phase 2.

Phase 2: Breakdown of Aggregate Due to Mixing and Compaction

The goal of Phase 2 was to quantify the aggregate breakdown due to mixing and compaction. The remaining three compacted specimens for each quarry were run through the ignition oven to remove the binder per ASTM D6307 (ASTM 2015). The gradation of the remaining aggregate was measured in accordance with ASTM C136 to identify any changes in the gradation resulting from aggregate breakdown due to mixing and compaction (ASTM 2014). The breakdown due to mixing alone was determined following the same procedure for three additional OGFC specimens that were mixed, but not compacted.

Results and Discussion

Phase 1: Performance of Compacted OGFC Specimens

The performance of OGFC mixtures was evaluated by measuring the porosity and Cantabro abrasion loss of compacted specimens. In Phase 1, the porosity of all 66 specimens (i.e., six per aggregate source) was measured and half of these specimens (i.e., three per aggregate source) were tested to quantify the resistance to raveling using the Cantabro abrasion test. The first observation from this phase was the relationship between the compacted specimen height and the aggregate LA Abrasion value shown in Figure 5.1. Shorter specimens resulted for aggregates having higher LA Abrasion values after compaction with 50 gyrations. Because the aggregates had similar specific gravities (G_{sb}), the differences in height could be the result of either aggregate shape or breakdown during mixing and compaction. If breakdown occurred, the aggregate gradation would change to become finer and more well-graded, which would result in tighter packing of the aggregates in the specimen. The aggregate from Quarry K had a specific gravity of 2.81, which is significantly higher than the other 10 sources. Because a constant aggregate mass of 3800 g was used for all mixtures, the total volume of aggregate from Quarry K was less than the others, thus resulting in significantly shorter specimens. For this reason, the specimens from Quarry K were not included in the trendlines for any of the analyses conducted in this study. However, the values from Quarry K are still included, but with a unique marker.

A Student's *t*-test was conducted to determine statistically significant differences between the heights of different aggregate sources at a significance level of 95% at $\alpha = 0.05$. These results are shown with the different letters next to the markers in Figure 5.1. Sources sharing a common letter were not statistically different from each other. This analysis indicated that Quarry K, having an LA Abrasion value of 30, was significantly different than the others. It also shows that the data was repeatable since relatively few quarries were statistically similar to each other.

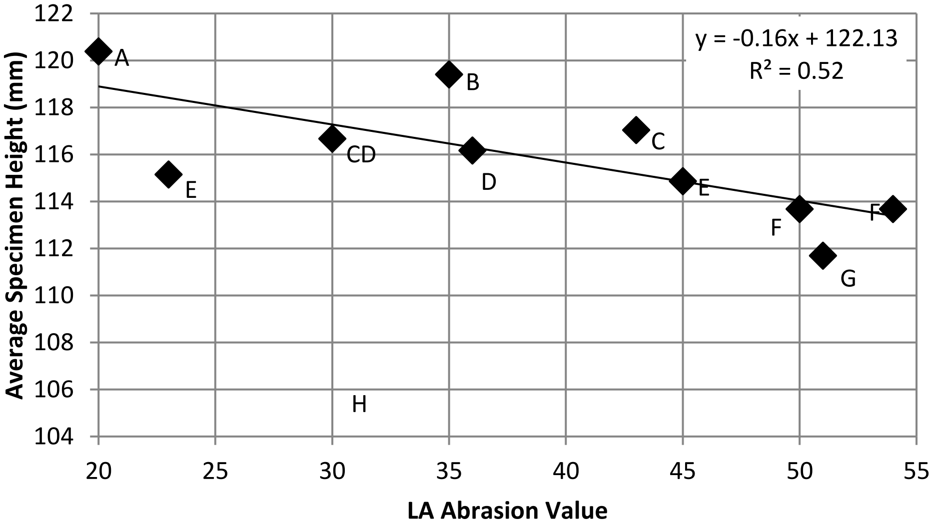


Figure 5.1. Relationship between aggregate LA Abrasion value and height of compacted specimens.

The average porosity results summarized in Figure 5.2 show that the porosity of the compacted specimens had a strong correlation to the LA Abrasion value. The porosity decreased as the LA value of the aggregate increased, which matches the trend observed with the specimen height. As noted with the specimen height, this relationship could be due to either differences in the shape of the aggregate from the different sources or the result of aggregate breakdown.

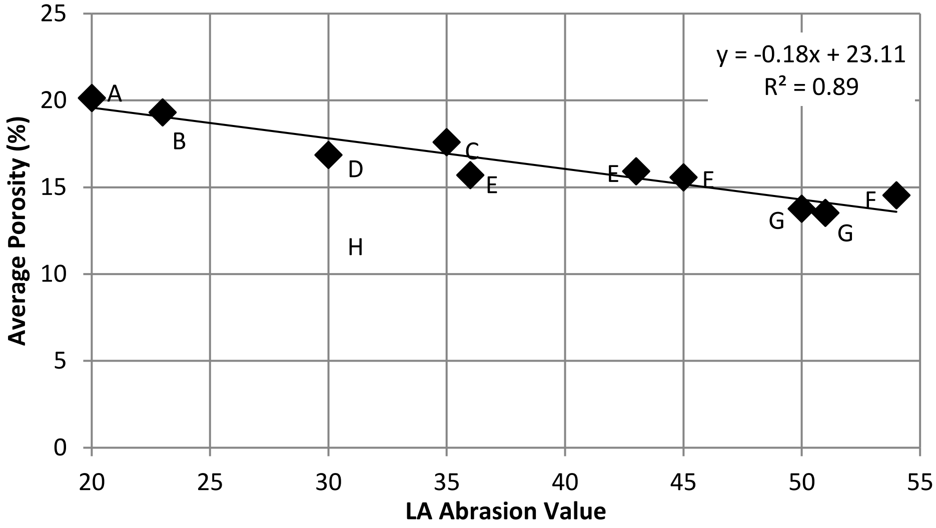


Figure 5.2. Relationship between aggregate LA Abrasion value and porosity of compacted specimens.

The results of the Student's *t*-Test show that specimens made with aggregates having similar LA Abrasion values generally exhibited similar porosity. It also indicated that the porosity of the Quarry K specimens were significantly different from the rest. For this reason, it was not included in the trendline describing the results.

Figure 5.3 presents the results of the Cantabro abrasion test and the relationship with aggregate LA Abrasion value. These results follow trends observed by Putman et al. in a previous study with some of the same aggregate sources—the Cantabro abrasion loss decreases as the aggregate LA Abrasion increases (2015). In other words, mixes made with weaker aggregates showed significantly greater resistance to raveling in the lab. This is also supported by the statistical analysis. It is interesting to note that, unlike the height and porosity, specimens made with aggregate from Quarry K were not significantly different from all other sources. However, the results of Quarry K were still excluded from the trendlines to maintain consistency throughout the analysis.

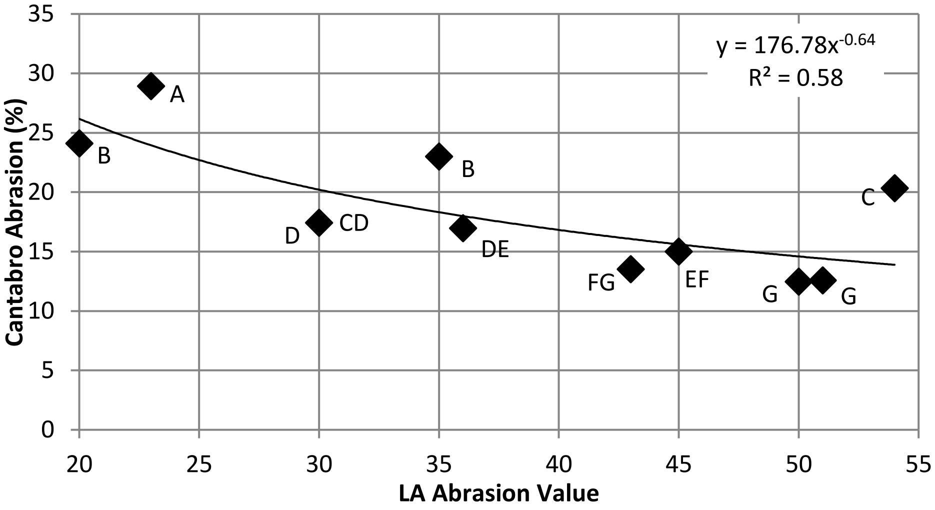


Figure 5.3. Relationship between aggregate LA Abrasion value and Cantabro abrasion loss.

The results presented in Figure 5.4, show a direct correlation between porosity and Cantabro abrasion loss. This correlation was also found in the previous study by the SCDOT and matches expectations for most materials—strength decreases with increasing void content (Putman et al. 2015).

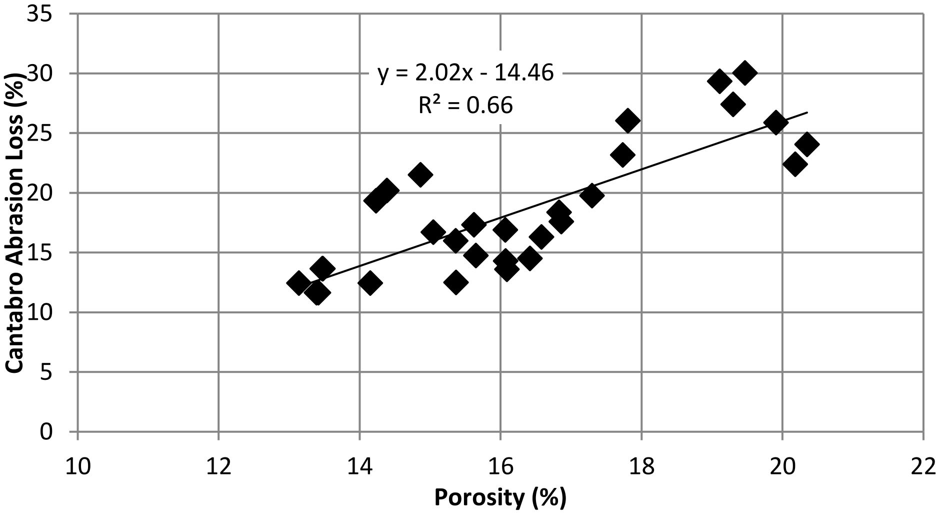


Figure 5.4. Relationship between porosity and Cantabro abrasion loss.

Phase 2: Breakdown of Aggregate Due to Mixing and Compaction

The results from Phase 1 verified the results of previous studies that led to the hypothesis that aggregate breakdown likely occurs during mixing and/or compaction, which alters the mixture gradation resulting in a more dense aggregate structure that increases the performance in the Cantabro abrasion test. This hypothesis was examined in this phase of the research by measuring the change in gradation resulting from the laboratory mixing and compaction processes.

Figure 5.5 shows the gradation curves of OGFC mixtures made with the highest LA aggregate (i.e., Quarry A; LA = 54) and lowest LA aggregate (i.e., Quarry I; LA = 20). The three curves in these figures show:

- The initial gradation of the aggregate as it was batched prior to mixing (original).
- The average gradation of the OGFC mixture after mixing in the bucket mixer for two minutes (mixing).
- The average gradation of the OGFC mixture after two minutes of mixing and compaction with 50 gyrations of the Superpave Gyratory Compactor (mixing + compacting).

The changes in percent passing between mixing and original indicate the amount of aggregate breakdown resulting from mixing action and the changes between mixing + compacting and mixing indicate the breakdown attributed to the compaction effort. As with the two aggregate sources shown in Figure 5.5, there was a change in gradation over the range of sieves for all sources due to both mixing and compaction. The largest change in gradation occurred on the middle sieves for this particular gradation (i.e., ⅜ in, No. 4, and No. 8) with the greatest change being on the No. 4 (4.75 mm) sieve. The average change from the original gradation sources on the ⅜ in, No. 4, and No. 8 sieves for all 11 aggregate sources after mixing and compaction was 7.6%, 14.7%, and 10.2% passing, respectively. These results are presented in Appendix A.

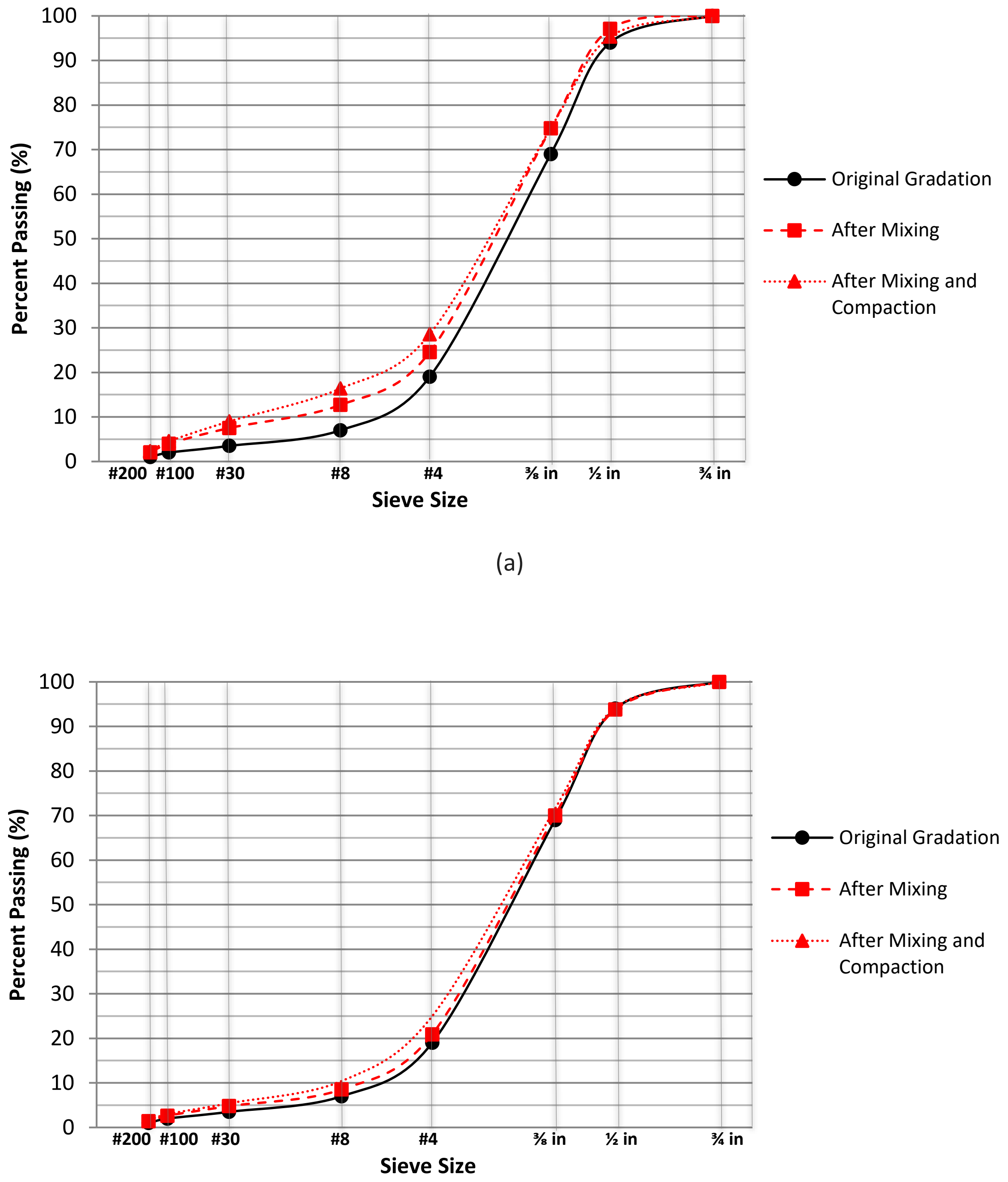
The degree of aggregate breakdown was quantified by calculating the uniformity coefficient (C_u) for each specimen (Equation 5.1). OGFC mixtures are uniformly graded and have a low C_u, which creates an open void structure to enable water flow. The C_u of the original OGFC gradation used in this study was 2.59 (i.e., D_{10} = 3.34 mm and D_{60} = 8.66 mm). An increase in C_u indicates that the gradation is becoming more well-graded, which results in a reduction in void content and porosity.

$$C_u = \frac{D_{60}}{D_{10}} \tag{5.1}$$

Where,

D_{60} = particle size for which 60% is finer
D_{10} = particle size for which 10% is finer

The relationship between C_u and porosity for the compacted specimens is presented in Figure 5.7. The strong correlation provides evidence that aggregate breakdown due to mixing and compacting causes a reduction in porosity of the compacted specimens.



(a)

(b)

Figure 5.5. Sample gradation curves illustrating the degree of gradation change after mixing and compaction for OGFC mixtures made with aggregate from (a) Quarry A (LA = 54) and (b) Quarry I (LA = 20).

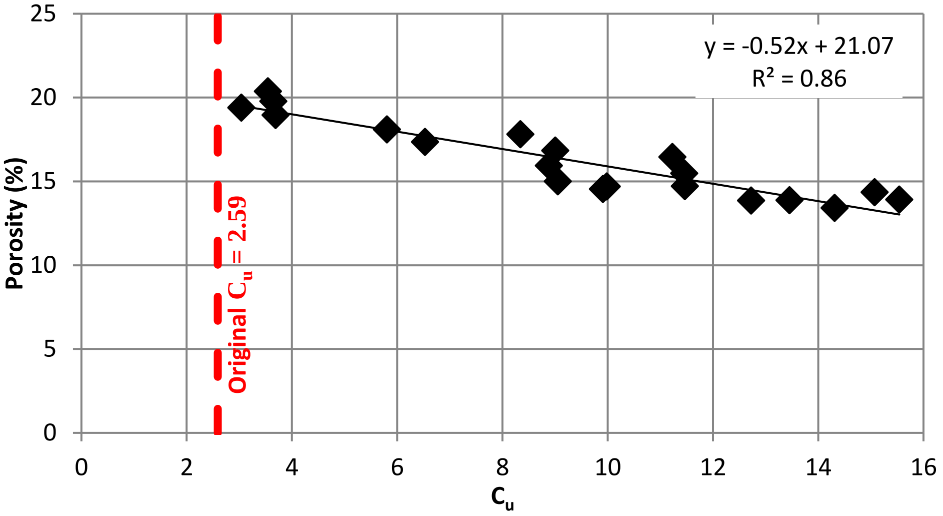


Figure 5.6. Relationship between uniformity coefficient (C_u) and porosity of compacted specimens.

The relationship between the aggregate LA Abrasion value and C_u is presented in Figure 5.7. The gradation of uncompacted OGFC mix, as well as compacted specimens, was measured for each aggregate source and the C_u was calculated to quantify the degree of breakdown for each condition. The results show that the weaker aggregates having a higher LA value exhibit greater breakdown than stronger aggregates. A closer look at Figure 5.7 reveals a clear delineation between aggregate sources with respect to breakdown due to mixing alone. There are four aggregate sources (i.e., Quarries H, I, J, and K) that had C_u values that were statistically similar to each other after mixing and these C_u results were significantly different than the other seven sources ($\alpha = 0.05$). Additionally, when comparing the C_u after mixing to that after compaction in Figure 5.8, the C_u increases by a factor of approximately 1.5 as a result of compaction alone.

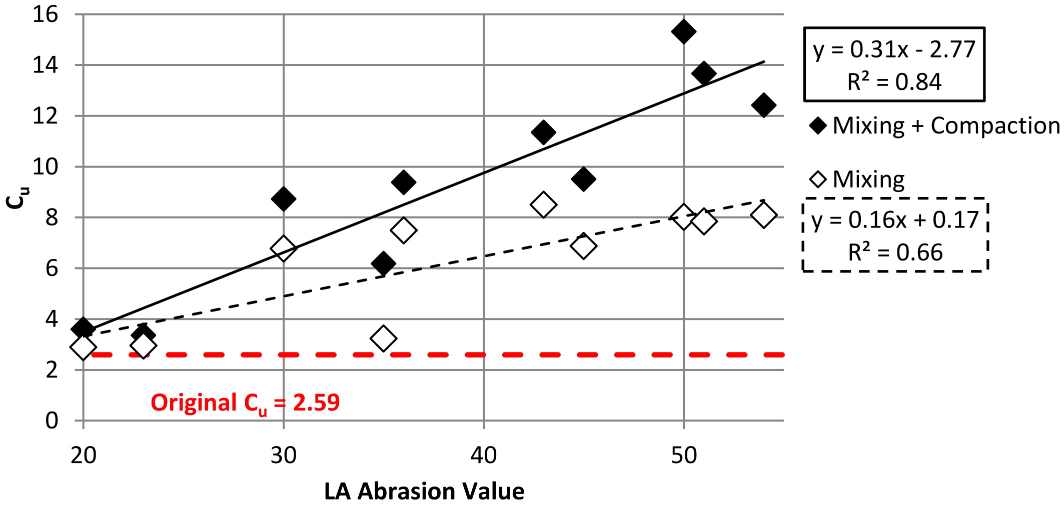


Figure 5.7. Relationship between aggregate LA Abrasion value and uniformity coefficient (C_u) of compacted specimens.

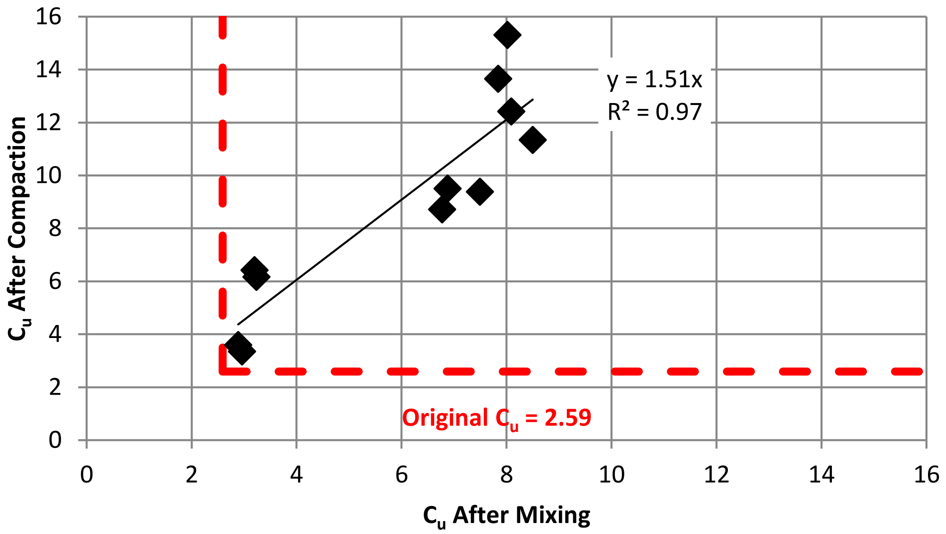


Figure 5.8. Comparison of uniformity coefficient (C_u) after mixing and after compaction.

Field Study

In the early stages of this project, the SCDOT constructed a test section using an aggregate source with an LA Abrasion value above the maximum allowable value of 52%. The aggregate was from Quarry A having a LA Abrasion value of 54% (Table 5.1). The goal of this pilot was to evaluate the breakdown of the aggregate during production and construction and to determine if OGFC could be constructed with aggregate sources having higher LA Abrasion values without sacrificing pavement performance.

This test section was constructed on River Road in Columbia, SC, in December 2015 using approximately 150 tons of OGFC mix having job mix formula included in Table 5.3. This test section was placed on a local road instead of an interstate due to its experimental nature with the primary goal to assess feasibility.

Table 5.3. Job mix formula for OGFC mix used for the high LA Abrasion test section with aggregate from Quarry A.

	Percent Passing	
Sieve Size	**Job Mix Formula**	**Specification**
¾ in	100	100
½ in	99	85-100
⅜ in	72	55-75
No. 4	16	15-25
No. 8	6	5-10
No. 200	1	0-4

During production and construction, materials were sampled at the following points during production/construction:

1. Prior to Mixing: Blended aggregate sampled from the conveyor belt between the lime pugmill and the mixing drum. This was to provide a baseline gradation prior to mixing. Only one sample was collected (n = 1).
2. After Mixing: OGFC mix sampled from three consecutive trucks prior to leaving the plant. This was sampled to determine any gradation effects due to the mixing process (n = 3).
3. After Paving: OGFC mix from the same trucks that were sampled at the plant was sampled from the roadway behind the paver prior to compaction. This was used to determine the impact of the paver and placement on gradation changes (n = 3).
4. After Rolling: OGFC mix from the same truck sampled at the plant was sampled from the roadway after rolling. This material was sampled to evaluate the degree of gradation change due to rolling (n = 3).

The collected samples were transported to the National Center for Asphalt Technology to be tested for gradation and the average results are summarized in Table 5.4 and Figure 5.9. Based on these results, there was some aggregate breakdown resulting from the mixing and construction processes, but the differences were not statistically significant ($\alpha = 0.5$). The percent passing the No. 4 and No. 8 sieve increased by approximately 5%, and the No. 200 increased by 1.3% on average, however, the resulting gradation was still within specifications. Based on these limited data, the placement/compaction processes have more impact on the aggregate breakdown then the mixing process used for this particular project.

Table 5.4. Gradation results from test section showing aggregate breakdown at different stages.

	Percent Passing					
Sieve Size	**Belt**	**Truck**	**Paver**	**Roller**	**JMF**	**Specification**
¾ in	100.0	100.0	100.0	100.0	100.0	100
½ in	99.3	99.5	99.3	99.4	99.0	85-100
⅜ in	77.6	76.1	75.6	77.7	72.0	55-75
No. 4	16.4	16.8	18.7	21.7	16.0	15-25
No. 8	4.8	6.8	8.3	10.0	6.0	5-10
No. 16	3.8	5.4	7.0	7.2		
No. 30	3.4	4.7	6.2	6.6		
No. 50	3.0	4.0	4.1	5.5		
No. 100	2.4	3.0	3.1	4.2		
No. 200	1.60	1.93	1.99	2.85	1.0	0-4
C_u	2.02	2.13	2.65	3.32		

The aggregate breakdown can also be seen in the changes in the uniformity coefficient (C_u) in Table 5.4. As noted previously, the C_u increased by a factor of approximately 1.51 when comparing the change between mixing and compaction in the lab study (Figure 5.8). The results found in this limited field study support this relationship as the C_u increased from 2.13 after mixing to 3.32 after compaction.

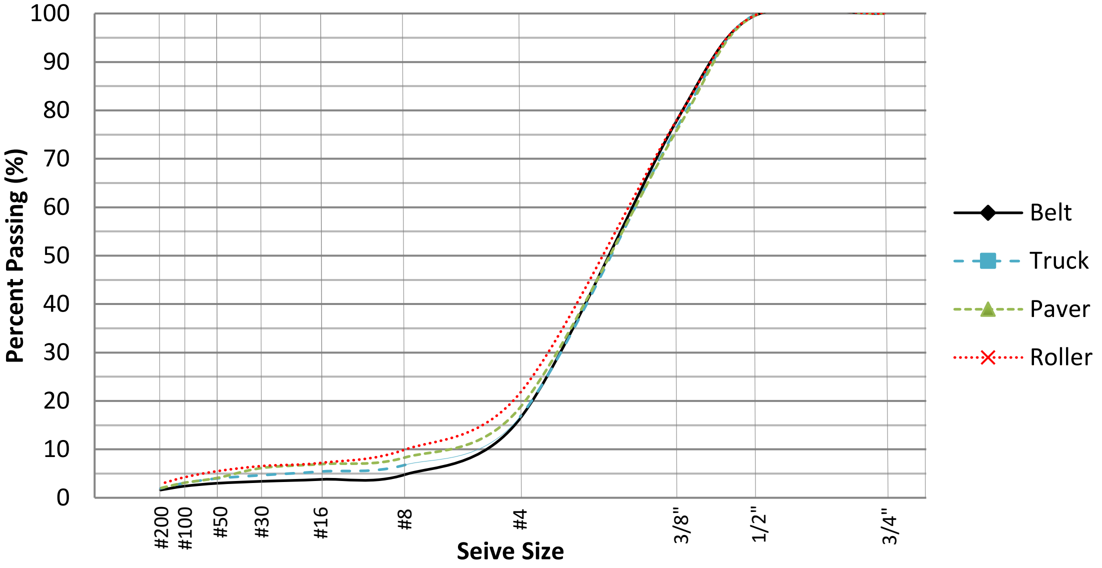


Figure 5.9. Gradation curves from test section of aggregate sampled from the belt and of mix sampled from a truck, behind the paver, and after rolling.

Following this preliminary study, the SCDOT constructed a test section on Interstate-20 in Columbia, SC, in July 2016.

6. Aggregate Gradation

Objectives and Scope

The main objective of this study was to investigate the performance properties of OGFC mixtures made with different gradations and nominal maximum aggregate sizes (NMAS). This study was conducted in two phases where Phase 1 focused on the percent passing the No. 4 sieve covering the ranges in the newly revised SCDOT OGFC gradations (Table 6.1) and retained on the No. 8 sieve and Phase 2 focused on the filler content (i.e., percent passing the No. 200 sieve). Eight gradations were evaluated in each phase to determine their respective effects on the porosity, surface texture, indirect tensile strength, shear strength, and Cantabro abrasion loss of the OGFC mixtures.

Table 6.1. SCDOT OGFC Gradation Specifications (SCDOT 2019)

	12.5 mm OGFC	**9.5 mm OGFC**
Sieve Size	**Percent Passing**	
¾ in (19.0 mm)	100	100
½ in (12.5 mm)	85 – 100	95 – 100
⅜ in (9.5 mm)	55 – 75	80 – 100
No. 4 (4.75 mm)	15 – 30	20 – 50
No. 8 (2.36 mm)	5 – 15	5 – 20
No. 200 (0.075 mm)	0 – 4	0 – 4
% Binder	5.5 – 7.0	5.5 – 7.0

Experimental Methods

The objectives of this study were accomplished in two phases by evaluating eight different OGFC mixtures in each phase, each mixture having a different gradation. The mixtures were produced using PG 76-22 binder at a binder content of 6% by total mix weight. Even though the gradation varied, this binder content was held constant as it is reflective of the typical binder content used in South Carolina for OGFC mixtures made with this aggregate. One granite aggregate source was used from a quarry in the upstate of South Carolina. The gradations in Tables 6.2 and 6.3 included in this study were selected based on the SCDOT specifications for two different OGFC mixes (SCDOT 2016; SCDOT 2010). The 9.5 mm NMAS mix was originally considered the Maintenance OGFC mix, then later added to the Supplemental Specifications for OGFC (SCDOT 2019). Hydrated lime was also included in each mix as an anti-stripping additive per SCDOT specifications at a rate of 1% by aggregate weight (SCDOT 2007).

Table 6.2. OGFC Gradations Evaluated in the Phase 1 Study on Percent Passing the No. 4 Sieve

	Percent Passing							
	12.5 mm NMAS				9.5 mm NMAS			
Sieve Size	**12.5-10**	**12.5-20**	**12.5-30**	**12.5-40**	**9.5-20**	**9.5-30**	**9.5-40**	**9.5-50**
¾ in (19.0 mm)	100	100	100	100	100	100	100	100
½ in (12.5 mm)	95	95	95	95	100	100	100	100
⅜ in (9.5 mm)	65	65	65	65	90	90	90	90
No. 4 (4.75 mm)	10	20	30	40	20	30	40	50
No. 8 (2.36 mm)	10	10	10	10	10	10	10	10
No. 200 (0.075 mm)	2	2	2	2	2	2	2	2

Table 6.3. OGFC Gradations Evaluated in the Phase 2 Study on Percent Passing the No. 200 Sieve

	Percent Passing							
	12.5 mm NMAS				9.5 mm NMAS			
Sieve Size	**12.5-0**	**12.5-2**	**12.5-4**	**12.5-6**	**9.5-0**	**9.5-2**	**9.5-4**	**9.5-6**
¾ in (19.0 mm)	100	100	100	100	100	100	100	100
½ in (12.5 mm)	95	95	95	95	100	100	100	100
⅜ in (9.5 mm)	65	65	65	65	90	90	90	90
No. 4 (4.75 mm)	25	25	25	25	35	35	35	35
No. 8 (2.36 mm)	10	10	10	10	10	10	10	10
No. 200 (0.075 mm)	0	2	4	6	0	2	4	6
Surface Area[1] (m^2/kg)	1.09	2.10	3.12	4.13	1.13	2.14	3.11	4.35

[1]*Aggregate surface area was estimated using surface area factors*

The focus of each gradation in Phase 1 was the percent passing the No. 4 (4.75 mm) sieve and retained on the No. 8 (2.36 mm) sieve. The variation of the percent passing the No. 4 sieve ranged from 20-50% passing for the 9.5 mm NMAS and 10-40% passing for the 12.5 mm NMAS mixes while the percent passing the No. 8 sieve remained constant at 10% for all gradations. These trial gradations were selected to encompass the complete specification range of percent passing the No. 4 sieve for both NMAS groups. While some of the extreme limits of this range may not be intentionally produced in the field, there is potential for aggregate breakdown due to production and compaction that can affect the in-place gradation of an OGFC mixture resulting in higher percent passing the No. 4 sieve, with minimal effect on other sieves as seen in Chapter 5 (Repik et al. 2018).

For Phase 2 of this study, the focus of each gradation was the percent passing the No. 200 (0.075 mm) sieve and the filler content ranged from 0-6% passing the No. 200 sieve for each NMAS. This range was selected based on the specification limits for OGFC mixes across the US (Watson et al. 2018). To focus solely on the filler content, the other size fractions of the gradation remained constant for each treatment.

A two-part naming convention was used for each mix as noted in Tables 2 and 3 and the results figures. The first part of the name before the hyphen states the NMAS of the gradation (i.e., 9.5 or 12.5 mm) and the second part states the percent passing the No. 4 sieve in Phase 1 and the percent passing the No 200 sieve in Phase 2. For example, the mixture labeled 12.5-20 in Phase 1 has a NMAS of 12.5 mm and 20% passing the No. 4 sieve and the Phase 2 mixture labeled 9.5-4 has a NMAS of 9.5 mm and 4% passing the No. 200 sieve.

For each mixture, nine 150 mm diameter specimens having a height of 115±5 mm were compacted in the lab with 50 gyrations of a Superpave gyratory compactor. The porosity of each specimen was measured using the procedure outlined in SC-T-128 (SCDOT 2013a). The specimens were then divided into three groups of three specimens each in such a way that the average porosity of each group was similar. Each group was tested as follows:

Group 1 *(three specimens per gradation):* The surface texture (mean texture depth) was measured using a variation of the sand patch method. After testing the MTD, the glass beads were removed before testing the indirect tensile strength of each specimen in accordance with SC-T-70 (SCDOT 2009). This test was conducted on specimens conditioned in air at 25°C using a loading rate of 2 in/min.

Group 2 *(three specimens per gradation):* This group of specimens was tested using the Cantabro method outlined in SC-T-127 to determine the resistance to abrasion of each mixture (SCDOT 2013b).

Group 3 *(three specimens per gradation):* The last group of specimens were tested to measure the shear strength of each mix using the procedure outlined in AASHTO TP-114 (AASHTO 2017).

Results and Discussion

Phase 1: Effects of Variation on the No. 4 Sieve

Porosity

The porosity results of the Phase 1 gradations are summarized in Figure 6.1. A Student's t-test was conducted to determine statistically significant differences between porosity of different mixes at a significance level of 95% at $\alpha = 0.05$. These results are indicated in Figure 1 with the use of letters at the bottom of each bar. Mixes that share a common letter are not statistically different from each other. This analysis was also conducted for the other properties evaluated in this study.

The general trend in Figure 6.1 shows that the porosity decreases with an increase in the percent passing the No. 4 sieve. This trend was expected because the addition of this finer material to the mix occupies space that is otherwise void space. However, this trend was more significant for the 12.5 mm NMAS mixtures compared to the 9.5 mm NMAS mixtures. The difference in porosity was statistically significant for all of the 12.5 mm NMAS mixtures, but the 9.5 mm NMAS mixtures having 30-50% passing the No. 4 sieve had statistically similar porosity, which was lower than the mix with 20% passing. This indicates that the 9.5 mm NMAS mixtures were less sensitive to changes in gradation with respect to porosity and will likely still possess sufficient functional properties related to permeability and infiltration with a more well graded aggregate blend. Based on the relationship between porosity and permeability established by Mansour and Putman (2013), the mixture yielding the lowest porosity (i.e., mix 12.5-40) would have an estimated permeability of 108 m/day, which exceeds the minimum recommended value of 100 m/day (ASTM 2013). Additionally, the 9.5 mm NMAS mixtures had higher porosity than the 12.5 mm NMAS mixtures having the same percent passing the No. 4 sieve.

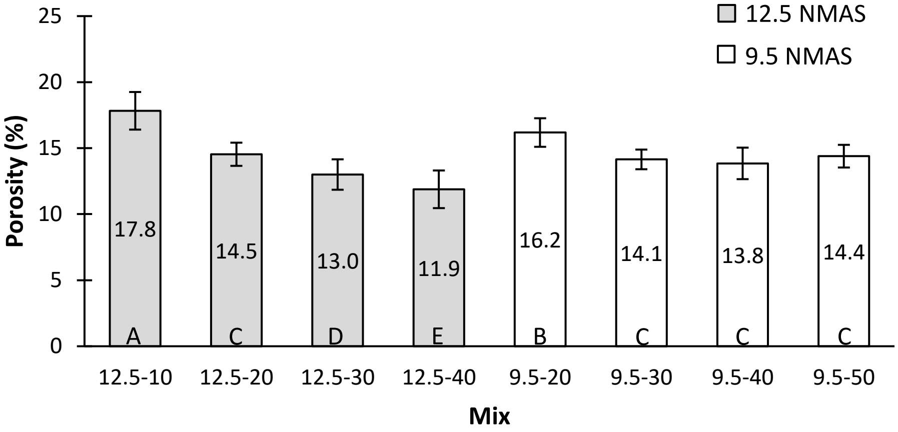


Figure 6.1. Porosity of OGFC mixtures. Mixes sharing a common letter were not statistically different at α = 0.05.

Mean Texture Depth (MTD)

The mean texture depth (MTD) is a characteristic that can influence the frictional skid resistance and drainage of a pavement surface and was evaluated for each OGFC mixture in this study. The results in Figure 6.2 indicate that the changes in gradation (i.e., percent passing the No. 4 sieve) generally had little effect on the MTD. The only exception was mix 12.5-10 having the lowest amount of material passing the No. 4 as well as the highest porosity. While not statistically significant, the MTD did generally follow the same trend as porosity with respect to the percent passing the No. 4 sieve. There was also no significant influence of the NMAS on the MTD.

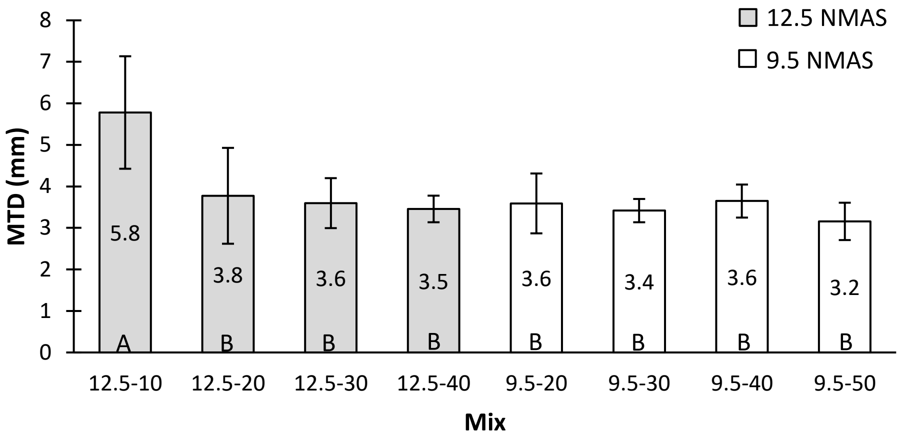


Figure 6.2. Mean texture depth (MTD) of OGFC mixtures. Mixes sharing a common letter were not statistically different at α = 0.05.

Indirect Tensile Strength (ITS)

Figure 6.3 summarizes the ITS results for each mixture and the results indicate that for the gradations tested, the mixes with 30% passing the No. 4 sieve exhibited the greatest ITS for both NMAS, but the differences were only statistically significant for the lowest percent passing the No. 4 sieve in each NMAS category. The results somewhat reflect the porosity results in that the mixes having the greatest porosity in each NMAS category also had the lowest ITS. This can be attributed to the addition of aggregate material that fits within the voids between other particles, thus creating a greater degree of aggregate interlock which increases the strength of the mix.

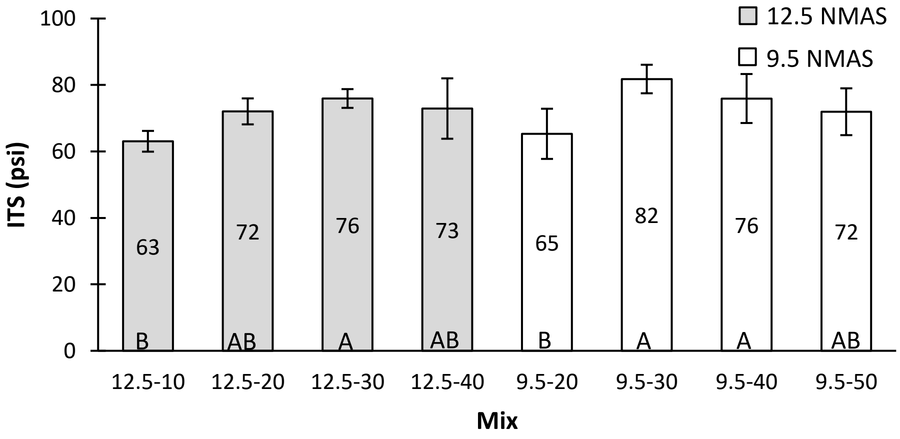


Figure 6.3. Indirect tensile strength (ITS) of OGFC mixtures. Mixes sharing a common letter were not statistically different at α = 0.05.

Cantabro Abrasion

The Cantabro abrasion test is typically used to characterize the raveling resistance of OGFC mixtures in the lab. At first look, it can be seen that the results for all mixes are lower than the recommended maximum value of 20% loss (ASTM 2013; Watson et al. 2018). The results presented in Figure 6.4 generally exhibit similar trends to the ITS results. In each NMAS category, the gradation having the lowest percent passing the No. 4 sieve exhibited the greatest Cantabro loss, meaning that it is likely more susceptible to raveling, however, these differences were not statistically significant. As with the ITS, the increase of percent passing the No. 4 sieve in the gradation, generally increased the resistance to raveling based on the Cantabro test. This could likely be due to the fact that when added, the smaller particles fill the voids and also create more points of contact with neighboring particles thus increasing the internal bond strength (or cohesion) of the mixture. Additionally, for a given percent passing the No. 4 sieve, the NMAS did not have any significant effect on the Cantabro loss.

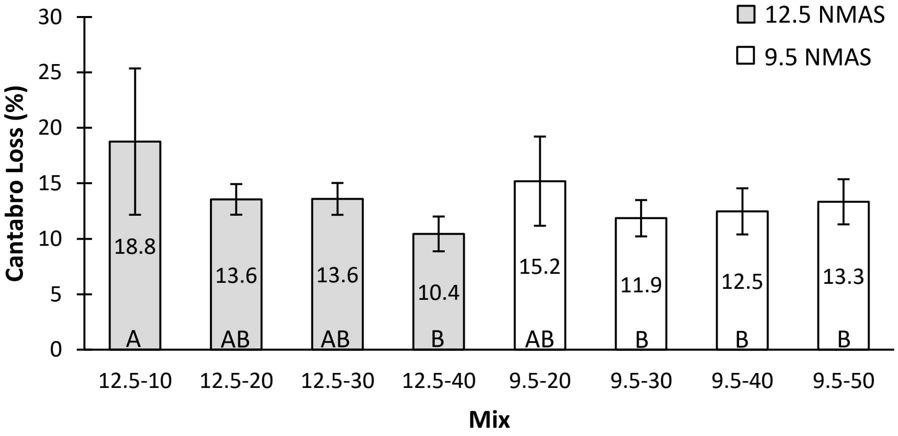


Figure 6.4. Cantabro abrasion test results of OGFC mixtures. Mixes sharing a common letter were not statistically different at α = 0.05.

Shear Strength

Figure 6.5 shows the shear strength results of the OGFC mixes in this study and the results follow similar trends as the ITS and Cantabro tests. As with the ITS and Cantabro tests, the shear strength was lowest for the 12.5-10 mix. The 9.5-40 mix was also lower than the others, which was not seen in the other tests. While these two gradations exhibited the lowest shear strength, they were not significantly different than the other mixtures with the exception of 12.5-20 and 12.5-40, which both had significantly higher shear strength. Additionally, with the exception of the gradations with 40% passing the No. 4 sieve, the NMAS did not have a significant effect on the shear strength.

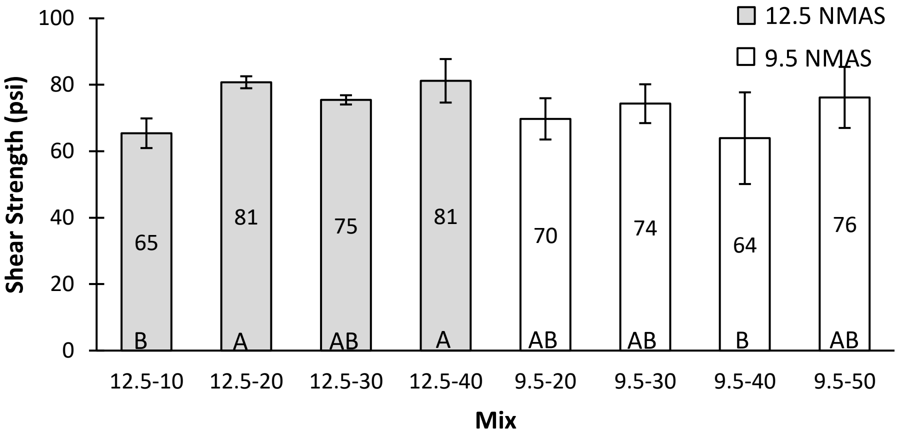


Figure 6.5. Shear strength of OGFC mixtures. Mixes sharing a common letter were not statistically different at α = 0.05.

Phase 2: Effects of Variation on the No. 200 Sieve

Porosity

The porosity results of all specimens are summarized in Figure 6.6. The general trend shows that the porosity increases when the filler increases from 0-2%, then decreases as the filler increases from 2-6%. However, the differences were not statistically significant in all cases. The porosity of each of the 12.5 mm mixes was not significantly different from each other as all four mixes share the letter "A" as noted in Figure 6.6. For the 9.5 mm NMAS, the mix with 6% filler had a statistically lower porosity than the other filler contents. Additionally, this was the only treatment where the porosity did not meet the minimum value of 13% required by the SCDOT (SCDOT 2019). Based on the relationship of porosity and permeability from Mansour and Putman (2013), a porosity of 13% would lead to a permeability of approximately 125 m/day. The average permeability of the 9.5-6 treatment having an average porosity of 10.2% would be approximately 85 m/day, which is lower than the minimum of 100 m/day recommended in ASTM D7064 (2013), but greater than the absolute minimum of 50 m/day recommended by Watson et al. (2018). The porosity decreased at a higher rate for the 9.5 mm NMAS mixes as the filler increased compared to the 12.5 mm mixes, which indicates that the porosity of the 9.5 mm OGFC mixes is more sensitive to changes in filler content than the 12.5 mm mixes within the range studied.

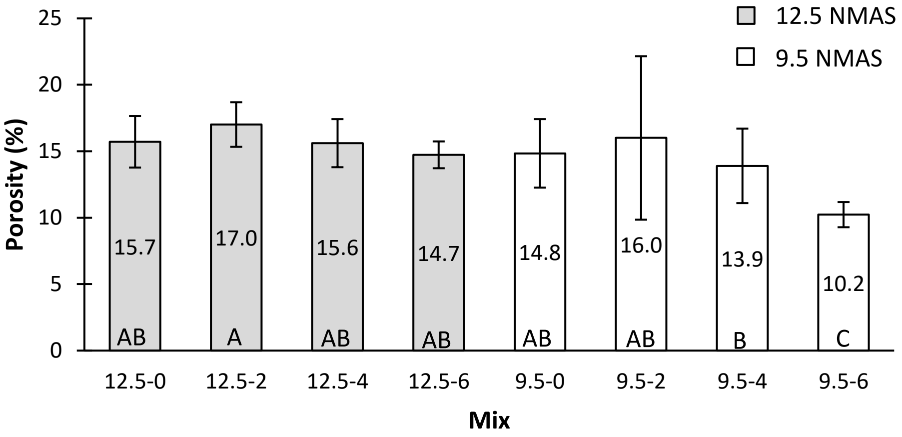


Figure 6.6. Porosity of OGFC mixtures. Mixes sharing a common letter were not statistically different at α = 0.05. Error bars indicate one standard deviation from the mean.

Mean Texture Depth (MTD)

The results in Figure 6.7 indicate that the changes in the filler content generally had little effect on the MTD, especially within each NMAS. With the exception of mix 9.5-2, all of the mixes within an NMAS (i.e., either 9.5 mm or 12.5 mm) had similar MTD values. This suggests that the filler content, within the range included in this study, has less effect on MTD of the pavement surface than the proportion of larger aggregates in the gradation.

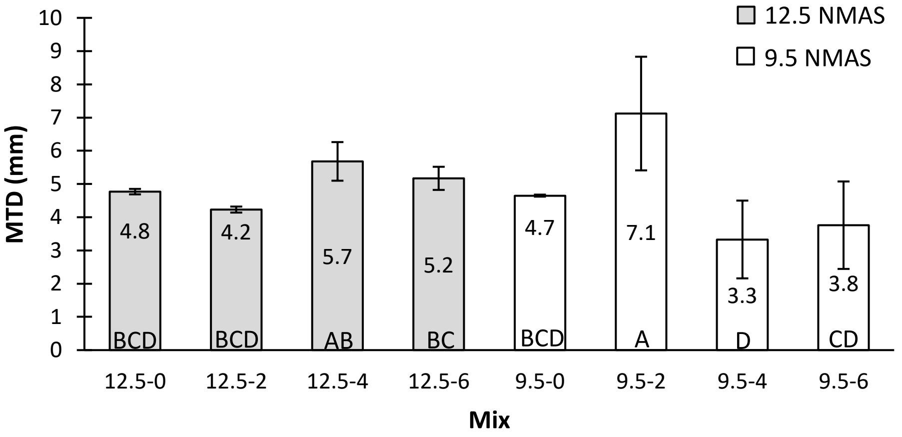


Figure 6.7. Mean texture depth (MTD) of OGFC mixtures. Mixes sharing a common letter were not statistically different at α = 0.05. Error bars indicate one standard deviation from the mean.

Indirect Tensile Strength (ITS)

The unconditioned ITS results for each mixture are summarized in Figure 6.8. Based on these results, the filler content had no significant influence on the ITS of the OGFC mixtures for the range studied (i.e., 0-6%). Additionally, the NMAS had no significant effect, which was also seen in Phase 1. It is also noted that mix 9.5-6, which had the lowest porosity (Figure 6), also exhibited the highest ITS of all mixes.

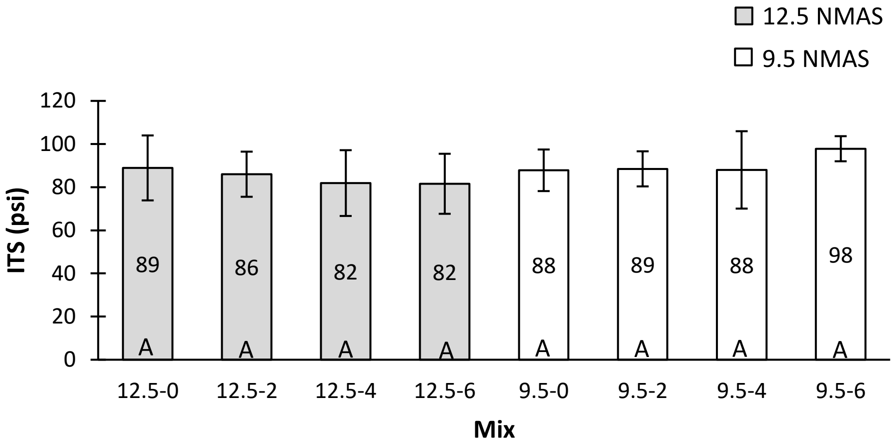


Figure 6.8. Indirect tensile strength (ITS) of OGFC mixtures. Mixes sharing a common letter were not statistically different at α = 0.05. Error bars indicate one standard deviation from the mean.

Cantabro Abrasion

As summarized in Figure 6.9, all mixes had an average Cantabro loss value below the maximum value of 20% recommended by Watson et al. (2018). The SCDOT limit of 15% was only exceeded by the 12.5-0 and 12.5-4 mixes (SCDOT 2019). The 9.5 mm NMAS mixes exhibited significantly greater abrasion resistance than the 12.5 mm mixes with the exception of the 12.5-6 mix containing 6% filler. The 9.5 mm mixes all met the SCDOT specification of 15% maximum loss. The filler content did not appear to have a significant effect on the Cantabro loss over the range evaluated in this study, but there was a decrease in abrasion loss by approximately 1.5% when the filler increased from 0% to 2%. The 12.5 mm mix having 6% filler (i.e., mix 12.5-6), generally performed better than the other 12.5 mm mixes.

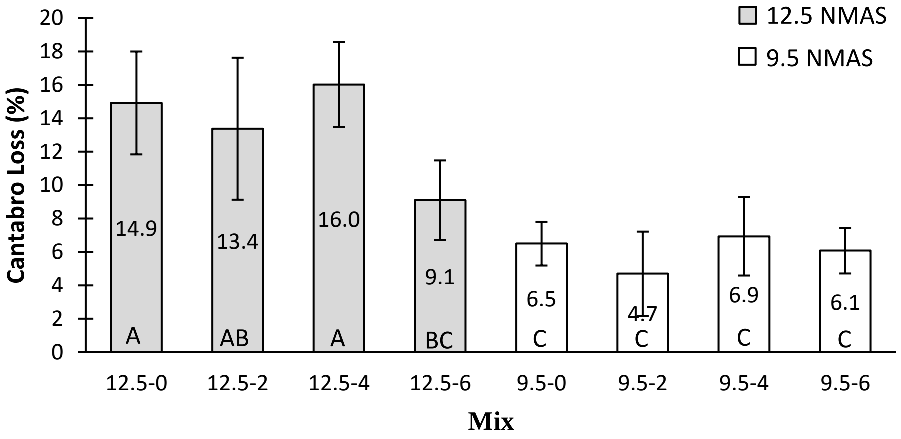


Figure 6.9. Cantabro abrasion test results of OGFC mixtures. Mixes sharing a common letter were not statistically different at α = 0.05. Error bars indicate one standard deviation from the mean.

Shear Strength

The shear strength results are presented in Figure 6.10 and show a general trend where the influence of filler content was different for the 12.5 mm NMAS mixes compared to the 9.5 mm mixes. The shear strength generally decreased as the filler content increased for the 12.5 mm mixes and the opposite trend was exhibited for the 9.5 mm mixes. Based on the statistical analysis, the only significant difference in shear strength was seen for the highest filler content of 6% for both NMAS—12.5-6 had a significantly lower shear strength than the other 12.5 mm mixes and 9.5-6 had a significantly higher shear strength than the 9.5 mm mixes having the lowest filler contents (i.e., mixes 9.5-0 and 9.5-2).

The hypothesis was that increasing the filler would increase the stiffness of the binder mastic, thereby increasing the shear strength of the entire mix. While the results of the 12.5 mm mixes were unexpected, the trend is similar to the subtle (i.e., not statistically significant) trend seen in the ITS results where there was a slight decrease in ITS as the filler content increased (Figure 6.8). This relationship between shear strength and ITS is illustrated in Figure 6.11 and shows that increasing shear strength of the mix also results in an increase in the ITS.

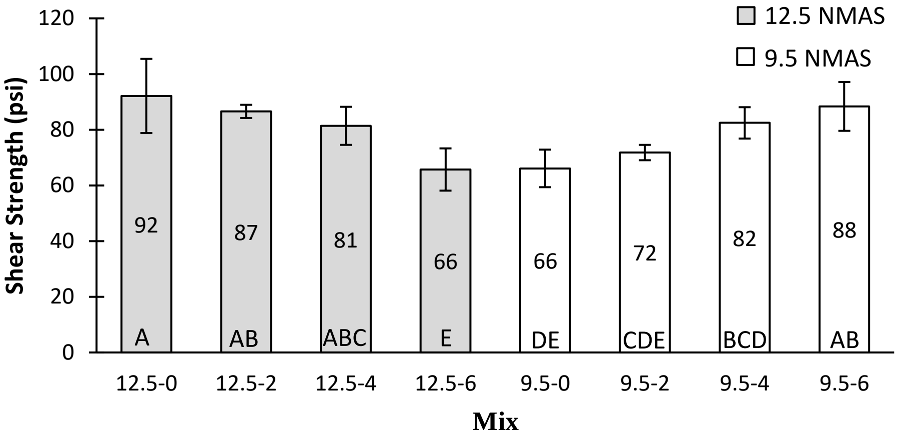


Figure 6.10. Shear strength of OGFC mixtures. Mixes sharing a common letter were not statistically different at α = 0.05. Error bars indicate one standard deviation from the mean.

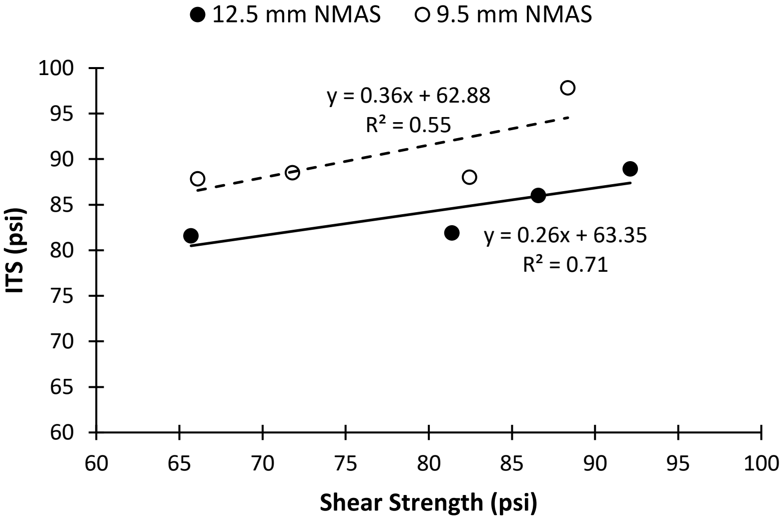


Figure 6.11. Relationship between shear strength and ITS of OGFC mixtures.

7. Influence of Compaction Temperature

Thermal segregation is a phenomenon that occurs due to inconsistency in asphalt mat temperature. Areas colder than those nearby at compaction have been shown to experience premature distresses due to lower density caused by poor compaction (Amirkhanian and Putman 2006). Several factors can lead to thermal segregation in asphalt paving including paver stops, cold spots, and hot spots. The threshold at which differences in mat temperature lead to significant loss in asphalt density is not well understood (Song et al. 2009).

Thermal imaging technologies like MOBA Pave-IR are used for real-time thermal profiling during the paving process. The Pave-IR system attaches to the back of the paver and takes thermal readings along both the width and longitudinal direction of the asphalt mat (Sebesta and Scullion 2012). This type of tool can be used to identify areas of thermal segregation and enhance pavement quality control.

Low mat temperatures can also result in issues with OGFC—perhaps even more so due to the already high void content of the OGFC mixes. In OGFC, low compaction temperature and the resulting lower density typically manifests as areas of isolated raveling commonly present at transverse cold joints, including tie-ins coming off of bridges (Putman 2012). This was further studied in OGFC test sections by Putman and Lyons (2014) where higher OGFC infiltration was present near the transverse joints, then decreased over a distance of approximately 100 ft. Infiltration has an inverse relationship with density, so the higher infiltration was due to decreased density of the OGFC. Further evaluation of the OGFC mat temperature at the time of paving showed that lower mat temperatures were recorded at the transverse joints, then gradually increased, thus supporting the original theory. The effect of lower mat temperature was more sensitive for hot mix (HMA) OGFC mixtures than for warm mix (WMA) OGFC mixtures, which exhibited a more consistent temperature during the paving start-up (Putman and Lyons 2014).

Objective

The objective of this study was to evaluate MOBA Pave-IR data from OGFC projects completed in South Carolina and determine if it can be used to identify potential areas of future distress. An additional objective was to evaluate the effect of compaction temperature on the performance HMA and WMA OGFC mixes in the lab.

Pavement Mat Temperature Field Data

MOBA Pave-IR thermal imaging data was analyzed using MATLAB and Microsoft Excel. Microsoft Excel was used to determine statistical information regarding the MOBA data obtained from the SCDOT. This information included a graphical representation of the temperature of the asphalt mat at placement along the longitudinal direction of the pavement. A sample graph of the data from a warm mix OGFC project can be seen in Figure 7.1. This sample data used in this chapter was from a WMA OGFC project on I-85 South.

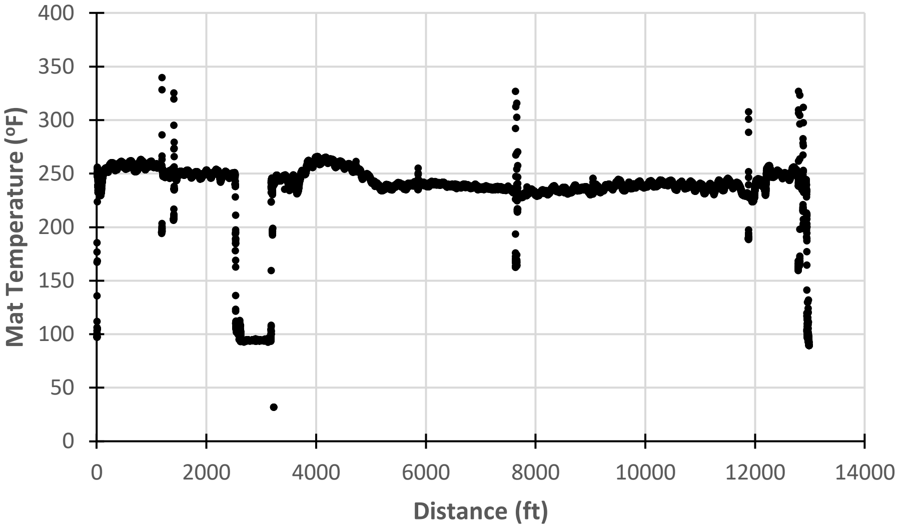


Figure 7.1. Raw pavement temperature data from a single sensor in the MOBA Pave-IR system.

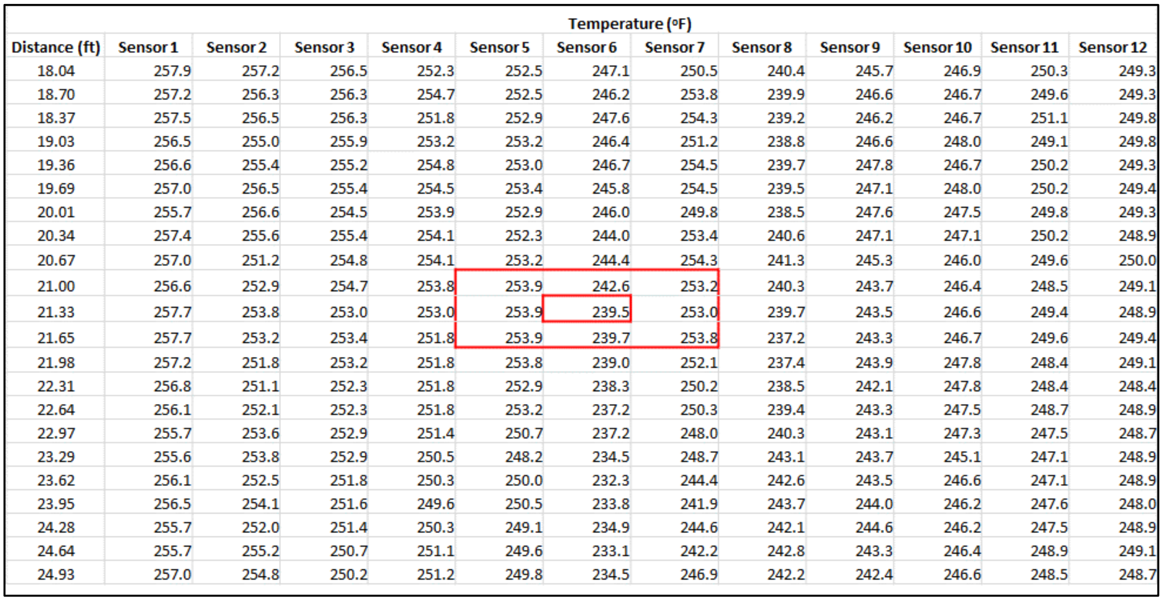
As can be seen in Figure 7.1, several temperature values are unrealistically low for placement temperatures. These temperatures can likely be attributed to the thermal sensors taking readings from existing, underlying layers or bridges. To avoid these non-mat related temperatures having an effect on further analysis, they were not considered. In the case of the project shown in Figure 1, temperatures less than 200°F were disregarded.

With non-relevant temperatures identified and disregarded, statistical analysis of the data was performed. The mean and standard deviation were found and the normal distribution and cumulative distribution functions were graphed.

MOBA currently defines thermal segregation as occurring in any section of pavement that has two temperatures varying by greater than 25°F within 150 ft of each other. While this definition may be effective in some cases, it may be ineffective in other cases. An example of a case where it may be ineffective is in the event of a gradual and uniform decrease in temperature along a 150 ft length of pavement. Although the temperature differential may be 25°F or higher within 150 ft, temperatures at any location in the mat will not vary greatly from temperatures of surrounding locations.

Using the MOBA data obtained from the SCDOT, a new technique of identifying thermal segregation was defined. A MATLAB code was written to isolate pavement temperatures varying by more than a certain temperature threshold in locations immediately surrounding the location of focus. The temperature threshold can be easily changed in the code due to the temperature threshold for thermal segregation not being well defined. Furthermore, the distance between the locations being compared can also be increased to evaluate the sensitivity of the impact that distance has on performance.

The code works by first focusing on a single cell (temperature value at a single location). The code then creates a three by three grid surrounding the center cell and compares the values of the eight cells around the center cell to the value of the center cell (Figure 7.2). If the difference is greater than the set threshold (i.e., 25°F for warm mix), a value of one is output. The code then moves on to the next cell in the row, then on to the row below once all of the values in a row have been analyzed. Hot and cold spots in the pavement mat were also identified as individual spots that either exceeded or were below threshold temperatures set in the analysis. Flexibility in identifying thresholds for thermal segregation and hot/cold spots was built-in to be able to adjust for hot mix and warm mix temperatures and ranges.



						Temperature (°F)						
Distance (ft)	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8	Sensor 9	Sensor 10	Sensor 11	Sensor 12
18.04	257.9	257.2	256.5	252.3	252.5	247.1	250.5	240.4	245.7	246.9	250.3	249.3
18.70	257.2	256.3	256.3	254.7	252.5	246.2	253.8	239.9	246.6	246.7	249.6	249.3
18.37	257.5	256.5	256.3	251.8	252.9	247.6	254.3	239.2	246.2	246.7	251.1	249.8
19.03	256.5	255.0	255.9	253.2	253.2	246.4	251.2	238.8	246.6	248.0	249.1	249.8
19.36	256.6	255.4	255.2	254.8	253.0	246.7	254.5	239.7	247.8	246.7	250.2	249.3
19.69	257.0	256.5	255.4	254.5	253.4	245.8	254.5	239.5	247.1	248.0	250.2	249.4
20.01	255.7	256.6	254.5	253.9	252.9	246.0	249.8	238.5	247.6	247.5	249.8	249.3
20.34	257.4	255.6	255.4	254.1	252.3	244.0	253.4	240.6	247.1	247.1	250.2	248.9
20.67	257.0	251.2	254.8	254.1	253.2	244.4	254.3	241.3	245.3	246.0	249.6	250.0
21.00	256.6	252.9	254.7	253.8	253.9	242.6	253.2	240.3	243.7	246.4	248.5	249.1
21.33	257.7	253.8	253.0	253.0	253.9	239.5	253.0	239.7	243.5	246.6	249.4	248.9
21.65	257.7	253.2	253.4	251.8	253.9	239.7	253.8	237.2	243.3	246.7	249.6	249.4
21.98	257.2	251.8	253.2	251.8	253.8	239.0	252.1	237.4	243.9	247.8	248.4	249.1
22.31	256.8	251.1	252.3	251.8	252.9	238.3	250.2	238.5	242.1	247.8	248.4	248.4
22.64	256.1	252.1	252.3	251.8	253.2	237.2	250.3	239.4	243.3	247.5	248.7	248.9
22.97	255.7	253.6	252.9	251.4	250.7	237.2	248.0	240.3	243.1	247.3	247.5	248.7
23.29	255.6	253.8	252.9	250.5	248.2	234.5	248.7	243.1	243.7	245.1	247.1	248.9
23.62	256.1	252.5	251.8	250.3	250.0	232.3	244.4	242.6	243.5	246.6	247.1	248.9
23.95	256.5	254.1	251.6	249.6	250.5	233.8	241.9	243.7	244.0	246.2	247.6	248.0
24.28	255.7	252.0	251.4	250.3	249.1	234.9	244.6	242.1	244.6	246.2	247.5	248.9
24.64	255.7	255.2	250.7	251.1	249.6	233.1	242.2	242.8	243.3	246.4	248.9	249.1
24.93	257.0	254.8	250.2	251.2	249.8	234.5	246.9	242.2	242.4	246.6	248.5	248.7

Figure 7.2. Sample of MOBA Pave-IR data showing the cell of interest and comparison cells in the thermal segregation process used in this study.

Once the data was organized and processed using MATLAB, the results were entered into ArcGIS to provide a visual representation of the results. The values represented in the GIS included locations of paver stops and thermal segregation. Results from the WMA OGFC project example are shown in Figures 7.3-7.6.

Figure 7.3 shows the temperature profile of the pavement across the width and along the length of the project (i.e., approximately 2.5 miles). This data reflects that seen in Figure 7.1. After start-up, there is 650 ft section where there appears to be a severe drop in temperature. This is a bridge section that was not paved with OGFC, but while traveling over the bridge, the data was still collected. This section is also seen in Figure 7.1.

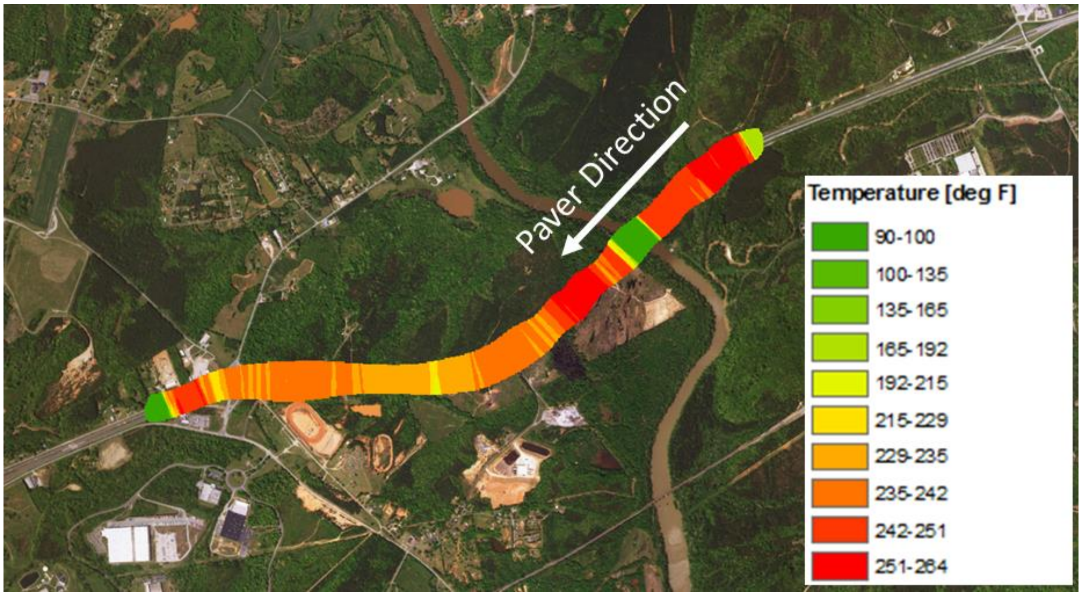


Figure 7.3. Temperature profile of the pavement mat during construction.

The locations where thermal segregation was present are shown in Figure 7.4. These could be areas to monitor over time for distress such as raveling. This type of information could also be used to follow-up with further evaluation of the OGFC mix such as in-place infiltration or coring. This would allow the SCDOT to identify whether the material in these areas meet certain threshold criteria.

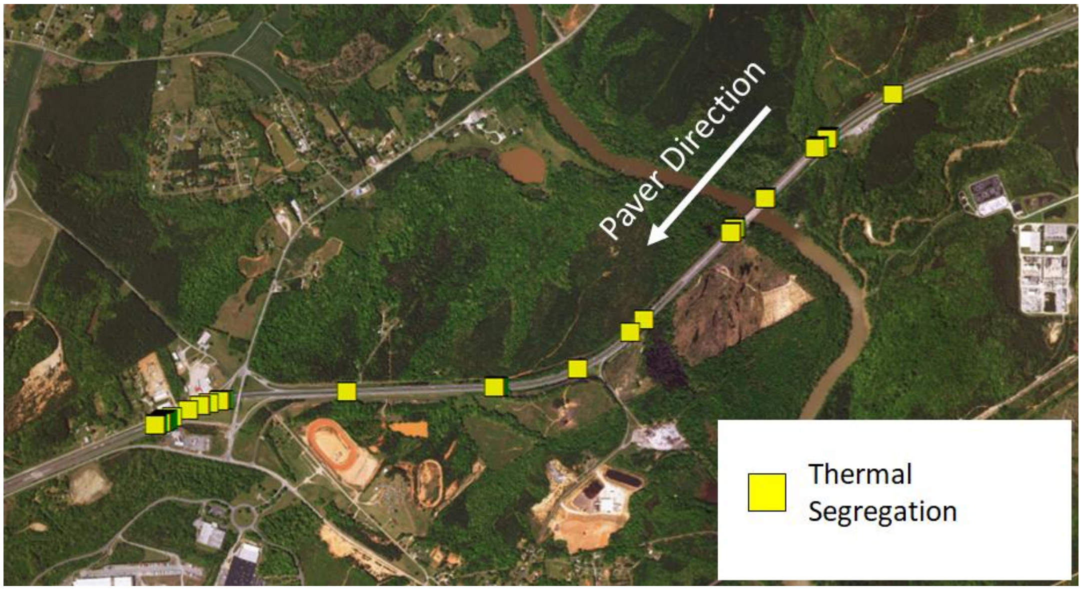


Figure 7.4. Locations of thermal segregation (25°F).

In addition to inconsistent mix temperature, paver stops also results in thermal segregation. While the paver waits during a stop, the section of the mat under and near the screed cannot be compacted by the rollers. As a result, when the paver starts to move again, the section under the paver has cooled, potentially substantially, and cannot be compacted to the same level as the surrounding areas. This can cause potential performance issues. The paver stops were overlaid with the locations of thermal segregation in Figure 7.5. In this data set there were 10 paver stops and nine (90%) were at locations of where thermal segregation was present.

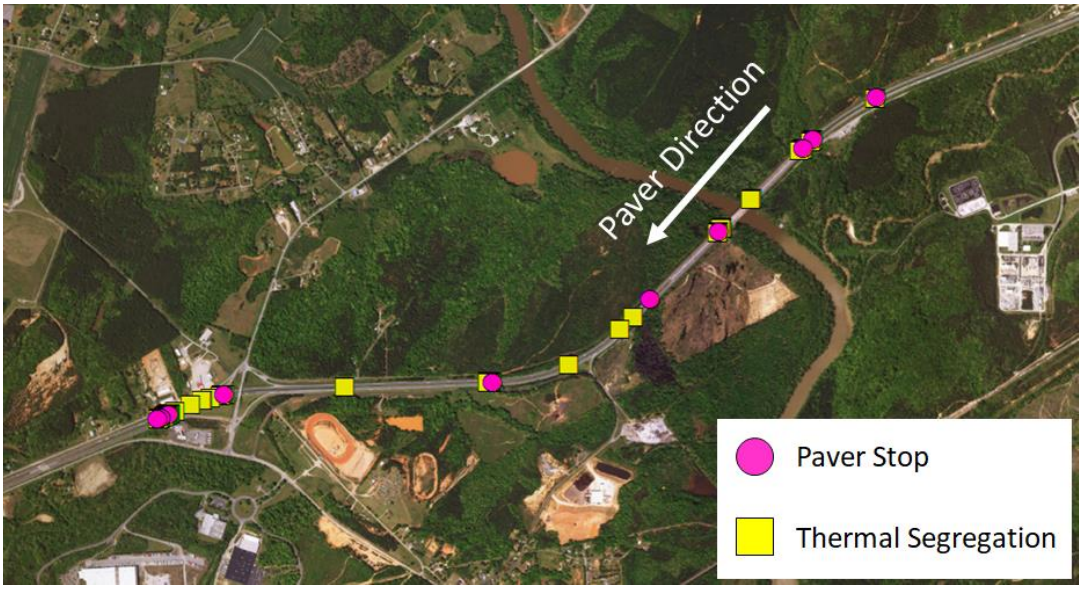


Figure 7.5. Locations of paver stops and thermal segregation overlaid.

At the time of this study, there was no evidence of distress at the thermal segregation or paver stops identified on this particular paving project.

Influence of Compaction Temperature

Following the review of pavement temperature data, a lab study was conducted to evaluate the potential impacts of reduced compaction temperature on the performance of OGFC mixtures in the lab. This included the evaluation of a plant-produced WMA OGFC mix and a lab-produced HMA OGFC mix. The plant-mix was sampled at the plant and transported to the lab where it was heated to a specific compaction temperature for two hours prior to compacting six specimens (150 mm diameter by 115±5 mm tall) with 50 gyrations of the Superpave Gyratory Compactor (SGC) for each temperature. For the WMA mix, the compaction temperatures included 215°F, 240°F, 265°F, and 290°F. The HMA mix was mixed in the lab at a single mixing temperature, then specimens were compacted at 265°F, 290°F, and 315°F. The compaction temperatures were selected to start with a typical temperature (about 290°F for

HMA and 250°F for WMA) and go above and below these temperatures. The range was increased for the WMA mix to gain a better understanding of the consequences of low compaction temperature.

Specimens prepared at each compaction temperature were tested to measure the porosity, then divided into two sample sets of three specimens each. One sample set was tested to measure the ITS and the other was tested using the Cantabro abrasion test. Figure 7.6 summarizes the effect of compaction temperature on the porosity of the mixes. The HMA follows the expected trend where the porosity generally increased with decreasing compaction temperature due to the increasing viscosity of the binder which reduces the workability/compactability of the mix. The WMA, however, was not affected by compaction temperature in the same manner as the HMA. The lower compaction temperatures resulted lower porosity compared to the higher temperatures. This is finding is likely due to the nature of the Evotherm® additive that was used in the WMA mixes. Evotherm® is a chemical additive that improves that compactability of an asphalt mixture at lower temperatures (Prowell et al. 2007; Wielinski et al. 2009). This was also seen in the field data collected by Putman and Lyons (2014).

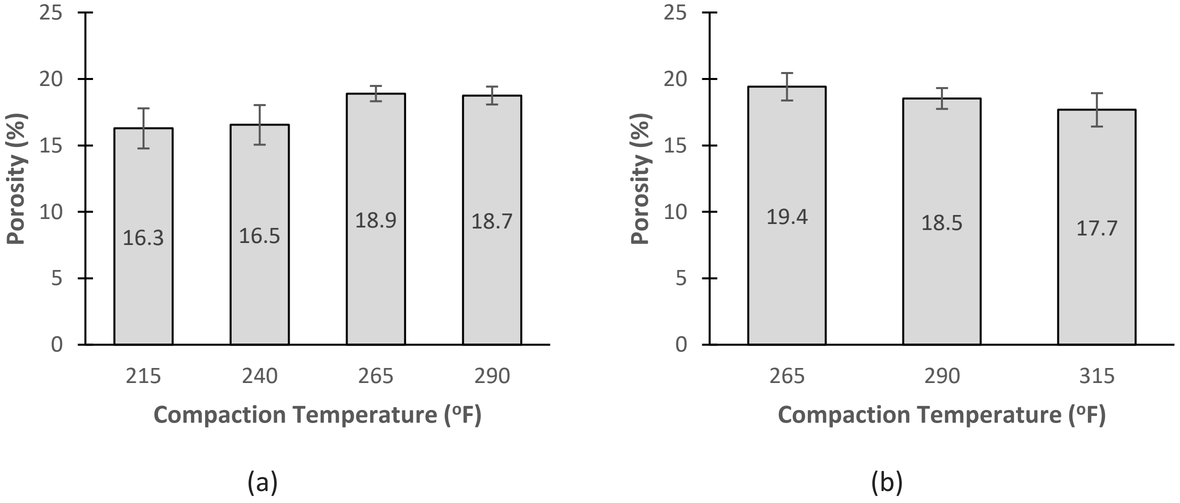
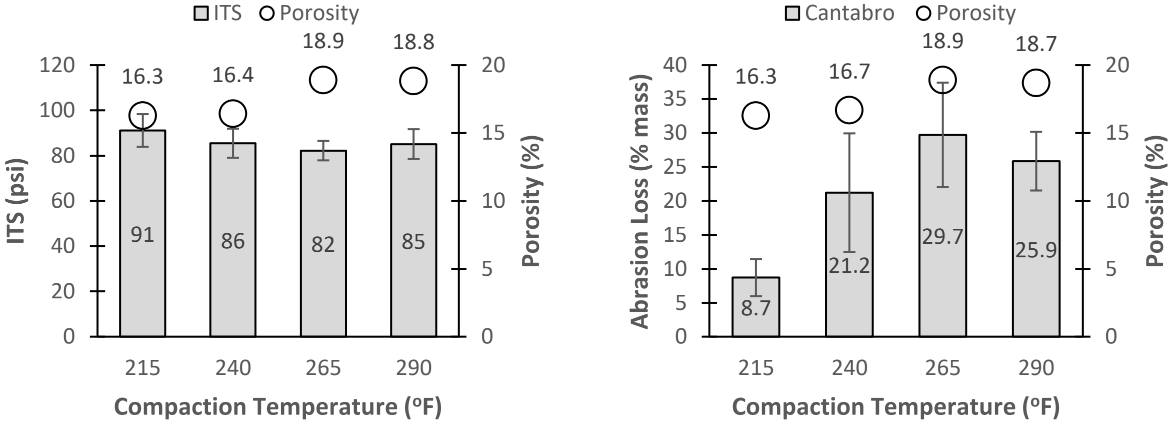


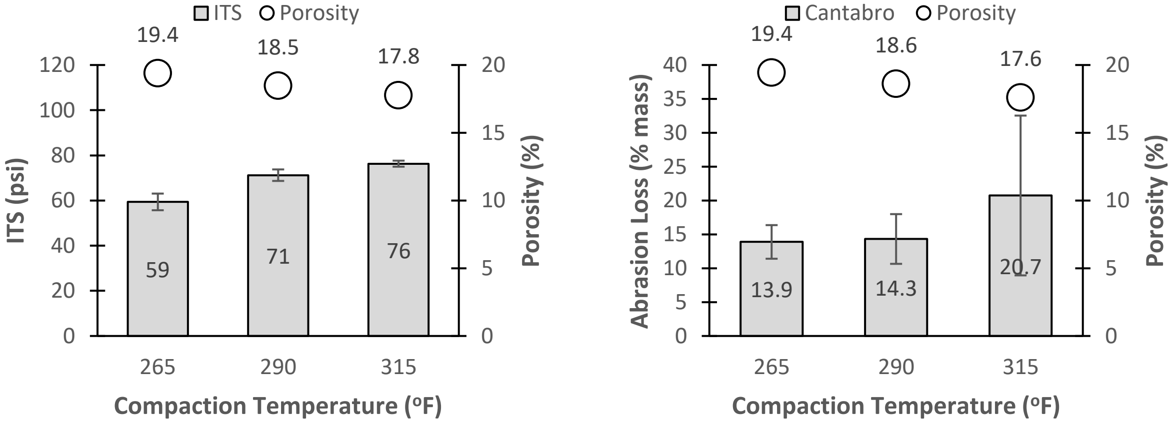
Figure 7.6. Porosity of (a) warm mix OGFC and (b) hot mix OGFC compacted at different temperatures.

The influence of the compaction temperature on the ITS and Cantabro tests are summarized in Figures 7.7 and 7.8 for the WMA and HMA mixes, respectively. It should be noted that the porosity values in these figures are the average values for the specimens used for the specific test (i.e., ITS or Cantabro), whereas the porosity reported in Figure 6 are the average porosity of all specimens combined for a given temperature. For the WMA mix, the results exhibit the trend that increasing the porosity generally reduces the ITS and increases the Cantabro loss. The results also showed that the abrasion loss in the Cantabro test was significantly lower for the specimens compacted at 215°F compared to those compacted at 240°F, even though the porosity was similar. This could potentially be due to the reduced level of oxidative aging experienced at the lower temperature while heating the mixes to the appropriate temperature. The HMA followed the anticipated trend for the ITS, but the Cantabro loss generally increased with decreasing porosity. The results were not significantly different, however.



(a) (b)

Figure 7.7. Lab performance of warm mix OGFC compacted at different temperatures (a) ITS and (b) Cantabro abrasion test.



(a) (b)

Figure 7.8. Lab performance of hot mix OGFC compacted at different temperatures (a) ITS and (b) Cantabro abrasion test.

8. Laboratory Durability Test Methods

Research Objectives and Scope

The primary objective of this study was to evaluate multiple laboratory test methods to assess the raveling susceptibility of OGFC mixtures and the study was divided into two phases:

1. Assess the influence of binder content on the performance in the different test methods.
2. Evaluate the influence of long-term aging on the performance of the OGFC mixture in the different test methods.

Experimental Methods

Materials

For Phase 1, the materials used in the preparation of the mixes consisted of aggregate (i.e., single source, one gradation), cellulose fibers (i.e., 0.3% by mixture weight), one grade of asphalt binder (PG 76-22), and hydrated lime (i.e., 1% by aggregate weight). The main component of each mix that was varied was the binder content (i.e., 5%, 6%, and 7%). For Phase 2, the materials used in the preparation of the specimens consisted of a plant-mixed OGFC that consisted of aggregate (i.e., single source, single gradation), one grade of asphalt binder (i.e., warm-mix asphalt using Evotherm® WMA additive), and hydrated lime (i.e., 1% by aggregate weight).

Table 8.1, shows the mix design data for the material. For Phase 1, the only component varied was the binder content for each set of specimens, which included 5%, 6%, and 7% by total mixture weight. Fifteen specimens were compacted per a binder content and tested for the porosity, indirect tensile strength, direct shear strength, Cantabro abrasion loss, and two surface raveling tests (i.e., circular and planetary).

For Phase 2, the only component that varied per set of specimens for the raveling susceptibility portion of this study was the type of aging that the specimen endured. One set of 24 specimens were tested un-aged and another set of 25 specimens were aged for 56 days at 60°C.

Table 8.1. Mix Design Information

Mix Design Properties	Phase 1 Lab Produced	Phase 2 Plant-Mix
Gradation		
¾ in.	100	100
½ in.	94.0	93.8
⅜ in.	69.0	67.9
No. 4	19.0	23.1
No. 8	6.0	-
No. 30	4.0	-
No. 100	2.3	10.7
No. 200	1.0	1.72
Binder Type	PG 76-22	PG 76-22
Viscosity @ 135°C	0.87 Pa-s	1.138 Pa-s
G*/sinδ @ 76°C	-	1.11 kPa
δ @ 76°C	-	74.8°
Binder Content	5.0, 6.0, & 7.0	6.03
Anti-Strip Additive	Hydrated Lime (1% by aggregate weight)	Hydrated Lime (1% by aggregate weight)
Production Temperature	325°F	270°F
Additives	Cellulose Fibers (0.3% by mixture weight)	Evotherm® added at the terminal at a rate of 0.5% by weight of binder.

Methods

To fulfill the objective of this study for Phase 1, 3800g compacted asphalt specimens were made for testing porosity, abrasion resistance, and indirect tension strength). Fifteen compacted specimens were made for each mix at a specific binder content (i.e., 5%, 6%, and 7%). The specimens were compacted with 50 gyrations of the Superpave Gyratory Compactor to a height of 115±5 mm.

For Phase 2, 3900g specimens were produced by reheating and weighing the sampled plant mix. The specimens were then compacted with 50 gyrations at the target temperature of 255°F to a height of 115±5 mm.

The porosity of each specimen was measured using the procedure outlined in SC-T-128 (SCDOT 2013a). After the porosity testing was complete, the porosity data was used to group the specimens to ensure that each group was representative of the overall mix design properties. To verify that the test groups were statistically similar with respect to porosity, an analysis of variance (ANOVA) was performed using $\alpha=0.05$.

In Phase 2, half of the specimens were tested un-aged and half were aged for 56 days at 60°C. OGFC specimens are susceptible to deformation at higher temperatures so all the aged specimen were wrapped with wire mesh before placement in the environmental chamber (Figure 3.1).

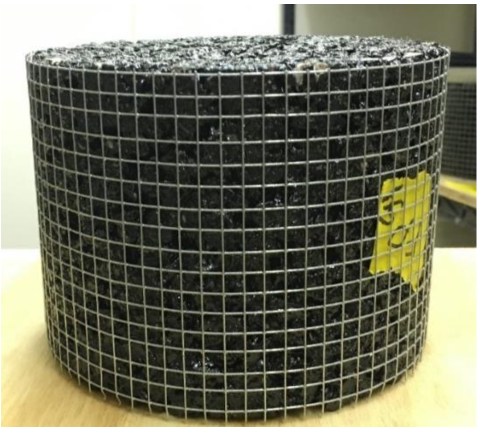


Figure 8.1. Specimen wrapped in wire mesh for aging at 60^{o}C

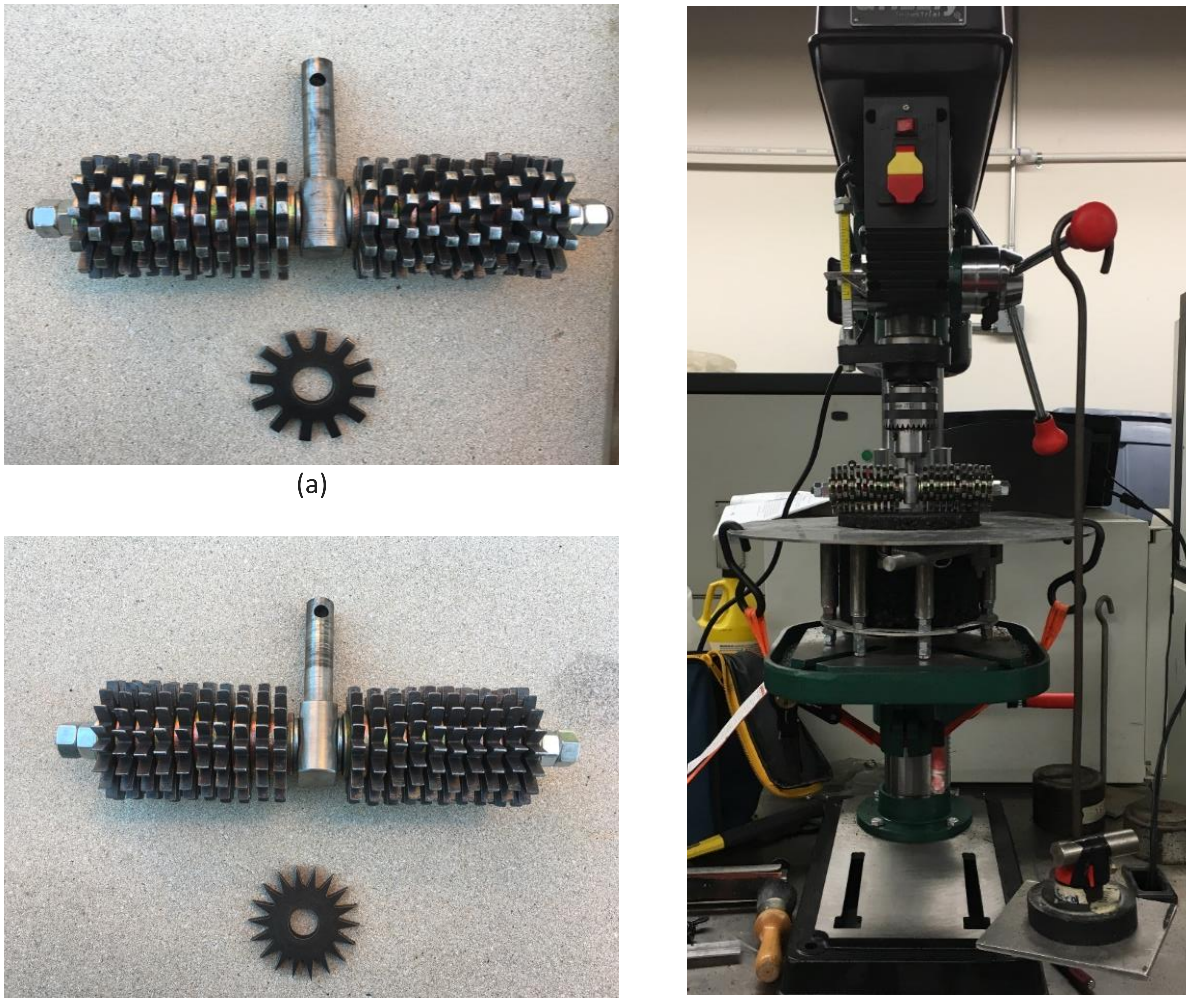
For both phases of this study, the un-aged and aged specimens were subjected to the following test methods: Cantabro abrasion (SC-T-127), indirect tension test (ITS) (SC-T-70), direct shear strength test (AASHTO TP-114), circular motion surface abrasion test, planetary motion surface abrasion test, and indirect tensile strength.

Experimental Surface Abrasion Tests

In this study, two experimental test methods were developed to evaluate the raveling resistance in comparison with the other test methods. These two experimental methods are referred to as the circular motion surface abrasion test and the planetary motion surface abrasion test.

Circular Motion Surface Abrasion Test

The circular motion surface abrasion test was used to measure the abrasion resistance of the surface of the OGFC specimens and used the procedure outlined in ASTM C944: *Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method* as a guideline (ASTM 2012). The test apparatus consists of two rotating cutter heads, a specimen adapter base and drill press (Figure 8.2). The difficulty in maintaining a constant load on the abrading cutter when using the lever, gear and spring system of a drill press was addressed by placing a constant load of 98 N (22 lb.) directly upon the spindle that turns the cutter. The cutter rotated at a constant rate of 240 rpm. The specimen was placed into the adapter base so that 10 mm of the specimen was above the raveling test adapter base.



(a)

(b)

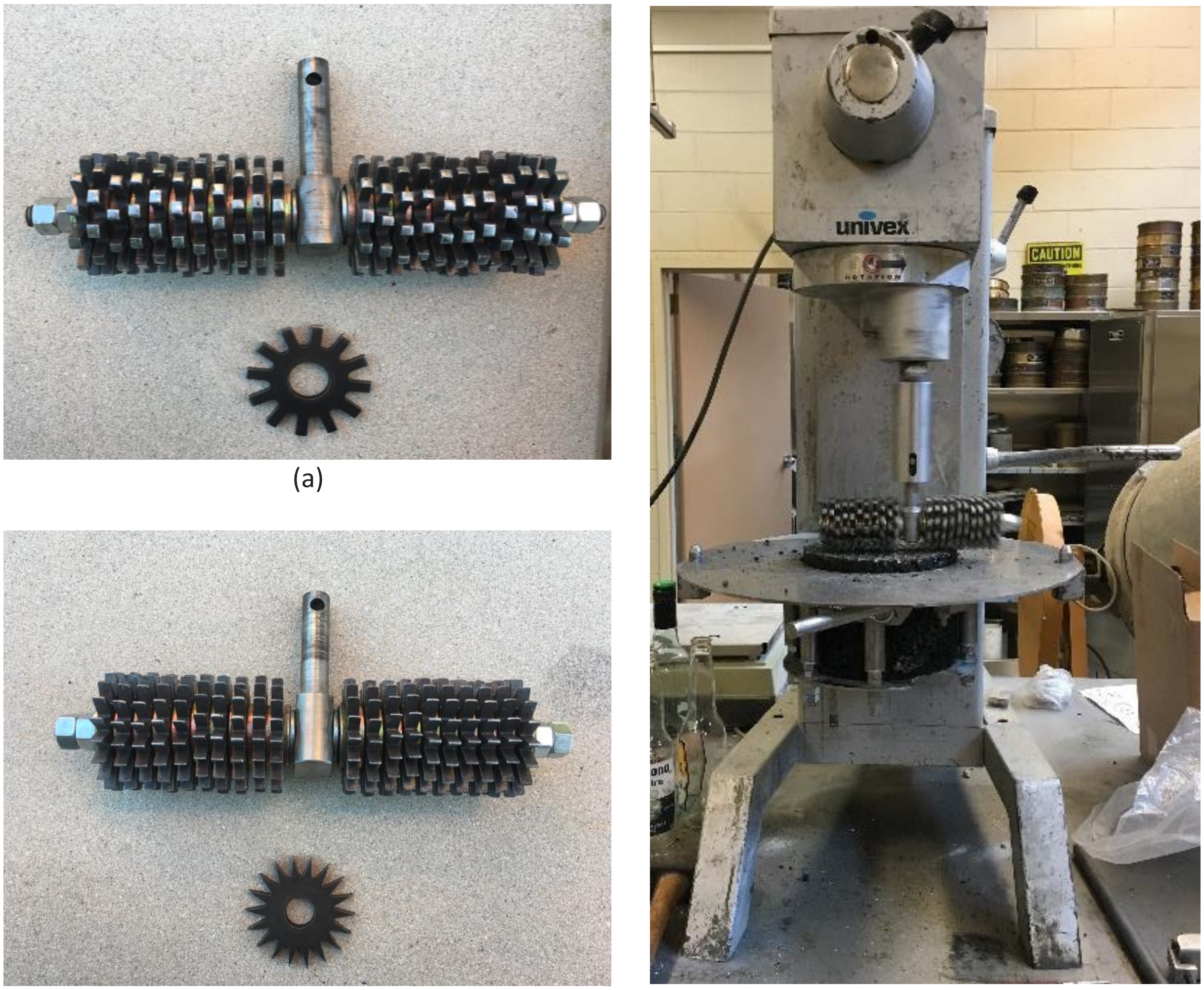
(c)

Figure 8.2. Components of the circular motion surface abrasion test set-up (a) test head A (square rotating cutter head, (b) test head B (triangular rotating cutter head, and (c) complete test set-up.

The initial weight of the specimen was recorded, then the specimen was placed in the adapter base and tightly secured. The motor was started, then the testing head was slowly lowered until it made contact with the surface of the specimen. The specimen was abraded for five minutes, then removed from the adapter base and the surface was cleaned with a soft brush to remove any loose debris followed by blowing the specimen with an air hose for ten seconds in a circular motion. After recording the mass of the specimen, the specimen was then placed back into the adapter base, and the process was repeated for five more five-minute cycles (i.e., 30 minutes total). The percent mass loss was then calculated after each cycle by dividing the cumulative mass loss by the initial mass of the specimen.

Planetary Motion Surface Abrasion Test

The Standard Test Method for Raveling Test for Cold Mixed Emulsified Asphalt Samples (ASTM D7196) was also used as a guideline to measure the surface abrasion resistance of the OGFC mixtures (ASTM 2012). This procedure was similar to the circular motion test, but instead using a drill press, a mixer similar to a Hobart Mixer, model A 120, having a compound planetary rotation that rotated at 72 rpm was used (Figure 8.3). Instead of using a rubber-testing adapter as per the standard, the same rotating cutter heads, A and B, used in the circular motion procedure where also used in this procedure. The test was conducted in the same manner as the circular motion method described above.



(a)

(b)

(c)

Figure 8.3. Components of the planetary motion surface abrasion test set-up (a) test head A (i.e., square rotating cutter head), (b) test head B (i.e., triangular rotating cutter head), and (c) complete test set-up.

RESULTS AND DISCUSSION

Phase 1: Effect of Binder Content on Performance

The average porosity of all specimens is presented in Figure 8.4 and the results of the performance tests are summarized in Figure 8.5. All of the results indicate that the strength and abrasion resistance increases as the binder content increases in all cases. This is the anticipated trend and preliminarily indicate that all of the test procedures are in agreement. The increases in ITS and shear strength indicate an increase in cohesion due to additional binder content, which also results in the decrease in abrasion resistance seen in the Cantabro and surface abrasion tests. The planetary motion surface abrasion test yielded greater mass loss due to the nature of the rotation compared to the circular motion test. It should be noted that the porosity could have also influenced the performance results. However, when comparing the different test procedures, the trends remain consistent whether the effect be due to binder content or porosity.

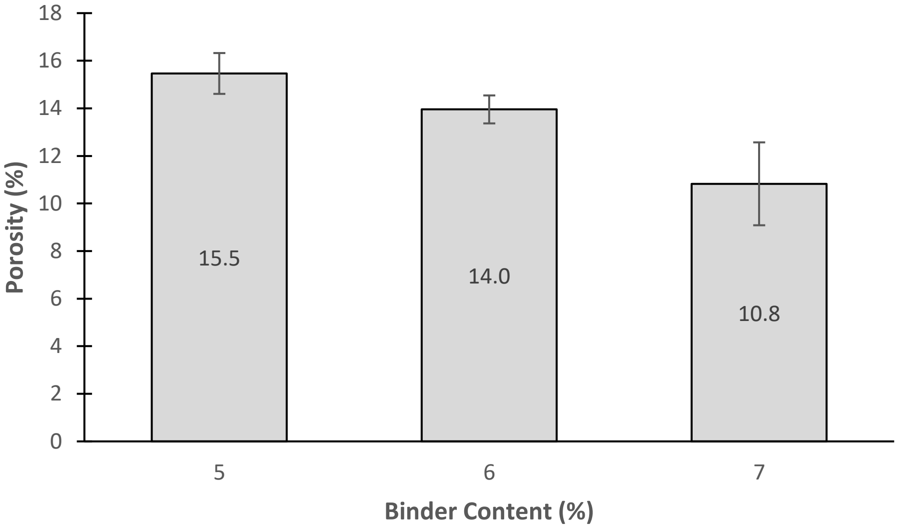
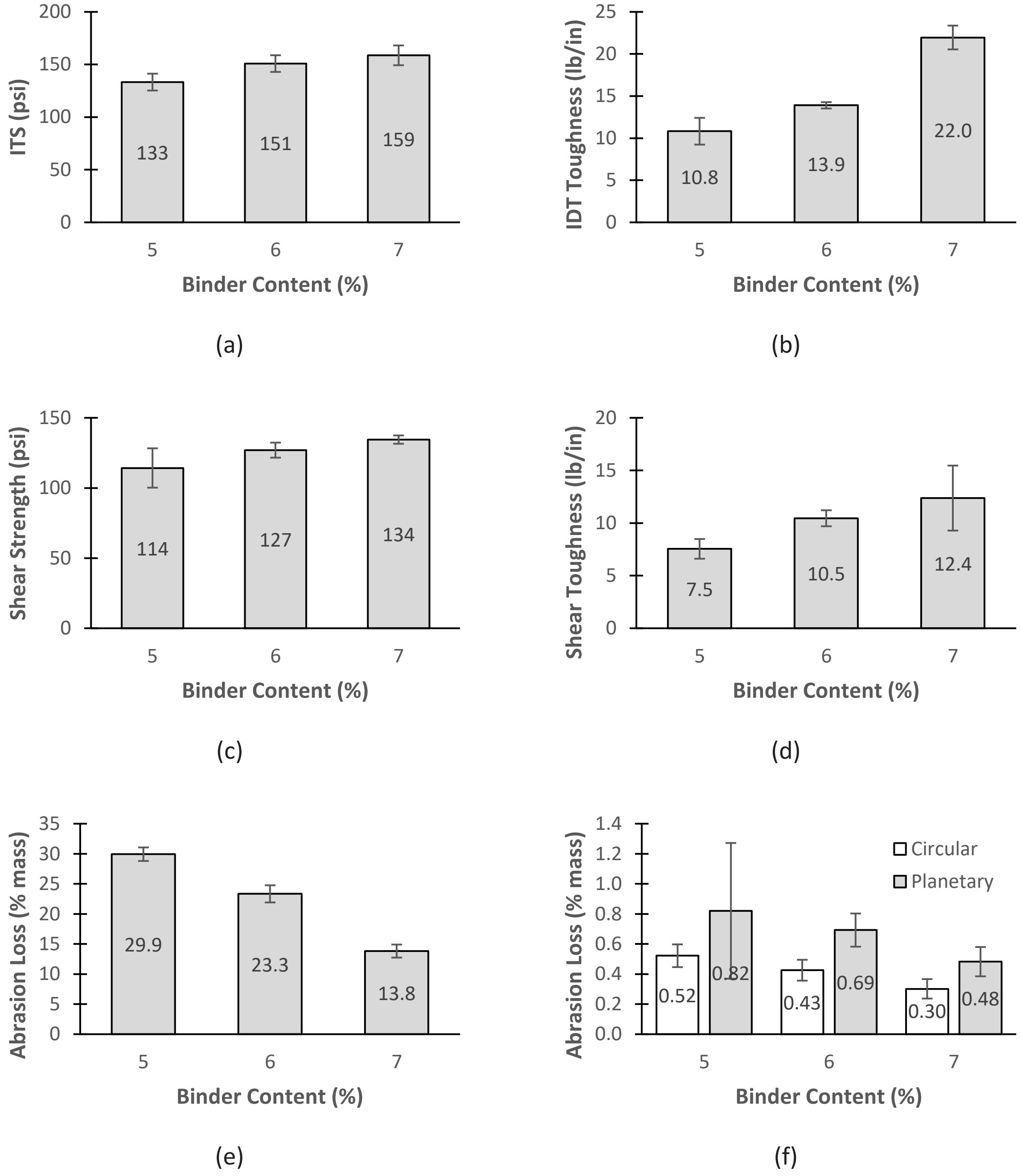


Figure 8.4. Average porosity of OGFC specimens with varying binder content



(a) (b) (c) (d) (e) (f)

Figure 8.5. Phase 1 test results: (a and b) indirect tension test, (c and d) direct shear test, (e) Cantabro abrasion test, and (f) surface abrasion tests. (Error bars indicate one standard deviation)

Phase 2 Effect of Long-Term Aging on Performance

The results of the performance tests conducted on plant-produced OGFC mix in an unaged condition and after aging at 60°C for 56 days are summarized in Figure 8.6. The results show that the ITS and shear strength increase after aging while the Cantabro abrasion loss also increase. This indicates that while the increase in binder stiffness due to aging increases the ultimate strength of the mix, it also increases the raveling susceptibility as measured by the Cantabro test. When looking at the surface abrasion tests, the aging results in a decrease in abrasion loss in all cases (i.e., both rotational methods and both testing heads). This reflects the trends seen in the strength tests, not the Cantabro test.

More detailed results of the surface abrasion tests are included in Figures 8.7 and 8.8 that show the abrasion loss over time for each aging condition (unaged and aged) and testing head (A and B). Also included are the rates of abrasion loss calculated as the slope of the data. The planetary motion was more severe than the circular motion resulting in greater loss of material during the test. In addition, test head B was generally more aggressive than head A due to its star-like shape which can dig into the surface and dislodge material more easily. This effect was especially compounded with the planetary motion test. It was interesting to note that the testing heads resulted in opposite trends in abrasion rate (slope) after aging for each test. For the circular motion test, the rate of abrasion increased for Head A after aging, but decreased for Head B. The opposite was seen for the planetary motion where the rate of abrasion decreased for Head A and increased for Head B after aging.

The trend seen with the planetary motion using Head B more closely reflects the hypothesis that aging will increase the raveling susceptibility over time—the as the binder becomes more brittle with age, it has the potential to fail under repeated stress, thus progressively causing particles to ravel. The same trend is seen in the Cantabro test. When comparing the dislodged particles from the Cantabro test with the planetary and circular motion surface abrasion tests in Figure 8.9, it is evident that the Cantabro test results in more fracturing of the aggregate particles due to impact than the surface abrasion test methods that exhibited both particle dislodgment and fracture.

Binder Properties

Table 8.2 shows the binder properties for the asphalt binder collected from the plant (prior to mixing), extracted from compacted un-aged specimens (after plant mixing and lab compaction), and extracted from compacted 56 day aged specimens (after plant mixing, lab compaction, and aging). The viscosity and G*/sinδ of the binder tested at 76°C increases with aging, indicating an increase in stiffness of the binder. The G*sinδ at 31°C and stiffness at -12°C of the PAV aged binder also increased significantly with aging, also indicating the increased stiffness at low temperatures that can result in more brittle failure of the material. The increase in brittleness of the binder, makes the OGFC mix more susceptible to raveling over its service life.

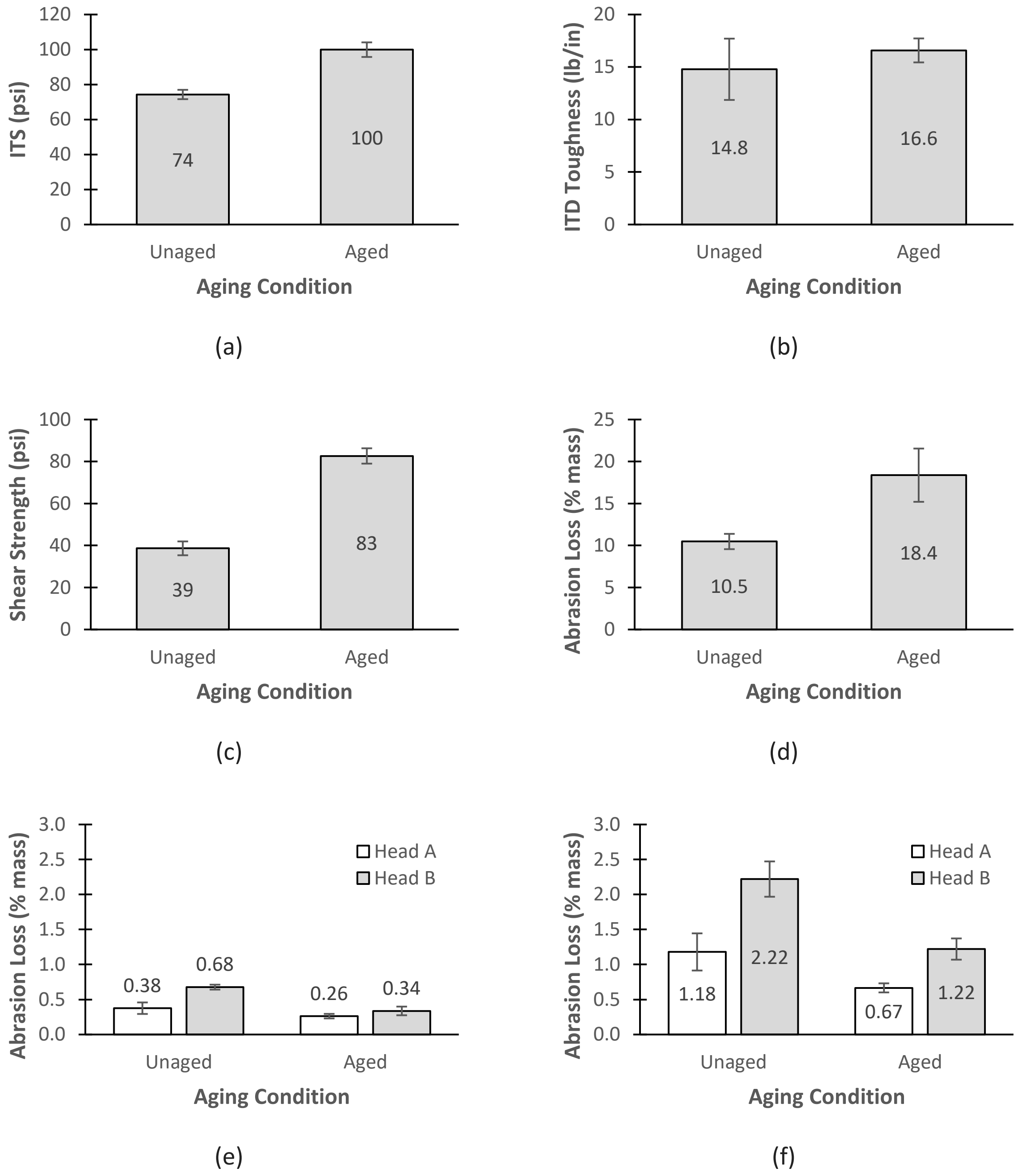
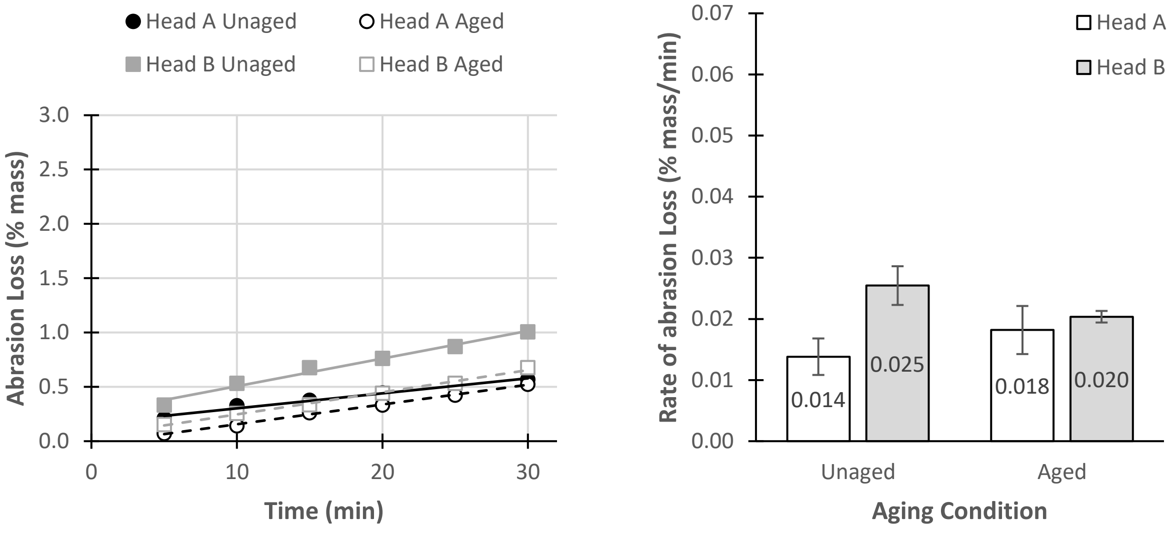
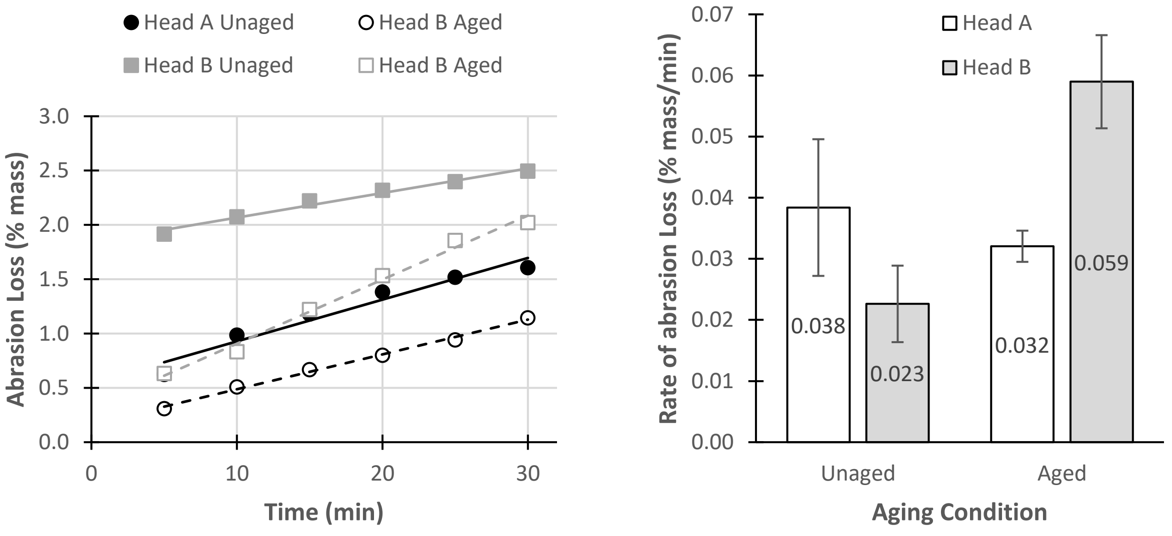


Figure 8.6. Phase 1 test results: (a and b) indirect tension test, (c) direct shear test, (d) Cantabro abrasion test, (e) circular motion surface abrasion test, and (f) planetary motion surface abrasion test. (Error bars indicate one standard deviation)



(a) (b)

Figure 8.7. Circular motion surface abrasion loss results in aged and unaged condition and with test heads A and B (a) loss over time and (b) average rate of abrasion loss.



(a) (b)

Figure 8.8. Planetary motion surface abrasion loss results in aged and unaged condition and with test heads A and B (a) loss over time and (b) average rate of abrasion loss.

Figure 8.9. Dislodged aggregate particles from the Cantabro abrasion test method, planetary motion test method, and circular motion test method (left to right).

Table 8.2. Binder Properties

Property	**Binder Condition**		
	Plant	**Compacted Un-Aged (Extracted)**	**Compacted Aged (Extracted)**
Original			
Viscosity @ 135°C	1.140 Pa·s	1.890 Pa·s	3.160 Pa·s
G*/sinδ@ 76°C	1.219 kPa	2.381 kPa	5.035 kPa
RTFO Aged			
Mass Change	-0.337%	N/A	N/A
G*/sinδ @ 76°C	2.702 kPa	N/A	N/A
PAV Aged			
G*sinδ@ 31°C	1477 kPa	1496 kPa	2213 kPa
Stiffness @ -12°C	143 MPa	135 MPa	174 MPa
m-value @ -12°C	0.358	0.359	0.321

9. Tack Coat

Objectives and Scope

The primary objective of this portion of the study was to investigate factors that affect bonding of OGFC layers to underlying asphalt layers. This was conducted in two phases:

1. Evaluate the influence of the tack coat products and application rates on the permeability and bond strength of composite specimens.
2. Evaluate the influence of OGFC gradation and compaction effort on the bond strength of composite layers.

Experimental Methods

To accomplish the objective of this study, composite specimens were prepared in the lab with OGFC mix (i.e., plant-mixed for Phase 1 and lab-produced for Phase 2) and plant-mixed Surface Type A mix meeting the respective SCDOT specifications (SCDOT 2016; SCDOT 2017). The plant-mixed materials were obtained from separate asphalt plants and the mixtures are summarized in Table 9.1.

Table 9.1. Job Mix Formulas (JMF) of Plant-Mixed Asphalt Mixes Used for This Study

Aggregate	**Surface Course**	**OGFC**
Sieve	**Percent Passing**	
¾ in (19 mm)	100	100
½ in (12.5 mm)	97.0	94.0
⅜ in (9.5 mm)	85.0	65.0
No. 4 (4.75 mm)	48.0	23.0
No. 8 (2.36 mm)	33.0	11.0
No. 30 (600 µm)	21.0	5.0
No. 100 (150 µm)	7.6	3.1
No. 200 (75 µm)	4.0	1.9
Binder	PG 76-22 (SBS) (5.2% by total mix weight)	PG 76-22 (SBS) (6.0% by total mix weight)
Anti-Stripping Agent	Hydrated Lime (1.0% by aggregate weight)	Hydrated Lime (1.0% by aggregate weight)
Other Additives	N/A	Evotherm® (0.5% by binder weight)
Production Temperature	325°F (163°C)	270°F (132°C)
Compaction Temperature	315°F (157°C)	260°F (127°C)

Five different tack coat products were evaluated in Phase 1. Two products were hot applied binder tack coat products (i.e., PG 64-22 and UltraFuse®) that are straight binder products that are applied to the pavement surface at temperatures high enough to reduce the viscosity to facilitate spraying (Table 9.2). Three emulsified asphalt products (i.e., CRS-2, HFMS-1H, and UltraTack®) were also evaluated (Table 9.3). Each tack coat product was evaluated at three different rates: 0.033, 0.065, and 0.098 gal/yd^2 of residual binder (i.e., equivalent to 0.05, 0.1 and 0.15 gal/yd^2 of emulsion).

Table 9.2. Properties of Hot Applied Binder Tack Coat Products

	PG 64-22	**UltraFuse®**
Viscosity (Pa·s)	0.482 @ 135°C	1.785 @ 149°C
Original G*/sinδ (kPa)	1.78 @ 64°C	17.3 @ 82°C
Original Phase Angle (°)	88.1 @ 64°C	68.3 @ 82°C
Notes		Non-tracking

Table 9.3. Properties of Emulsion Tack Coat Products

	CRS-2	**HFMS-1H**	**UltraTack®**
Viscosity, SFS (s)	329 @ 50°C	46 @ 25°C	64 @ 25°C
Distillation Residue (%)	73.4	59.9	52.7
Penetration @ 25°C (dmm)	133	61	3
Notes			Non-tracking

In Phase 2, eight different OGFC aggregate gradations were designed and analyzed for the upper layer of composite specimens that also included a lower layer of Surface Type A as in Phase 2 and a tack coat of UltraTack at an application rate of 0.033 gal/yd^2. These OGFC gradations were designed by varying the percent passing the No. 4 sieve (i.e., 10, 20, 30, and 40% for the 12.5 mm NMAS mix and 20, 30, 40, and 50% for the 9.5 mm NMAS) as described in Chapter 6 (Table 9.4). However, a different aggregate source was used in this study to be consistent with the materials used in Phase 1. As in Chapter 6, each treatment is named with a two number code (e.g., 12.5-30). In this code, the 12.5 and 9.5 represent the nominal maximum aggregate size (NMAS) and the number after the dash represents the percent passing the No. 4 sieve (4.75 mm). For example, 12.5-30 means the NMAS was 12.5 mm and there was 30 percent passing the No. 4 sieve.

Table 9.4. OGFC Gradations Evaluated in the Phase 1 Study on Percent Passing the No. 4 Sieve

	Percent Passing							
	12.5 mm NMAS				9.5 mm NMAS			
Sieve Size	**12.5-10**	**12.5-20**	**12.5-30**	**12.5-40**	**9.5-20**	**9.5-30**	**9.5-40**	**9.5-50**
¾ in (19.0 mm)	100	100	100	100	100	100	100	100
½ in (12.5 mm)	95	95	95	95	100	100	100	100
⅜ in (9.5 mm)	65	65	65	65	90	90	90	90
No. 4 (4.75 mm)	10	20	30	40	20	30	40	50
No. 8 (2.36 mm)	10	10	10	10	10	10	10	10
No. 200 (0.075 mm)	2	2	2	2	2	2	2	2
D_{10}	2.36	2.36	2.36	2.36	2.36	2.36	2.36	2.36
D_{60}	8.99	8.88	8.71	8.41	7.24	6.90	6.44	5.77
C_u	3.81	3.76	3.69	3.56	3.07	2.92	2.73	2.45

Methods

For this study, three 150 mm diameter by 100 mm tall composite specimens were prepared for each treatment. Each specimen was prepared in two stages: (1) compaction of the base layer and (2) compaction of OGFC surface layer. The 50 mm tall base layers were prepared by compacting 4315 g of the plant-mixed Surface Type A (STA) to a height of 105 mm with the Superpave gyratory compactor (SGC) at a temperature of 315°F (157°C). Each specimen was then cut in half to yield two 50 mm tall specimens. This was repeated to produce all of the needed base specimens. The target air void content for the base specimens was 7±1% and all specimens met this target and were deemed to be statistically similar to each other ($\alpha = 0.05$).

In Phase 1, the permeability *(k)* of each base specimen was measured using the falling head permeameter as outlined in FM 5-565 (FDOT 2015). This permeability was designated as k_1. After permeability testing, the specimens were dried before creating the composite specimens. Composite specimens were prepared by uniformly applying the appropriate amount of tack material to the compacted surface of the base specimen using a brush. The application rate was based on the residual binder, so the appropriate emulsion content was calculated based on the percent distillation residue of the emulsion. After application, the tack coats were allowed to cure for 30 minutes before placing the specimen into an SGC mold, then compacting 1700 g of plant-mixed OGFC on the base specimen at 265°F (130°C). The OGFC mix included Evotherm® as a warm mix asphalt (WMA) additive, which allowed for the lower compaction temperature. The OGFC mix was compacted to a height of 50 mm using the SGC to yield a finished composite specimen height of 100 mm. Each composite specimen was tested to measure its permeability (FM 5-565) and the bond strength using the interface shear strength (ISS) test per AASHTO TP-114 (AASHTO 2016).

In addition to the composite specimens, 150 mm diameter by 100 mm tall specimens were made from the Surface Course and OGFC mixtures to evaluate the shear strength of each mixture using the AASHTO TP-114 procedure. This was completed to compare the bond strength of the composite specimens to the shear strength of each mix type.

In Phase 2, composite specimens were made in the same manner as for Phase 1 with a few exceptions. Only one tack coat material, UltraFuse, and one application rate, 0.033 gal/yd^2, was used in this phase to isolate the effects of the gradation. The OGFC mixes were lab-produced to achieve the appropriate gradations and compacted to 50 mm using 30 gyrations of the Superpave Gyratory Compactor.

Results and Discussion

Phase 1: Effect of Tack Coat and Application Rate

Permeability

The falling head permeability test was used to measure the water penetration rate of each STA base specimen before and after application of tack coat and OGFC (Figure 9.1). To determine the degree to which the tack coat affected the permeability of the base layer of asphalt, the difference in the permeability *(Δk)* of each specimen before and after the application of tack coat and OGFC was calculated using Equation 9.1. In all cases, the permeability decreased after the OGFC overlay was compacted, so the results in Figure 9.2 show the resulting percent reduction in permeability relative to the original base specimen permeability. A Student's *t*-test was conducted to determine statistically significant differences between the change in permeability of different tack coat treatments (product and application rate) at a significance level of 95% at α = 0.05. These results are indicated in Table 6 with the use of letters. Treatments that share a common letter are not statistically different from each other. This analysis was also conducted for the other properties evaluated in this study.

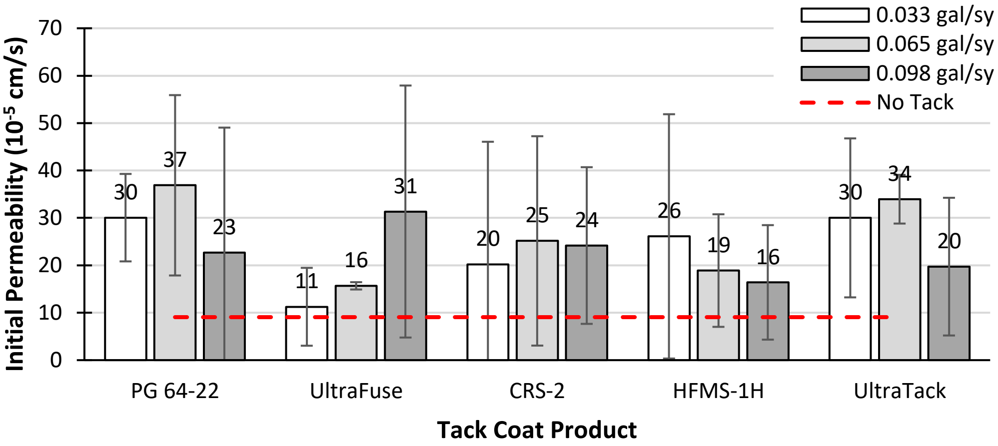
$$\Delta k = \frac{k_2 - k_1}{k_1} \times 100\% \qquad (9.1)$$

where,

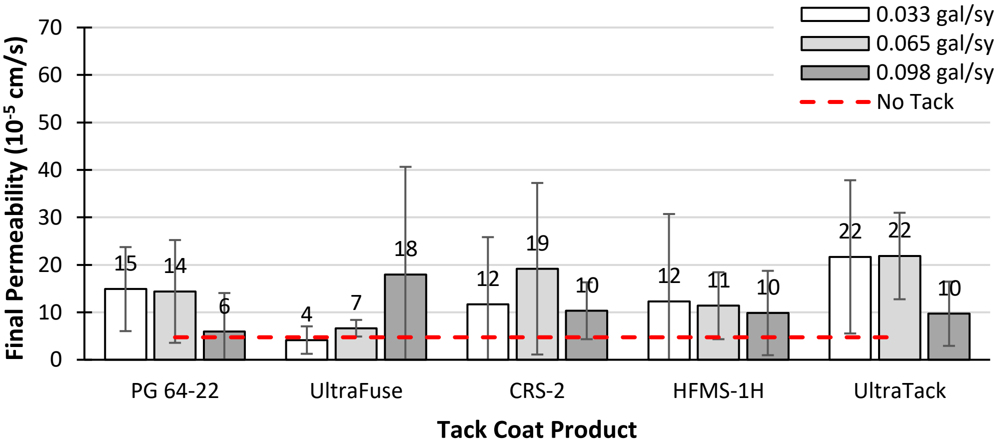
Δk = Change in permeability (%)
k_1 = Permeability of base specimen before tack coat and OGFC
k_2 = Permeability of composite specimen

The results show that there was a substantial reduction in permeability after the tack coat application and compaction of OGFC on the top of the STA. In most cases, the permeability was reduced by 50% or more after the OGFC was applied. The control treatment made with no tack coat also resulted in a significant permeability reduction of 56%, which indicates that the tack coat is not the only factor leading to the permeability reduction. Additionally, the No Tack treatment exhibited the lowest initial base layer permeability compared to the other treatments.

Due the variability of the results, it is difficult to discern the performance improvement of any of the tack coats from another based on permeability reduction. The aggregates in the OGFC overlay block a portion of the surface of the base specimens due to masking the surface or embedment into the surface, thus reducing the available surface area for water to penetrate. Similar reduction was seen in subgrade soils due to placement and compaction of aggregate base material (Martin et al. 2015). Additionally, the compaction of the OGFC overlay adds further compaction effort to the base layer, thus reducing the void content and permeability.

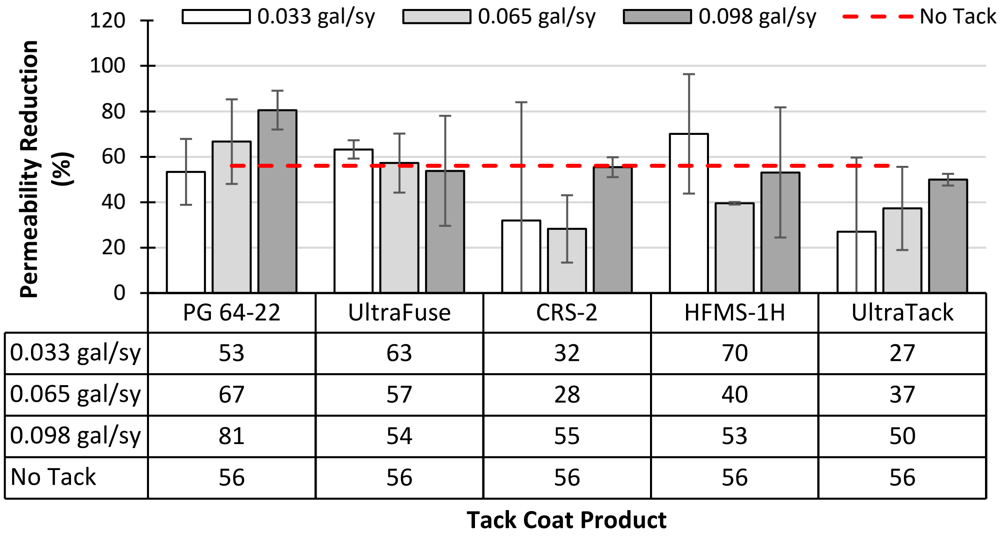


(a)



(b)

Figure 9.1. Permeability of (a) base specimens and (b) composite specimens after application of tack coat and OGFC. (Tack coat rate is based on amount of residual binder.)



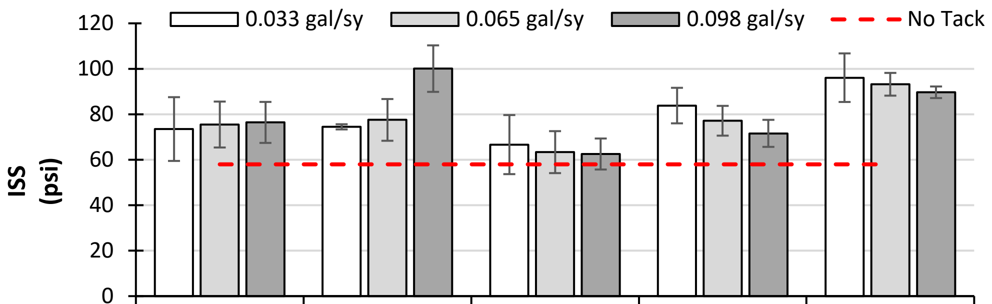
	PG 64-22	UltraFuse	CRS-2	HFMS-1H	UltraTack
0.033 gal/sy	53	63	32	70	27
0.065 gal/sy	67	57	28	40	37
0.098 gal/sy	81	54	55	53	50
No Tack	56	56	56	56	56

Figure 9.2. Reduction in permeability after application of tack coat and OGFC. (Tack coat rate is based on amount of residual binder.)

Interface Shear Strength

The bonding performance of each tack coat treatment was evaluated using the Interface Shear Strength (ISS) test and the results are summarized in Figure 9.3. At first glance, the results indicate that all tack coat treatments generally exhibited greater ISS than the No Tack control treatment, however the ISS of the CRS-2 tack coat at all three application rates was not significantly different than the No Tack treatment. In addition, the HFMS-1H tack coat at the highest treatment was also not significantly different from the No Tack treatment. On the other end of the spectrum, the UltraTack® generally resulted in the highest ISS values, especially at the lower application rates, however, the UltraFuse® performed similarly at the highest tack rate.

The ISS results for each category of tack coat (emulsions and hot applied binders) follow the same trends as the properties of the tack coat materials themselves as summarized in Tables 9.2 and 9.3. For the three emulsions, the CRS-2 residual had the highest penetration value of the three products, indicating that it possessed the lowest stiffness. The UltraTack® residual was the stiffest of the three emulsions having a penetration of only 3 dmm at 25°C (Table 9.3), indicating a much higher stiffness than the CRS-2 at 133 dmm and the HFMS-1H at 61 dmm. This stiffness translated to the bonding performance in the ISS test. The hot applied binder stiffness had a similar relationship with the ISS as the UltraFuse® had a much higher G*/sinδ value than the PG 64-22 binder.

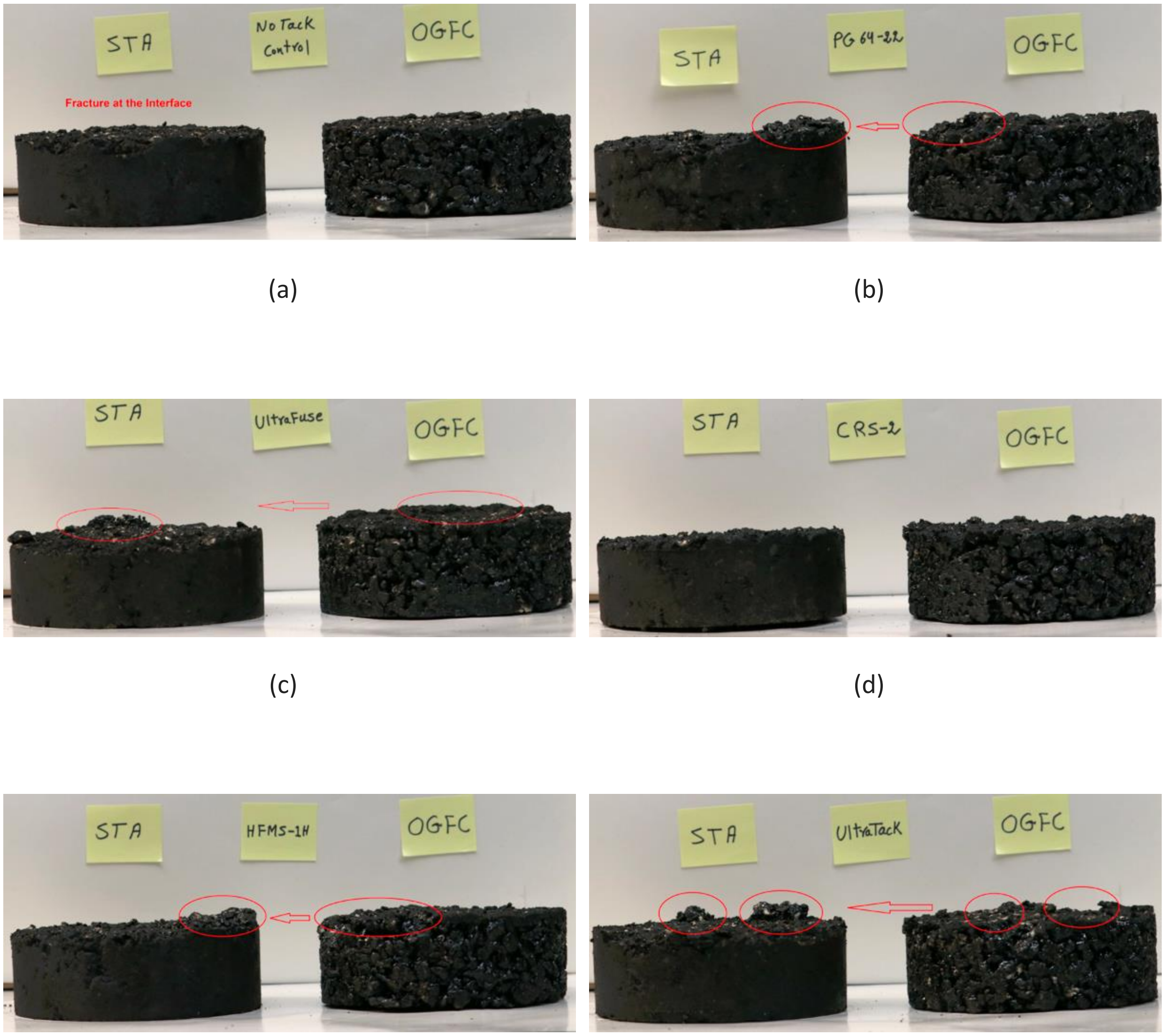


	PG 64-22	UltraFuse	CRS-2	HFMS-1H	UltraTack
0.033 gal/sy	73	74	67	84	96
0.065 gal/sy	75	78	63	77	93
0.098 gal/sy	76	100	63	72	90
No Tack	58	58	58	58	58

Tack Coat Product

Figure 9.3. ISS of composite specimens. (Tack coat rate is based on amount of residual binder.)

When comparing the failure mode of specimens from each treatment, the qualitative evaluation matches quantitative ISS results. Figure 9.4 includes representative images of specimens after the ISS test. When evaluating the failure planes in these specimens, it is clear that the No Tack and CRS-2 specimens had a relatively clean failure at the bond interface, while the other treatments had a rougher texture post failure indicating that the failure plane went through the OGFC overlay. This shows that the bond strength was greater than the OGFC shear strength. To further examine this, full-depth OGFC and Surface Type A (the mix used for the base layer) specimens were tested using the ISS test to measure the shear strength each mix. The shear strength of the OGFC and Surface mixes were measured to be 76 psi and 232 psi, respectively. These results verify that that bond strength for some of the treatments was less than the shear strength of the OGFC, which caused the clean failure at the interface. However, for some treatments like the UltraTack® and UltraFuse® (at the highest tack rate), the bond strength exceeded the OGFC shear strength.



(a) (b)

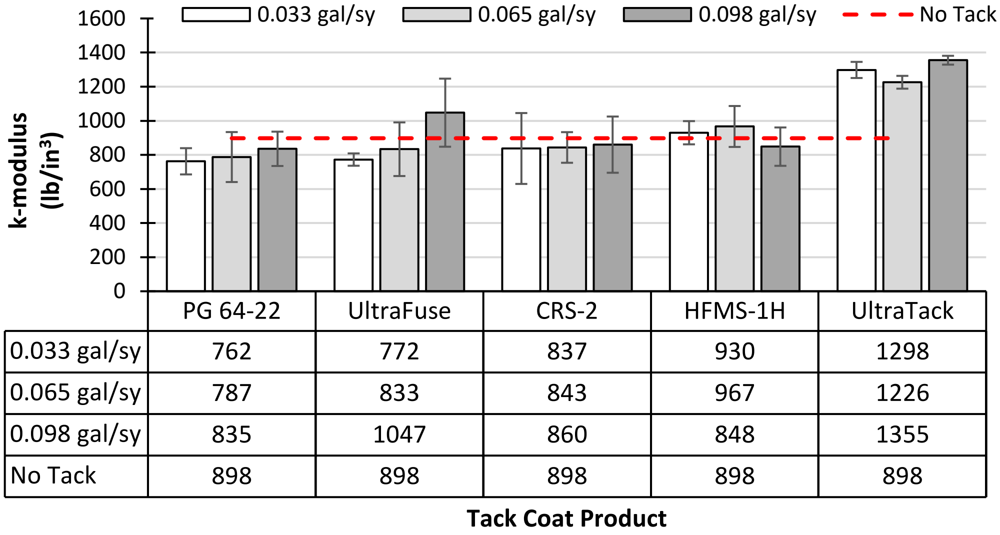
(c) (d)

(e) (f)

Figure 9.4. Photos of failed composite specimens following the ISS test (a) No Tack, (b) PG 64-22, (c) UltraFuse®, (d) CRS-2, (e) HFMS-1H, (f) UltraTack®.

The results in Figure 9.3 also show differing trends with respect to tack coat rate for the two different categories of tack coat products (i.e., emulsions and hot applied binders). For the hot applied binders (i.e., PG 64-22 and UltraFuse®), the ISS generally increased with an increase in application rate for the rates evaluated in this study, but the differences were not significant, with the exception that the highest rate of UltraFuse® yielded the highest ISS of any treatment. This is likely due to the fact that application rates included in this study were lower than those recommended for UltraFuse® (i.e., 0.08-0.12 gal/yd^2 or 0.13-0.18 gal/yd^2, depending on the application) (Blacklidge Emulsions, Inc. 2016). The emulsions showed the opposite trend where the ISS was generally greatest for the lowest tack coat rate of 0.033 gal/yd^2, then decreased with an increase in tack coat rate, however, the differences were not significant.

Another parameter of interest when evaluating ISS is the k-modulus, which is calculated by dividing the ISS by the displacement at peak stress. The k-modulus is an indication of the stiffness of the bond prior to failure. As with the ISS, the differences between the different treatments were generally not significant with the exception of the UltraTack® (Figure 9.5), which resulted in a much higher k-modulus than the other treatments. UltraFuse® also had a high k-modulus, but only at the highest application rate of 0.098 gal/yd^2, which can again be attributed to the fact that the two lowest rates included in this study were lower than recommended by the manufacturer. The k-modulus values of the other treatments were similar to the No Tack treatment.



	PG 64-22	UltraFuse	CRS-2	HFMS-1H	UltraTack
0.033 gal/sy	762	772	837	930	1298
0.065 gal/sy	787	833	843	967	1226
0.098 gal/sy	835	1047	860	848	1355
No Tack	898	898	898	898	898

Figure 9.5. k-modulus of composite specimens. (Tack coat rate is based on amount of residual binder.)

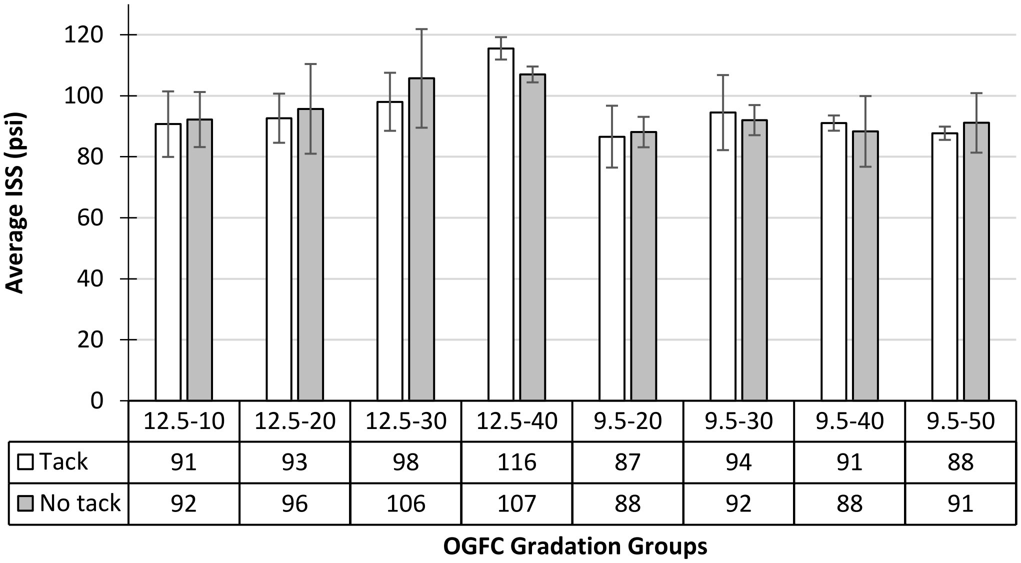
Phase 2: Effect of Gradation and Compaction

Effect of Gradation

In Phase 2 of this study, eight different OGFC aggregate gradations were designed and analyzed for the upper layer of composite specimens (Table 9.4). In this phase, only one type of tack coat, UltraTack, was used at a rate of 0.033 g/yd^2 based on the Phase 1 results. Comparison specimens were also made without tack for each gradation. The hypothesis was that different aggregate gradations would have different degrees of contact area at the interface between the asphalt layers of a composite specimen, which can influence the bond strength between the asphalt layers.

ISS test results for the eight OGFC gradations are summarized in Figure 9.6. The ISS generally increased for the 12.5 mm NMAS mixes as the percent passing the No. 4 sieve increased, but the differences were only significant for the 12.5-40 mix. The changes in gradation did not have any significant effect on ISS for the 9.5 mm mixes. In all cases, the ISS of the composite specimens exceeded the shear strength of the respective OGFC mix by more than 30% indicating that the failure mode was due to the shearing of the OGFC mix, not the bond interface. This was confirmed by visual inspection of the failed specimens.

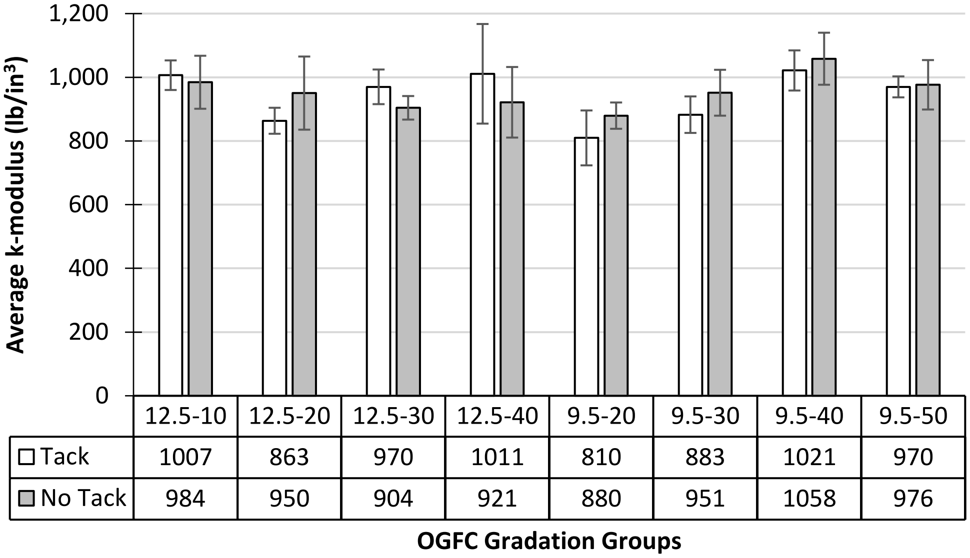
Additionally, the tack coat did not have a significant effect on bond strength in this lab study. This could likely be due to the binder content of the OGFC that leads to greater film thickness to promote bonding to the new base layer.



	12.5-10	12.5-20	12.5-30	12.5-40	9.5-20	9.5-30	9.5-40	9.5-50
☐ Tack	91	93	98	116	87	94	91	88
■ No tack	92	96	106	107	88	92	88	91

Figure 9.6. Interface shear strength (ISS) test results (tack and no tack coat)

Figure 9.7 shows the average stiffness (i.e., k-modulus) of the specimens for each group of specimens with and without tack coat. The k-modulus results showed no significant effect of gradation for the 12.5 mm NMAS mixes. However, there was a general increase in stiffness with increasing percent passing the No. 4 material for the 9.5 mm mixes with the 9.5-40 mix having greater stiffness than the mixes containing less than 30% passing the No. 4 sieve. As with ISS, the presence of tack coat had no significant effect in this particular study. This could likely be due to the mix having an appropriate binder content that results in a slight amount of short-term binder draindown during, or shortly after compaction. This was also conducted in a controlled laboratory environment.

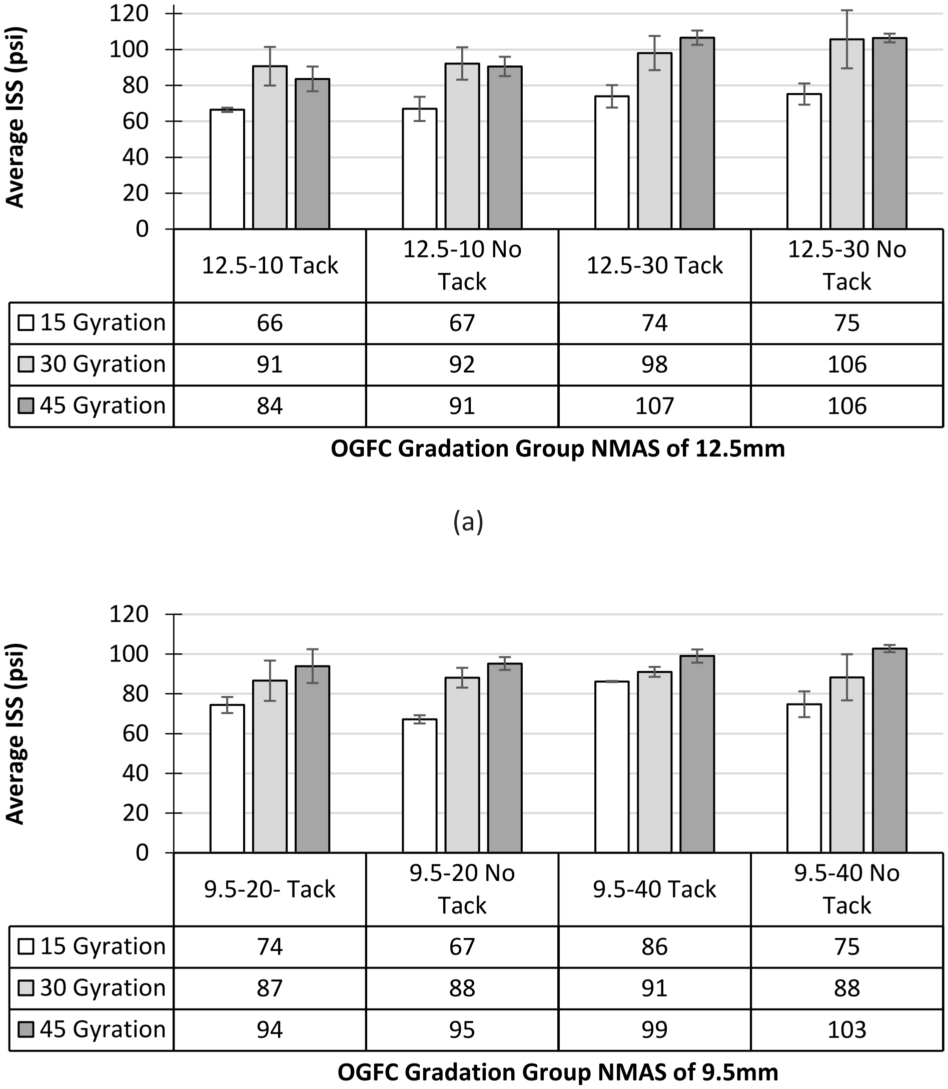


	12.5-10	12.5-20	12.5-30	12.5-40	9.5-20	9.5-30	9.5-40	9.5-50
☐ Tack	1007	863	970	1011	810	883	1021	970
▨ No Tack	984	950	904	921	880	951	1058	976

Figure 9.7. k-modulus (lb/in^3) test results (tack and no tack coat)

Effect of Compaction Effort

To evaluate the effects of compaction effort on the bond strength of OGFC mixes, composite specimens were made using 15 and 45 gyrations for OGFC mixes having four of the gradations studied previously (i.e., 12.5-10, 12.5-30, 9.5-20, and 9.5-40). The performance of these specimens were compared with the 30 gyration specimens previously discussed (Figures 6.10 and 6.14). The results in Figure 9.8 show that the bond strength generally increases with level of compaction and the trends were generally similar for all gradations evaluated. Again, the presence of tack coat did not have an impact on the ISS as the bond strength exceeded the shear strength of the OGFC mix in all cases at each compaction level.



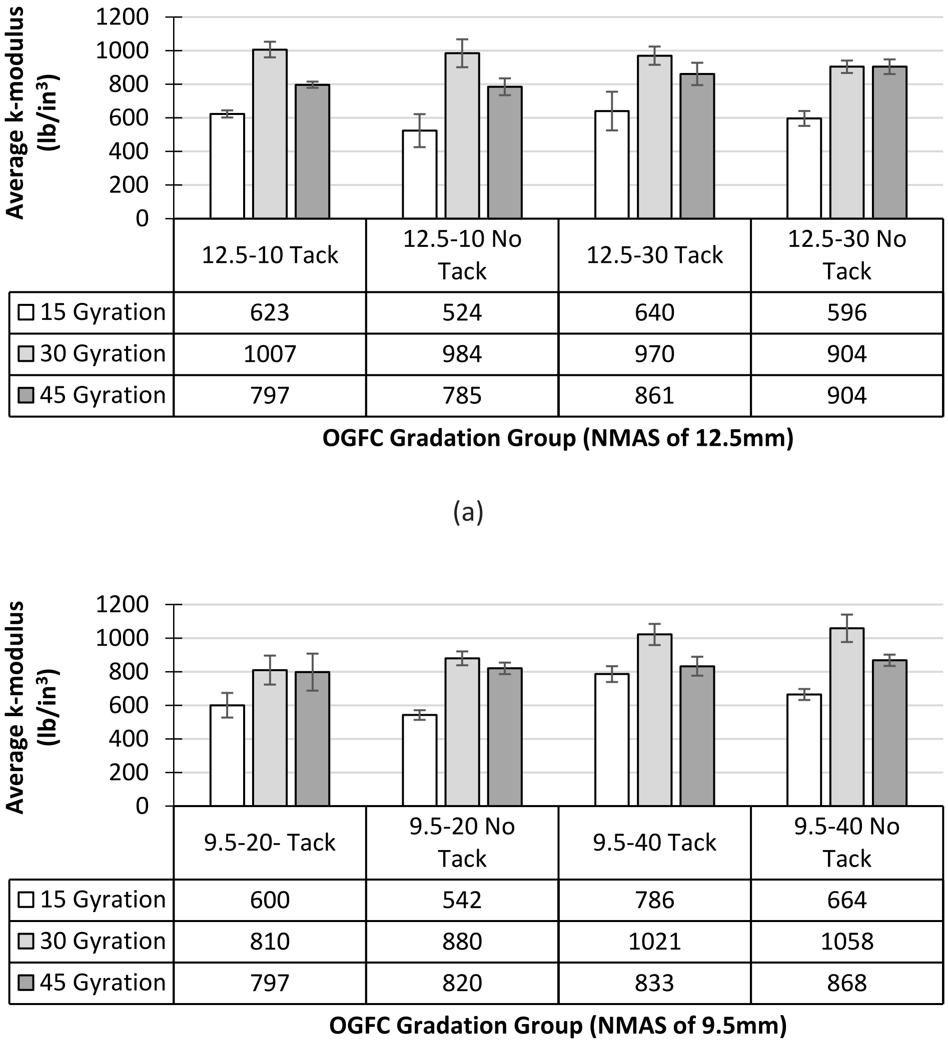
(a)

(b)

Figure 9.8. Interface shear strength (ISS) test results versus gyration number (a) NMAS of 12.5 mm, and (b) NMAS of 9.5 mm

The results show that indicated that a compaction effort of 15 gyrations resulted in significantly lower bond strength values than 30 and 45 gyrations, which produced values that were similar to each other. This indicates that 15 gyrations or its equivalent compaction effort in the field may not be enough to result in a strong bond between OGFC and the underlying asphalt layer. However, more compaction effort, beyond a certain point, will not significantly increase the bond strength.

The k-modulus results presented in Figure 9.9 show similarities in the trends for all gradations. The specimens compacted with 15 gyrations yielded considerably lower stiffness while 30 gyrations generally resulted in the highest stiffness. In some cases, the k-modulus for specimens made with 30 gyrations was statistically greater than that resulting from 45 gyrations, while in other cases, the results were similar. The highest k-modulus does not necessarily mean the best results, because the k-modulus results are dependent on displacement and displacement can be effected by bond whether its behavior is ductile or brittle under load. The lower k-modulus results for the specimens made with 45 gyrations can be due to aggregate embedment and ultimately ductile behavior of bond compared to the specimens made with 30 gyrations which were more brittle. Similarly, it can be assumed that 15 gyrations are not enough to create a strong bond as the k-modulus test results were the lowest among each gradation group.



	12.5-10 Tack	12.5-10 No Tack	12.5-30 Tack	12.5-30 No Tack
☐ 15 Gyration	623	524	640	596
▨ 30 Gyration	1007	984	970	904
■ 45 Gyration	797	785	861	904

(a)

	9.5-20- Tack	9.5-20 No Tack	9.5-40 Tack	9.5-40 No Tack
☐ 15 Gyration	600	542	786	664
▨ 30 Gyration	810	880	1021	1058
■ 45 Gyration	797	820	833	868

(b)

Figure 9.9. k-modulus test results versus gyration number (a) NMAS of 12.5 mm, and (b) NMAS of 9.5 mm

10. Field Performance

In addition to the variety of laboratory studies on different aspects of OGFCs, this study included a limited evaluation of the field performance of OGFC mixtures in South Carolina. The field evaluation was divided into functional performance (i.e., infiltration) and durability performance (i.e., raveling).

Functional Performance

Two pavement sections were recommended to evaluate the surface infiltration of the OGFC layer. The first was a new section of OGFC placed in 2020 on Interstate 26 in Newberry County between mile markers 60-75 in both the Eastbound (EB) and Westbound (WB) directions. The OGFC mixture had a 9.5 mm NMAS and was produced as a warm mix asphalt (WMA) without fibers. This was one of the first OGFC mixes placed using the 9.5 mm OGFC mixes in South Carolina using the new supplemental specification that was implemented in January 2019. The job mix formula (JMF) is summarized in Table 10.1. This section was selected by the SCDOT for two main reasons:

1. This was one of the first sections using the 9.5 mm OGFC and there was an interest to investigate the infiltration rate.
2. There was a question about the infiltration of the OGFC following a few heavy rainstorms shortly after placement.

Table 10.1. Job mix formula for OGFC mixture used on I-26 in Newberry County.

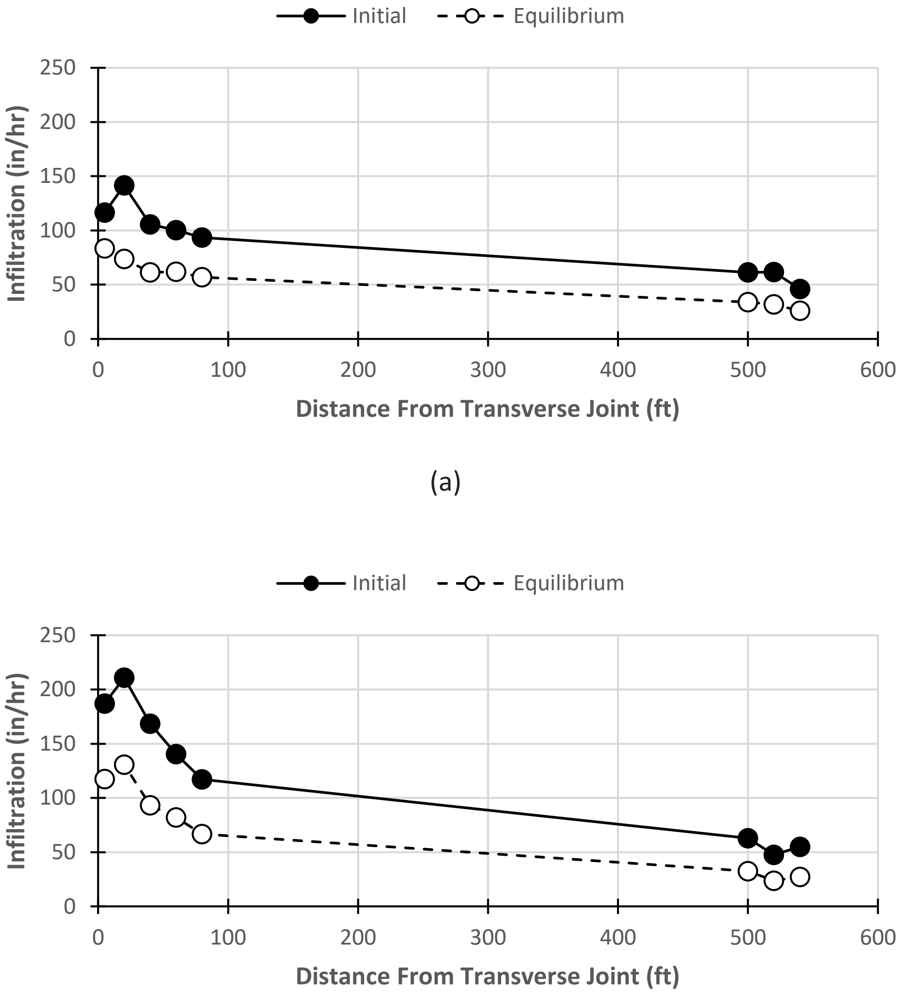
Mix Design Composition	
Sieve Size	**% Passing**
¾ in.	100
½ in.	99.0
⅜ in.	94.0
No. 4	39.0
No. 8	13.0
No. 200	2.0
Binder Type	PG 76-22
Binder Content	6.0% (by total mix weight)
Anti-Strip Additive	Hydrated Lime (1% by aggregate weight)
Warm Mix Additive	Evotherm® M1 added at the terminal at a rate of 0.5% by weight of binder.
Other	No fibers added.

The infiltration of this section was measured using the infiltration test procedure outlined in Appendix B that was based on an adaptation of the procedure outlined in ASTM C1701. The infiltration was tested near the transverse cold joints located in the inside lane at Station 170+70 in the WB direction and the outside lane at Station 159+70 in the EB direction, both near rest areas. Testing was conducted in the center of the lane five feet from the transverse joint and then again at 20, 40, 60, and 80 ft from the joint. The purpose of the testing near the joint was to determine the consistency of the infiltration near the joint. This method has previously been used by the authors to assess the consistency in the density/porosity of the OGFC layer (Putman and Lyons 2014). The infiltration was also measured at points 500, 520, and 540 ft beyond the transverse joint to assess the "steady-state" infiltration of the OGFC layer.

The results are presented in Figure 10.1 and show that the infiltration is higher nearest the joint, then decreases as the distance from the joint increases to a point at which the infiltration levels out. This trend reflects the findings of Putman and Lyons (2014) who found similar results for 12.5 mm OGFC mixtures. At a distance of 500 ft beyond the joint, the infiltration rate had leveled out and was relatively consistent in the local area, which is more indicative of the overall OGFC layer than the infiltration measured near the joint.

Figure 10.1 includes both an initial and equilibrium infiltration value at each location. The initial value is the average of the first to tests conducted at each location, and the equilibrium is the average of the second two tests. Since the four tests were conducted in succession, the pavement had become saturated after the first two tests, thus resulting in a reduction in the infiltration rate. This is also shown in Figure 10.2 that presents the combined average infiltration rates measured at 500, 520, and 540 ft in each direction.

Cores were also taken at the same locations where the infiltration was tested at 500, 520, and 540 ft beyond the joint. Each core was cut to isolate the OGFC layer and measure the porosity. The average porosity corresponding to each direction is included in Figure 10.2. The porosity was relatively consistent when comparing the WB and EB directions even though the EB porosity was slightly lower than the WB direction. All individual porosity values were above 17% and the OGFC layer thickness averaged approximately 1.25 inches.



(a)

(b)

Figure 10.1. Infiltration results from I-26 in the (a) Westbound direction and (b) Eastbound direction.

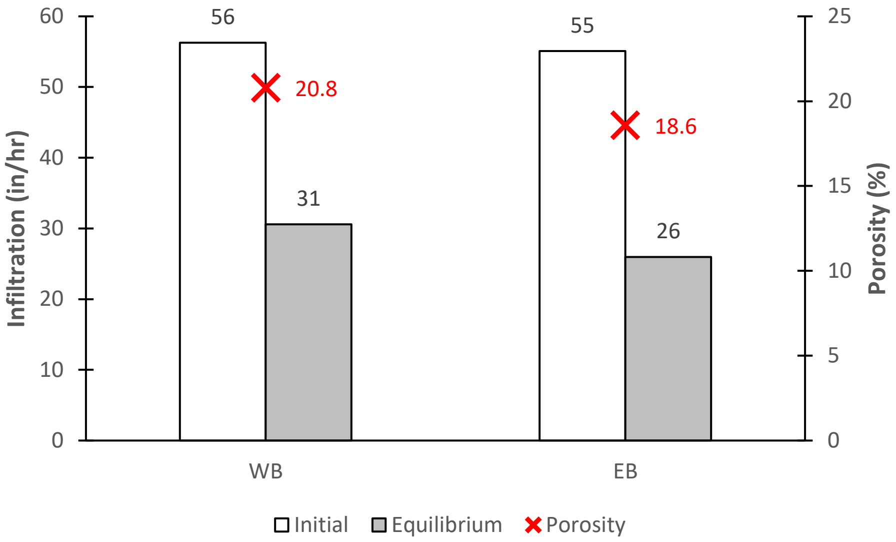


Figure 10.2. Combined average infiltration results tested 500, 520, and 540 feet after the transverse joint in the (a) Westbound direction and (b) Eastbound direction.

The second OGFC section of interest was located on Interstate 85 Northbound (NB) at the interchange with SC-153 (Exit 40) in Powdersville, SC. This OGFC was placed prior to 2010 and was selected due to the prevalence of wet-weather crashes and reports of standing water. Specific details about the mix design were not available, but based on common practice at the time of construction, it can be assumed that it did use a 12.5 mm NMAS aggregate gradation and fibers as this was constructed before the SCDOT allowed warm mix asphalt for OGFC without fibers. Infiltration testing was conducted in four locations (i.e., two in the outside travel lane and two in the acceleration lane). Cores were also taken at each test location. The results are summarized in Table 10.2 and show that the acceleration lane exhibited no infiltration despite having a porosity of approximately 15%, indicating that the OGFC mix is clogged (i.e., surface pores filled with sediment or other foreign material). The travel lane immediately adjacent to the acceleration lane exhibited very low infiltration rates, but also had what should be sufficient porosity (i.e., 13-21%). These results support the observations of standing water at this location, which is likely due to the accumulation of water in the outside travel lane at the longitudinal joint with the acceleration lane. Once the OGFC become saturated, the water spills over and drains over the acceleration lane instead of flowing laterally within the layer.

Table 10.2. Test results from I-85 NB at Exit 40.

Station	Lane	Infiltration (in/hr)	Porosity (%)
1	Acceleration lane	0	14.9
	Outside travel lane	17	21.0
2	Acceleration lane	0	15.2
	Outside travel lane	3	13.5

OGFC Durability

An assessment of the performance of the durability of in-service OGFC in South Carolina was studied to identify trends. Data for this evaluation was collected by the SCDOT and documented in a report by Johnston (2019). In 2018, "windshield surveys" were conducted on interstate routes in South Carolina having OGFC surfaces. A windshield survey is a visual survey conducted while traveling on the roadway. The primary indicator of durability used in this evaluation was occurrences of localized raveling, as had been documented previously (Putman 2012). For each OGFC section, the GPS locations of localized raveling were marked and categorized into three failure types:

> **Transverse Joints**: Raveling that occurs at or near a transverse joint where one day of production ended and another began, thus forming a cold joint.
>
> **Bridge Joints**: Raveling that occurs at or near a bridge where the OGFC meets the concrete bridge deck. Bridge tie-ins are common locations for localized raveling of OGFC mixes. As relatively few bridges are overlaid with asphalt, the OGFC terminates at the bridge approach and resumes at the departure end. Raveling that occurs at a bridge joint will be divided in to two categories: Bridge Approach and Bridge Departure.
>
> **Mid-Shift Raveling**: Raveling that does not occur at or near either a transverse joint or a bridge joint will considered mid-shift raveling because they occur between the beginning of a shift and the end of a shift.

In all, data was collected for 46 OGFC pavement sections totaling approximately 1,515 lane-miles of OGFC in South Carolina on Interstate Routes 20, 26, 77, 85, 95, 520, and 526 that had been in service for one to eight years at the time of data collection. The data are presented in Appendix C and summarized in Figures 10.3 and 10.4. In an effort to identify the effect of pavement age on the performance, all of the sections were grouped by age, then occurrences of raveling were aggregated for all sections within each age group. For the mid-shift and transverse joint raveling, the data are reported in occurrences per lane-mile to normalize by section length as shown in Figure 10.3. The results show that a slightly higher prevalence of raveling at transverse joints than at mid-shift locations. This is similar to previous findings in South Carolina where approximately 55% of localized raveling occurred at joints, of pavements evaluated (Putman 2012). It should be noted however, that some sections had significantly less frequency of raveling compared to others.

The analysis of the raveling data at bridge joints was more polarizing where the majority of raveling at bridges occurs at the departure as compared to the approach (Figure 10.4). In Figure 10.4, the data are reported in the percentage of bridges in a section with raveling. This was also done to normalize by the number of bridges in a pavement section as some sections may have many bridges and others may have few. The prevalence of raveling at the bridge departure compared to the approach was expected because the departure is essentially another cold joint and where production stops to move across the bridge before restarting the paving process. During this move, the mix in the paver can cool down enough that when paving commences, it can be more difficult to achieve appropriate compaction of the OGFC layer.

This decrease in density can be seen in the trends of higher infiltration rates at the joint similar to the trends seen in Figure 10.1.

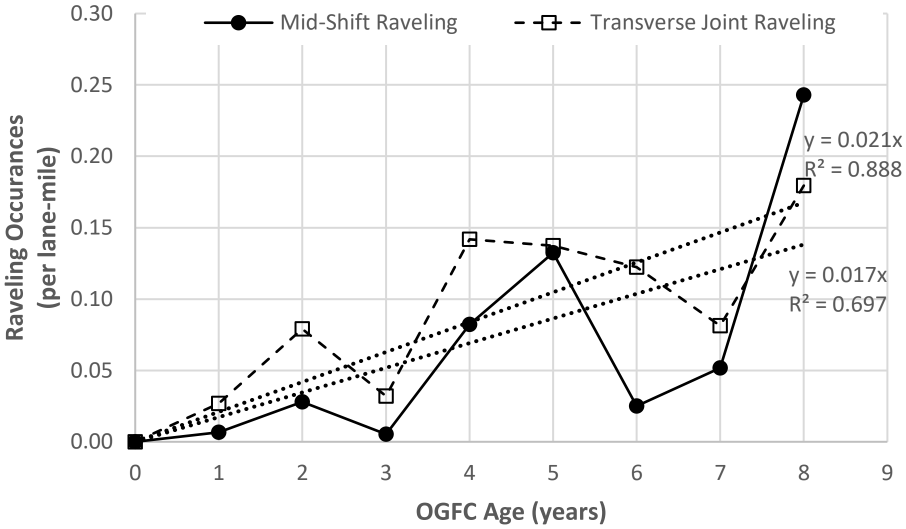


Figure 10.3. OGFC raveling location frequency at non-bridge locations.

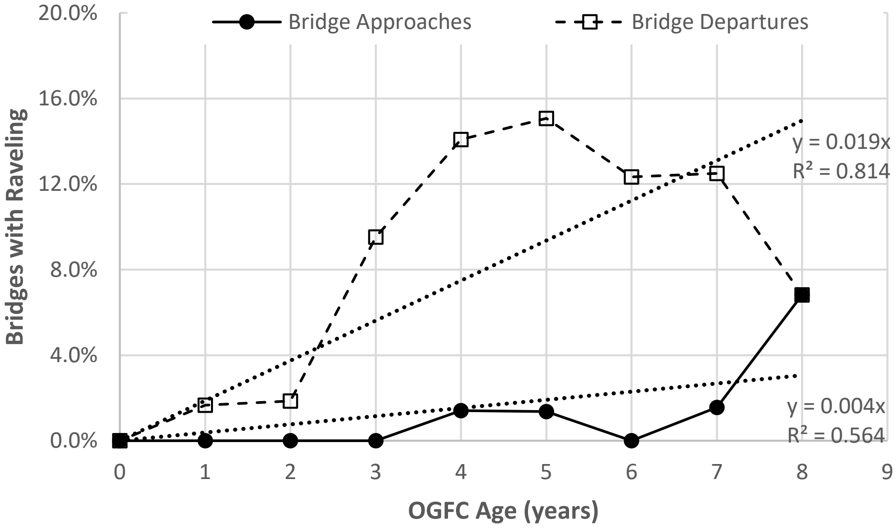


Figure 10.4. OGFC raveling frequency at bridge locations.

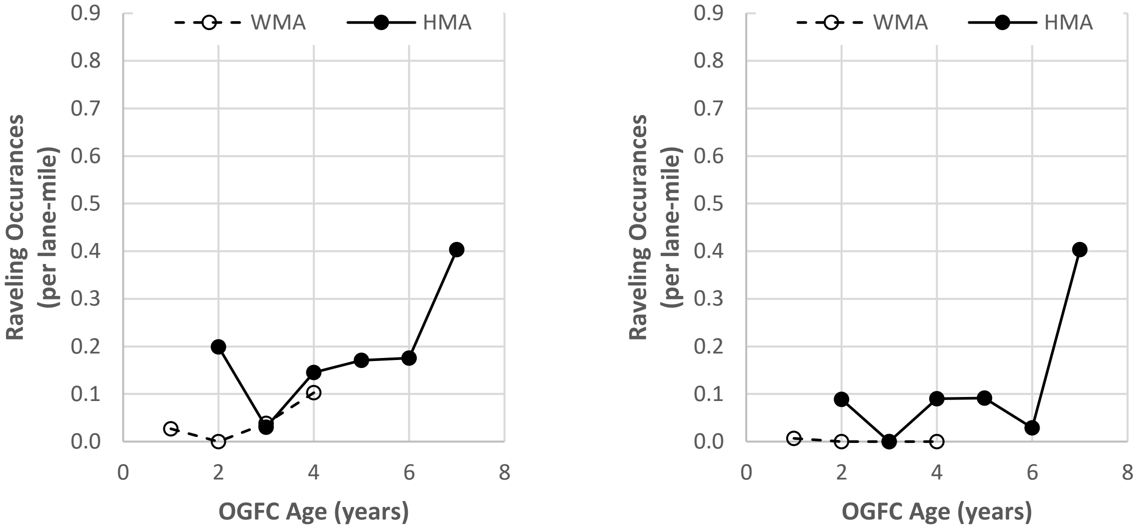
OGFC Mix Factors

Of the 46 OGFC sections included in this performance evaluation, job mix formulas (JMF) were available for 27 of them. The JMFs provide information about the mix design and materials used for the mixes and were analyzed to determine if there were any mix factors that could potentially influence the performance.

The first factor that was investigated was the comparison of hot mix asphalt (HMA) OGFC mixes to warm mix asphalt OGFC. In 2012, the SCDOT started to experiment with WMA for OGFC with the construction of two test sections using the Evotherm® WMA additive without including fibers. After evaluating the performance of these sections for a few years, the specification was changed to allow the use of approved WMA chemical additives. Since the allowance of WMA for OGFC, it has been the preferred mix type for OGFC in South Carolina. To compare the performance of the WMA mixes to the HMA mixes, the same analysis method was used as previously described, with the exception that the WMA and HMA mixes were separated. For the sections having JMFs available, five were WMA projects and 20 were HMA projects.

At the same time, the SCDOT started field trials with WMA, they also constructed field trials with OGFC mixtures made with ground tire rubber (GTR) modified binders. Some of these sections were included in this study, but GTR was not analyzed in the depth that WMA was because all of the GTR sections were also paired with HMA and/or WMA sections and the researchers were not able to separate the data to isolate only the performance of the GTR, WMA, or HMA sections. Therefore, those sections are not included in the further analysis of mix factors.

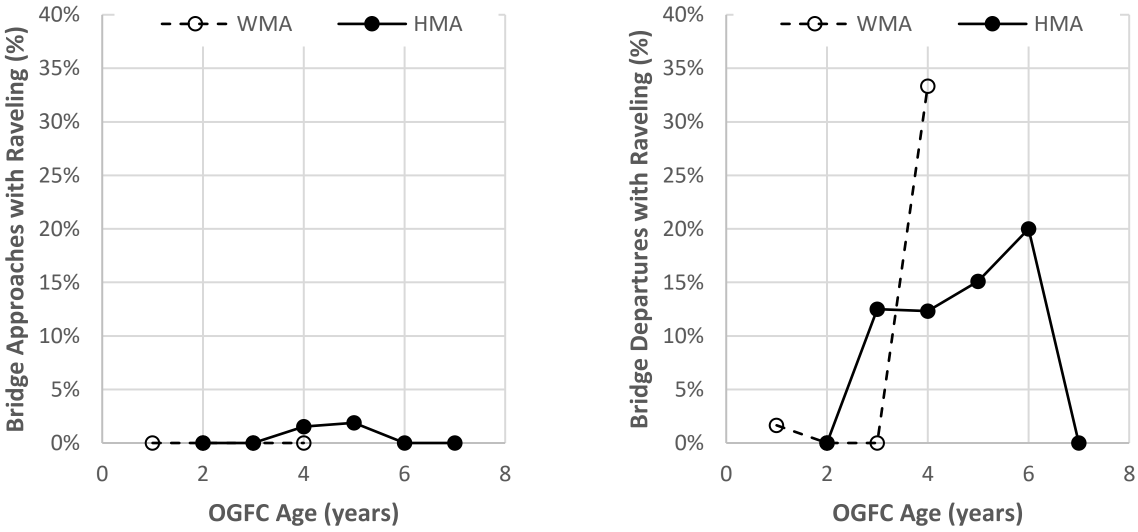
Figure 10.5 shows the occurrence of raveling at the transverse joints and mid-shift locations for the WMA and HMA sections. The available data show that there is not a substantial difference in transverse joint raveling occurrences per mile for WMA and HMA. There was more of a difference between the two with respect to the mid-shift raveling where the WMA exhibited lower frequency than the HMA. It is important to note that there are several factors that can influence the OGFC performance with WMA/HMA being only one of them.



(a) (b)

Figure 10.5. OGFC raveling location frequency at non-bridge locations for WMA and HMA mixes at (a) transverse joint locations and (b) mid-shift locations.

The raveling frequency at bridge locations is presented in Figure 10.6. As with the full data set, there is minimal raveling at bridge approaches, but the frequency increases significantly at bridge departures for both types of mixes. Based on the limited number of WMA projects in this data set and limited number of bridges per project, a reasonable comparison cannot be made.



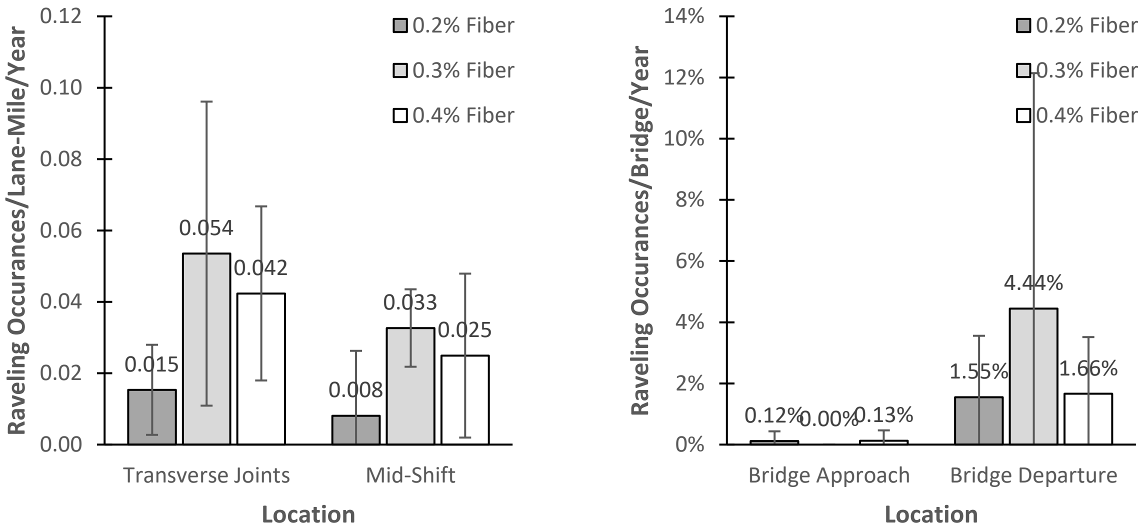
(a) (b)

Figure 10.6. OGFC raveling location frequency at bridge locations for WMA and HMA mixes at (a) the bridge approach and (b) bridge departure.

The data presented in Figures 10.5 and 10.6 were further analyzed to normalize for age by dividing the occurrences per lane-mile by pavement age to allow for aggregation of the data and comparison of the mix type and the results are summarized in Figure 10.7. The same was done for raveling at bridges. The results show that the WMA mixes show lower frequency of raveling at non-bridge locations compared to the HMA mixes. Again, this could be due to multiple factors, of which age could be one. The WMA sections are not as old as many of the HMA sections, the prevalence of raveling in the HMA sections could be greater to the age at which the evaluation was conducted. When looking at the raveling at bridge locations in Figure 10.7(b), there is generally no difference in raveling frequency at either the approaches or departures when comparing WMA and HMA.

Figure 10.7. OGFC raveling location frequency normalized for age for WMA and HMA mixes at (a) non-bridge locations and (b) bridge locations.

Upon further review of the JMFs, it was noticed that the cellulose fiber content in the HMA mixes varied from 0.2-0.4%. The same analysis comparing the WMA to HMA in Figure 10.7 was also done to compare the performance of HMA mixes with varying fiber contents to determine if there were any trends related to fiber content. The results in Figure 10.8 generally indicate that the mixes containing 0.2% cellulose fiber exhibited less raveling than mixes with higher fiber contents.



(a) (b)

Figure 10.8. OGFC raveling location frequency normalized for age for HMA mixes containing different cellulose fiber contents at (a) non-bridge locations and (b) bridge locations. (Error bars indicate one standard deviation.)

Additional mix information was evaluated to determine relationships with performance and no particular factors stood out from the others. For example, the gradations of all of all of the mixes were quite similar, with all having an NMAS of 12.5 mm; the percent passing the No. 4 sieve ranged from 17-21% (Figure 10.9(a)); and the percent passing the No. 200 sieve ranged from 1-2%. Since these projects were constructed the SCDOT has implemented some changes to the OGFC specification to include a 9.5 mm NMAS mix and adjusting the limits of the percent passing the No. 4 sieve from 15-25% to 15-30% (SCDOT 2019).

The binder content of the mixes ranged from 5.5-6.5% and Figure 10.9(b) shows the comparison for the WMA, HMA, and the HMA mixes made with ground tire rubber (GTR). The WMA mixes had lower binder contents than the HMA mixes and the GTR mixes had a slightly higher binder content. The lower binder content in the WMA mixes is due to the absence of fibers in the mix that are typically added to stabilize the higher binder contents necessary to promote durability. The fibers are not as important in WMA mixtures because the lower production temperatures result in a higher binder viscosity that does not require the stabilization provided by the fibers. On the other side of the spectrum, the GTR mixes typically have higher viscosity at production temperatures, thus requiring slightly higher binder contents in some cases to ensure proper aggregate coating.

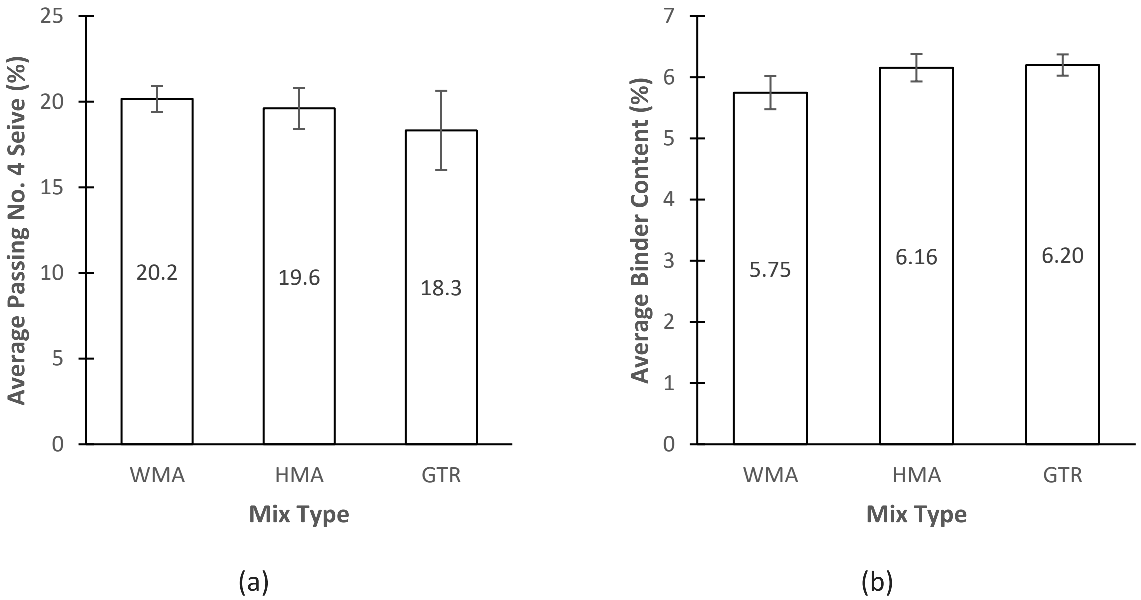


Figure 10.9. Comparison for WMA, HMA, and GTR OGFC mixes for (a) percent passing the No. 4 sieve and (b) binder content. (Error bars indicate one standard deviation.)

11. Conclusions, Recommendations, and Implementation

Throughout the course of this project, multiple studies were conducted related to open graded friction courses and the overall project objectives. Specifically, these studies addressed:

- Breakdown of aggregates in OGFC mixtures due to mixing and compaction (Chapter 5)
- Gradation of OGFC mixtures and the influence on laboratory performance (Chapter 6)
- Compaction temperature of OGFC mixtures (Chapter 7)
- Laboratory test methods to assess OGFC durability and influencing variables (Chapter 8)
- Bonding of OGFC layers and influencing variables (Chapter 9)
- Field performance of OGFC (Chapter 10)

The conclusions and recommendations based on each of these studies are summarized in this Chapter.

Conclusions

Breakdown of Aggregates in OGFC Mixtures

This study evaluated the influence of aggregate LA Abrasion value on the laboratory performance of OGFC mixtures. Aggregate material from 11 different quarries across the state of South Carolina were used to make compacted OGFC specimens that were evaluated for porosity and raveling resistance (i.e., Cantabro abrasion test). A test section was also constructed early on in the project to evaluate the breakdown in the field. Analysis of the results of this study, led to the following primary conclusions:

- The LA Abrasion value of the aggregate affected the raveling resistance of the OGFC mix, in that mixes made with the higher LA Abrasion aggregate (i.e., weaker aggregate) generally outperformed those made with lower LA aggregates. While this result was unexpected, it had also been seen in previous studies. The reason for this relationship was linked to aggregate breakdown during mixing and compacting. The weaker aggregates (i.e., higher LA values) fractured more during mixing and compaction, thus creating a more well-graded gradation with greater packing density that resulted in a lower porosity compared to the original gradation. The lower porosity resulting from aggregate breakdown yielded lower Cantabro abrasion loss values.

- The change in gradation was quantified using the uniformity coefficient (C_u) to compare the original gradation to the gradation after mixing and compaction. The C_u of the aggregate blend increased after mixing and compaction with increasing LA value. The compaction effort of 50 gyrations of the Superpave Gyratory Compactor resulted in breakdown that increased the C_u by a factor of approximately 1.5 compared to the C_u after mixing alone in the laboratory bucket mixer. This relationship was validated in the field trial.

These conclusions suggest that lab performance testing of OGFC mixtures may not accurately represent the field performance due to changes in gradation. When mixtures are prepared in the lab, the aggregate is carefully batched to meet the design gradation. This study showed that the aggregate gradation changes after both mixing and compaction, thus influencing the void structure of the compacted specimens, which in turn affects the mechanical performance. By comparison, in the field, the OGFC gradation is tested for acceptance compared to the design gradation after mixing—after it has already experienced some degree of breakdown during mixing in the plant. This could potentially be addressed with an aggregate source specific breakdown factor to account for the gradation changes that result from mixing and/or compaction in the lab.

Aggregate Gradation in OGFC Mixtures

This laboratory study evaluated the influence of aggregate gradation, specifically the percent passing the No. 4 and No. 200 sieves, on OGFC mixtures having NMAS of 9.5 mm and 12.5 mm. Based on the analysis of the results of this study, the following primary conclusions were drawn:

Influence of Percent Passing the No. 4 Sieve

- Changes in the percent passing the No. 4 sieve in an OGFC gradation resulted in changes in the mixture porosity—increasing the amount of material finer than the No. 4 sieve generally resulted in a decrease in the mixture porosity. However, the effect was more significant for 12.5 mm NMAS mixtures than for 9.5 mm NMAS mixtures that were largely unaffected for mixes having 30-50% passing the No. 4 sieve. Because porosity is closely linked to the permeability of the mixture (Mansour and Putman 2013), the results indicate that the 9.5 mm NMAS mixtures will likely be less sensitive to changes in the functional performance (permeability and infiltration) due to changes in gradation than 12.5 mm NMAS mixtures.

- The macrotexture of the OGFC mixtures was largely unaffected by the percent passing the No. 4 sieve, with the exception of the 12.5 mm NMAS mixture having only 10% passing the No. 4. This mixture had a mean texture depth (MTD) that was approximately 65% greater than the other mixes. This could be due to the fact that this gradation had no material between the No. 8 and No. 4 sieves, therefore resulting in significant voids.

- The mechanical performance of the OGFC mixtures as measured by the ITS, Cantabro loss, and shear strength and these properties were also affected by the changes in gradation (% passing the No. 4 sieve) to an extent similar to the porosity, but inversely—as the percent passing the No. 4 sieve increased, the strength also generally increased, but the differences were not always significant.

- The NMAS had no significant influence on the performance of the OGFC mixtures evaluated in this study. However, the 9.5 mm NMAS mixtures were generally less sensitive to changes in the percent passing the No. 4 sieve than the 12.5 mm NMAS mixtures.

The results of this study provide laboratory-based evidence that adjusting the gradation as the SCDOT did by increasing the allowable percent passing the No. 4 sieve from 15-25% to 15-30% could potentially have positive effects on mixture durability while also maintaining adequate permeability for water drainage. Additionally, the use of the 9.5 mm NMAS gradation for mainline OGFC paving could also yield performance benefits. These changes should be further evaluated in pavement test sections.

Influence of Percent Passing the No. 200 Sieve

- The porosity generally increased when the filler content increased from 0-2% for both the 9.5 mm and 12.5 mm NMAS mixes. There is some speculation that this may be due to the additional filler in the binder film that slightly pushes the aggregates away from each other, thus reducing the packing density of the aggregates for a given compaction effort. Increasing the filler content from 2-6% resulted in decreased mix porosity, but the differences were not always statistically significant. The rate of decline of the porosity with increasing filler content was greater for the 9.5 mm mixes indicating that the permeability, or infiltration, of OGFC pavements made with 9.5 mm mixes may be more sensitive to changes in filler content than the 12.5 mm NMAS mixes due to the relationship between porosity and permeability.

- There were no consistent trends of the influence of filler content on the mean texture depth (MTD) of the two mixes evaluated as the MTD of the four 12.5 mm mixes were similar to each other and the MTD of the 9.5 mm mixes were similar to each other with the exception that the mix containing 2% filler, which had a higher MTD than the others. This finding indicates that the percent filler (i.e., material passing the No. 200 sieve) have little effect on the surface texture compared to larger aggregate sizes.

- The mechanical properties of the OGFC mixtures (ITS, Cantabro loss, and shear strength) were impacted to different degrees with changes in the filler content and the changes did not reflect the changes in porosity.

    - While there were some subtle differences, the ITS was generally unaffected by changes in the filler content. As anticipated, the mix with the lowest porosity had the highest ITS value.

    - The effect of filler content on Cantabro loss was dependent on the NMAS of the mix. The 9.5 mm mixes exhibited similar values across the range of filler content from 0-6% and the values were well below the maximum recommended values (i.e., 15% by SCDOT and 20% by Watson et al). For the 12.5 mm mixes, there was more variability and the differences started to become more significant when the filler content reached 6%, where the percent loss was well below the maximum recommended values. Increasing the filler content from 0% to just 2% resulted in an abrasion loss reduction of approximately 1.5%.

    - The effect on shear strength was also dependent on the NMAS. The shear strength of the 9.5 mm NMAS mixes generally increased as the filler content increased, as expected, due to the filler increasing the stiffness of the binder mastic, which in turn increases the shear strength of the mix. The 12.5 mm mixes, however, exhibited the opposite trend where the shear strength generally decreased as the filler content increased from 0-6%.

  - The shear strength of the OGFC mixes directly influenced the ITS—the ITS increased as the shear strength increased.

- While not a main focus of this study, the NMAS had a significant effect on the Cantabro loss where the 9.5 mm mixes exhibited significantly higher resistance to abrasion loss compared to the 12.5 mm mixes. It must be noted, however, that only one gradation was evaluated for each NMAS and all size fractions were kept constant except for the percent passing the 200 sieve. As previously mentioned, the 9.5 mm mix also showed a different shear strength trend than the 12.5 mm mix.

The results of this this laboratory study provide evidence that increasing the filler content of OGFC mixes, within reason, has the potential to result in positive effects on the durability while still maintaining adequate permeability for drainage performance, which has been seen by others (Watson et al. 2018). This supports the recommendation to require some level of filler content in OGFC gradation specifications and this should be further evaluated in pavement test sections.

Compaction Temperature of OGFC

Pavement mat temperature data collected using the MOBA Pave-IR system was analyzed to determine relationships between thermal segregation and paving operations. A lab study was also conducted to determine potential implications on performance of OGFC mixtures compacted at different temperatures. The results of this study led to the following conclusions:

- Thermal data, such as that from a system like MOBA Pave-IR, can be used to identify areas of thermal segregation in OGFC pavements that could potentially exhibit future distress. The data also showed that paver stops typically result in areas of thermal segregation.

- Lab results indicate that the porosity of hot mix OGFC mixtures generally increased as the result of lower compaction temperatures. This increase in porosity can result in a decrease in durability as seen in the ITS results in this study. By contrast, the warm mix OGFC made with Evotherm®, actually exhibited a reduction (or no change) in porosity due to compaction at lower temperatures. This reduction in porosity resulted in a more durable mixture as exhibited in the ITS and Cantabro test results in this study. However, to maintain the functional performance, the porosity should not be too low.

- OGFC made with a warm mix additive like Evotherm® may be less sensitive than conventional hot mix OGFC to changes in the temperature of the pavement mat during construction resulting in lower compaction temperature, within reason.

Laboratory Test Methods and Influencing Variables

This study compared five different test methods (ITS, direct shear, Cantabro, circular motion surface abrasion, and planetary motion surface abrasion) to assess the durability of OGFC mixtures in the laboratory and the effects of binder content and aging on mix performance. The results led to the following conclusions:

- Increasing the binder content of the OGFC mix from 5% to 7%, increased the performance in all test procedures evaluated in this study, however it also resulted in a porosity reduction, which needs to be monitored to ensure sufficient permeability.

- Subjecting the OGFC mixture to aging at 60°C resulted in increased stiffness of the binder at both high and low temperatures. At higher temperatures, this increased stiffness is beneficial in minimizing permanent deformation. This was seen in the increase in shear strength and indirect tensile strength of the mixture. However, at lower temperatures, the increased stiffness reduces the ductility of the binder increasing the susceptibility to fracture. This was seen in the increase in mass loss in the Cantabro test. This was also seen in the planetary motion surface abrasion test using Head B where the rate of abrasion loss over time was significantly higher after aging compared to the unaged condition.

- The surface abrasion tests resulted in a combination of dislodged particles and fractured particles, which may be a more representative failure mode than the Cantabro test.

- The planetary motion surface abrasion test method was more abrasive than the circular motion surface abrasion test method. The planetary motion surface abrasion test dislodged larger aggregate particles when compared to the singular motion surface abrasion test method due to the compound rotation of the testing head over the surface of the specimen.

- Test head B (triangular) was more abrasive than test head A (square) for both test methods (circular and planetary) due to its sharper shape, which allowed it to dig deeper into the pavement surface.

Bonding of OGFC Layers

This laboratory study evaluated the influence of five different tack coat products on the permeability and bond strength of composite specimens consisting of the OGFC surface layer over a Surface Course base layer. Additionally, the effect of gradation and compaction effort on bond strength was also evaluated. Based on the analysis of the results of this study, the following primary conclusions were drawn:

- The permeability of all composite specimens was lower than the permeability of the base layer itself. This was due to the application of the OGFC layer, but the contribution of the tack coat could not be isolated in this study. While the tack coat may have had some effect on the permeability reduction, the larger contributing factor was likely the masking and embedment effect of the aggregate particles in the OGFC mix reducing the accessible surface area of the base layer. The compaction of the OGFC layer also likely increased the density of the base layer, thus further reducing the permeability.

- The interlayer shear strength (ISS), or bond strength, was generally influenced by the stiffness of the tack coat material residual where the stiffer materials resulted in higher ISS.

- The non-tracking tack coat products (UltraTack® and UltraFuse®) yielded the highest ISS results compared to the other traditional tack coat materials (PG 64-22, CRS-2, and HFMS-1H). The non-tracking products used in this study were both polymer modified products, which significantly increases the shear stiffness of the material. The increased stiffness results in a higher resistance to deformation and higher shear strength exceeding that of the OGFC mix ultimately causing failure within the OGFC layer instead of at the interface between the OGFC and the base layer.

- The emulsion products exhibited the highest ISS at the lowest application rate of 0.033 gal/yd^2 (residual) and additional material resulted in a decrease in strength. However, for the hot applied binder products, the ISS performance generally increased with increase application rate. It is expected that there would be a maximum tack rate beyond which the ISS would decrease. The maximum ISS of the UltraFuse® was likely not reached in this study because the tack coat rates evaluated were lower than the manufacturers recommended range for this product.

- In all cases, the ISS values of the composite specimens were greater than the shear strength of the OGFC mix itself, which indicates that the mechanical bond and adhesive bond (aggregate embedment and tack coat) at the interface between layers was stronger than the OGFC mix itself. This was also evident after visual inspection of the failed specimens. This was true for specimens with and without tack coat.

- The ISS increased with the increase in percent passing No. 4 sieve for the composite specimens with a NMAS of 12.5 mm. It was assumed that with higher percent passing No. 4 sieve the aggregate potentially has more contact points at the interface which can improve the adhesive bond and increase the bond strength. For the specimens with NMAS of 9.5 mm, there was no clear correlation between the percent passing No. 4 and ISS test results.

- The ISS increased with an increase in compaction effort to a point where it leveled off. This was evident in this study where a compaction effort of 15 gyrations resulted in ISS values that were less than those compacted with 30 and 45 gyrations. However, there was not a significant gain in ISS by increasing the compaction effort from 30 to 45 gyrations.

OGFC Field Performance

This study included an evaluation of the field performance of OGFC pavements and included limited testing to assess the functional performance (i.e., infiltration) as well as an evaluation of durability performance (i.e., raveling) data collected by the SCDOT. Based on this portion of the study, the following primary conclusions were drawn:

- Infiltration results on the 9.5 mm NMAS OGFC on I-26 in Newberry County showed similar trends to other infiltration testing conducted previously on 12.5 mm NMAS OGFC mixes. The infiltration was higher closer to the transverse joint, then decreased until leveling out approximately 100 ft beyond the joint. This decrease in infiltration is the result of the decrease in OGFC density typically seen at start-up.

- OGFC pavements can become clogged, thus reducing the infiltration of the surface and the ability of the layer to drain water. This was seen in a pavement section that, despite cores having porosity values ranging from 13-21%, exhibited low to no surface infiltration.

- The majority of localized areas of raveling occur at either transverse joints or bridge departures.

- WMA OGFC mixes generally exhibited better field performance (durability) than HMA OGFC mixes. However, the data set was limited, so this is merely an observation at this time.

Recommendations

Based on the findings of the study, the following recommendations have been developed for implementation and further investigation:

Aggregate LA Abrasion

- Consider adjusting the maximum LA Abrasion value to 55%, but include guidance to account for the change in gradation resulting from aggregate breakdown during placement and compaction. The lab and field study suggested that the uniformity coefficient (C_u) will increase by a factor of 1.5 between mixing and compaction. This could be factored in when checking the gradation of the mix sampled from the haul truck. The uniformity coefficient can be calculated using the procedure outlined in Appendix E.

Aggregate Gradation

- Consider adjusting the gradation specifications for the 12.5 mm OGFC as follows:
    - Increase the allowable percent passing on the No. 4 sieve from 15-25% to 15-30%. *This change was implemented in 2016.*
    - Change the percent passing on the No. 200 sieve from 0-4% to 2-5%.

- Consider adjusting the gradation specifications for the 9.5 mm OGFC as follows:
    - Change the percent passing on the No. 200 sieve from 0-4% to 1-5%.

- Consider allowing the use of 9.5 mm OGFC mixtures for mainline paving instead of just for maintenance or patching. *This change was implemented in 2019 and multiple sections have been paved.*

Paving Operations

- Continue to limit paver stops. Consider requiring the contractor to report specific locations of paver stops experienced during construction of OGFC pavements and the mat temperature prior to compaction when the paver starts moving again. This will provide more data to help identify the impacts of paver stops on long-term pavement performance. Contractors already need to report a written explanation of paver stops that exceed 15 minutes, so this will not require a significant amount of additional work. If it does not already exist, consider creating a standard form to document paver stops. This could be an online form.

- Consider allowing up to four roller passes (instead of three) within the first 50-100 feet of a transverse cold joint (i.e., the beginning a paving for the day or coming off of a bridge tie-in) to account for the potential reduction in mix temperature. However, it should still be emphasized that adjustments should be made if aggregate breakdown is observed.

- Consider requiring methods to ensure smooth transitions at transverse joints and bridge joints to minimize potential damage from snowplows. This could be accomplished by using a straight edge to ensure the OGFC is at the same grade as the bridge deck (bridge joint) or the previous day's paving (transverse joint).

Tack Coat

- Consider limiting tack coats to low-tracking tack coats such as UltraTack and UltraFuse that were evaluated in this study. PG 64-22 binder can also be used. Ensure that the appropriate application rate is used for any product (e.g., at least 0.08 gal/yd^2 for UltraFuse and similar products, 0.033 gal/yd^2 residual for UltraTack and similar products, and 0.05 gal/yd^2 for PG 64-22). *Specification of hot applied bond coats and PG 64-22 was implemented in 2019.*

Field Quality Testing

- Consider a field infiltration test on newly paved OGFC layers (see Appendix B). This will not only provide a measure of the functional performance of the OGFC layer, but also an indicator of potentially durability issues in areas of excessively high infiltration. This testing could be conducted the same day as placement after the mat has cooled for at least two hours. Test locations could focus on select transverse cold joints (check for high infiltration/under-compaction) and locations between transverse joints (check for minimum infiltration and consistency). Prior to full implementation, this could be done on a trial basis to determine the value.

Further Investigation

- With the renewed use of Stone Matrix Asphalt (SMA) in South Carolina on routes that would typically use an OGFC surface, the SCDOT might consider a study on the safety performance (and factors affecting safety) of the pavements surfaced with SMA compared to those surfaces with OGFC.

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Appendices

Appendix A: Aggregate Breakdown by Mixing and Compaction

Appendix B: Infiltration Test for OGFC Pavements

Appendix C: Data from Field Performance Assessment

Appendix D: OGFC Job Mix Formulas

Appendix E: Determination of Uniformity Coefficient (C_u)

Appendix A: Aggregate Breakdown by Mixing and Compaction

Table A.1. Gradation after mixing for two minutes with no compaction.

	Percent Passing												
Sieve Size	**Original Gradation 12.5mm**	**Quarry A (LA: 51)**	**Quarry B (LA: 51)**	**Quarry C (LA: 50)**	**Quarry D (LA: 40)**	**Quarry E (LA: 39)**	**Quarry F (LA: 38)**	**Quarry G (LA: 30)**	**Quarry H (LA: 21)**	**Quarry I (LA: 21)**	**Quarry J (LA: 33)**	**Quarry K (LA: 30)**	**Avg. Change from Original**
3/4"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0
1/2"	94.0	97.1	95.9	95.4	97.3	96.7	96.1	95.0	94.3	93.8	94.8	93.0	1.4
3/8"	69.0	74.7	78.8	74.1	85.2	81.5	77.0	72.8	69.5	70.0	69.0	69.9	5.8
#4	19.0	24.5	30.7	28.4	41.3	33.6	29.4	26.5	21.4	20.9	22.0	22.6	8.4
#8	7.0	12.7	14.4	14.3	20.2	16.2	14.9	13.8	8.5	8.5	8.8	9.4	5.9
#30	3.5	7.5	7.9	7.7	7.4	6.8	7.6	6.9	4.8	4.8	5.6	5.8	3.1
#100	2.0	4.0	4.0	3.9	3.6	3.3	3.9	3.6	2.8	2.6	3.2	3.7	1.5
#200	1.00	2.04	1.96	1.86	1.80	1.69	1.95	1.84	1.52	1.38	1.6	2.1	0.8

Table A.2. Gradation after mixing for two minutes and compaction with 50 gyrations.

		Percent Passing											
Sieve Size	**Original Gradation 12.5mm**	**Quarry A (LA: 51)**	**Quarry B (LA: 51)**	**Quarry C (LA: 50)**	**Quarry D (LA: 40)**	**Quarry E (LA: 39)**	**Quarry F (LA: 38)**	**Quarry G (LA: 30)**	**Quarry H (LA: 21)**	**Quarry I (LA: 21)**	**Quarry J (LA: 33)**	**Quarry K (LA: 30)**	**Avg. Change from Original**
3/4"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0
1/2"	94.0	95.3	96.6	95.9	98.4	97.4	96.6	95.4	94.6	94.2	94.8	92.9	1.6
3/8"	69.0	74.8	80.6	77.4	87.7	82.6	79.8	74.7	70.9	71.5	71.8	71.0	7.6
#4	19.0	28.5	40.8	36.9	47.7	38.6	38.5	30.7	23.2	25.0	27.7	33.0	14.7
#8	7.0	16.4	21.7	19.9	25.2	20.1	20.1	16.1	9.8	10.4	13.7	15.5	10.2
#30	3.5	9.0	11.3	10.4	9.2	8.4	9.6	7.8	5.4	5.4	7.0	8.5	4.9
#100	2.0	4.5	5.2	5.0	4.4	4.1	4.7	4.2	3.1	3.0	3.9	5.4	2.3
#200	1.00	2.31	2.57	2.45	2.24	2.07	2.37	2.13	1.8	1.63	2.0	2.9	1.2

Appendix B: Infiltration Test for OGFC Pavements

Standard Method of Test for

In-situ Infiltration Rate of Open Graded Friction Course (OGFC) Pavements

SC Designation: SC-T-XX

(This procedure has been adopted from ASTM C1701)

1. SCOPE

This procedure is to measure the infiltration rate of in place OGFC pavements.

2. REFERENCED DOCUMENTS

2.1.

3. APPARATUS

3.1. Brush or broom – A brush or broom to sweep the area to be tested.

3.2. Infiltration ring – A cylindrical ring, open at both ends that is watertight and sufficiently rigid to retain its shape when filled with water. The ring shall have a diameter of 12 ± 0.5 in. with a minimum height of 2 in. The bottom edge of the ring shall be even. The inner surface of the ring shall be marked or scored with two lines at a distance of 0.4 and 0.6 in. from the bottom of the ring.

3.3. Measuring container – Graduated container capable of measuring 1 gallon of water.

3.4. Container – A plastic 5 gallon bucket to be used to pour water into the infiltration ring.

3.5. Stop watch – Accurate to 0.1s.

3.6. Plumbers putty (non-hardening)

3.7. Water

4. TEST LOCATIONS

4.1. Perform tests at multiple locations at a site.

4.2. Provide at least 3 ft. of clear distance between test locations, unless at least 24 hours have elapsed between tests.

4.3. Do not test if there is standing water on the pavement or within 24 hours of the last precipitation.

5. PROCEDURE

5.1. Clean the pavement surface by brushing loose material from the pavement surface where the test is to be conducted.

5.2. Apply plumbers putty around the bottom of the infiltration ring and place the ring onto the pavement surface. Press the putty into the surface and around the bottom edge of the ring to create a watertight seal. Use additional putty as needed.

5.3. Pour 1 gallon of water into the ring at a sufficient rate to maintain the water level between the two marked lines. Begin timing as soon as the water impacts the pavement surface and stop timing when water is no longer present on the pavement surface. Record the time to the nearest 0.1 s.

5.4. Repeat step 5.3 so the test has been conducted a total of three times.

6. CALCULATIONS

6.1. Calculate the infiltration rate (*I*) using Equation 1.

$$I = \frac{832000}{A \times t} \qquad (1)$$

Where,

A = inside area of the infiltration ring (in^2)
t = time (s)

6.2. Calculate the average infiltration rate of tests 2 and 3.

7. REPORT

7.1. Time elapsed since last rain event, if known.
7.2. Inside diameter of infiltration ring to the nearest 0.01 in.
7.3. Time elapsed for each of the three test runs to the nearest 0.1 s.
7.4. Infiltration rate of each test run to the nearest 1 in/hr.
7.5. Average infiltration rate of test runs 2 and 3 to the nearest 1 in/hr.

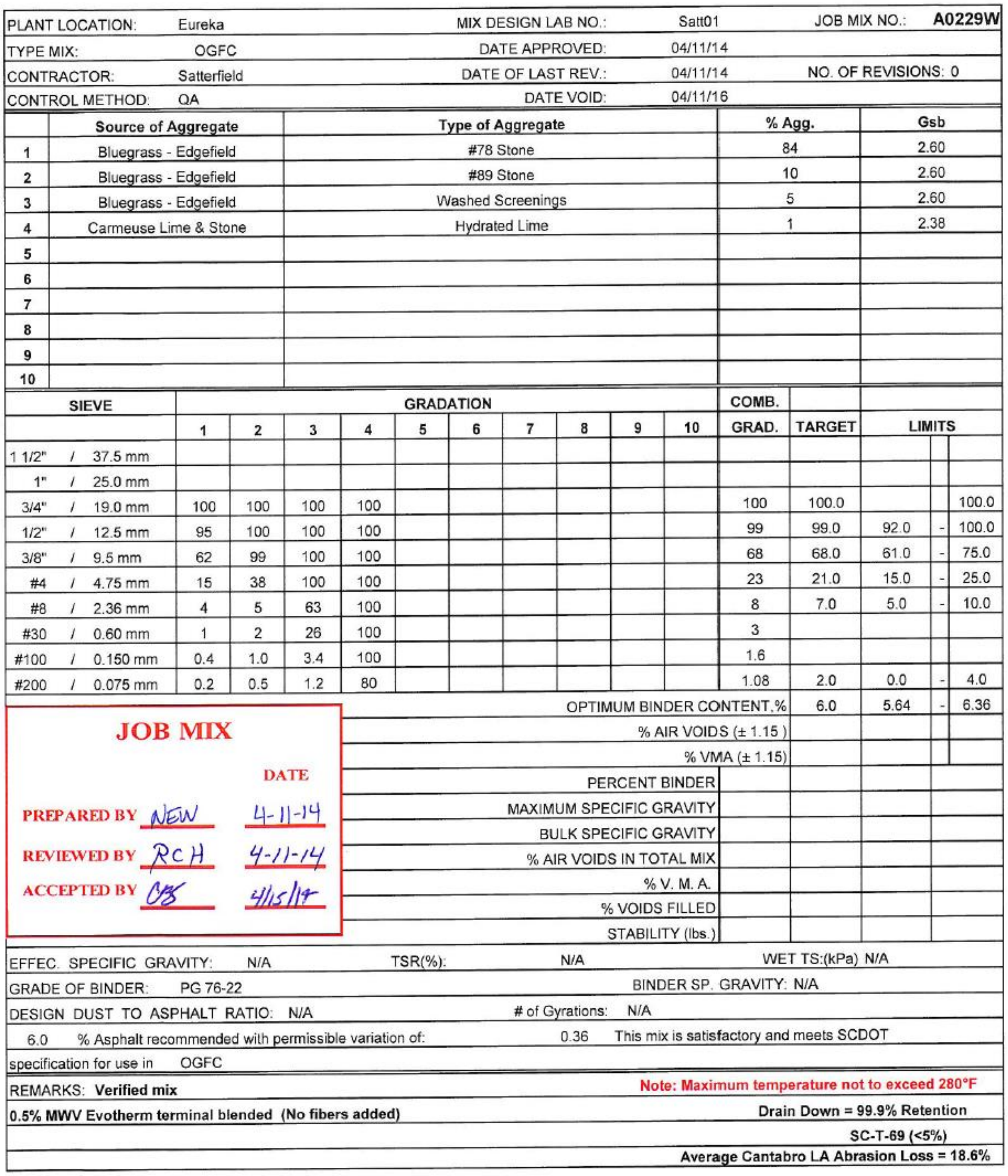
Appendix C: Data from Field Performance Assessment

The following data was adapted from report by Jason Johnston in 2019 titled “Maximizing the Lifespan of Open-Graded Friction Course on South Carolina Highways.”

Rte	Dir	Beg MP	End MP	No. Lanes	File	Contractor	Completion Date	Lane Miles	Total Cold Joint Issues	Cold Joint Issues/Mile	# of Bridges	Bridge Approach Issues	Total Bridge Approaches	% Bridge Approaches with Issues	Bride Departure Issues	Total Bridge Departures	% Bridge Departures with Issues	Total Bridge Joint Issues	Total Bridge Joints	Total Mid-Shift Issues	Mid-Shift Issues/Mile	Total Cold Joint and Mid-Shift Issues per Lane-Mile	JMF
I-20	W	6.5	13	2	2.040654	Reeves	Jul-12	13	5	0.38	0	0	0	0.0%	0	0	0.0%	0	0	0	0.00	0.38	N0041
I-20	W	13	22.74	2	280860	Satterfield	Dec-14	19.48	2	0.1	3	0	6	0.0%	2	6	33.3%	2	12	0	0.00	0.10	A0229W
I-20	E	22.7	37.7	2	02..37242A	REA	Feb-12	30	1	0.03	3	0	6	0.0%	1	6	16.7%	1	12	0	0.00	0.03	
I-20	W	37.7	54.4	2	32.037179A	CR Jackson	May-12	33.4	6	0.18	4	0	8	0.0%	0	8	0.0%	0	16	0	0.00	0.18	
I-20	E&W	60.28	69.9	4	3240.037174A	CR Jackson	May-12	38.48	2	0.05	10	0	20	0.0%	4	20	20.0%	4	40	0	0.00	0.05	
I-20	E&W	69.9	76.1	4	4090840	CR Jackson	Apr-17	24.8	0	0	6	0	12	0.0%	0	12	0.0%	0	24	0	0.00	0.00	B0375W, C0219W
I-20	E&W	84.55	94.5	4	28.040658	Sloan	Sep-12	39.8	7	0.18	4	0	8	0.0%	1	8	12.5%	1	16	5	0.13	0.30	N0345, N0364W, N0432
I-20	E&W	94.5	105.8	4	28.039535	Boggs	May-16	45.2	5	0.11	14	0	28	0.0%	1	28	3.6%	1	56	1	0.02	0.13	P0075, P0076
I-20	W	133.8	139.15	2	Unknown	Unknown	2016??	10.7	0	0	0	0	0	0.0%	0	0	0.0%	0	0	0	0.00	0.00	B0408W
I-20	E	135.4	139.15	2	Unknown	Unknown	2016??	7.5	0	0	0	0	0	0.0%	0	0	0.0%	0	0	0	0.00	0.00	
I-26	E	0	5	2	42.037126A	Sloan	Aug-12	10	0	0	0	0	0	0.0%	0	0	0.0%	0	0	0	0.00	0.00	
I-26	E	5	11.1	2	43.0384	Sloan	May-11	12.2	1	0.08	1	0	2	0.0%	1	2	50.0%	1	4	0	0.00	0.08	
I-26	W	5.1	13.8	2	42.039719	Sloan	Dec-12	17.4	1	0.06	1	0	2	0.0%	0	2	0.0%	0	4	0	0.00	0.06	N0380
I-26	E	11.1	22	2	42.038624A	Sloan	Jan-13	21.8	4	0.18	0	0	0	0.0%	0	0	0.0%	0	0	0	0.00	0.18	P0362
I-26	E&W	43.8	60.3	4	30.038567	Sloan	Apr-15	66	2	0.03	4	0	8	0.0%	1	8	12.5%	1	16	0	0.00	0.03	P0362
I-26	E&W	85.16	85.75	4	Unknown	Unknown	Nov-12	2.36	2	0.85	0	0	0	0.0%	0	0	0.0%	0	0	0	0.00	0.85	L0484, N0380, N0432
I-26	W	98.01	99.25	2	Unknown	Unknown	Nov-11	2.48	1	0.4	0	0	0	0.0%	0	0	0.0%	0	0	1	0.40	0.81	N0377
I-26	E&W	107.9	109.72	7	32.038831	CR Jackson	Oct-14	12.74	2	0.16	2	0	7	0.0%	1	7	14.3%	1	14	1	0.08	0.24	N0377
I-26	E&W	109.72	114.88	7	32.038831	CR Jackson	Oct-14	36.12	1	0.03	8	1	28	3.6%	1	28	3.6%	2	56	2	0.06	0.08	N0377
I-26	E&W	114.88	125.7	6	932.03817	Ander/Cola	Nov-16	64.92	1	0.02	2	0	6	0.0%	0	6	0.0%	0	12	1	0.02	0.03	
I-26	E&W	125.7	136	4	932.03817	Ander/Cola	Nov-16	41.2	2	0.05	0	0	0	0.0%	0	0	0.0%	0	0	0	0.00	0.05	
I-26	E&W	136	149.1	4	9.040661	CR Jackson	Oct-14	52.4	10	0.19	0	0	0	0.0%	1	0	0.0%	1	0	12	0.23	0.42	N0409
I-26	E&W	181.7	197.67	4	8.040656	Banks	Nov-12	63.88	8	0.13	4	0	8	0.0%	2	8	25.0%	2	16	3	0.05	0.17	N0175, N0177
I-26	E&W	197.67	198.28	6	8.040656	Banks	Nov-12	3.66	0	0	0	0	0	0.0%	0	0	0.0%	0	0	0	0.00	0.00	N0175, N0178
I-26	E&W	198.28	204	6	8.038314	Banks	Oct-10	34.32	3	0.09	0	0	0	0.0%	0	0	0.0%	0	0	3	0.09	0.17	
I-26	E&W	204	208.54	6	8.038314	Banks	Oct-10	27.24	5	0.18	0	0	0	0.0%	0	0	0.0%	0	0	7	0.26	0.44	
I-26	E&W	208.54	209.8	8	8.038314	Banks	Oct-10	10.08	1	0.1	2	0	8	0.0%	1	8	12.5%	1	16	7	0.69	0.79	
I-520	E&W	5.87	11.74	4	290470	Satterfield	Nov-15	23.48	0	0	9	0	18	0.0%	0	18	0.0%	0	36	0	0.00	0.00	
I-526	E&W	10.12	15.89	4	8.038314	Banks	Oct-10	23.08	8	0.35	18	3	36	8.3%	2	36	5.6%	5	72	6	0.26	0.61	
I-526	E&W	17.51	19.56	4	10.039363A	Banks	Dec-13	8.2	1	0.12	12	1	24	4.2%	3	24	12.5%	4	48	2	0.24	0.37	N0175, N0177
I-77	N&S	27	33.56	4	8888400	Lane	Nov-15	26.24	1	0.04	0	0	0	0.0%	0	0	0.0%	0	0	0	0.00	0.04	B0375W
I-77	N&S	48.18	64.7	4	1220.039419	Boggs	Jun-13	66.08	7	0.11	8	0	16	0.0%	1	16	6.3%	1	32	1	0.02	0.12	N0100, N0101
I-77	N&S	64.7	76	4	12.042242	Lane	Sep-16	45.2	9	0.2	10	0	20	0.0%	0	20	0.0%	0	40	4	0.09	0.29	P0296
I-77	N&S	76	91.5	8	4680840	Lane	Mar-17	124	4	0.03	12	0	48	0.0%	1	48	2.1%	1	96	1	0.01	0.04	B0079W
I-85	N&S	0	10.8	4	4.040655	Sloan	Oct-14	43.2	1	0.02	0	0	0	0.0%	0	0	0.0%	0	0	0	0.00	0.02	N0380
I-85	N&S	10.8	18.8	4	04.036559A	Sloan	Jan-11	32	4	0.13	0	1	0	0.0%	1	0	0.0%	2	0	1	0.03	0.16	
I-85	N&S	34	43	6	0423.037173A	Sloan	May-12	54	7	0.13	6	0	18	0.0%	1	18	5.6%	1	36	0	0.00	0.13	
I-85	S	43	47.3	3	23.038622	Sloan	Mar-12	12.9	0	0	1	0	3	0.0%	0	3	0.0%	0	6	0	0.00	0.00	
I-85	N	43	47.3	3	2342.039847	REA	Aug-13	12.9	1	0.08	2	0	6	0.0%	0	6	0.0%	0	12	2	0.16	0.23	N0454
I-85	S	47.3	56.1	3	2342.039847	REA	Aug-13	26.4	6	0.23	1	0	3	0.0%	2	3	66.7%	2	6	3	0.11	0.34	N0454
I-85	N&S	88	106	4	11.041486R1	Sloan	Nov-15	72	3	0.04	8	0	16	0.0%	3	16	18.8%	3	32	1	0.01	0.06	
I-95	N&S	0	4	4	27.041488	RB Baker	Nov-13	16	1	0.06	10	0	20	0.0%	3	20	15.0%	3	40	1	0.06	0.13	P0430
I-95	N&S	85.7	99.4	4	38.039031	CR Jackson	Jul-14	54.8	15	0.27	15	0	30	0.0%	5	30	16.7%	5	60	3	0.05	0.33	N0409
I-95	N	114.14	131.48	2	14.037231A	CR Jackson	Feb-13	34.68	3	0.09	1	0	2	0.0%	1	2	50.0%	1	4	7	0.20	0.29	
I-95	S	114.2	119.4	2	14.038645	Palmetto	Feb-13	10.4	4	0.38	1	0	2	0.0%	1	2	50.0%	1	4	10	0.96	1.35	
I-95	N&S	171.2	193.4	4	1721.037175A	Costello	Jan-11	88.8	5	0.06	31	0	62	0.0%	6	62	9.7%	6	124	5	0.06	0.11	

Appendix D: OGFC Job Mix Formulas

The job mix formulas (JMF) included in this appendix were used for some of the OGFC sections included in the field performance evaluation as noted on the data table in Appendix C.



PLANT LOCATION: Eureka MIX DESIGN LAB NO.: Satt01 JOB MIX NO.: **A0229W**
TYPE MIX: OGFC DATE APPROVED: 04/11/14
CONTRACTOR: Satterfield DATE OF LAST REV.: 04/11/14 NO. OF REVISIONS: 0
CONTROL METHOD: QA DATE VOID: 04/11/16

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Bluegrass - Edgefield	#78 Stone	84	2.60
2	Bluegrass - Edgefield	#89 Stone	10	2.60
3	Bluegrass - Edgefield	Washed Screenings	5	2.60
4	Carmeuse Lime & Stone	Hydrated Lime	1	2.38
5				
6				
7				
8				
9				
10				

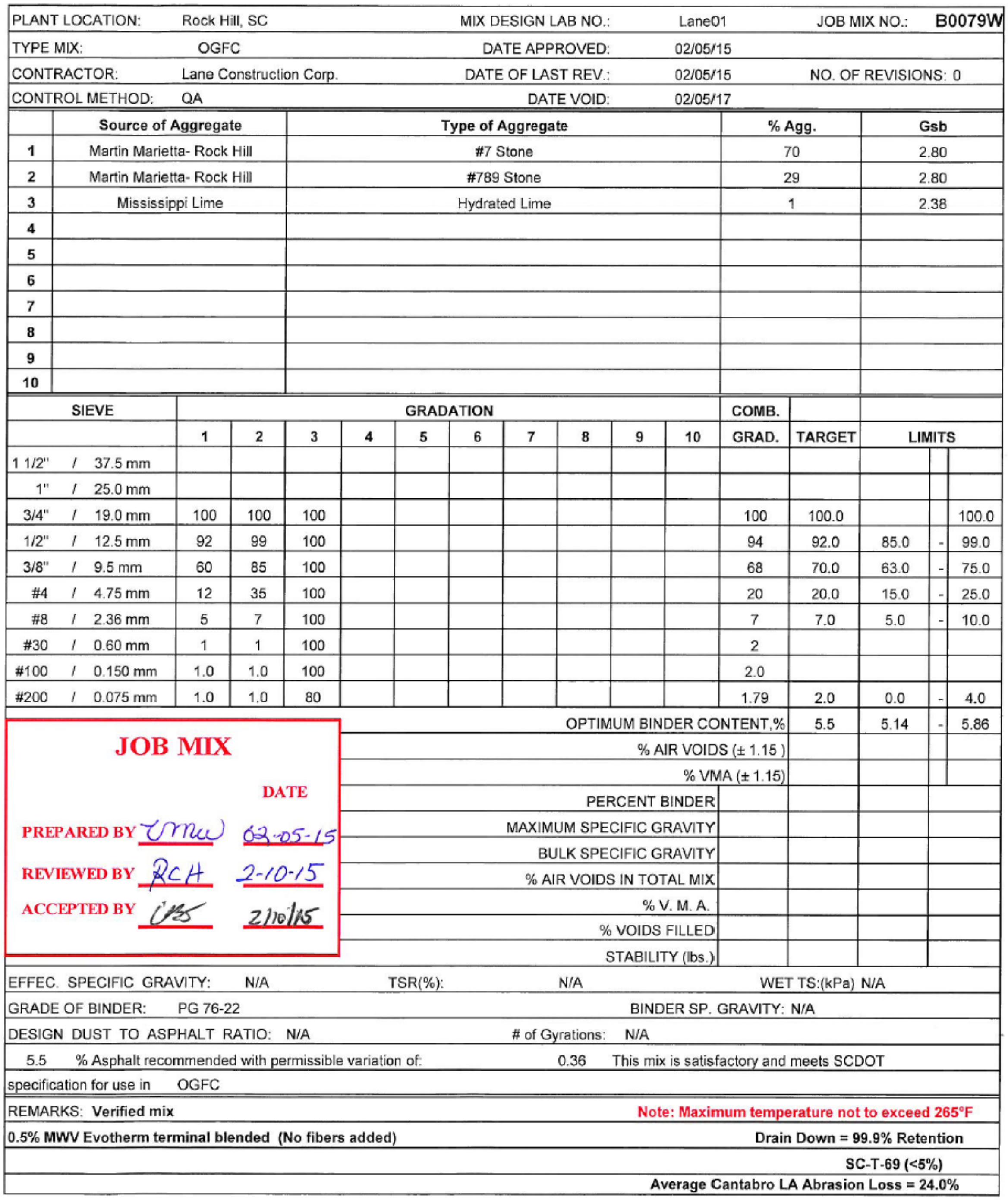
SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100	100							100	100.0			100.0
1/2" / 12.5 mm	95	100	100	100							99	99.0	92.0	-	100.0
3/8" / 9.5 mm	62	99	100	100							68	68.0	61.0	-	75.0
#4 / 4.75 mm	15	38	100	100							23	21.0	15.0	-	25.0
#8 / 2.36 mm	4	5	63	100							8	7.0	5.0	-	10.0
#30 / 0.60 mm	1	2	26	100							3				
#100 / 0.150 mm	0.4	1.0	3.4	100							1.6				
#200 / 0.075 mm	0.2	0.5	1.2	80							1.08	2.0	0.0	-	4.0

OPTIMUM BINDER CONTENT,%	6.0	5.64	-	6.36
% AIR VOIDS (± 1.15)				
% VMA (± 1.15)				
PERCENT BINDER				
MAXIMUM SPECIFIC GRAVITY				
BULK SPECIFIC GRAVITY				
% AIR VOIDS IN TOTAL MIX				
% V. M. A.				
% VOIDS FILLED				
STABILITY (lbs.)				

JOB MIX

		DATE
PREPARED BY	NEW	4-11-14
REVIEWED BY	RCH	4-11-14
ACCEPTED BY	CB	4/15/14

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A
GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A
DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A
6.0 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT
specification for use in OGFC
REMARKS: **Verified mix** **Note: Maximum temperature not to exceed 280°F**
0.5% MWV Evotherm terminal blended (No fibers added) **Drain Down = 99.9% Retention**
SC-T-69 (<5%)
Average Cantabro LA Abrasion Loss = 18.6%



PLANT LOCATION:	Rock Hill, SC	MIX DESIGN LAB NO.:	Lane01	JOB MIX NO.:	**B0079W**
TYPE MIX:	OGFC	DATE APPROVED:	02/05/15		
CONTRACTOR:	Lane Construction Corp.	DATE OF LAST REV.:	02/05/15	NO. OF REVISIONS: 0	
CONTROL METHOD:	QA	DATE VOID:	02/05/17		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Martin Marietta- Rock Hill	#7 Stone	70	2.80
2	Martin Marietta- Rock Hill	#789 Stone	29	2.80
3	Mississippi Lime	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100								100	100.0			100.0
1/2" / 12.5 mm	92	99	100								94	92.0	85.0	-	99.0
3/8" / 9.5 mm	60	85	100								68	70.0	63.0	-	75.0
#4 / 4.75 mm	12	35	100								20	20.0	15.0	-	25.0
#8 / 2.36 mm	5	7	100								7	7.0	5.0	-	10.0
#30 / 0.60 mm	1	1	100								2				
#100 / 0.150 mm	1.0	1.0	100								2.0				
#200 / 0.075 mm	1.0	1.0	80								1.79	2.0	0.0	-	4.0
OPTIMUM BINDER CONTENT,%												5.5	5.14	-	5.86
% AIR VOIDS (± 1.15)															
% VMA (± 1.15)															

JOB MIX

		DATE
PREPARED BY		02-05-15
REVIEWED BY	RCH	2-10-15
ACCEPTED BY		2/10/15

PERCENT BINDER				
MAXIMUM SPECIFIC GRAVITY				
BULK SPECIFIC GRAVITY				
% AIR VOIDS IN TOTAL MIX				
% V. M. A.				
% VOIDS FILLED				
STABILITY (lbs.)				

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A

DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

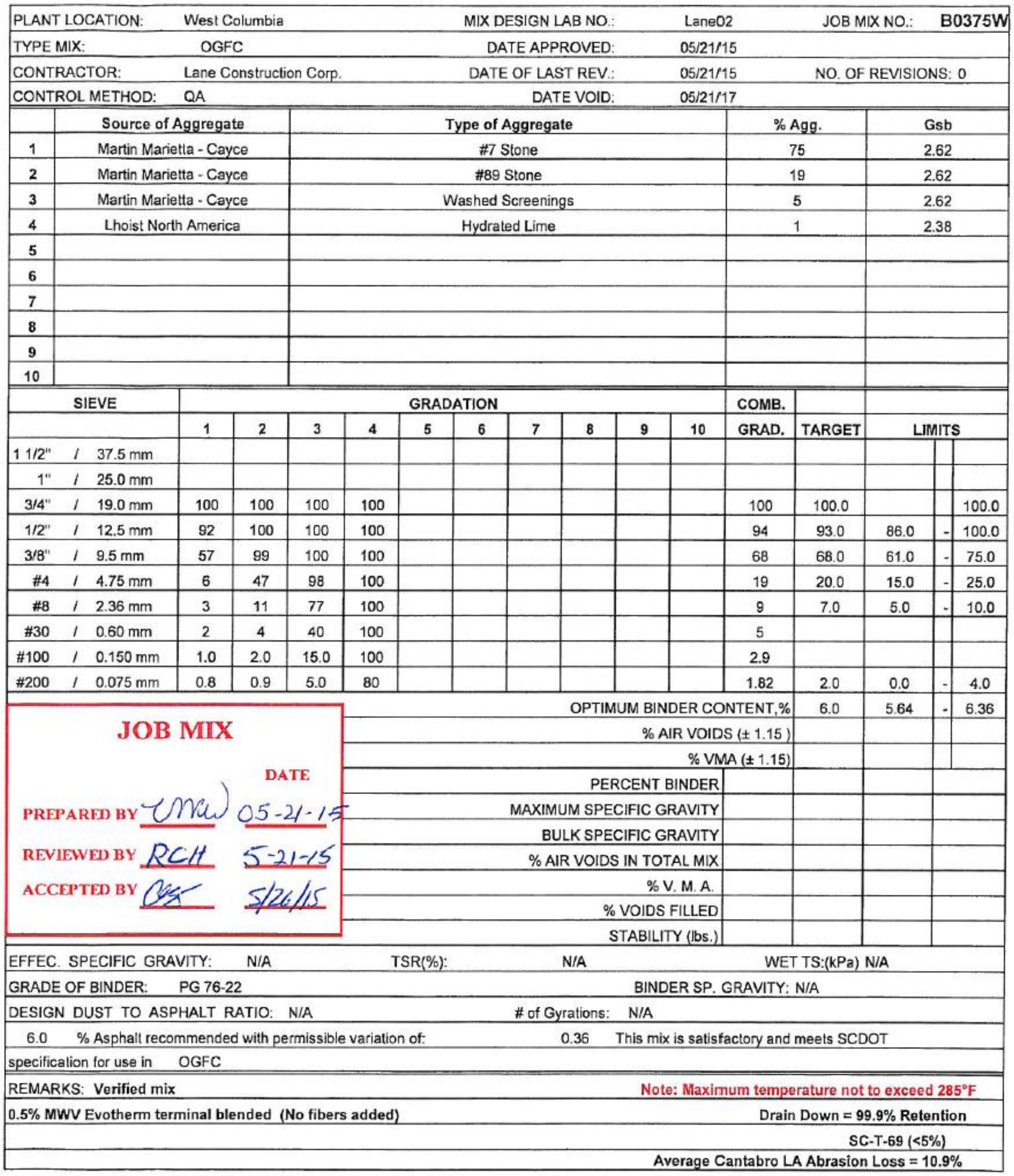
5.5 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT specification for use in OGFC

REMARKS: **Verified mix** **Note: Maximum temperature not to exceed 265°F**

0.5% MWV Evotherm terminal blended (No fibers added) **Drain Down = 99.9% Retention**

SC-T-69 (<5%)

Average Cantabro LA Abrasion Loss = 24.0%



PLANT LOCATION: West Columbia MIX DESIGN LAB NO.: Lane02 JOB MIX NO.: **B0375W**
TYPE MIX: OGFC DATE APPROVED: 05/21/15
CONTRACTOR: Lane Construction Corp. DATE OF LAST REV.: 05/21/15 NO. OF REVISIONS: 0
CONTROL METHOD: QA DATE VOID: 05/21/17

	Source of Aggregate	Type of Aggregate	% Agg.	Gsb
1	Martin Marietta - Cayce	#7 Stone	75	2.62
2	Martin Marietta - Cayce	#89 Stone	19	2.62
3	Martin Marietta - Cayce	Washed Screenings	5	2.62
4	Lhoist North America	Hydrated Lime	1	2.38
5				
6				
7				
8				
9				
10				

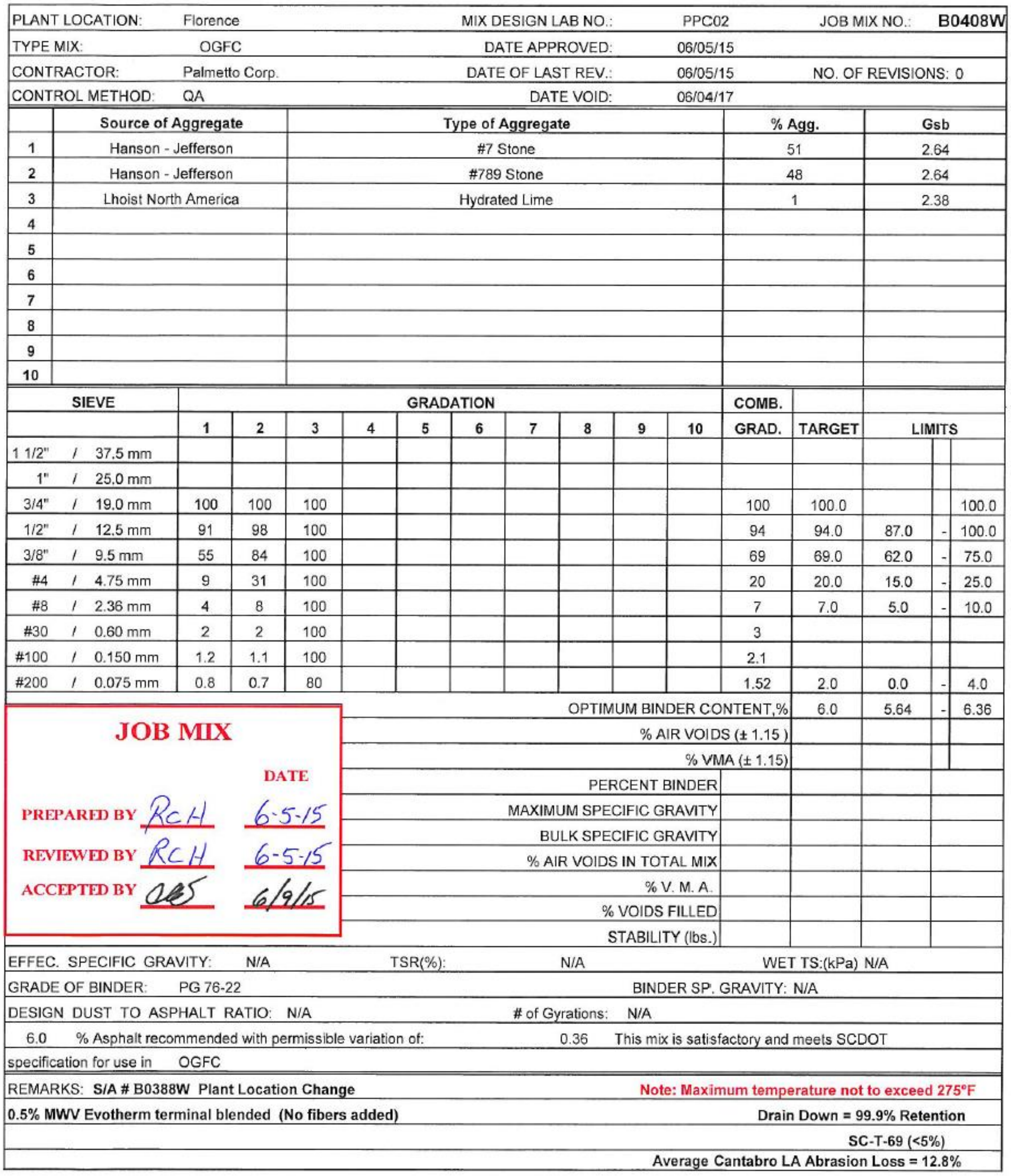
SIEVE	GRADATION										COMB.				
	1	2	3	4	5	6	7	8	9	10	GRAD.	TARGET	LIMITS		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100	100							100	100.0			100.0
1/2" / 12.5 mm	92	100	100	100							94	93.0	86.0	-	100.0
3/8" / 9.5 mm	57	99	100	100							68	68.0	61.0	-	75.0
#4 / 4.75 mm	6	47	98	100							19	20.0	15.0	-	25.0
#8 / 2.36 mm	3	11	77	100							9	7.0	5.0	-	10.0
#30 / 0.60 mm	2	4	40	100							5				
#100 / 0.150 mm	1.0	2.0	15.0	100							2.9				
#200 / 0.075 mm	0.8	0.9	5.0	80							1.82	2.0	0.0	-	4.0

OPTIMUM BINDER CONTENT,%	6.0	5.64	-	6.36
% AIR VOIDS (± 1.15)				
% VMA (± 1.15)				
PERCENT BINDER				
MAXIMUM SPECIFIC GRAVITY				
BULK SPECIFIC GRAVITY				
% AIR VOIDS IN TOTAL MIX				
% V. M. A.				
% VOIDS FILLED				
STABILITY (lbs.)				

JOB MIX

DATE
PREPARED BY UMW 05-21-15
REVIEWED BY RCH 5-21-15
ACCEPTED BY 5/26/15

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A
GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A
DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A
6.0 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT
specification for use in OGFC
REMARKS: **Verified mix** **Note: Maximum temperature not to exceed 285°F**
0.5% MWV Evotherm terminal blended (No fibers added) **Drain Down = 99.9% Retention**
SC-T-69 (<5%)
Average Cantabro LA Abrasion Loss = 10.9%



PLANT LOCATION:	Florence	MIX DESIGN LAB NO.:	PPC02	JOB MIX NO.:	**B0408W**
TYPE MIX:	OGFC	DATE APPROVED:	06/05/15		
CONTRACTOR:	Palmetto Corp.	DATE OF LAST REV.:	06/05/15	NO. OF REVISIONS: 0	
CONTROL METHOD:	QA	DATE VOID:	06/04/17		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Hanson - Jefferson	#7 Stone	51	2.64
2	Hanson - Jefferson	#789 Stone	48	2.64
3	Lhoist North America	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100								100	100.0			100.0
1/2" / 12.5 mm	91	98	100								94	94.0	87.0	-	100.0
3/8" / 9.5 mm	55	84	100								69	69.0	62.0	-	75.0
#4 / 4.75 mm	9	31	100								20	20.0	15.0	-	25.0
#8 / 2.36 mm	4	8	100								7	7.0	5.0	-	10.0
#30 / 0.60 mm	2	2	100								3				
#100 / 0.150 mm	1.2	1.1	100								2.1				
#200 / 0.075 mm	0.8	0.7	80								1.52	2.0	0.0	-	4.0

OPTIMUM BINDER CONTENT,%		6.0	5.64	-	6.36
% AIR VOIDS (± 1.15)					
% VMA (± 1.15)					
PERCENT BINDER					
MAXIMUM SPECIFIC GRAVITY					
BULK SPECIFIC GRAVITY					
% AIR VOIDS IN TOTAL MIX					
% V. M. A.					
% VOIDS FILLED					
STABILITY (lbs.)					

JOB MIX

		DATE
PREPARED BY	RCH	6-5-15
REVIEWED BY	RCH	6-5-15
ACCEPTED BY		6/9/15

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A

DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

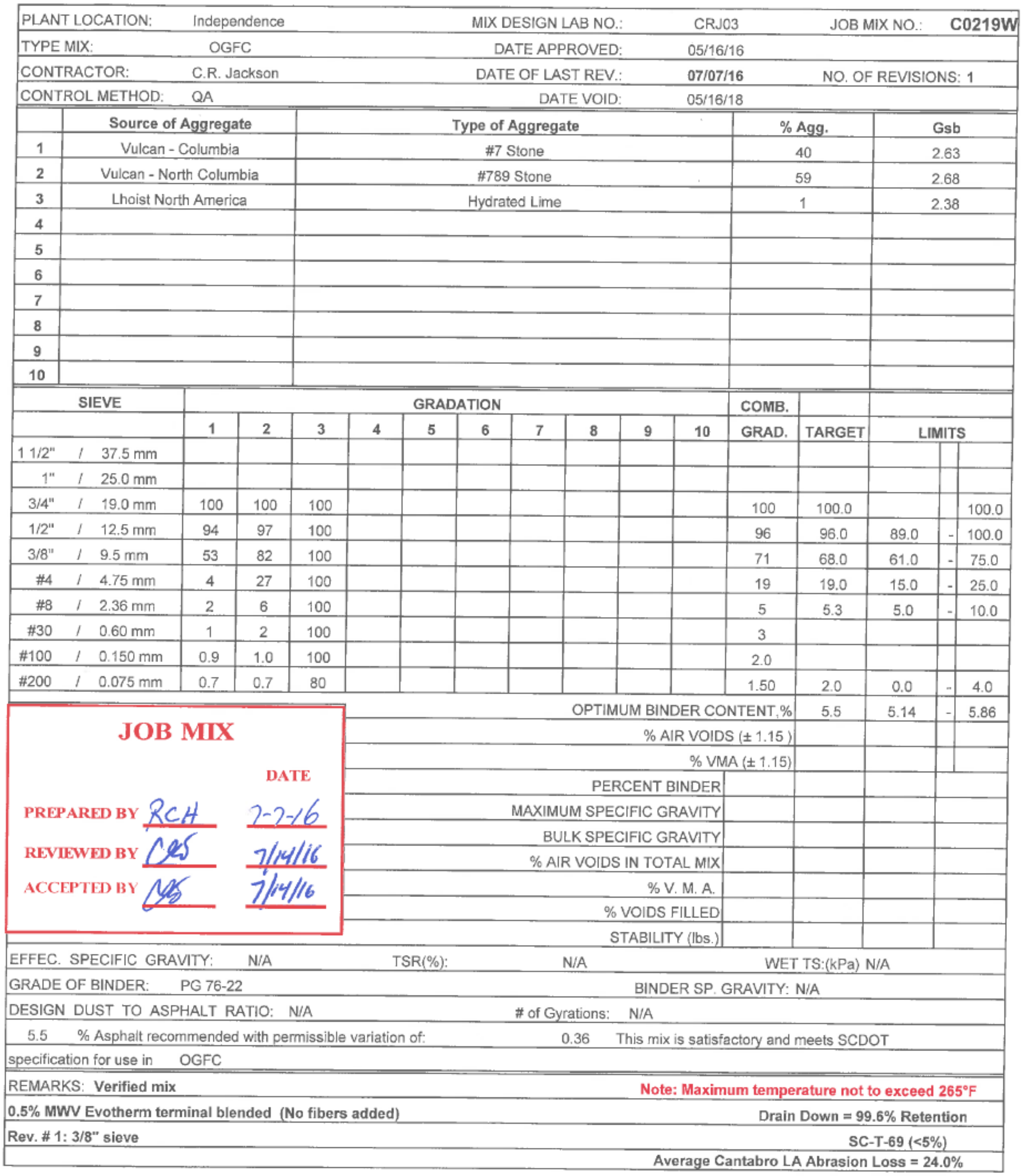
6.0 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT specification for use in OGFC

REMARKS: **S/A # B0388W Plant Location Change** **Note: Maximum temperature not to exceed 275°F**

0.5% MWV Evotherm terminal blended (No fibers added) **Drain Down = 99.9% Retention**

SC-T-69 (<5%)

Average Cantabro LA Abrasion Loss = 12.8%



PLANT LOCATION:	Independence	MIX DESIGN LAB NO.:	CRJ03	JOB MIX NO.:	**C0219W**
TYPE MIX:	OGFC	DATE APPROVED:	05/16/16		
CONTRACTOR:	C.R. Jackson	DATE OF LAST REV.:	**07/07/16**	NO. OF REVISIONS: 1	
CONTROL METHOD:	QA	DATE VOID:	05/16/18		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Vulcan - Columbia	#7 Stone	40	2.63
2	Vulcan - North Columbia	#789 Stone	59	2.68
3	Lhoist North America	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100								100	100.0			100.0
1/2" / 12.5 mm	94	97	100								96	96.0	89.0	-	100.0
3/8" / 9.5 mm	53	82	100								71	68.0	61.0	-	75.0
#4 / 4.75 mm	4	27	100								19	19.0	15.0	-	25.0
#8 / 2.36 mm	2	6	100								5	5.3	5.0	-	10.0
#30 / 0.60 mm	1	2	100								3				
#100 / 0.150 mm	0.9	1.0	100								2.0				
#200 / 0.075 mm	0.7	0.7	80								1.50	2.0	0.0	-	4.0

OPTIMUM BINDER CONTENT,%	5.5	5.14	-	5.86	
% AIR VOIDS (± 1.15)					
% VMA (± 1.15)					
PERCENT BINDER					
MAXIMUM SPECIFIC GRAVITY					
BULK SPECIFIC GRAVITY					
% AIR VOIDS IN TOTAL MIX					
% V. M. A.					
% VOIDS FILLED					
STABILITY (lbs.)					

JOB MIX

DATE

PREPARED BY RCH 7-7-16

REVIEWED BY 7/14/16

ACCEPTED BY 7/14/16

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A

DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

5.5 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT

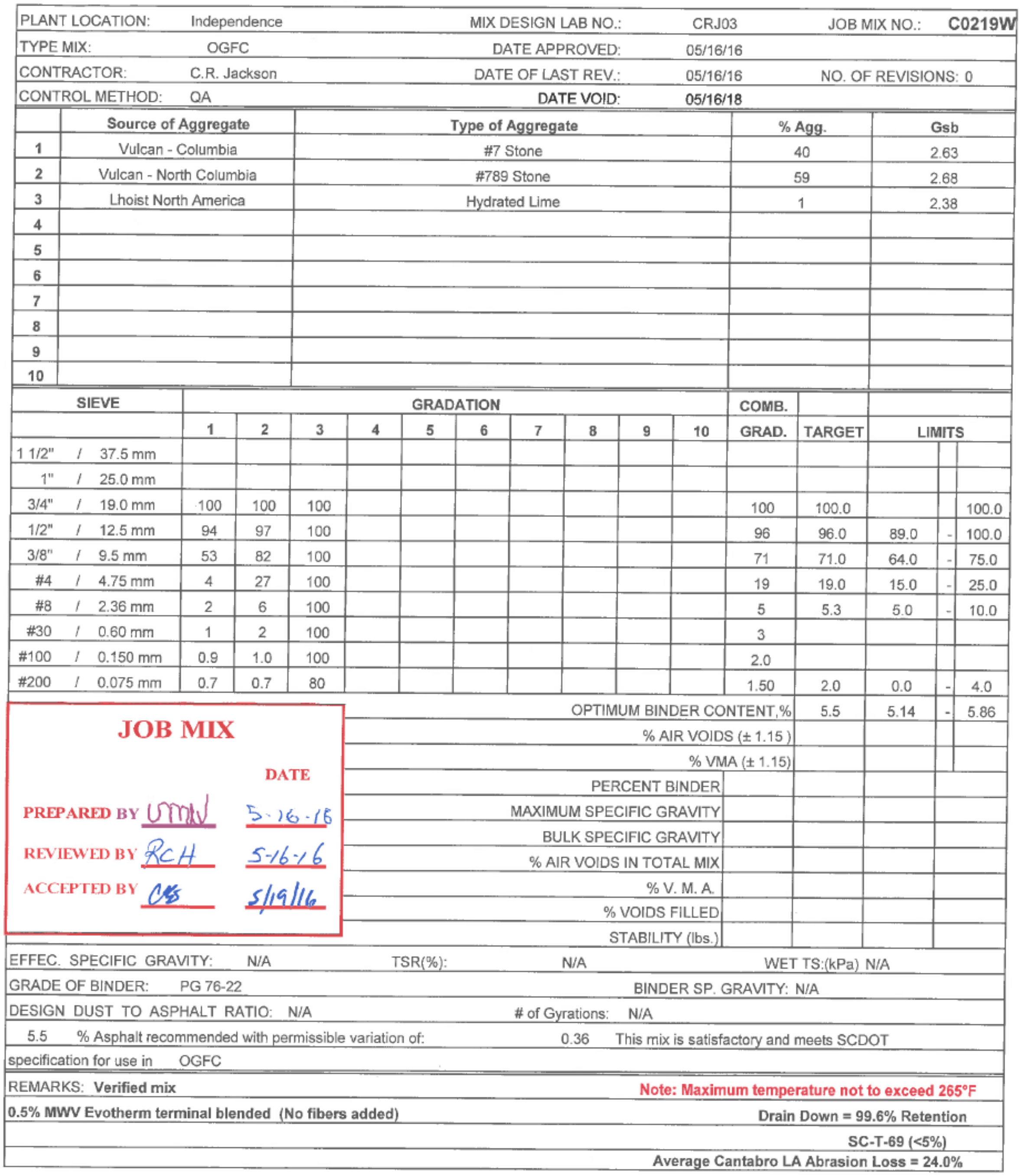
specification for use in OGFC

REMARKS: **Verified mix** **Note: Maximum temperature not to exceed 265°F**

0.5% MWV Evotherm terminal blended (No fibers added) **Drain Down = 99.6% Retention**

Rev. # 1: 3/8" sieve **SC-T-69 (<5%)**

Average Cantabro LA Abrasion Loss = 24.0%



PLANT LOCATION: Independence MIX DESIGN LAB NO.: CRJ03 JOB MIX NO.: **C0219W**
TYPE MIX: OGFC DATE APPROVED: 05/16/16
CONTRACTOR: C.R. Jackson DATE OF LAST REV.: 05/16/16 NO. OF REVISIONS: 0
CONTROL METHOD: QA **DATE VOID:** **05/16/18**

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Vulcan - Columbia	#7 Stone	40	2.63
2	Vulcan - North Columbia	#789 Stone	59	2.68
3	Lhoist North America	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100								100	100.0			100.0
1/2" / 12.5 mm	94	97	100								96	96.0	89.0	-	100.0
3/8" / 9.5 mm	53	82	100								71	71.0	64.0	-	75.0
#4 / 4.75 mm	4	27	100								19	19.0	15.0	-	25.0
#8 / 2.36 mm	2	6	100								5	5.3	5.0	-	10.0
#30 / 0.60 mm	1	2	100								3				
#100 / 0.150 mm	0.9	1.0	100								2.0				
#200 / 0.075 mm	0.7	0.7	80								1.50	2.0	0.0	-	4.0

OPTIMUM BINDER CONTENT,%	5.5	5.14	-	5.86
% AIR VOIDS (± 1.15)				
% VMA (± 1.15)				
PERCENT BINDER				
MAXIMUM SPECIFIC GRAVITY				
BULK SPECIFIC GRAVITY				
% AIR VOIDS IN TOTAL MIX				
% V. M. A.				
% VOIDS FILLED				
STABILITY (lbs.)				

JOB MIX

DATE
PREPARED BY 5-16-16
REVIEWED BY RCH 5-16-16
ACCEPTED BY 5/19/16

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A
GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A
DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A
5.5 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT
specification for use in OGFC
REMARKS: **Verified mix** **Note: Maximum temperature not to exceed 265°F**
0.5% MWV Evotherm terminal blended (No fibers added) **Drain Down = 99.6% Retention**
SC-T-69 (<5%)
Average Cantabro LA Abrasion Loss = 24.0%

PLANT LOCATION:	Duncan	MIX DESIGN LAB NO.:	Sloan01	JOB MIX NO.:	**L0484**
TYPE MIX:	OGFC	DATE APPROVED:	08/24/10		
CONTRACTOR:	Sloan Construction	DATE OF LAST REV.:	08/24/10	NO. OF REVISIONS: 0	
CONTROL METHOD:	QA	DATE VOID:	08/24/12		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Hanson - Sandy Flat	#7 Stone	71	2.68
2	Hanson - Sandy Flat	#89 Stone	28	2.68
3	Mississippi Lime	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				

SIEVE	**GRADATION**								**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm											
1" / 25.0 mm											
3/4" / 19.0 mm	100	100	100						100	100.0	100.0 - 100.0
1/2" / 12.5 mm	94	99	100						96	96.0	89.0 - 100.0
3/8" / 9.5 mm	57	95	100						68	68.0	61.0 - 75.0
#4 / 4.75 mm	7	42	100						18	20.0	15.0 - 25.0
#8 / 2.36 mm	3	9	100						6	7.0	5.0 - 10.0
#30 / 0.60 mm	2	4	100						4		
#100 / 0.150 mm	1.3	1.6	100						2.4		
#200 / 0.075 mm	0.8	0.9	80						1.63	2.0	0.0 - 4.0

OPTIMUM BINDER CONTENT,%	6.5	6.14 - 6.86		
% AIR VOIDS (± 1.15)				
% VMA (± 1.15)				
PERCENT BINDER				
MAXIMUM SPECIFIC GRAVITY				
BULK SPECIFIC GRAVITY				
% AIR VOIDS IN TOTAL MIX				
% V. M. A.				
% VOIDS FILLED				
STABILITY (lbs.)				

JOB MIX

		DATE
PREPARED BY	RCH	**8/24/10**
REVIEWED BY	CEC/CBS	**8/25/10**
ACCEPTED BY	MLC	**8/26/10**

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A

DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

6.5 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT specification for use in OGFC

REMARKS: **Verified mix** Suggested HMA Weight (g): N/A

0.2% used by weight of total mix of Hi-Tech Asphalt Soultions Cellulose fibers **Drain Down = 99.8% Retention**

PLANT LOCATION:	Augusta	MIX DESIGN LAB NO.:	RCC01	JOB MIX NO.:	**N0041**
TYPE MIX:	OGFC	DATE APPROVED:	01/27/12		
CONTRACTOR:	Reeves Const.	DATE OF LAST REV.:	01/27/12	NO. OF REVISIONS: 0	
CONTROL METHOD:	QA	DATE VOID:	01/27/14		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Martin Marietta - Augusta	#7 Stone	65	2.66
2	Martin Marietta - Augusta	#8 Stone	29	2.66
3	Martin Marietta - Augusta	W10	5	2.66
4	Carmeuse Lime & Stone	Hydrated Lime	1	2.38
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100	100							100	100.0			100.0
1/2" / 12.5 mm	87	100	100	100							92	93.0	86.0	-	100.0
3/8" / 9.5 mm	50	96	100	100							66	66.0	59.0	-	73.0
#4 / 4.75 mm	7	27	96	100							18	20.0	15.0	-	25.0
#8 / 2.36 mm	3	4	65	100							7	7.0	5.0	-	10.0
#30 / 0.60 mm	2	3	31	100							5				
#100 / 0.150 mm	1.1	1.7	13.0	100							2.9				
#200 / 0.075 mm	0.8	1.0	4.0	80							1.81	2.0	0.0	-	4.0

JOB MIX

		DATE
PREPARED BY	RCH	1/27/12
REVIEWED BY	CEC/CBS	2/7/12
ACCEPTED BY	MLC	2/14/12

OPTIMUM BINDER CONTENT,%		6.0	5.64	-	6.36
% AIR VOIDS (± 1.15)					
% VMA (± 1.15)					
PERCENT BINDER					
MAXIMUM SPECIFIC GRAVITY					
BULK SPECIFIC GRAVITY					
% AIR VOIDS IN TOTAL MIX					
% V. M. A.					
% VOIDS FILLED					
STABILITY (lbs.)					

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A

DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

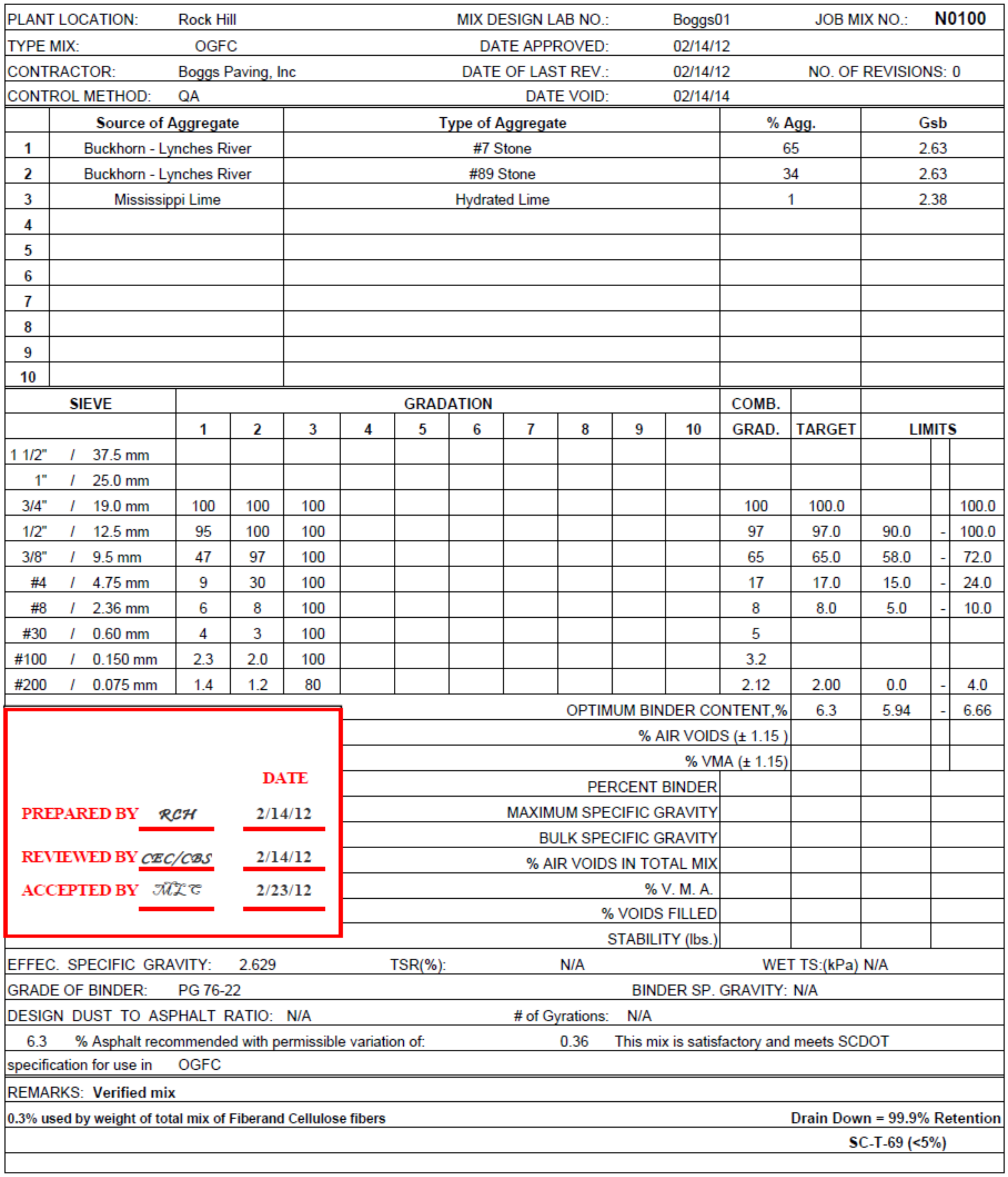
6.0 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT

specification for use in OGFC

REMARKS: **Verified mix**

0.4% used by weight of total mix of Hi-Tech Asphalt Solutions Cellulose fibers **Drain Down = 99.9% Retention**

SC-T-69 (5%)



PLANT LOCATION:	Rock Hill	MIX DESIGN LAB NO.:	Boggs01	JOB MIX NO.:	**N0100**
TYPE MIX:	OGFC	DATE APPROVED:	02/14/12		
CONTRACTOR:	Boggs Paving, Inc	DATE OF LAST REV.:	02/14/12	NO. OF REVISIONS: 0	
CONTROL METHOD:	QA	DATE VOID:	02/14/14		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Buckhorn - Lynches River	#7 Stone	65	2.63
2	Buckhorn - Lynches River	#89 Stone	34	2.63
3	Mississippi Lime	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**									**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100								100	100.0			100.0
1/2" / 12.5 mm	95	100	100								97	97.0	90.0	-	100.0
3/8" / 9.5 mm	47	97	100								65	65.0	58.0	-	72.0
#4 / 4.75 mm	9	30	100								17	17.0	15.0	-	24.0
#8 / 2.36 mm	6	8	100								8	8.0	5.0	-	10.0
#30 / 0.60 mm	4	3	100								5				
#100 / 0.150 mm	2.3	2.0	100								3.2				
#200 / 0.075 mm	1.4	1.2	80								2.12	2.00	0.0	-	4.0

OPTIMUM BINDER CONTENT,%	6.3	5.94	-	6.66
% AIR VOIDS (± 1.15)				
% VMA (± 1.15)				
PERCENT BINDER				
MAXIMUM SPECIFIC GRAVITY				
BULK SPECIFIC GRAVITY				
% AIR VOIDS IN TOTAL MIX				
% V. M. A.				
% VOIDS FILLED				
STABILITY (lbs.)				

DATE

PREPARED BY RCH 2/14/12

REVIEWED BY CEC/CBS 2/14/12

ACCEPTED BY MLC 2/23/12

EFFEC. SPECIFIC GRAVITY: 2.629 TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A

DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

6.3 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT specification for use in OGFC

REMARKS: **Verified mix**

0.3% used by weight of total mix of Fiberand Cellulose fibers **Drain Down = 99.9% Retention**

SC-T-69 (<5%)

PLANT LOCATION:	Jefferson, SC	MIX DESIGN LAB NO.:	Boggs01	JOB MIX NO.:	**N0101**
TYPE MIX:	OGFC	DATE APPROVED:	02/08/12		
CONTRACTOR:	Boggs Paving, Inc	DATE OF LAST REV.:	02/08/12	NO. OF REVISIONS: 0	
CONTROL METHOD:	QA	DATE VOID:	02/08/14		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Buckhorn - Lynches River	#7 Stone	65	2.63
2	Buckhorn - Lynches River	#89 Stone	34	2.63
3	Mississippi Lime	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE		**GRADATION**										**COMB.**				
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2"	/ 37.5 mm															
1"	/ 25.0 mm															
3/4"	/ 19.0 mm	100	100	100								100	100.0			100.0
1/2"	/ 12.5 mm	95	100	100								97	97.0	90.0	-	100.0
3/8"	/ 9.5 mm	47	97	100								65	65.0	58.0	-	72.0
#4	/ 4.75 mm	9	30	100								17	17.0	15.0	-	24.0
#8	/ 2.36 mm	6	8	100								8	8.0	5.0	-	10.0
#30	/ 0.60 mm	4	3	100								5				
#100	/ 0.150 mm	2.3	2.0	100								3.2				
#200	/ 0.075 mm	1.4	1.2	80								2.12	2.0	0.0	-	4.0

OPTIMUM BINDER CONTENT,%	6.3	5.94	-	6.66
% AIR VOIDS (± 1.15)				
% VMA (± 1.15)				
PERCENT BINDER				
MAXIMUM SPECIFIC GRAVITY				
BULK SPECIFIC GRAVITY				
% AIR VOIDS IN TOTAL MIX				
% V. M. A.				
% VOIDS FILLED				
STABILITY (lbs.)				

		DATE
PREPARED BY	RCH	2/8/12
REVIEWED BY	CEC/CBS	2/14/12
ACCEPTED BY	MLC	2/23/12

EFFEC. SPECIFIC GRAVITY: 2.651 TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: **PG 76-22 GTR** BINDER SP. GRAVITY: 1.043

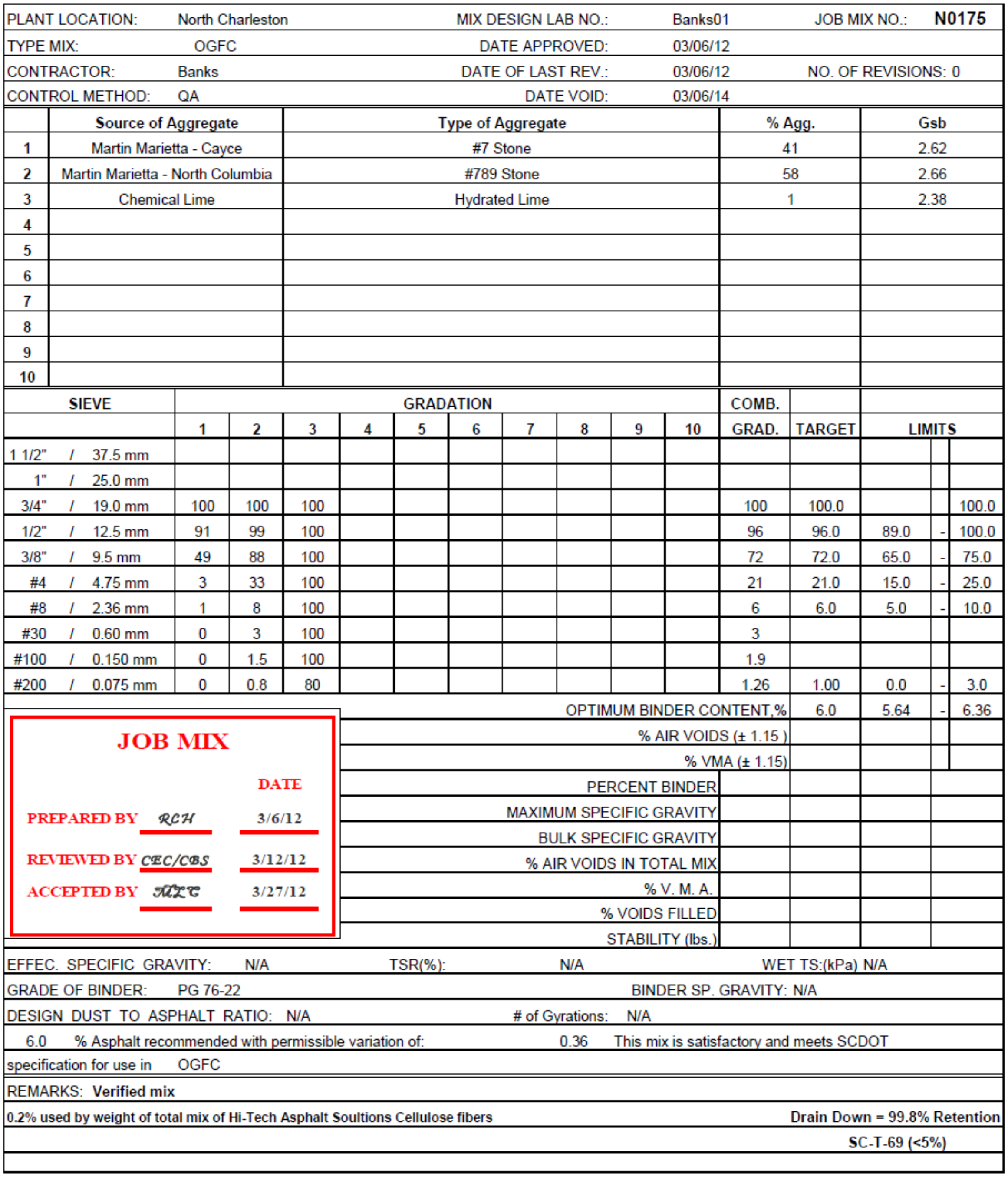
DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

6.3 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT specification for use in OGFC

REMARKS: **Verified mix**

For use on File 1220.039419 **Drain Down = 99.9% Retention**

SC-T-69 (5%)



PLANT LOCATION:	North Charleston	MIX DESIGN LAB NO.:	Banks01	JOB MIX NO.:	**N0175**
TYPE MIX:	OGFC	DATE APPROVED:	03/06/12		
CONTRACTOR:	Banks	DATE OF LAST REV.:	03/06/12	NO. OF REVISIONS: 0	
CONTROL METHOD:	QA	DATE VOID:	03/06/14		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Martin Marietta - Cayce	#7 Stone	41	2.62
2	Martin Marietta - North Columbia	#789 Stone	58	2.66
3	Chemical Lime	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100								100	100.0			100.0
1/2" / 12.5 mm	91	99	100								96	96.0	89.0	-	100.0
3/8" / 9.5 mm	49	88	100								72	72.0	65.0	-	75.0
#4 / 4.75 mm	3	33	100								21	21.0	15.0	-	25.0
#8 / 2.36 mm	1	8	100								6	6.0	5.0	-	10.0
#30 / 0.60 mm	0	3	100								3				
#100 / 0.150 mm	0	1.5	100								1.9				
#200 / 0.075 mm	0	0.8	80								1.26	1.00	0.0	-	3.0

JOB MIX

		DATE
PREPARED BY	RCH	3/6/12
REVIEWED BY	CEC/CBS	3/12/12
ACCEPTED BY	MLC	3/27/12

OPTIMUM BINDER CONTENT,%	6.0	5.64	-	6.36
% AIR VOIDS (± 1.15)				
% VMA (± 1.15)				
PERCENT BINDER				
MAXIMUM SPECIFIC GRAVITY				
BULK SPECIFIC GRAVITY				
% AIR VOIDS IN TOTAL MIX				
% V. M. A.				
% VOIDS FILLED				
STABILITY (lbs.)				

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A

DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

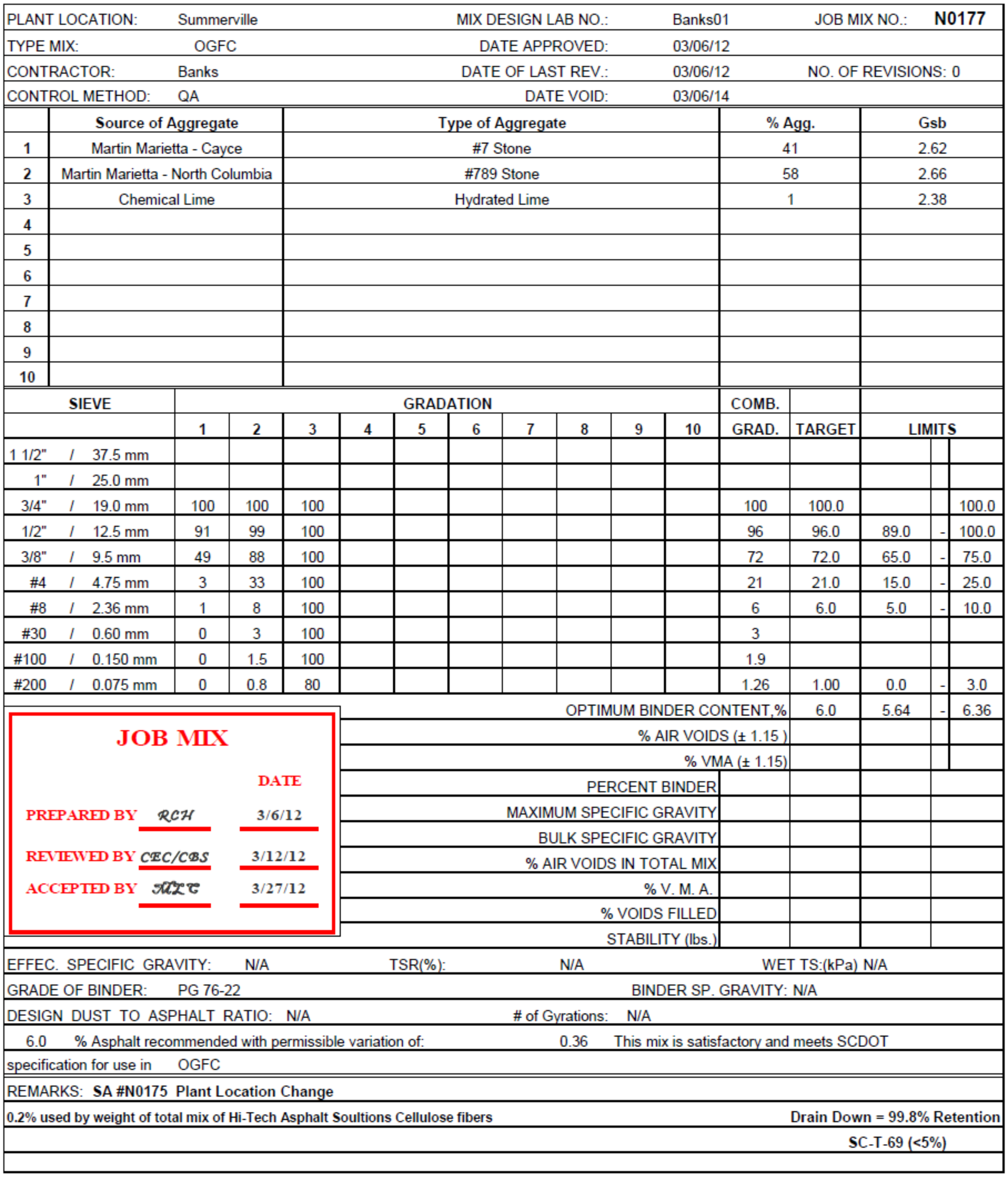
6.0 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT

specification for use in OGFC

REMARKS: **Verified mix**

0.2% used by weight of total mix of Hi-Tech Asphalt Soultions Cellulose fibers **Drain Down = 99.8% Retention**

SC-T-69 (<5%)



PLANT LOCATION:	Summerville	MIX DESIGN LAB NO.:	Banks01	JOB MIX NO.:	**N0177**
TYPE MIX:	OGFC	DATE APPROVED:	03/06/12		
CONTRACTOR:	Banks	DATE OF LAST REV.:	03/06/12	NO. OF REVISIONS: 0	
CONTROL METHOD:	QA	DATE VOID:	03/06/14		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Martin Marietta - Cayce	#7 Stone	41	2.62
2	Martin Marietta - North Columbia	#789 Stone	58	2.66
3	Chemical Lime	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm													
1" / 25.0 mm													
3/4" / 19.0 mm	100	100	100								100	100.0	100.0
1/2" / 12.5 mm	91	99	100								96	96.0	89.0 - 100.0
3/8" / 9.5 mm	49	88	100								72	72.0	65.0 - 75.0
#4 / 4.75 mm	3	33	100								21	21.0	15.0 - 25.0
#8 / 2.36 mm	1	8	100								6	6.0	5.0 - 10.0
#30 / 0.60 mm	0	3	100								3		
#100 / 0.150 mm	0	1.5	100								1.9		
#200 / 0.075 mm	0	0.8	80								1.26	1.00	0.0 - 3.0

JOB MIX

		DATE
PREPARED BY	RCH	3/6/12
REVIEWED BY	CEC/CBS	3/12/12
ACCEPTED BY	MLC	3/27/12

OPTIMUM BINDER CONTENT,%	6.0	5.64 - 6.36	
% AIR VOIDS (± 1.15)			
% VMA (± 1.15)			
PERCENT BINDER			
MAXIMUM SPECIFIC GRAVITY			
BULK SPECIFIC GRAVITY			
% AIR VOIDS IN TOTAL MIX			
% V. M. A.			
% VOIDS FILLED			
STABILITY (lbs.)			

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A

DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

6.0 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT specification for use in OGFC

REMARKS: **SA #N0175 Plant Location Change**

0.2% used by weight of total mix of Hi-Tech Asphalt Soultions Cellulose fibers **Drain Down = 99.8% Retention**

SC-T-69 (<5%)

PLANT LOCATION:	Columbia	MIX DESIGN LAB NO.:	Sloan02	JOB MIX NO.:	**N0345**
TYPE MIX:	OGFC	DATE APPROVED:	07/23/12		
CONTRACTOR:	Sloan Constuction	DATE OF LAST REV.:	07/23/12	NO. OF REVISIONS: 0	
CONTROL METHOD:	QA	DATE VOID:	07/23/14		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Vulcan - Columbia	#7 Stone	63	2.64
2	Vulcan - Columbia	#89 Stone	36	2.64
3	Chemical Lime	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100								100	100.0			100.0
1/2" / 12.5 mm	92	100	100								95	95.0	88.0	-	100.0
3/8" / 9.5 mm	46	94	100								63	66.0	59.0	-	73.0
#4 / 4.75 mm	3	51	100								21	21.0	15.0	-	25.0
#8 / 2.36 mm	1	10	100								5	6.0	5.0	-	10.0
#30 / 0.60 mm	0	3	100								2				
#100 / 0.150 mm	0	1.4	100								1.5				
#200 / 0.075 mm	0	0.9	80								1.12	1.0	0.0	-	3.0

OPTIMUM BINDER CONTENT,%	6.0	5.64	-	6.36
% AIR VOIDS (± 1.15)				
% VMA (± 1.15)				
PERCENT BINDER				
MAXIMUM SPECIFIC GRAVITY				
BULK SPECIFIC GRAVITY				
% AIR VOIDS IN TOTAL MIX				
% V. M. A.				
% VOIDS FILLED				
STABILITY (lbs.)				

JOB MIX

		DATE
PREPARED BY	VMW	7/23/12
REVIEWED BY	CBS	7/24/12
ACCEPTED BY	MLC	7/24/12

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: **PG 76-22 GTR** BINDER SP. GRAVITY: N/A

DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

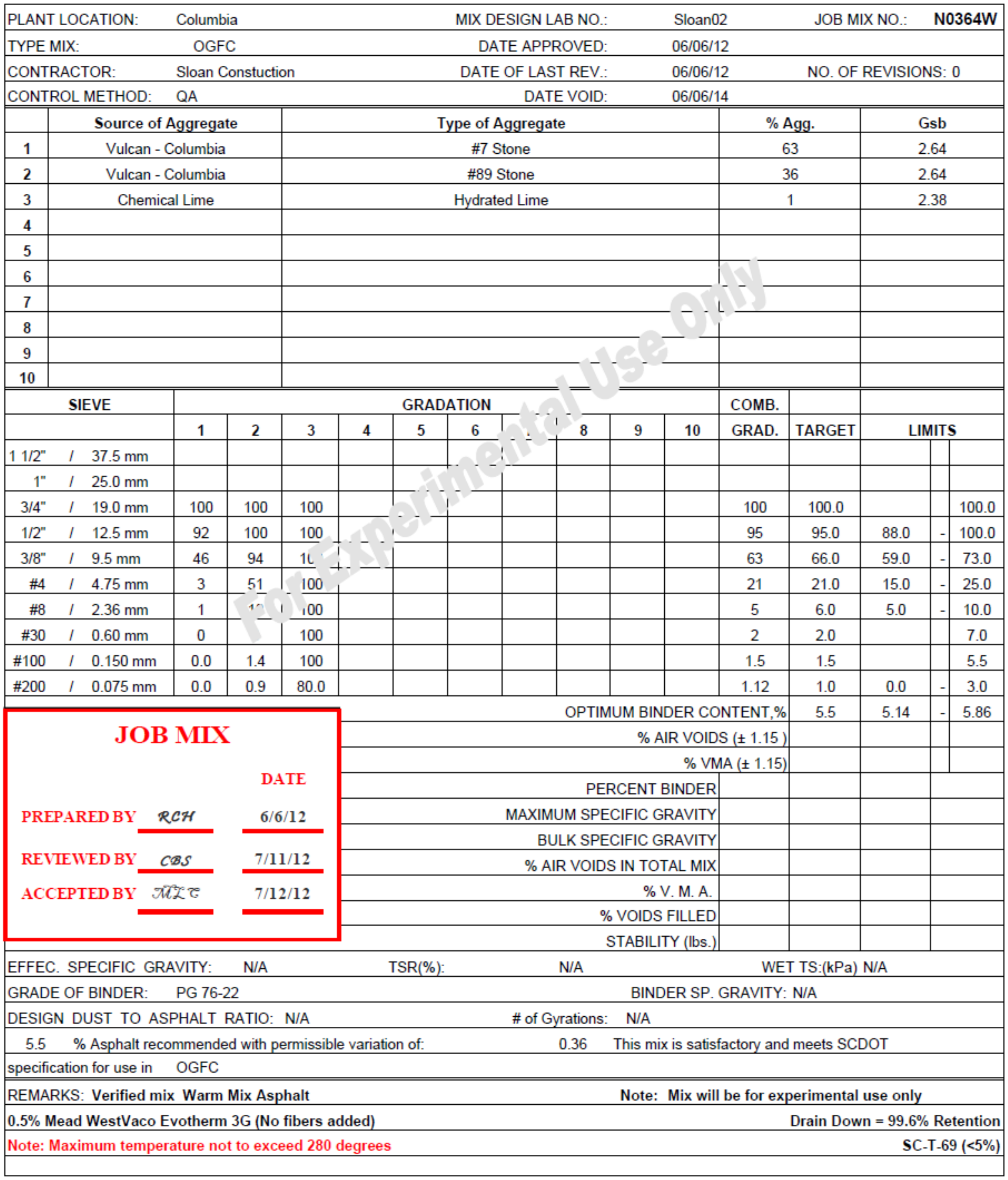
6.0 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT specification for use in OGFC

REMARKS: **Verified mix**

For use on File 28.040658

8.0% GTR Pre-blended Blacklidge - Greer **Drain Down = 99.9% Retention**

SC-T-69 (<5%)



PLANT LOCATION:	Columbia	MIX DESIGN LAB NO.:	Sloan02	JOB MIX NO.:	**N0364W**
TYPE MIX:	OGFC	DATE APPROVED:	06/06/12		
CONTRACTOR:	Sloan Constuction	DATE OF LAST REV.:	06/06/12	NO. OF REVISIONS: 0	
CONTROL METHOD:	QA	DATE VOID:	06/06/14		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Vulcan - Columbia	#7 Stone	63	2.64
2	Vulcan - Columbia	#89 Stone	36	2.64
3	Chemical Lime	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100								100	100.0			100.0
1/2" / 12.5 mm	92	100	100								95	95.0	88.0	-	100.0
3/8" / 9.5 mm	46	94	100								63	66.0	59.0	-	73.0
#4 / 4.75 mm	3	51	100								21	21.0	15.0	-	25.0
#8 / 2.36 mm	1	[illegible]	100								5	6.0	5.0	-	10.0
#30 / 0.60 mm	0		100								2	2.0			7.0
#100 / 0.150 mm	0.0	1.4	100								1.5	1.5			5.5
#200 / 0.075 mm	0.0	0.9	80.0								1.12	1.0	0.0	-	3.0

OPTIMUM BINDER CONTENT,%	5.5	5.14	-	5.86
% AIR VOIDS (± 1.15)				
% VMA (± 1.15)				
PERCENT BINDER				
MAXIMUM SPECIFIC GRAVITY				
BULK SPECIFIC GRAVITY				
% AIR VOIDS IN TOTAL MIX				
% V. M. A.				
% VOIDS FILLED				
STABILITY (lbs.)				

JOB MIX

		DATE
PREPARED BY	RCH	6/6/12
REVIEWED BY	CBS	7/11/12
ACCEPTED BY	MLC	7/12/12

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A

DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

5.5 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT specification for use in OGFC

REMARKS: **Verified mix Warm Mix Asphalt** **Note: Mix will be for experimental use only**

0.5% Mead WestVaco Evotherm 3G (No fibers added) **Drain Down = 99.6% Retention**

Note: Maximum temperature not to exceed 280 degrees **SC-T-69 (<5%)**

PLANT LOCATION:	Santee	MIX DESIGN LAB NO.:	CRJ03	JOB MIX NO.:	**N0377**
TYPE MIX:	OGFC	DATE APPROVED:	05/15/12		
CONTRACTOR:	C.R. Jackson, Inc.	DATE OF LAST REV.:	05/15/12	NO. OF REVISIONS: 0	
CONTROL METHOD:	QA	DATE VOID:	05/15/14		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Vulcan - Columbia	#7 Stone	70	2.64
2	Vulcan - Columbia	#89 Stone	29	2.64
3	Chemical Lime	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100								100	100.0			100.0
1/2" / 12.5 mm	94	100	100								96	96.0	89.0	-	100.0
3/8" / 9.5 mm	53	99	100								67	67.0	60.0	-	74.0
#4 / 4.75 mm	4	57	100								20	20.0	15.0	-	25.0
#8 / 2.36 mm	2	11	100								6	6.0	5.0	-	10.0
#30 / 0.60 mm	1	3	100								3				5.0
#100 / 0.150 mm	0.9	1.5	100								2.1				4.0
#200 / 0.075 mm	0.7	1.0	80								1.60	1.6	0.0	-	3.6

OPTIMUM BINDER CONTENT,%	6.5	6.14	-	6.86
% AIR VOIDS (± 1.15)				
% VMA (± 1.15)				
PERCENT BINDER				
MAXIMUM SPECIFIC GRAVITY				
BULK SPECIFIC GRAVITY				
% AIR VOIDS IN TOTAL MIX				
% V. M. A.				
% VOIDS FILLED				
STABILITY (lbs.)				

JOB MIX

		DATE
PREPARED BY	RCH	5/15/12
REVIEWED BY	CBS	5/18/12
ACCEPTED BY	MLC	5/24/12

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A

DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

6.5 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT specification for use in OGFC

REMARKS: **Verified mix**

0.4% used by weight of total mix of Hi-Tech Asphalt Solutions Cellulose fibers **Drain Down = 99.9% Retention**

SC-T-69 (<5%)

PLANT LOCATION:	Duncan	MIX DESIGN LAB NO.:	Sloan01	JOB MIX NO.:	**N0380**
TYPE MIX:	OGFC	DATE APPROVED:	05/18/12		
CONTRACTOR:	Sloan Construction	DATE OF LAST REV.:	**09/07/12**	NO. OF REVISIONS:	**1**
CONTROL METHOD:	QA	DATE VOID:	05/18/14		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Hanson - Sandy Flats	#7 Stone	78	2.65
2	Hanson - Sandy Flats	#89 Stone	21	2.65
3	Mississippi Lime	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm	100	100	100								100	100.0			100.0
1" / 25.0 mm	100	100	100								100	100.0	100.0	-	100.0
3/4" / 19.0 mm	100	100	100								100	100.0	100.0	-	100.0
1/2" / 12.5 mm	95	100	100								96	93.0	86.0	-	100.0
3/8" / 9.5 mm	58	100	100								67	68.0	61.0	-	75.0
#4 / 4.75 mm	12	46	100								20	20.0	15.0	-	25.0
#8 / 2.36 mm	5	11	100								7	8.0	5.0	-	10.0
#30 / 0.60 mm	3	4	100								4				
#100 / 0.150 mm	1.7	1.8	100								2.7				
#200 / 0.075 mm	1.1	1.1	80								1.88	2.0	0.0	-	4.0

OPTIMUM BINDER CONTENT,%		6.0	5.64	-	6.36
% AIR VOIDS (± 1.15)					
% VMA (± 1.15)					
PERCENT BINDER					
MAXIMUM SPECIFIC GRAVITY					
BULK SPECIFIC GRAVITY					
% AIR VOIDS IN TOTAL MIX					
% V. M. A.					
% VOIDS FILLED					
STABILITY (lbs.)					

JOB MIX

		DATE
PREPARED BY	RCH	9/7/12
REVIEWED BY	CBS	9/7/12
ACCEPTED BY	MLC	9/10/12

EFFEC. SPECIFIC GRAVITY:	N/A	TSR(%):	N/A	WET TS:(kPa)	N/A
GRADE OF BINDER:	PG 76-22			BINDER SP. GRAVITY:	N/A
DESIGN DUST TO ASPHALT RATIO:	N/A			# of Gyrations:	N/A

6.0 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT specification for use in OGFC

REMARKS: **Verified mix** **Rev. #1: 3/8" sieve**

0.2% used by weight of total mix of Hi-Tech Asphalt Soultions Cellulose fibers **Drain Down = 99.9% Retention**

SC-T-69 (<5%)

PLANT LOCATION:	Independence	MIX DESIGN LAB NO.:	CRJ03	JOB MIX NO.:	**N0409**
TYPE MIX:	OGFC	DATE APPROVED:	05/24/12		
CONTRACTOR:	C.R. Jackson, Inc.	DATE OF LAST REV.:	05/24/12	NO. OF REVISIONS: 0	
CONTROL METHOD:	QA	DATE VOID:	05/15/14		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Vulcan - Columbia	#7 Stone	70	2.64
2	Vulcan - Columbia	#89 Stone	29	2.64
3	Chemical Lime	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100								100	100.0			100.0
1/2" / 12.5 mm	94	100	100								96	96.0	89.0	-	100.0
3/8" / 9.5 mm	53	99	100								67	67.0	60.0	-	74.0
#4 / 4.75 mm	4	57	100								20	20.0	15.0	-	25.0
#8 / 2.36 mm	2	11	100								6	6.0	5.0	-	10.0
#30 / 0.60 mm	1	3	100								3				5.0
#100 / 0.150 mm	0.9	1.5	100								2.1				4.0
#200 / 0.075 mm	0.7	1.0	80								1.60	1.6	0.0	-	3.6

OPTIMUM BINDER CONTENT,%	6.5	6.14	-	6.86
% AIR VOIDS (± 1.15)				
% VMA (± 1.15)				
PERCENT BINDER				
MAXIMUM SPECIFIC GRAVITY				
BULK SPECIFIC GRAVITY				
% AIR VOIDS IN TOTAL MIX				
% V. M. A.				
% VOIDS FILLED				
STABILITY (lbs.)				

JOB MIX

		DATE
PREPARED BY	VMW	5/23/12
REVIEWED BY	CBS	5/24/12
ACCEPTED BY	MLC	5/24/12

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A

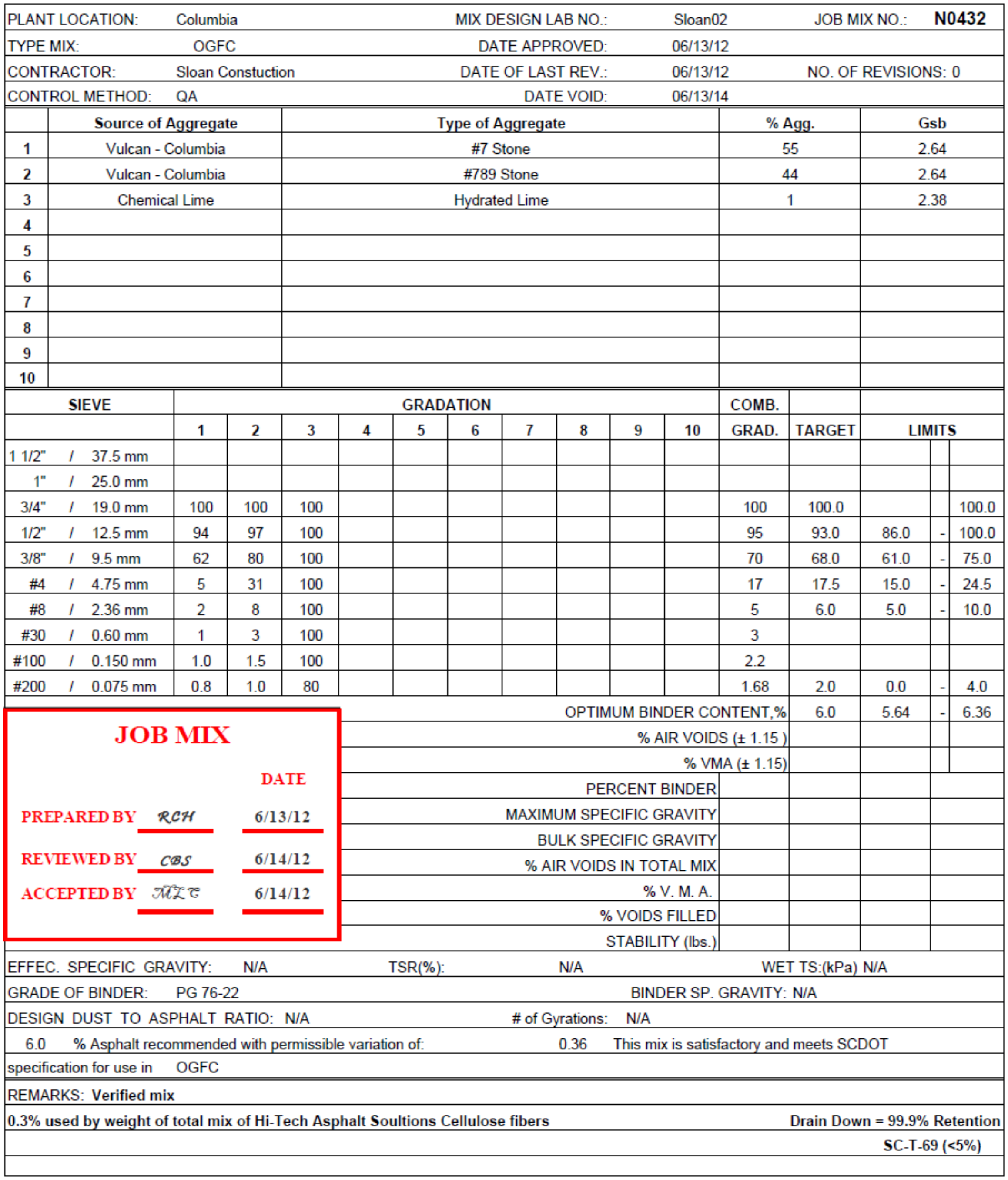
DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

6.5 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT specification for use in OGFC

REMARKS: **S/A N0377 - Plant location change.**

0.4% used by weight of total mix of Hi-Tech Asphalt Solutions Cellulose fibers **Drain Down = 99.9% Retention**

SC-T-69 (<5%)



PLANT LOCATION:	Columbia	MIX DESIGN LAB NO.:	Sloan02	JOB MIX NO.:	**N0432**
TYPE MIX:	OGFC	DATE APPROVED:	06/13/12		
CONTRACTOR:	Sloan Constuction	DATE OF LAST REV.:	06/13/12	NO. OF REVISIONS: 0	
CONTROL METHOD:	QA	DATE VOID:	06/13/14		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Vulcan - Columbia	#7 Stone	55	2.64
2	Vulcan - Columbia	#789 Stone	44	2.64
3	Chemical Lime	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**		**LIMITS**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**			
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100								100	100.0			100.0
1/2" / 12.5 mm	94	97	100								95	93.0	86.0	-	100.0
3/8" / 9.5 mm	62	80	100								70	68.0	61.0	-	75.0
#4 / 4.75 mm	5	31	100								17	17.5	15.0	-	24.5
#8 / 2.36 mm	2	8	100								5	6.0	5.0	-	10.0
#30 / 0.60 mm	1	3	100								3				
#100 / 0.150 mm	1.0	1.5	100								2.2				
#200 / 0.075 mm	0.8	1.0	80								1.68	2.0	0.0	-	4.0

OPTIMUM BINDER CONTENT,%	6.0	5.64	-	6.36	
% AIR VOIDS (± 1.15)					
% VMA (± 1.15)					
PERCENT BINDER					
MAXIMUM SPECIFIC GRAVITY					
BULK SPECIFIC GRAVITY					
% AIR VOIDS IN TOTAL MIX					
% V. M. A.					
% VOIDS FILLED					
STABILITY (lbs.)					

JOB MIX

		DATE
PREPARED BY	RCH	6/13/12
REVIEWED BY	CBS	6/14/12
ACCEPTED BY	MLC	6/14/12

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A

DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

6.0 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT specification for use in OGFC

REMARKS: **Verified mix**

0.3% used by weight of total mix of Hi-Tech Asphalt Soultions Cellulose fibers **Drain Down = 99.9% Retention**

SC-T-69 (<5%)

PLANT LOCATION:	Gray Court	MIX DESIGN LAB NO.:	Rea02	JOB MIX NO.:	**N0454**
TYPE MIX:	OGFC	DATE APPROVED:	07/06/12		
CONTRACTOR:	Rea Contracting	DATE OF LAST REV.:	07/06/12	NO. OF REVISIONS: 0	
CONTROL METHOD:	QA	DATE VOID:	07/06/14		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Vulcan - Columbia	#7 Stone	60	2.64
2	Vulcan - Columbia	#789 Stone	39	2.64
3	Chemical Lime	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100								100	100.0			100.0
1/2" / 12.5 mm	98	98	100								98	95.0	88.0	-	100.0
3/8" / 9.5 mm	55	88	100								68	68.0	61.0	-	75.0
#4 / 4.75 mm	7	38	100								20	20.0	15.0	-	25.0
#8 / 2.36 mm	4	9	100								7	7.0	5.0	-	10.0
#30 / 0.60 mm	2	2	100								3				
#100 / 0.150 mm	1.0	1.0	100								2.0				
#200 / 0.075 mm	0.7	0.5	80								1.42	2.0	0.0	-	4.0

OPTIMUM BINDER CONTENT,%	6.0	5.64	-	6.36
% AIR VOIDS (± 1.15)				
% VMA (± 1.15)				
PERCENT BINDER				
MAXIMUM SPECIFIC GRAVITY				
BULK SPECIFIC GRAVITY				
% AIR VOIDS IN TOTAL MIX				
% V. M. A.				
% VOIDS FILLED				
STABILITY (lbs.)				

JOB MIX

		DATE
PREPARED BY	RCH	7/6/12
REVIEWED BY	CBS	7/11/12
ACCEPTED BY	MLC	7/12/12

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A

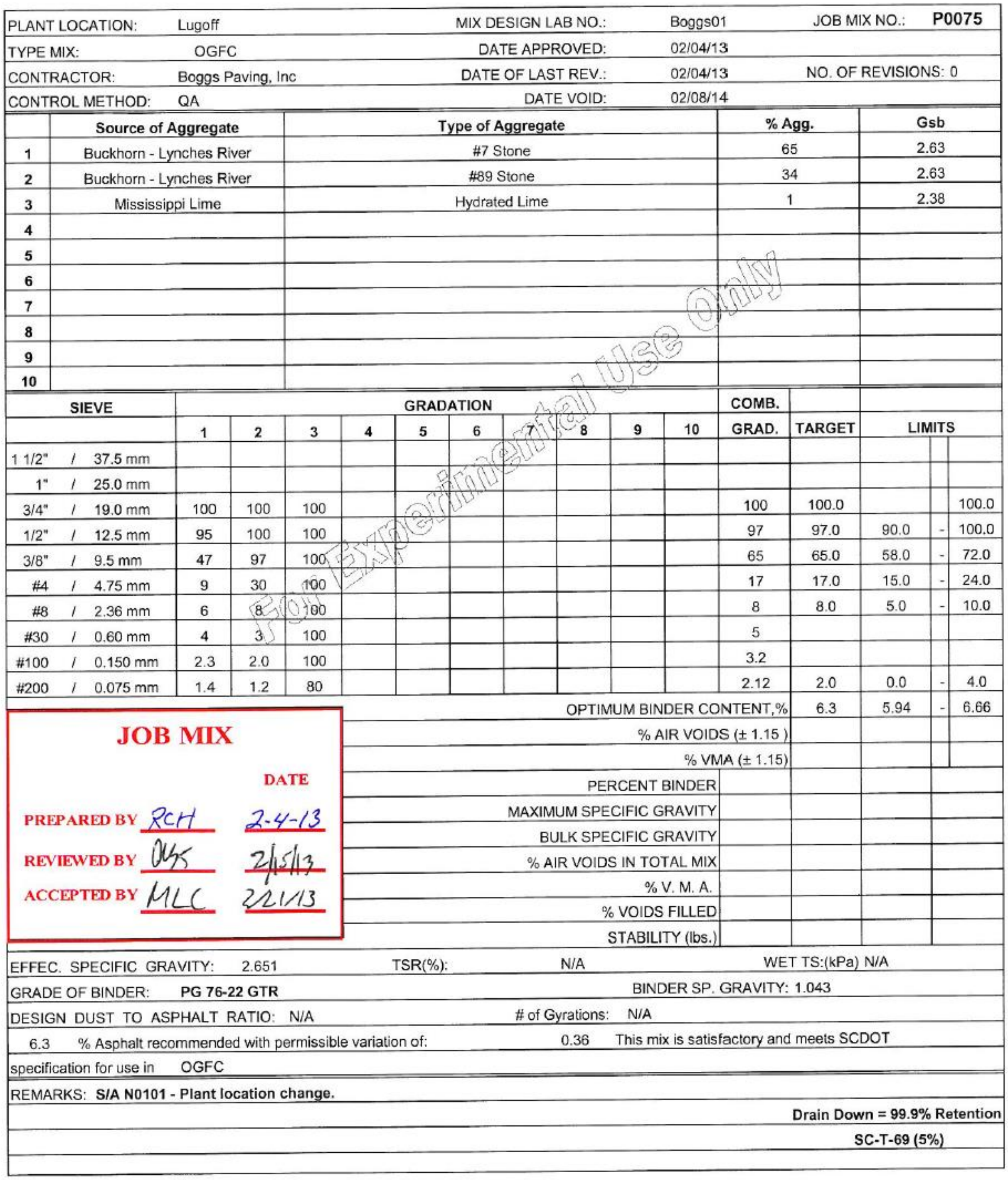
DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

6.0 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT specification for use in OGFC

REMARKS: **Verified mix**

0.3% used by weight of total mix of Hi-Tech Asphalt Soultions Cellulose fibers **Drain Down = 99.9% Retention**

SC-T-69 (<5%)



PLANT LOCATION: Lugoff
MIX DESIGN LAB NO.: Boggs01
JOB MIX NO.: **P0075**
TYPE MIX: OGFC
DATE APPROVED: 02/04/13
CONTRACTOR: Boggs Paving, Inc
DATE OF LAST REV.: 02/04/13
NO. OF REVISIONS: 0
CONTROL METHOD: QA
DATE VOID: 02/08/14

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Buckhorn - Lynches River	#7 Stone	65	2.63
2	Buckhorn - Lynches River	#89 Stone	34	2.63
3	Mississippi Lime	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100								100	100.0			100.0
1/2" / 12.5 mm	95	100	100								97	97.0	90.0	-	100.0
3/8" / 9.5 mm	47	97	100								65	65.0	58.0	-	72.0
#4 / 4.75 mm	9	30	100								17	17.0	15.0	-	24.0
#8 / 2.36 mm	6	8	100								8	8.0	5.0	-	10.0
#30 / 0.60 mm	4	3	100								5				
#100 / 0.150 mm	2.3	2.0	100								3.2				
#200 / 0.075 mm	1.4	1.2	80								2.12	2.0	0.0	-	4.0

JOB MIX

DATE

PREPARED BY RCH 2-4-13
REVIEWED BY OKS 2/15/13
ACCEPTED BY MLC 2/21/13

OPTIMUM BINDER CONTENT,%	6.3	5.94	-	6.66
% AIR VOIDS (± 1.15)				
% VMA (± 1.15)				
PERCENT BINDER				
MAXIMUM SPECIFIC GRAVITY				
BULK SPECIFIC GRAVITY				
% AIR VOIDS IN TOTAL MIX				
% V. M. A.				
% VOIDS FILLED				
STABILITY (lbs.)				

EFFEC. SPECIFIC GRAVITY: 2.651
TSR(%): N/A
WET TS:(kPa) N/A
GRADE OF BINDER: **PG 76-22 GTR**
BINDER SP. GRAVITY: 1.043
DESIGN DUST TO ASPHALT RATIO: N/A
\# of Gyrations: N/A
6.3 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT
specification for use in OGFC
REMARKS: **S/A N0101 - Plant location change.**

Drain Down = 99.9% Retention

SC-T-69 (5%)

PLANT LOCATION:	Lugoff	MIX DESIGN LAB NO.:	Boggs01	JOB MIX NO.:	**P0076**
TYPE MIX:	OGFC	DATE APPROVED:	**02/04/13**		
CONTRACTOR:	Boggs Paving, Inc	DATE OF LAST REV.:	**02/04/13**	NO. OF REVISIONS: 0	
CONTROL METHOD:	QA	DATE VOID:	02/14/14		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Buckhorn - Lynches River	#7 Stone	65	2.63
2	Buckhorn - Lynches River	#89 Stone	34	2.63
3	Mississippi Lime	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100								100	100.0			100.0
1/2" / 12.5 mm	95	100	100								97	97.0	90.0	-	100.0
3/8" / 9.5 mm	47	97	100								65	65.0	58.0	-	72.0
#4 / 4.75 mm	9	30	100								17	17.0	15.0	-	24.0
#8 / 2.36 mm	6	8	100								8	8.0	5.0	-	10.0
#30 / 0.60 mm	4	3	100								5				
#100 / 0.150 mm	2.3	2.0	100								3.2				
#200 / 0.075 mm	1.4	1.2	80								2.12	2.00	0.0	-	4.0

OPTIMUM BINDER CONTENT,%		6.3	5.94	-	6.66
% AIR VOIDS (± 1.15)					
% VMA (± 1.15)					
PERCENT BINDER					
MAXIMUM SPECIFIC GRAVITY					
BULK SPECIFIC GRAVITY					
% AIR VOIDS IN TOTAL MIX					
% V. M. A.					
% VOIDS FILLED					
STABILITY (lbs.)					

JOB MIX

DATE

PREPARED BY CMW 02-04-13

REVIEWED BY OBS 2/8/13

ACCEPTED BY MLC 2/14/13

EFFEC. SPECIFIC GRAVITY: 2.629 TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A

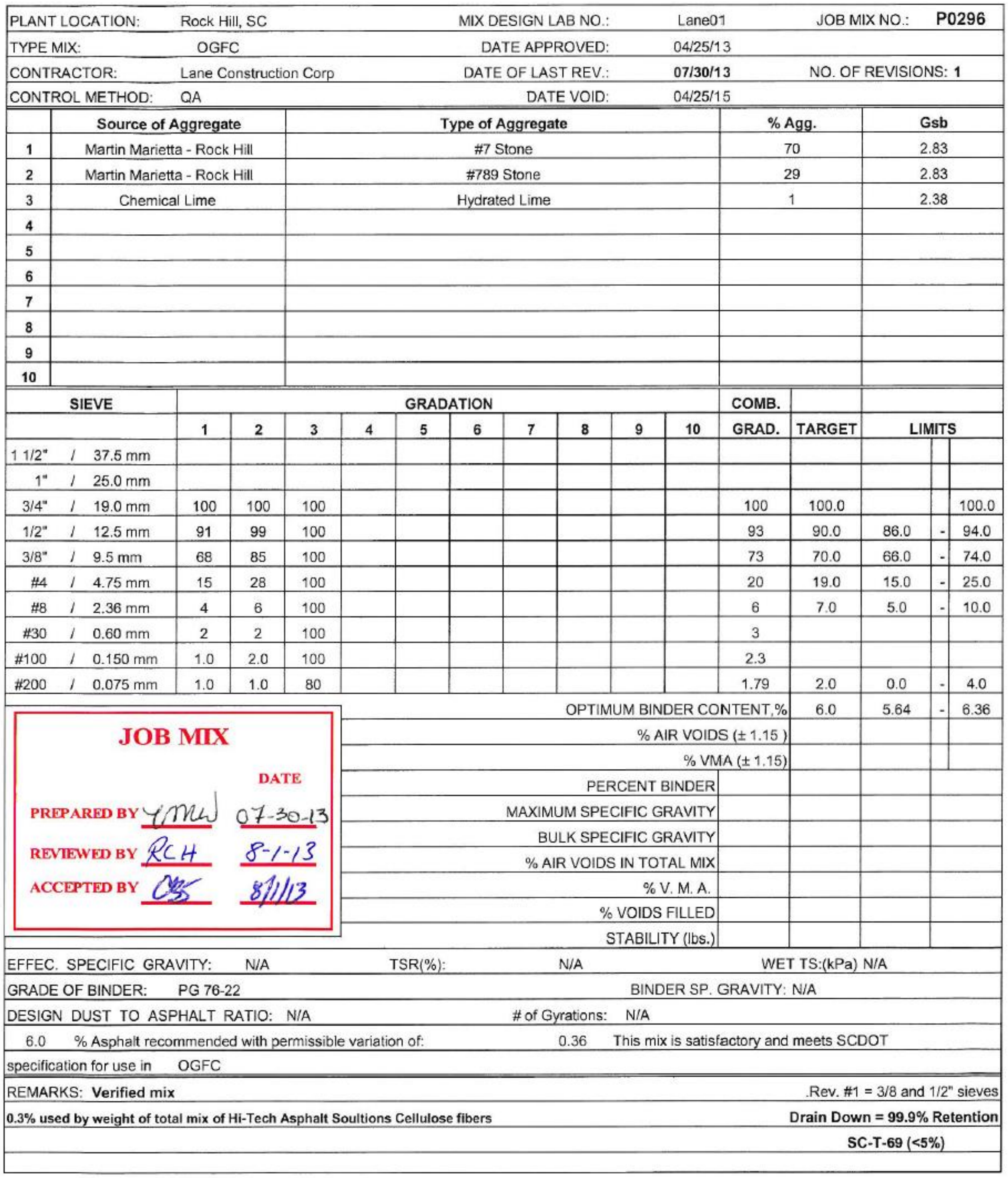
DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

6.3 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT specification for use in OGFC

REMARKS: **S/A N0283 - Plant location change.**

0.3% used by weight of total mix of Fiberand Cellulose fibers **Drain Down = 99.9% Retention**

SC-T-69 (<5%)



PLANT LOCATION: Rock Hill, SC	MIX DESIGN LAB NO.: Lane01	JOB MIX NO.: **P0296**	
TYPE MIX: OGFC	DATE APPROVED: 04/25/13		
CONTRACTOR: Lane Construction Corp	DATE OF LAST REV.: **07/30/13**	NO. OF REVISIONS: **1**	
CONTROL METHOD: QA	DATE VOID: 04/25/15		

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Martin Marietta - Rock Hill	#7 Stone	70	2.83
2	Martin Marietta - Rock Hill	#789 Stone	29	2.83
3	Chemical Lime	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100								100	100.0			100.0
1/2" / 12.5 mm	91	99	100								93	90.0	86.0	-	94.0
3/8" / 9.5 mm	68	85	100								73	70.0	66.0	-	74.0
#4 / 4.75 mm	15	28	100								20	19.0	15.0	-	25.0
#8 / 2.36 mm	4	6	100								6	7.0	5.0	-	10.0
#30 / 0.60 mm	2	2	100								3				
#100 / 0.150 mm	1.0	2.0	100								2.3				
#200 / 0.075 mm	1.0	1.0	80								1.79	2.0	0.0	-	4.0

OPTIMUM BINDER CONTENT,%	6.0	5.64	-	6.36
% AIR VOIDS (± 1.15)				
% VMA (± 1.15)				
PERCENT BINDER				
MAXIMUM SPECIFIC GRAVITY				
BULK SPECIFIC GRAVITY				
% AIR VOIDS IN TOTAL MIX				
% V. M. A.				
% VOIDS FILLED				
STABILITY (lbs.)				

JOB MIX

DATE

PREPARED BY YMW 07-30-13

REVIEWED BY RCH 8-1-13

ACCEPTED BY 8/1/13

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A

GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A

DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A

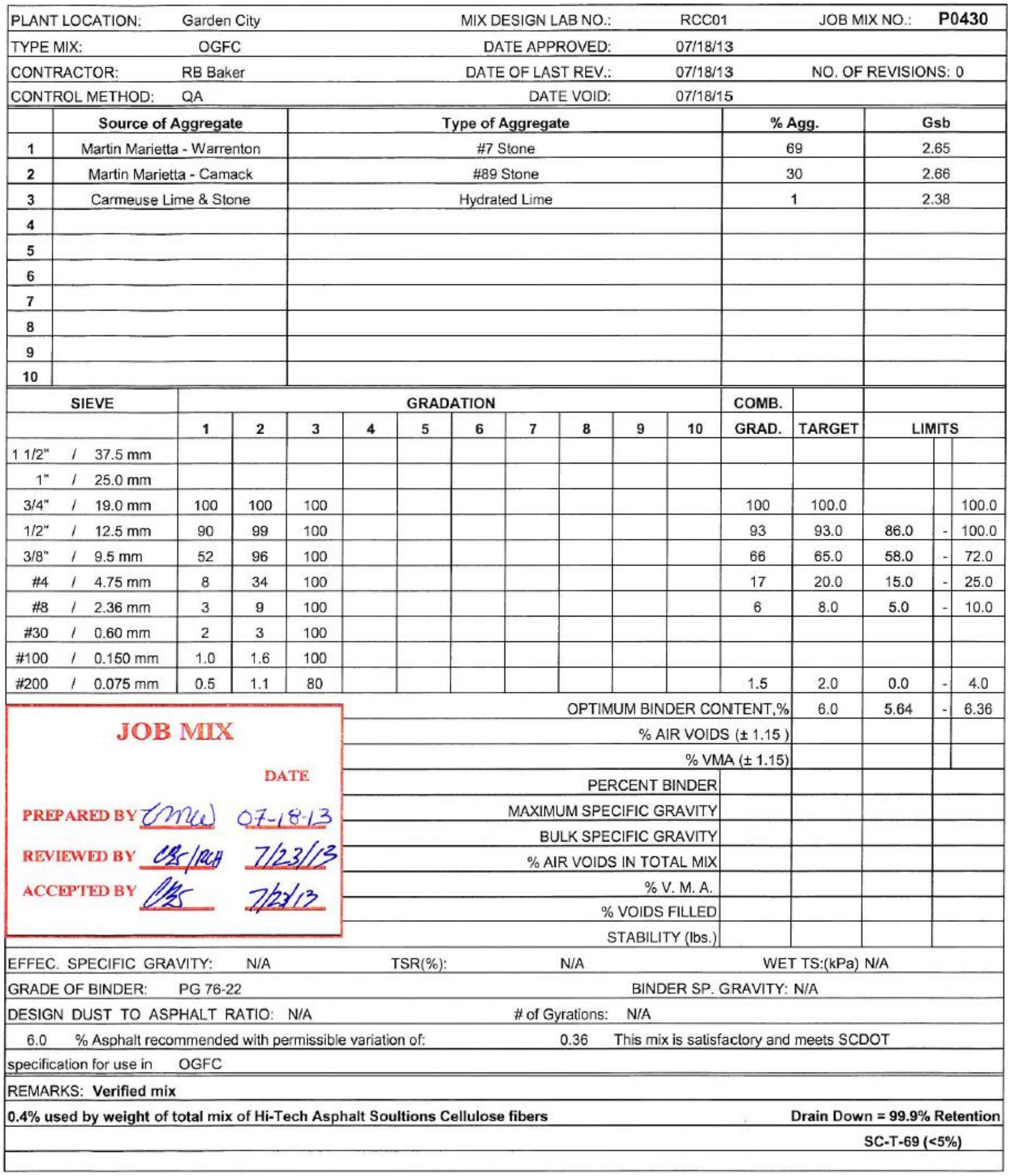
6.0 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT

specification for use in OGFC

REMARKS: **Verified mix** .Rev. #1 = 3/8 and 1/2" sieves

0.3% used by weight of total mix of Hi-Tech Asphalt Soultions Cellulose fibers **Drain Down = 99.9% Retention**

SC-T-69 (<5%)



PLANT LOCATION: Garden City MIX DESIGN LAB NO.: RCC01 JOB MIX NO.: **P0430**
TYPE MIX: OGFC DATE APPROVED: 07/18/13
CONTRACTOR: RB Baker DATE OF LAST REV.: 07/18/13 NO. OF REVISIONS: 0
CONTROL METHOD: QA DATE VOID: 07/18/15

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Gsb**
1	Martin Marietta - Warrenton	#7 Stone	69	2.65
2	Martin Marietta - Camack	#89 Stone	30	2.66
3	Carmeuse Lime & Stone	Hydrated Lime	1	2.38
4				
5				
6				
7				
8				
9				
10				

SIEVE	**GRADATION**										**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm															
1" / 25.0 mm															
3/4" / 19.0 mm	100	100	100								100	100.0			100.0
1/2" / 12.5 mm	90	99	100								93	93.0	86.0	-	100.0
3/8" / 9.5 mm	52	96	100								66	65.0	58.0	-	72.0
#4 / 4.75 mm	8	34	100								17	20.0	15.0	-	25.0
#8 / 2.36 mm	3	9	100								6	8.0	5.0	-	10.0
#30 / 0.60 mm	2	3	100												
#100 / 0.150 mm	1.0	1.6	100												
#200 / 0.075 mm	0.5	1.1	80								1.5	2.0	0.0	-	4.0

OPTIMUM BINDER CONTENT,%		6.0	5.64	-	6.36
% AIR VOIDS (± 1.15)					
% VMA (± 1.15)					
PERCENT BINDER					
MAXIMUM SPECIFIC GRAVITY					
BULK SPECIFIC GRAVITY					
% AIR VOIDS IN TOTAL MIX					
% V. M. A.					
% VOIDS FILLED					
STABILITY (lbs.)					

JOB MIX

DATE

PREPARED BY CMW 07-18-13
REVIEWED BY CBS/RCH 7/23/13
ACCEPTED BY CBS 7/23/13

EFFEC. SPECIFIC GRAVITY: N/A TSR(%): N/A WET TS:(kPa) N/A
GRADE OF BINDER: PG 76-22 BINDER SP. GRAVITY: N/A
DESIGN DUST TO ASPHALT RATIO: N/A # of Gyrations: N/A
6.0 % Asphalt recommended with permissible variation of: 0.36 This mix is satisfactory and meets SCDOT
specification for use in OGFC
REMARKS: **Verified mix**
0.4% used by weight of total mix of Hi-Tech Asphalt Soultions Cellulose fibers **Drain Down = 99.9% Retention**
SC-T-69 (<5%)

Appendix E: Determination of Uniformity Coefficient (C_u)

1. SCOPE

This procedure is used to calculate the uniformity coefficient of an aggregate gradation.

2. REFERENCED DOCUMENTS

SC-T-4
SC-T-102

3. PROCEDURE

3.1. Conduct a sieve analysis on a representative aggregate sample.

3.2. Calculate the percent passing for each sieve. An example gradation is included in Table D-1.

Table D.1. Example gradation.

Sieve Size	Sieve Size (mm)	Passing (%)
3/4"	19.0	100.0
1/2"	12.5	94.0
3/8"	9.5	69.0
#4	4.75	19.0
#8	2.36	7.0
#30	0.6	3.5
#100	0.15	2.0
#200	0.075	1.00

4. CALCULATIONS

4.1. Calculate D_{60}

First sieve having greater than 60% passing, *in mm* (A): ______________

Percent passing this sieve (B): ______________

First sieve having less than 60% passing, *in mm* (C): ______________

Percent passing this sieve (D): ______________

$$D_{60} = \frac{(60 - D)(A - C)}{(B - D)} + C$$

4.2. Calculate D_{10}

First sieve having greater than 10% passing, *in mm* (E): ______________

Percent passing this sieve (F): ______________

First sieve having less than 10% passing, *in mm* (G): ______________

Percent passing this sieve (H): ______________

$$D_{10} = \frac{(10 - H)(E - G)}{(F - H)} + G$$

4.3. Calculate C_u

$$C_u = \frac{D_{60}}{D_{10}}$$

5. EXAMPLE CALCULATIONS

The following is a set of example calculations to determine the uniformity coefficient of the gradation listed in Table D.1.

First sieve having greater than 60% passing, *in mm* (A): 9.5

Percent passing this sieve (B): 4.75

First sieve having less than 60% passing, *in mm* (C): 69

Percent passing this sieve (D): 19

$$D_{60} = \frac{(60 - 19)(9.5 - 4.75)}{(69 - 19)} + 4.75 = 8.65\,mm$$

First sieve having greater than 10% passing, *in mm* (E): 4.75

Percent passing this sieve (F): 2.36

First sieve having less than 10% passing, *in mm* (G): 19

Percent passing this sieve (H): 7

$$D_{10} = \frac{(10 - 7)(4.75 - 2.36)}{(19 - 7)} + 2.36 = 2.96\,mm$$

$$C_u = \frac{8.65\,mm}{2.96\,mm} = 2.92$$