NCAT Report 19-01

PRELIMINARY EVALUATION OF RECYCLED ASPHALT SHINGLES IN WARM MIX ASPHALT IN WILSON, NORTH CAROLINA

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ABSTRACT

A recycled asphalt shingles (RAS) using warm mix asphalt (WMA) field demonstration was conducted in Wilson, North Carolina in June 2015 to compare using post-consumer RAS (PC RAS) and manufacturer waste RAS (MW RAS). Mixes were produced using both types of RAS in conventional hot mix asphalt (HMA) and WMA. The WMA technology used the chemical additive Evotherm 3G M1. The National Center for Asphalt Technology (NCAT) documented the production and construction of the demonstration projects and evaluated both mixes using a range of state-of-the-art laboratory tests. Results of the comparison are detailed in this report.

TABLE OF CONTENTS

1 INTRODUCTION

In response to growing economic and environmental concerns, new technologies are being developed and tested by the asphalt pavement industry to reduce the consumption of natural resources and the cost of asphalt mixtures. Two of these new technologies that have received much attention in the last few years are the use of recycled asphalt shingles (RAS) and warm mix asphalt (WMA). These new technologies address important issues that face the asphalt industry in different ways. RAS contains a high percentage of asphalt binder, which can be used to reduce the amount of virgin asphalt binder needed when producing a new mixture. Since binder is the most expensive component of an asphalt mixture, the use of RAS can significantly reduce mixture costs. WMA, on the other hand, uses additives or other means of decreasing the viscosity of asphalt binders in order to allow lower production and compaction temperatures compared to conventional hot mix asphalt (HMA). Lowering the temperature reduces the amount of energy required for heating, resulting in cost savings for mixture production.

The use of WMA technologies has become more widely accepted, and the use of RAS is significant to the reduction in costs and resources of asphalt mixtures. One question that needs to be answered is whether or not RAS can be used with WMA. Many in the industry have questioned if the lower temperatures being used for WMA are sufficient to soften and activate the aged binder in RAS. Hence, research is needed to determine the amount of mixing between the RAS binder and the virgin binder when WMA is used.

While the use of both RAS and WMA have increased over the past ten years, additional guidance for designing, producing, and constructing asphalt mixtures that use both RAS and WMA is needed. There are numerous gaps in the state-of-the-knowledge on how these two technologies work, either in harmony or dissonance with each other.

This report documents the construction and materials evaluation of a WMA demonstration in Wilson, North Carolina. Four separate mixes were produced as part of this demonstration: post-consumer RAS (PC RAS), hot mix asphalt (HMA), WMA and manufacturer waste RAS (MW RAS), and HMA and WMA mixtures. The chemical additive Evotherm 3G M1 was used as the WMA additive for this field demonstration. The four mixes were produced and placed over a span of four days from June 15 to June 18, 2015. Each mix was placed in a four-lane portion of SR 58 in Wilson, North Carolina by S.T. Wooten Corporation.

1.1 Background

The asphalt binder in RAS decreases the demand for virgin asphalt binder, which provides several benefits to both the industry and state agencies. First, recycled asphalt from RAS can reduce costs by lowering the amount of virgin binder needed for mixture production.

Waste from shingle factories can be ground up and immediately be added to the hot mix asphalt process or renewed with rejuvenating chemicals prior to the mix process. Second, asphalt mixtures require specific aggregate gradations with certain durability properties. The mineral or ceramic aggregate in the shingles provides a source of fine aggregate, which reduces the demand for mined virgin aggregate. Finally, certain properties of asphalt pavement (i.e. stiffness and stability) have been shown to improve with the addition of recycled asphalt shingles (*1*).

While the composition of shingles varies depending on manufacturer and roofing application, most RAS is composed of four basic materials: asphalt cement, felt or fiber, mineral or ceramic aggregate, and mineral filler. Organic or fiberglass felt backings form the basic structure for shingles. The organic felt is typically composed of either cellulose or wood fibers and is designed to support the asphalt and aggregate granules. Fiberglass backings are manufactured by mixing fine glass with water in the form of a glass pulp which is, in turn, formed into a fiberglass sheet (*2, 3*). The backing is then saturated with asphalt cement. This asphalt cement has been "air blown," which increases its stiffness when compared to conventional paving asphalt. The asphalt can be further stabilized with a lime dust (70% passing the #200 sieve) (*4, 5*). A second application of "air blown" asphalt is applied as a covering for both sides of the shingle. The top of the shingle is then covered with granules designed to protect the asphalt from both the sun's ultraviolet rays and physical damage due to abrasion on rooftops. Most shingle manufacturers use a combination of crushed rocks coated with ceramic metal oxides as granules. Additional headlap granules can be used in this application. Both aggregate granules are ideal for roofing shingles due to their uniform size, toughness, and angular shapes (*3*). In some cases, chemicals are added to the aggregate to prevent algae growth (*4*).

Though there are differences between organic and fiberglass shingles, there are also differences in the material composition based on shingle source. Loss of aggregate particles in post-consumer (PC) shingles generally causes the PC shingles to have higher asphalt content than the manufacturer-waste (MW) shingles. Exposure to contaminants also causes PC shingles to contain more deleterious materials such as paper, wood, and nails than MW shingles. While many of these contaminants are removed during the grinding process, further removal of deleterious materials may be necessary before the RAS can be used in asphalt mixtures (*3*).

PC shingle stockpiles also tend to exhibit more variability than MW shingles in size, aggregate gradation, and asphalt content as well as material properties such as specific gravity. However, the processing of the shingles by grinding to a maximum size can reduce variability. Shingle type, manufacturer, and age can significantly influence these factors (*6*).

While states and organizations vary in how much they believe RAS binder blends with virgin asphalt binder, quantifying the asphalt content of RAS is a critical component of material proportioning in an asphalt mixture design and the driving economic incentive for using RAS in asphalt mixtures. Recent research studies have shown that PC shingles can contain 30-36% asphalt binder (on average) while MW shingles have closer to 19-20% (*7*).

1.2 Field Trials and Performance

While laboratory performance is a critical component of understanding how new asphalt mixtures will behave, laboratory experiments must be validated in the field. This section presents a summary of some of the field projects that have been documented in literature to date.

Minnesota has conducted the most field trials investigating the use of RAS in asphalt mixtures. Minnesota's first test section containing RAS was completed on the recreational trail in Saint Paul in 1990. The subbase was an old railroad track bed, which was placed under four inches of crushed concrete base. A 2.5-inch thick wearing course containing MW shingles was placed 12-feet wide. In 2003, after 13 years in service, the mixtures were still performing well (*8*).

In 1991, the Minnesota Department of Transportation (MNDOT) completed another trial section in Mayer, Minn. In both 1995 and 2003, the mixture performance of the RAS asphalt mixture was equivalent to the control mixture. Transverse reflective cracking had been noticed in both sections; however, no other distresses were noticed (*8*).

The New Jersey Department of Transportation (NJDOT) also conducted early experiments using an asphalt cold-patch material from RAS. After 22 months in service, only minor signs of distress were noted. The conventional patch for NJDOT only lasted approximately six months; therefore, the use of RAS more than tripled the life expectancy of the patch (*9*).

In a 1994 survey, only three state departments of transportation responded to using RAS in asphalt mixtures. States such as Illinois only used RAS as an aggregate in cold patch materials. Illinois also evaluated the use of shingles in asphalt paving mixtures and determined that roofing shingles could be placed in both dense and stone matrix asphalt (SMA) mixtures. In 1993, a MnDOT pavement containing 5-7% shingles by weight reported good performance after two years (*10*).

Canada Highway 86 near Waterloo, Ontario was expanded from a two-lane road to a four-lane highway in 1996. The lower binder layer was a 1.5-inch layer containing no RAS; however, the 2-inch upper binder layer and the 1.5-inch wearing course contained 3% RAS. A control mixture was placed along with the RAS mixtures for comparison purposes. Three years after construction, the control mixture had more raveling, longitudinal joint openings, and fatigue cracking than the RAS mixtures (*8*).

In 1997, the Texas Department of Transportation (TxDOT) constructed test sections using both PC and MW RAS in asphalt surface mixtures. In addition, a control section was also constructed to monitor any significant deviation in performance from that of conventional materials. The mix designs for test sections containing roofing shingles (MW and PC) were performed according to TxDOT Standard Specification Item 340. The control section mix design was based on the TxDOT Special Specification Item 3000 for QC/QA mixes. The asphalt concrete mix was tested for Hveem stability, moisture susceptibility, static creep, and voids in mineral aggregate (VMA). In addition, the boil test (Tex-530-C) was completed to determine the stripping susceptibility of the mix (*11*). The performance of the test sections containing roofing shingles appears to be comparable to conventional mixes, and no severe distresses were observed after two years of service. The area engineer noted that the RAS mixtures did show signs of reflective cracking, but the time at which the cracks appeared was similar to that of conventional asphalt mixtures.

MnDOT completed five field projects between 2005 and 2008 that used both MW and PC RAS. In each of these five projects, 500-foot performance sections were set up to monitor cracking, rutting, and surface characteristics. The study was designed to assess the virgin binder to total binder ratio that MnDOT was considering specifying at a 70% minimum. The research suggested that the 70% new binder ratio worked for some projects and not for others. The projects also seemed to confirm that using a softer binder grade could improve the cracking performance of the mixtures. Unlike previous laboratory testing, this research also suggested that little difference was noticed in the performance between sections with PC and MW RAS (*12*).

In 2009, a field project conducted by the Washington State Department of Transportation (WSDOT) and King County Department of Transportation (KCDOT) was designed to assess the viability of using RAS and RAP in asphalt mixtures. Two miles of roadway were divided into half-mile test sections containing two different overlay asphalt mixtures: 15% RAP HMA, and 3% RAS and 15% RAP HMA (*13*). The RAS was tested for gradation, deleterious materials, moisture content, and asbestos before it was used to ensure that a high-quality product could be constructed that would meet the current standards of the state. Laboratory and field testing suggested that the RAS had no negative impacts on the pavement's performance. Additionally, there was no change in the skid resistance of the roadway when changing between mixtures.

In 2014, the National Cooperative Highway Research Program (NCHRP) initiated project 09-55 entitled "Recycled Asphalt Shingles in Asphalt Mixtures with Warm Mix Asphalt Technologies." NCHRP 9-55 included a field experiment designed to document the production of HMA and WMA mixtures containing RAS as well as to evaluate the short-term pavement performance of the pavements constructed with the mixtures. Laboratory test results and field evaluations for this report were extracted from the results of the NCHRP 9-55 project.

1.3 Objectives and Scope

The main objective of this research was to evaluate laboratory performance of HMA and WMA asphalt mixtures containing post-consumer RAS and manufacturer-waste RAS. A second objective was to evaluate the short-term (up to three years) field performance of mixtures constructed in Wilson, North Carolina in June 2015. In order to accomplish this objective, the National Center for Asphalt Technology (NCAT) documented the production and construction of the demonstration projects and evaluated both mixes using a range of state-of-the-art laboratory tests. Results of the comparison are detailed in this report.

2 MIX DESIGN

The mix design was conducted by the contractor and approved by the state agency. The following mix design results were reported to NCAT and no details were provided regarding selection of additives or any technology used in the production of the asphalt mixture.

The asphalt mixtures used for this trial consisted of a fine-graded 9.5-mm nominal maximum aggregate size (NMAS) Superpave mix design with a compactive effort of 65 gyrations. Volumetric designs for both the MW RAS and PC RAS mixes were conducted with the intention of having similar volumetric and gradations for all mixes. All four mixes contained 20% reclaimed asphalt pavement (RAP) and 5% RAS with a granite virgin aggregate. The RAP used was a multiple-source crushed RAP. The PC RAS used was obtained from local landfills, while the MW RAS was obtained from Saint-Gobain in Oxford, North Carolina. Tables 1 and 2 show the material percentages used for mix design submittal and production for the MW RAS and PC RAS mixes, respectively.

Table 1. Aggregate Percentages Used in Mix Design and Production for MW RAS Mixes

Aggregate Type	Mix Design MW RAS Mixes (%)	Production MW RAS HMA (%)	Production MW RAS WMA (%)
#78s Granite	29	25	26
Dry Screenings	13	19	19
Coarse Sand	33	31	30
RAP	20	20	20
RAS	5	5	5

Table 2. Aggregate Percentages Used in Mix Design and Production for PC RAS Mixes

Aggregate Type	Mix Design PC RAS Mixes (%)	Production PC RAS HMA (%)	Production PC RAS WMA (%)
#78s Granite	29	26	27
Dry Screenings	19	19	19
Coarse Sand	27	30	29
RAP	20	20	20
RAS	5	5	5

The asphalt mixtures used a PG 58-28 asphalt binder supplied by NuStar in Wilmington, North Carolina. All four mixes contained terminally blended Evotherm 3G M1 at a rate of 0.25% by weight of virgin binder. Therefore, the only difference in the HMA and WMA mixes was the production and compaction temperatures since all mixes contained Evotherm. The aggregate gradation, optimum asphalt content, design volumetric, and specifications are shown in Table 3.

Table 3 Design Gradation, Asphalt Content, and Volumetrics for Mix Design

Sieve Size, mm (in.)	MW RAS Mixes	PC RAS Mixes	Specifications
	% Passing		
12.5 (1/2")	100	100	100 Max
9.5 (3/8")	96	96	90-100
4.75 (#4)	72	72	<90
2.36 (#8)	57	57	32-67
1.18 (#16)	42	42	--
0.6 (#30)	29	29	--
0.3 (#50)	16	17	--
0.15 (#100)	10	10	--
0.075 (#200)	6.2	6.2	4-8
AC, %	5.4	5.4	--
Air Voids, %	4.0	4.0	--
VMA, %	16.0	16.1	>16
VFA, %	75.0	74.9	73-76
D/A Ratio	1.16	1.16	0.6-1.2

3 PRODUCTION

As stated previously, all four mixes contained 0.25% Evotherm 3G M1 for use as an antistrip. For the two WMA mixes, Evotherm's WMA properties allowed the production temperature to be significantly reduced (compared to the HMA). The mixes were produced using an Astec Double Barrel drum mix plant located in Simms, North Carolina. The plant was powered using natural gas and incorporated four 300-ton silos. Figure 1 shows the asphalt plant used in this study.

Figure 1. Astec Double Barrel Plant Used in Simms, North Carolina

Production temperatures and rates were monitored and recorded throughout production of the four mixes. Table 4 shows production temperature information for the four mixes, and Table 5 shows the production rates and totals.

Table 4. Production Temperatures

	MW RAS HMA	MW RAS WMA	PC RAS HMA	PC RAS WMA
Average	297.1	276.2	304.8	277.0
Standard Deviation	5.9	5.7	5.8	9.7
Max	307.0	287.0	318.0	302.0
Min	284.0	262.0	290.0	260.0

Table 5. Production Rates and Totals

	MW RAS HMA	MW RAS WMA	PC RAS HMA	PC RAS WMA
Average Production Rate, tons per hour (tph)	182	209	209	219
Total Tons Shipped	1,666	1,724	1,847	1,580

The asphalt content of each mix was determined both by ignition method and by solvent extraction using trichloroethane (AASHTO T 164 Method A). The binders were recovered and graded after extraction. The average asphalt contents for the mixture samples, shown in Table 6, were similar for both methods. For the RAP, the ignition method yielded 0.56% higher asphalt content, but this is likely due to mass loss for the RAP aggregate rather than a true difference in asphalt content. For the PC RAS samples, the larger difference in results from the two methods is likely due to burning off cellulose fibers in the ignition oven. The fibers currently used in shingles are fiberglass, which would not be affected by the ignition method for the MW RAS samples.

Table 6. Asphalt Content Test Results

Material	Corrected Ignition Method	Solvent Extraction	Difference, Ignition – Extraction
	Average	Average	
MW RAS HMA Mix	5.16	4.99	0.17
MW RAS WMA Mix	5.34	5.24	0.10
PC RAS HMA Mix	5.45	5.36	0.09
PC RAS WMA Mix	5.40	5.40	0.00
RAP	5.81	5.25	0.56
MW RAS	18.27	17.99	0.28
PC RAS	18.64	16.84	1.80

Table 7 shows the binder grade test results for both the mixes and the recycled materials. The true grades and ΔTc (20-hour Pressure Aging Vessel) of the recovered binders from the HMA and WMA mixes containing MW RAS were similar, as were the results for the two mixes containing PC RAS. The binder properties of the RAP and RAS materials followed the expected trends (higher critical temperatures for RAS binders than RAP binders). The ΔTc (unaged) results for the RAS binders were very low.

Table 7 shows that the high temperature continuous grade of both RAP and RAS binders are higher than the true grade of the virgin PG 58-28 binder. This trend is expected since the RAP binder is field aged and the RAS binder is produced through an air-blowing oxidation process. It can also be observed that the high temperature continuous grade of the post-consumer RAS binder (i.e., PC RAS HMA Mix and PC RAS WMA Mix) are higher than the true grade of the manufacturer-waste RAS binder (i.e., MW RAS HMA Mix and MW RAS WMA Mix). An explanation for this behavior relates to the post-consumer RAS binders being oxidized after an in-service period (i.e., binder from roofing shingles that have experienced years of field aging).

Considering the low temperature behavior, the ΔTc parameter represents a means of indexing the non-load associated cracking potential of asphalt binders and is predicted using the Bending Beam Rheometer (BBR) Stiffness (*S*) and m-slope (m-value) parameters. A limit to reduce the risk of crack initiation was set by Asphalt Institute's Mike Anderson in 2011 at ΔTc = -2.5 °C, at which point a preventive maintenance is suggested to avoid the pavement reaching a critical stage. Based on this limit, it can seen from Table 7 that the post-consumer RAS binders (i.e., PC RAS HMA Mix and PC RAS WMA Mix) are more susceptible for cracking than the manufacturer-waste RAS binder containing WMA (i.e., MW RAS WMA Mix). It can also be seen from the ΔTc results that the binder modification with WMA allows a lower cracking potential regardless of the type of RAS binder used (i.e., post-consumer or manufacturer-waste RAS binder).

Table 7. Performance Grade Test Results

Material	T_{crit} High	T_{crit} Int	T_{crit} Low s	T_{crit} Low m	True-Grade	PG	ΔT_c (20-hr)
MW RAS HMA Mix	85.2	26.2	-27.4	-24.6	85.2 - 24.6	82 - 22	-2.7
MW RAS WMA Mix	80.2	24.1	-26.8	-24.7	80.2 - 24.7	76 - 22	-2.0
PC RAS HMA Mix	90.4	26.4	-24.4	-21.3	90.4 - 21.3	88 - 16	-3.2
PC RAS WMA Mix	90.4	28.5	-24.4	-21.5	90.4 - 21.5	88 - 16	-2.9
RAP	110.4	43.0	-9.3	-9.7	110.4 - 9.3	106 - 4	+0.4
MW RAS	151.2	33.5	-39.5	-3.5	151.2 - 3.5	148 + 2	-36.0
PC RAS	207.0	55.5	-15.4	19.5	207.0 + 19.5	202 + 20	-34.9

4 MIX PROPERTIES

During production, NCAT personnel collected three samples from each mix. The first sample for each mix was taken after approximately two hundred tons had been produced. These first samples were used to fabricate a variety of specimens for determining volumetric and performance properties. For each mix, the first sample was taken at one time in order to ensure consistency between the performance tests. Two additional smaller samples were taken throughout the day to ship back to NCAT for future testing. The samples from each mix design were taken at the same tonnage point to allow the plant to achieve steady state production.

Volumetric specimens were compacted using 65 gyrations in the Superpave Gyratory Compactor (SGC). These volumetric samples were plant mixed / lab compacted (PMLC) on-site in the NCAT mobile lab so that the mixes would not have to be reheated, which may affect asphalt absorption and other volumetric properties. This is often referred to as being hot-compacted. The samples were placed in an oven for a short time after sampling in order to return to the compaction temperature. The compaction temperature for each mix was determined using the average compaction temperature observed on the test section through the first couple of hours of construction for each mix.

Water absorption levels were low (<2%), therefore bulk specific gravity (G_{mb}) was determined in accordance with AASHTO T 166. The mixes were sent to the main NCAT lab where the asphalt content and gradation of each mix were tested according to AASHTO T 164 and AASHTO T 30, respectively, as shown in Tables 8-10. Tables 8 and 9 show the results from NCAT's testing on the MW RAS and PC RAS mixes, respectively. It should be noted that the values shown in these tables are based on NCAT's work with the large sample taken once the mix production was considered stable. The contractor's quality control (QC) results for all four days are shown in the Appendix.

Table 8. Gradation, Asphalt Content, and Volumetrics for the MW RAS Mixes

	MW RAS JMF	**MW RAS HMA**	**MW RAS WMA**
Sieve Size	**% Passing**		
19.0 mm (3/4”)	100	100	100
12.5 mm (1/2”)	100	99	99
9.5 mm (3/8”)	96	93	93
4.75 mm (#4)	72	69	70
2.36 mm (#8)	57	54	54
1.18 mm (#16)	42	41	41
0.60 mm (#30)	29	28	28
0.30 mm (#50)	16	15	16
0.15 mm (#100)	10	7	7
0.075 mm (#200)	6.2	4.6	4.9
AC, %	5.4	5.0	5.2
Air Voids, %	4.0	6.4	4.9
Gmb @ Ndes	2.350	2.301	2.329
Gmm	2.448	2.459	2.448
VMA, %	16.0	16.5	15.8
VFA, %	75.0	61.3	69.2
Gsb	2.648	2.620	2.620
Gse	2.653	2.649	2.646
Pba %	0.10	0.44	0.40
Pbe %	5.32	4.58	4.86
D/B Ratio	1.16	1.00	1.00

Table 9 Gradation, Asphalt Content, and Volumetrics for the PC RAS Mixes

	PC RAS JMF	PC RAS HMA	PC RAS WMA
Sieve Size	**% Passing**		
19.0 mm (3/4”)	100	100	100
12.5 mm (1/2”)	100	98	99
9.5 mm (3/8”)	96	92	93
4.75 mm (#4)	72	69	71
2.36 mm (#8)	57	53	55
1.18 mm (#16)	42	41	43
0.60 mm (#30)	29	29	30
0.30 mm (#50)	16	16	18
0.15 mm (#100)	10	8	9
0.075 mm (#200)	6.2	5.3	5.7
AC, %	5.4	5.4	5.4
Air Voids, %	4.0	4.2	4.2
Gmb @ Ndes	2.349	2.333	2.340
Gmm	2.447	2.436	2.443
VMA, %	16.1	15.8	15.6
VFA, %	74.9	73.2	73.0
Gsb	2.647	2.622	2.622
Gse	2.652	2.637	2.647
Pba %	0.10	0.22	0.38
Pbe %	5.33	5.15	5.04
D/B Ratio	1.16	1.04	1.13

5 CONSTRUCTION

The test sections are located on SR 58 in Wilson, North Carolina. The portion of SR 58 being paved during this field demonstration was approximately 18 miles from the asphalt plant with a haul time of about 20 to 30 minutes. The project consisted of paving all four lanes of SR 58 with one of the test mixes from US 264 Alternate on the north end to US 264 on the south end. All mixes were placed as surface mixes at a target thickness of 1.5-inches. A CRS-1H was used as the tack coat at a rate of 0.06 gal/yd^2. Figure 2 shows the layout of the test sections.

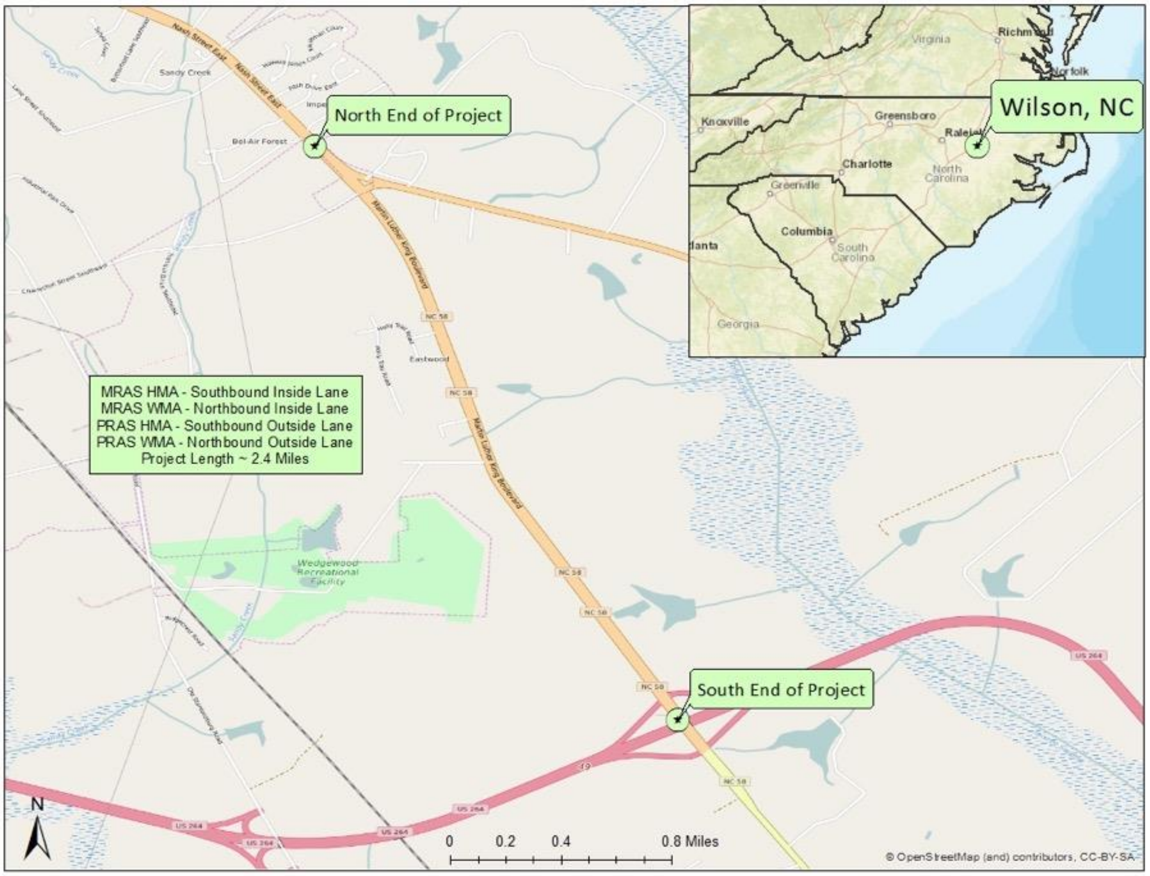

Figure 2. Location of Test Sections in Wilson, North Carolina

The mixes were delivered using a cycle of 15 to 22 tarped dump trucks. Once on site, a RoadTec MTV1000D material transfer vehicle was used to transfer the mixes to the Caterpillar AP1000E paver, shown in Figure 3.

Figure 3. MTV Transferring Mix to Paver

The temperature of the mix behind the paver was measured every 10 to 30 minutes using a hand-held temperature gun. The temperatures measured behind the screed for each mix are shown in Table 10.

Table 10. Temperatures Behind the Screed

	MW RAS HMA	MW RAS WMA	PC RAS HMA	PC RAS WMA
Average (°F)	281.8	254.4	279.9	249.0
Standard Deviation	9.5	6.0	9.1	7.9
Max	300.0	264.5	293.5	268.0
Min	259.5	243.5	249.5	229.0

Two Caterpillar CB-634D rollers were used for compaction. For the two HMA mixes, the breakdown roller operated in vibratory mode for two passes and static mode for two passes. This was then repeated on the other side of the mat, followed by a final static pass back up the middle. The finishing roller used the same rolling pattern. The rolling pattern was changed slightly for the two WMA mixes. The breakdown roller operated in vibratory mode for three passes on one side of the mat, followed by one static pass back. This was repeated on the other side of the mat and was then followed by one last static pass back up the middle of the mat. Figure 4 shows both rollers compacting the mat.

Figure 4. Breakdown and Finishing Rollers Compacting Mat

Three cores were cut from each mix section the day after construction. These cores were then checked by NCAT for density. Figure 5 shows the densities from these cores. The results show that the PC RAS mixes had slightly higher densities compared to the MW RAS mixtures. A combination of a softer (lower binder grade) MW RAS binder compared to the PC RAS binder and a slightly higher asphalt content of the MW RAS mixtures (0.2%) could have made MW RAS mixtures easier to compact in the field, but that was not the case. The filler to binder ratios of the MW RAS mixes were significantly lower. This could also contribute to the lower in place density of the MW RAS mixes.

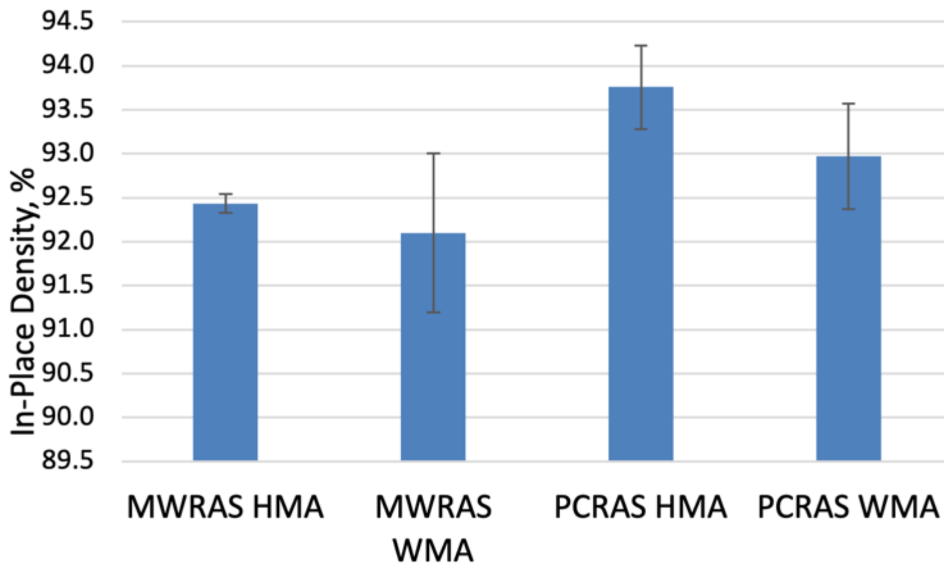

Figure 5. In-place Densities Based on Cores at Construction

Table 11 shows the results of the ANOVA test performed to evaluate how the mix type (HMA and WMA), type of RAS (MW RAS and PC RAS), and the interaction between these two variables affected the initial in-place density. Only the RAS type had a significant effect (p-value = 0.013) on the in-place density for this project. Table 11 also shows the results of the Tukey's test of multiple comparisons.

Table 11. Initial Density ANOVA Analysis

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
RAS Type	1	3.61	3.61	10.16	0.013
Mix Type	1	0.94	0.94	2.64	0.143
Mix Type × RAS Type	1	0.16	0.16	0.44	0.527
Error	8	2.84	0.36		
Total	11	7.54			
	Statistical Grouping				
RAS Type	N	Mean	Grouping		
PC RAS	6	93.4	A		
MW RAS	6	92.3	B		

6 MIXTURE PERFORMANCE TESTING

6.1 Hamburg Wheel-Track Testing

Hamburg wheel-track testing, shown in Figure 6, was performed in accordance with AASHTO T 324-14 to determine both the rutting and stripping susceptibility of the mixtures tested for this project. Specimens for Hamburg testing were compacted at the project location in the NCAT mobile lab. Three replicates were tested per mix, with each replicate consisting of two trimmed specimens (six specimens total per mix). The specimens were originally compacted using an SGC to a diameter of 150 mm and a height of 60 mm. The specimen ends were then trimmed to fit in the Hamburg molds for testing. The air voids on the Hamburg specimens were 7.0 ± 1.0 percent.

The specimens were tested under a 158 ± 1 lb. wheel load for 10,000 cycles (20,000 passes) while submerged in a water bath maintained at a temperature of 50°C. While being tested, rut depths were measured by an LVDT, which recorded the relative vertical position of the load wheel after each load cycle. After testing, these data were used to determine the point at which stripping occurred in the mixture under loading and the relative rutting susceptibility of those mixtures. Testing would be terminated early in the event of severe rutting (greater than 1/2” of rutting).

Figure 7 illustrates typical data output from the Hamburg device. These data show the progression of rut depth with number of cycles. From this curve two tangents are evident, the steady-state rutting portion of the curve and the portion of the curve after stripping. The intersection of these two curve tangents defines the stripping inflection point (SIP) of the mixture. Comparing the stripping inflection points and total rutting of the different mixtures gives a measure of the relative moisture and deformation susceptibility of these mixtures. A stripping inflection point of greater than 10,000 passes has been shown to be a good indicator of a moisture-resistant mix (*14*). Texas uses the criteria in Table 12 to evaluate the rutting resistance of their asphalt mixtures (*15*). These criteria specify the total allowable rut depth in the Hamburg test as a function of the mixture base binder grade.

Table 12. Texas Hamburg Test Requirements

High Temperature Binder Grade	Minimum Passes to 0.5-Inch Rut Depth
PG 64 or Lower	10,000
PG 70	15,000
PG 76 or Higher	20,000

Figure 6. Hamburg Wheel-Tracking Device

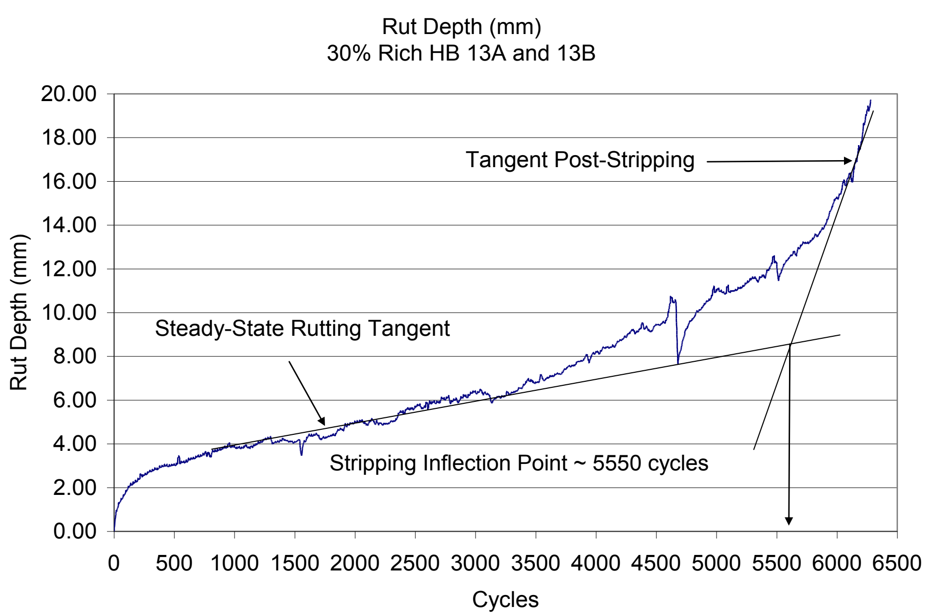

Figure 7. Example of Hamburg Data Analysis

The Hamburg test results are summarized in Table 13 with a summary table of the average and standard deviation of the final rut depths. None of the specimens exhibited stripping in the Hamburg test, nor did any of the final rut depths approach the documented failure criterion. This result was expected for mixtures containing 20% RAP and 5% RAS. The mixtures with WMA had slightly higher rut depths than the HMA mixtures (around 1 mm), which can be supported by the softer binder being present in the mix as shown in Table 7. A General Linear Model (GLM) ($\alpha = 0.05$) was performed to determine the statistical impact of the RAS type and the presence or absence of WMA. The results in Table 14 show that the mixes with WMA have statistically higher rut depths than the HMA mixes, but the type of RAS had no statistical impact on the Hamburg results. It should be noted that while the differences in the WMA and HMA mixes were statistically significant, they did not constitute a practical difference in the results, as all of the mix rut depths fell well below the documented Hamburg failure criterion.

Table 13. Hamburg Data Summary

Mix ID	**Replicates**	**Specimen Air Voids (%)**	**Rut Depth at 20,000 Passes (mm)**		**SIP (Passes)**
		Average	***Average***	***Std. Dev.***	***Average***
MW RAS HMA	3	6.9	1.68	0.22	20,000+
MW RAS WMA	3	7.2	2.90	0.21	20,000+
PC RAS HMA	3	6.8	1.62	0.06	20,000+
PC RAS WMA	3	7.1	2.54	0.40	20,000+

Table 14. GLM Results Summary – Hamburg Rut Depths
General Linear Model: Minimum Rut Depth (mm) @ 20,000 versus RAS ID, WMA

Factor	Type	Levels	Values
RAS ID	fixed	2	MRAS, PRAS
WMA	fixed	2	N, Y

Analysis of Variance for Minimum Rut Depth (mm) @ 20,000, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
RAS ID	1	0.1323	0.1323	0.1323	2.07	0.188
WMA	1	3.4133	3.4133	3.4133	53.49	0.000
RAS ID*WMA	1	0.0705	0.0705	0.0705	1.11	0.324
Error	8	0.5105	0.5105	0.0638		
Total	11	4.1267				

S = 0.252620   R-Sq = 87.63%   R-Sq(adj) = 82.99%

Grouping Information Using Tukey Method and 95.0% Confidence

RAS ID	N	Mean	Grouping
PRAS	6	-2.080	A
MRAS	6	-2.290	A

WMA	N	Mean	Grouping
N	6	-1.652	A
Y	6	-2.718	B

RAS ID	WMA	N	Mean	Grouping
PRAS	N	3	-1.623	A
MRAS	N	3	-1.680	A
PRAS	Y	3	-2.537	B
MRAS	Y	3	-2.900	B

Means that do not share a letter are significantly different.

6.2 Illinois Flexibility Index (I-FIT) Testing

Illinois Flexibility Index Testing (I-FIT) was performed at NCAT for this project using a Test Quip® I-FIT testing device. Semi-circular asphalt specimens were prepared from reheated plant-produced mix to an air void level of 7.0 ± 0.5 percent after trimming. Six replicates were prepared for this study, each trimmed from a larger gyratory specimen measuring 160-mm tall and 150-mm in diameter. Four replicates could be obtained per specimen. A notch was then trimmed into each specimen at a target depth of 15 mm and width of 1.5 mm along the center axis of the specimen (Figure 8). The specimens were tested at target test temperature of 25.0 ± 0.5°C after being conditioned in an environmental chamber for two hours. Specimens were loaded monotonically at a rate of 50 mm/min until the load dropped below 0.1 kN after the peak was recorded. Both force and actuator displacement were recorded at a rate of 50 Hz by the system.

Figure 8. NCAT I-FIT Test Setup

The collected data were used to calculate two critical parameters for each tested specimen, the fracture energy (FE) and the flexibility index (FI). The FE (Equation 1) represents the area under the stress-strain curve normalized for the specimen dimensions and is calculated by integrating the area under the raw load-displacement curve and dividing by the ligament area (the area of the semi-circular specimen through which the crack will propagate). To calculate the FI (Equation 2), the slope of the post-peak portion of the curve must be determined. This is the maximum slope of the curve immediately after the peak. The flexibility index was then calculated by dividing the fracture energy by the post-peak slope and then multiplying that quotient by a scaling factor. In general, a higher FI is indicative of a mix exhibiting a more ductile failure while a lower FI indicates a more brittle failure.

$$G_f = \frac{w_f}{a_{lig}} \tag{1}$$

$$FI = \frac{G_f}{|m|}\, x\, A \tag{2}$$

where:

- G_f = Fracture Energy (J/m^2);
- W_f = Work of Fracture (J);
- a_{lig} = Ligament Area (mm^2) = (Specimen Radius – Notch Length) x Specimen Width;
- FI = Flexibility Index;
- m = Post-Peak Slope (kN/mm); and
- A = Scaling Factor (0.01 for gyratory specimens).

Data analysis for this project was performed using a data analysis tool developed by the Illinois Center for Transportation (ICT) at the University of Illinois at Urbana-Champaign (UIUC). An example of processed I-FIT data from this software is shown in Figure 9.

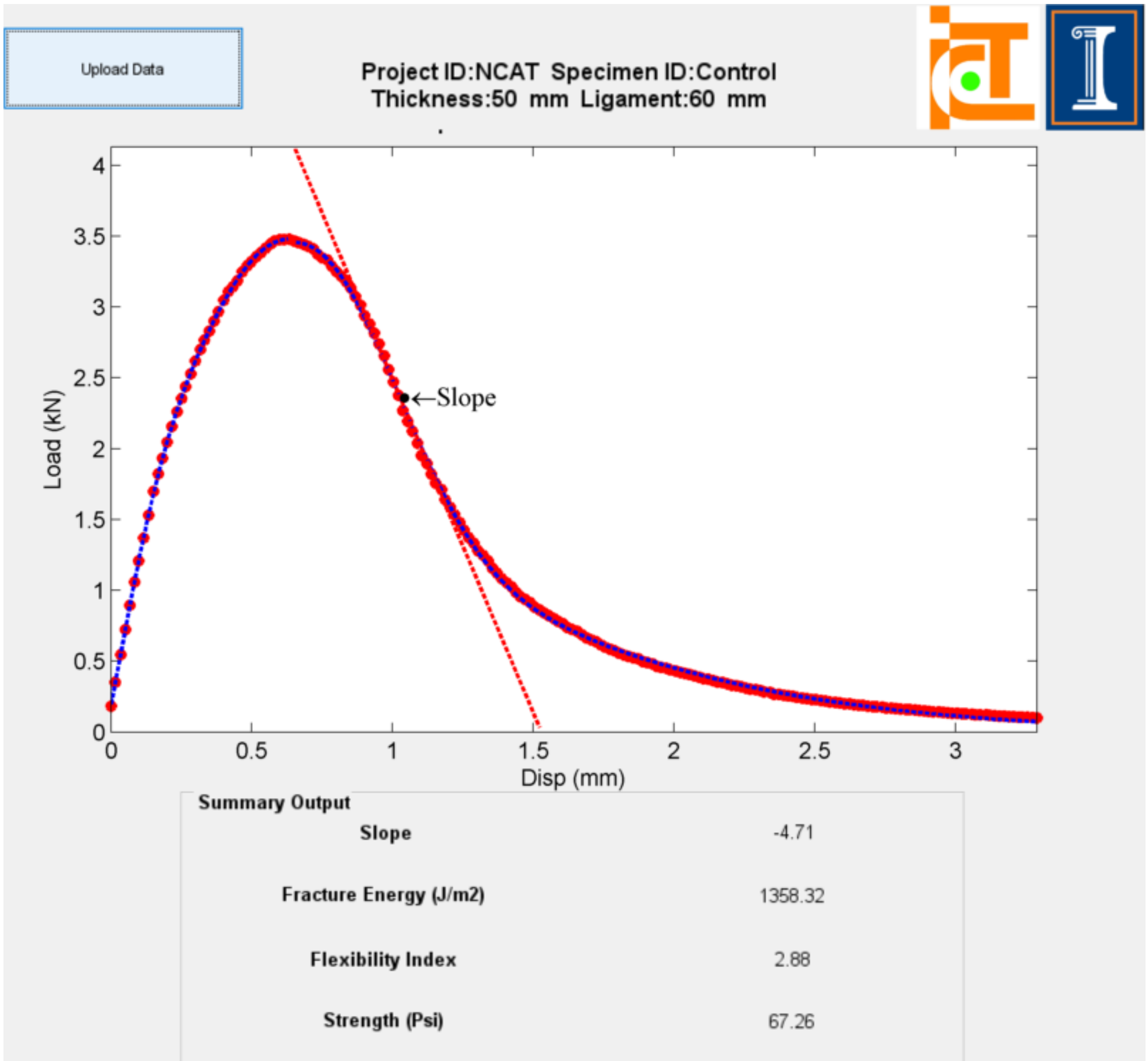

Figure 9. Example of Processed I-FIT Data using UIUC/ICT IL-SCB Analysis Tool

The development of flexibility index threshold values is ongoing. The University of Illinois at Urbana-Champaign has conducted lab to field comparisons between FI and field cracking performance for the Illinois Center for Transportation. Comparisons of the FI results from loose mix samples and mixture performance at FHWA's accelerated loading facility (ALF) showed good agreement between FI and load repetitions to failure of the accelerated sections. For the FHWA ALF, the three poor-performing sections had an FI value less than 2, whereas the control section (which was among the top performers) had an FI value of 10. Additionally, some correlation was seen between the FI and cores obtained from nine different IDOT (Illinois Department of Transportation) districts. The FI clearly showed the effects of aging on these cores with a clear reduction in FI for cores from pavements over ten years old. Sections with an FI of less than 4 to 5 on the field cores generally exhibited premature cracking (*16*).

The results of the flexibility index values are summarized in Figure 10 with the summary statistics tabulated in Table 15. A GLM (α = 0.05) of the FI results is summarized in Table 16. The statistical analysis results show that the WMA MW RAS has the highest FI of the four mixes tested while the HMA MW RAS has the lowest. The low FI results for the HMA MW RAS relative to the HMA PC RAS may be partially driven by the difference in design pill air voids (see Tables 8 and 9). The results of the GLM show the RAS type to have no statistical impact on the FI results, while the WMA mixes have statistically higher FI than the HMA mixes.

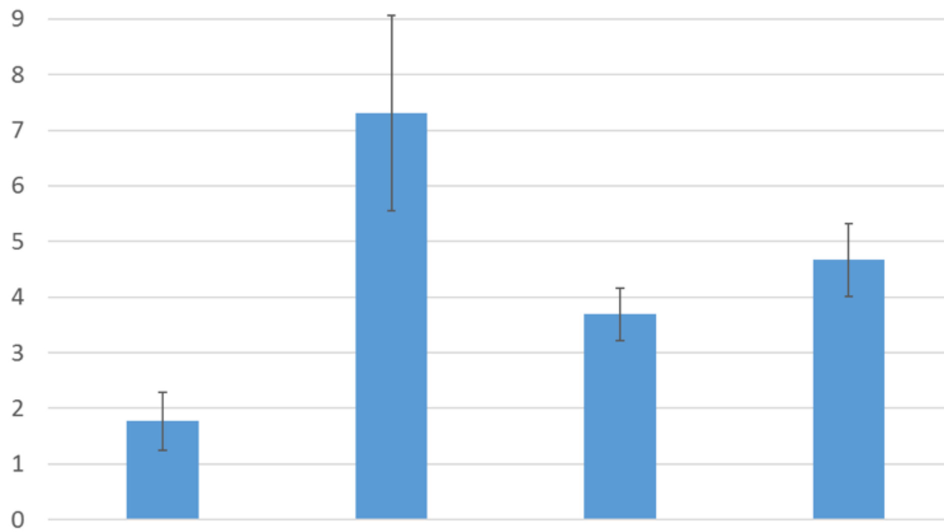

Figure 10. I-FIT Flexibility Index Summary

Table 15. I-FIT Results Summary

Mix ID	**Replicates**	**Air Voids (%)**	**Fracture Energy (J/m2)**			**Flexibility Index (FI)**		
		Avg.	***Avg.***	***Std. Dev***	***CV (%)***	***Avg.***	***Std. Dev***	***CV (%)***
HMA MW RAS	6	6.8	1,488	79	5.3	1.77	0.56	31.9
WMA MW RAS	6	7.0	2,042	140	6.9	7.31	0.56	7.7
HMA PC RAS	6	7.0	1,759	61	3.4	3.69	0.81	22.0
WMA PC RAS	6	7.0	1,680	147	8.7	4.67	0.52	11.1

Table 16. GLM (α = 0.05) Results Summary – I-FIT Flexibility Index
General Linear Model: Flexibility Index (FI) versus RAS ID, WMA

Factor	Type	Levels	Values
RAS ID	fixed	2	MRAS, PRAS
WMA	fixed	2	N, Y

Analysis of Variance for Flexibility Index (FI), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
RAS ID	1	0.756	0.756	0.756	1.94	0.179
WMA	1	63.831	63.831	63.831	163.76	0.000
RAS ID*WMA	1	31.145	31.145	31.145	79.90	0.000
Error	20	7.796	7.796	0.390		
Total	23	103.528				

S = 0.624334   R-Sq = 92.47%   R-Sq(adj) = 91.34%

Unusual Observations for Flexibility Index (FI)

Obs	Flexibility Index (FI)	Fit	SE Fit	Residual	St Resid
17	4.95000	3.68833	0.25488	1.26167	2.21 R

R denotes an observation with a large standardized residual.

Grouping Information Using Tukey Method and 95.0% Confidence

RAS ID	N	Mean	Grouping
MRAS	12	4.535	A
PRAS	12	4.180	A

WMA	N	Mean	Grouping
Y	12	5.988	A
N	12	2.727	B

RAS ID	WMA	N	Mean	Grouping
MRAS	Y	6	7.305	A
PRAS	Y	6	4.672	B
PRAS	N	6	3.688	B
MRAS	N	6	1.765	C

Means that do not share a letter are significantly different.

6.3 Texas Overlay Test

The Texas Overlay Tester (OT) is a device designed to simulate accelerated reflective cracking in asphalt concrete overlays— specifically, the reflective cracking of an asphalt concrete overlay atop a jointed Portland cement concrete (PCC) pavement surface. The TxDOT Tex 248-F specification is the current testing methodology used for running the overlay tester. NCAT conducts the overlay test using a fixture and software within the IPC Global Asphalt Mixture Performance Tester (AMPT) (Figure 11). Testing for this project was performed using the original version (version 1) of this fixture. For this study, SGC specimens were compacted in NCAT's mobile lab to a target height of 125 mm. Upon achieving the desired height, two specimens per core were trimmed to measure 150 mm long, 75 mm wide, and 38 mm tall. The target air voids number for the cut specimens was 7.0 ± 1.0 percent. The specimens were glued to two aluminum plates using a two-part epoxy. Four replicates were tested per mix.

The samples were tested at 25°C in controlled displacement mode. Loading occurs when a movable steel plate attached to the asphalt specimen slides away from the other plate. Loading occurs at a rate of one cycle every ten seconds with a sawtooth waveform, and the maximum displacement per cycle is 0.63 mm (0.025 in.). The maximum load the specimen resists in controlled displacement mode is recorded for each cycle. The test continues until sample failure, which is defined as a 93% reduction in load magnitude from the first cycle.

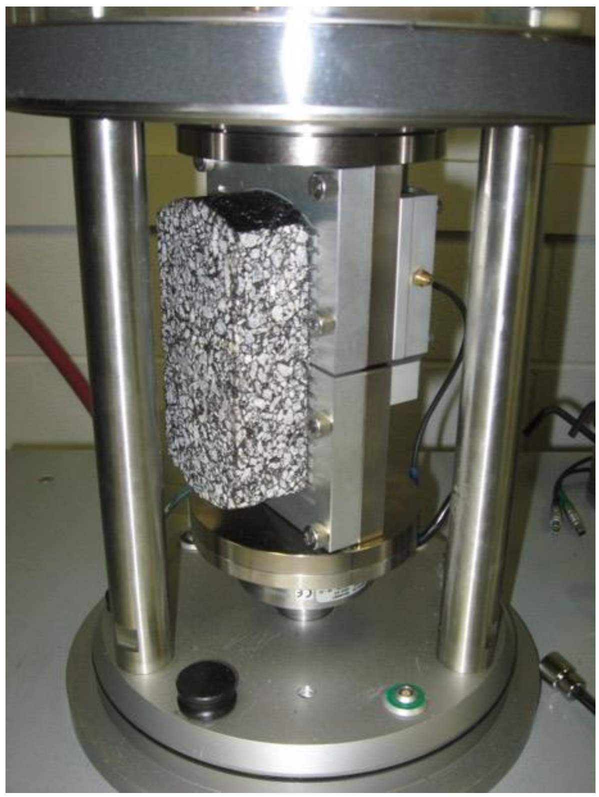

Figure 11. Overlay Test Fixture – Version 1 – IPC Global AMPT

The OT results are summarized in Table 17, and a graph of the average and standard deviation of the cycles to failure is shown in Figure 12. A GLM (α = 0.05) was conducted on the OT cycles to failure with the results summarized in Table 18. The results show the WMA MW RAS mix to have the highest OT cycles to failure, falling in a statistical grouping by itself. The MW RAS HMA and PC RAS HMA fell in the same statistical grouping and had the lowest OT cycles to failure. The GLM results show WMA to statistically improve OT cycles to failure, while the RAS type did not. However, it should be noted the p-value for the RAS type is borderline with the significance level (p-value = 0.064 versus α = 0.05).

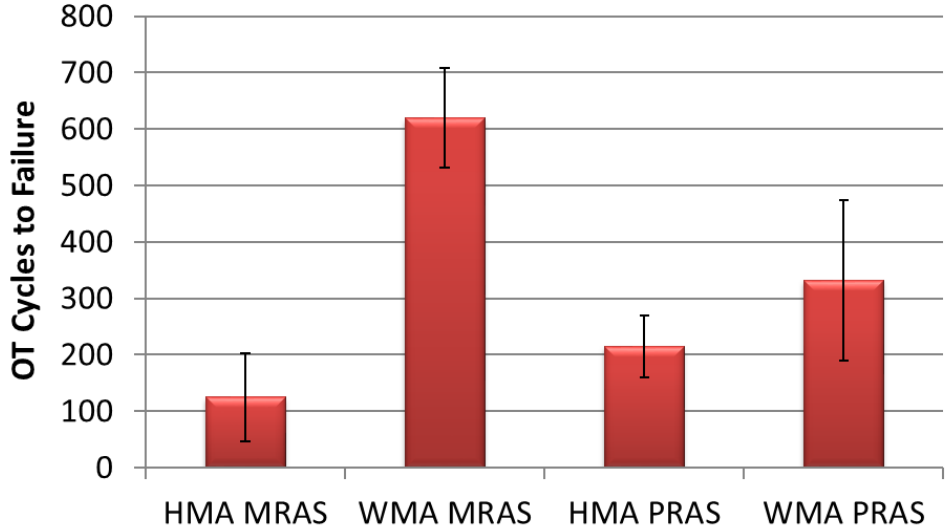

Figure 12. OT Cycles to Failure

Table 17. OT Results Summary

Mix ID	Replicates	Air Voids (%)	Peak Load (lb)	OT Cycles to Failure		
		Avg.	***Avg.***	***Avg.***	***Std. Dev.***	***CV(%)***
HMA MW RAS	4	6.8	708	125	78.6	63.0
WMA MW RAS	4	7.3	521	619	88.4	14.3
HMA PC RAS	4	6.9	697	215	54.9	25.6
WMA PC RAS	4	7.1	572	333	142.2	42.8

Table 18. GLM (α = 0.05) Results Summary – OT Failure Cycles
General Linear Model: Load Reduction - Cycles to Fail versus RAS, WMA

Factor	Type	Levels	Values
RAS	fixed	2	MRAS, PRAS
WMA	fixed	2	N, Y

Analysis of Variance for Load Reduction - Cycles to Fail, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
RAS	1	38612	38612	38612	4.15	0.064
WMA	1	374544	374544	374544	40.25	0.000
RAS*WMA	1	142129	142129	142129	15.27	0.002
Error	12	111668	111668	9306		
Total	15	666954				

S = 96.4661   R-Sq = 83.26%   R-Sq(adj) = 79.07%

Grouping Information Using Tukey Method and 95.0% Confidence

RAS	N	Mean	Grouping
MRAS	8	372.0	A
PRAS	8	273.8	A

WMA	N	Mean	Grouping
Y	8	475.9	A
N	8	169.9	B

RAS	WMA	N	Mean	Grouping
MRAS	Y	4	619.2	A
PRAS	Y	4	332.5	B
PRAS	N	4	215.0	B C
MRAS	N	4	124.8	C

Means that do not share a letter are significantly different.

6.4 Indirect Tension (IDT) Low Temperature Creep Compliance and Strength

The low temperature cracking potential of the mixes used in this study was evaluated using the AASHTO T 322-07 procedure, *Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device.* The testing was conducted using an indirect tensile testing (IDT) system with an MTS® load frame and an environmental chamber capable of maintaining the required temperatures. Creep compliances at +10°C, 0°C, and -10°C and a tensile strength at -10°C were measured in accordance with AASHTO T 322-07. These temperatures are specified as a function of the low temperature PG grade of the binder in AASHTO T 322-07. Figure 13 shows the MTS® load frame and the load guide device used for IDT testing.

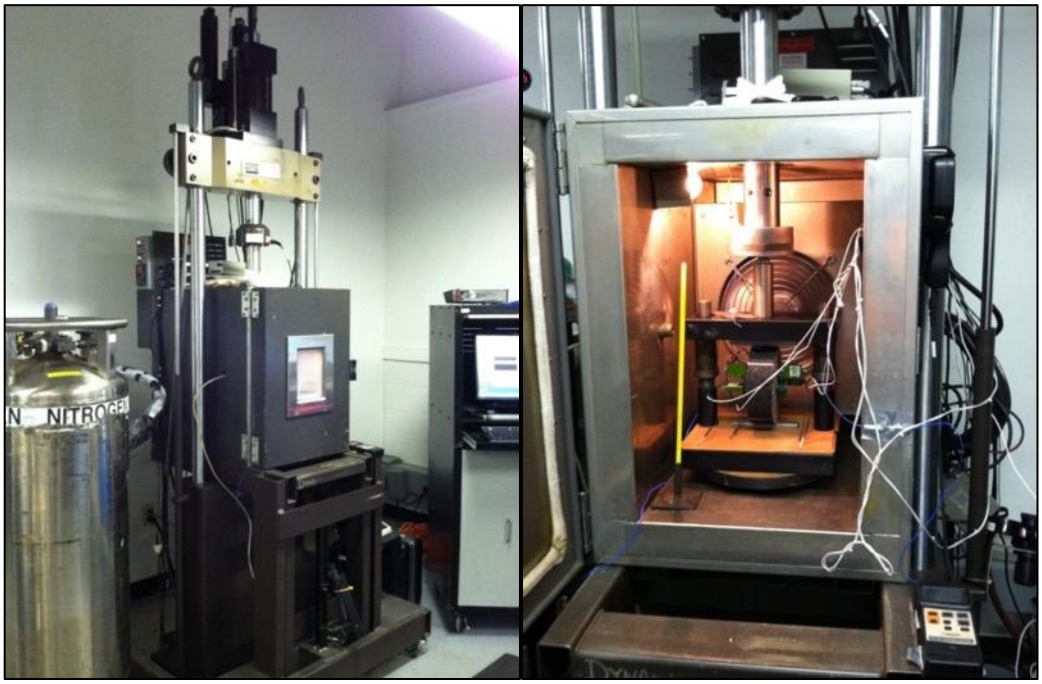

Figure 13. MTS® Device used for IDT Testing

Specimens for IDT testing were compacted at the project location (to 125 mm tall and 150 mm in diameter prior to being trimmed) in the NCAT mobile lab. Four cut specimens were prepared for each mixture. Specimens used for the creep and strength tests were 150 mm in diameter and trimmed to a thickness of 38 to 50 mm. Trimmed specimens were prepared to 7.0 ± 0.5% air voids.

The creep test applies a constant load to the asphalt specimen for 100 seconds while the horizontal and vertical strains are measured on each face of the specimen using on-specimen instrumentation (38 mm gage length). The first specimen was used to find a suitable creep load for that particular mix at each testing temperature. This load produced an average horizontal micro-strain between 33 and 500 on the specimen. The remaining three specimens were tested at this load for data analysis. This process was repeated at each of the three test temperatures. Upon completion of creep testing, the specimens were tested for indirect tensile strength at the middle creep temperature. The specimens were broken at the middle creep temperature using a constant loading rate of 12.5 mm of vertical movement per minute. The peak load was used to calculate the indirect tensile strength for each specimen.

The AASHTO T 322-07 data was used to conduct a critical temperature analysis. In this analysis, the temperature at which the estimated thermal stress in a pavement due to contraction exceeds the tested indirect tensile strength of a mixture is used to assess low-temperature cracking performance of an asphalt mixture. This temperature is referred to as the critical cracking temperature. A mixture exhibiting a lower critical cracking temperature than those of the other mixtures would have better resistance to thermal cracking.

The critical temperature analysis for this project was conducted using the EXCEL® worksheet 'LTSTRESS_JUN_2013' developed by Don Christensen (*17*). The user inputs the following data into the worksheet for the critical temperature analysis: specimen dimensions, testing temperatures, specimen volumetrics, creep compliance data at three temperatures, and peak loads from the strength tests. Default parameters were used for the remaining user options. The program fits a master-curve to the creep compliance data using the lowest temperature as the default reference temperature. These data are then used to model the development of thermal stresses in the mixture as a function of temperature. The modeled thermal stresses, along with the tested mixture indirect tensile strength, are then used to estimate the critical cracking temperature of the mixture. This analysis is described in-depth elsewhere by Christensen and Hiltunen (*17, 18*).

A summary of the modeled thermal stress versus temperature curves and critical cracking temperatures for each of the four mixes are shown in Figures 14 and 15, respectively. The results show very similar behavior for each of the four mixes with respect to low temperature cracking. The HMA MW RAS had the lowest (best) critical pavement temperature at -20°C, while the HMA PC RAS had the highest at -17°C. These results are supported by the ΔTc results presented in Table 7, where the post-consumer RAS binder was more susceptible to cracking than the manufacturer-waste RAS binder. The four tested mixtures had very similar stress development curves, while the difference between the maximum and minimum critical pavement temperature was only 3°C.

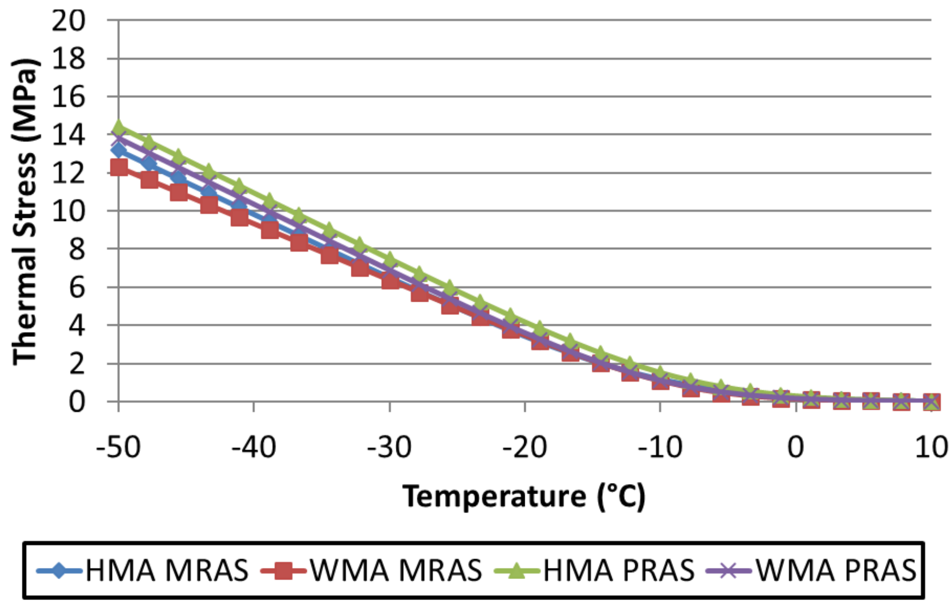

Figure 14. Thermal Stress vs. Temperature Curves – IDT Testing

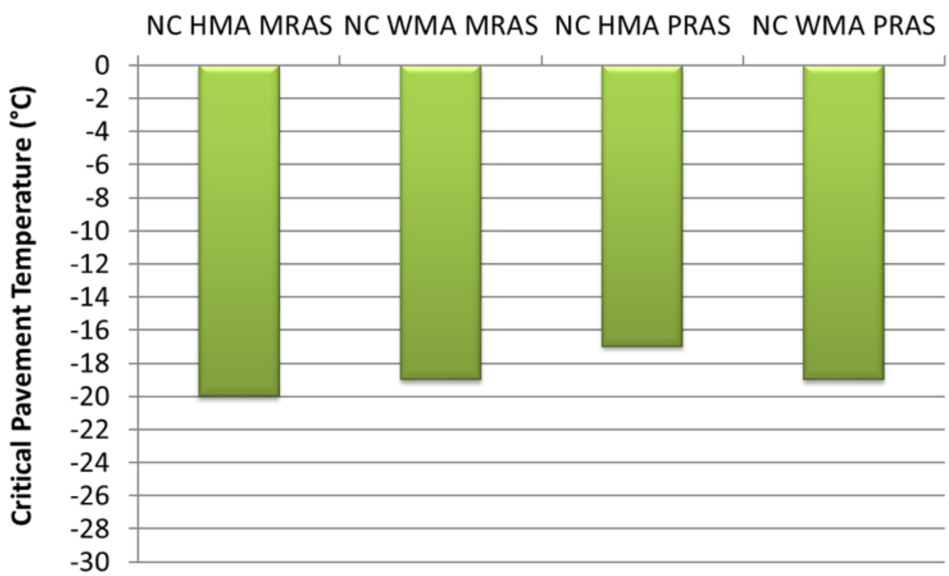

Figure 15. Summary of Critical Pavement Cracking Temperatures – IDT Testing

7 FIELD PERFORMANCE AFTER 14 MONTHS

A field performance evaluation was conducted on August 23, 2016 after approximately 14 months of traffic had been applied to the test sections. Data were collected on each section to document performance regarding rutting, cracking, and raveling. This was performed by selecting three 200-foot (61-m) data sections within each mix section. These sections had been marked at the time of construction based on the location of the three mix samples NCAT took during production. When a mix was sampled at the plant, the truck was marked when it arrived at the paving site.

Each data section was inspected at the time of the field evaluation to assess performance. In addition, five 6-inch (150-mm) diameter cores were taken from between the wheel paths for each mix to determine the in-place density after 14 months.

Rutting

The rut depths were measured at the beginning of each 200-foot section with a straight edge and a wedge. After 14 months, none of the sections exhibited any measurable rutting.

Cracking

The entirety of each 200-foot section was carefully inspected for visual signs of cracking and rated based on the *LTPP Distress Identification Manual*. All four mixes performed very well in terms of cracking. Out of all 12 data sections, only one section exhibited any cracking. The second data section for the HMA PC RAS exhibited four total feet of low-severity transverse cracking. However, at this location, there was cracking observed in the adjacent lane as well, which tends to suggest that an underlying issue caused the cracking at this location.

Raveling and Weathering

The surface textures of the test sections were measured using the sand patch test in accordance with ASTM E965. The sand patch test was conducted at the beginning of each 200-foot section in the outside wheel path. The calculated mean texture depths for both mixes are shown in Table 19. These values represent the average and standard deviation of the three tests conducted on each mix. A smaller mean texture depth indicates a smoother pavement or one with less surface texture. These results show that all four mixes had very similar mean texture depths at the time of the inspection. Figure 16 shows an example of the surface texture of both the MW RAS WMA (left) and the PC RAS WMA (right) at the time of the 14-month inspection. Figure 17 shows an example of the surface texture of both the MW RAS HMA (left) and the MW RAS WMA (right) at the time of the 14-month inspection.

Table 19. Mean Texture Depths

	MW RAS HMA	MW RAS WMA	PC RAS HMA	PC RAS WMA
Mean Texture Depth (mm)	0.369	0.347	0.378	0.416
Standard Deviation	0.031	0.021	0.031	0.036

Figure 16. MW RAS WMA (left) and PC RAS WMA (right) at 14-Month Inspection

Figure 17. MW RAS HMA (left) and PC RAS HMA (right) at 14-Month Inspection

14-Month Cores

At the time of the project inspection, five 6-inch (150-mm) cores were taken from each mix section. These cores were spread throughout the mix sections with one or two cores taken directly before each data section. The densities of these cores were measured using

AASHTO T 166. A summary of the core densities at the time of the inspections is shown in Figure 18.

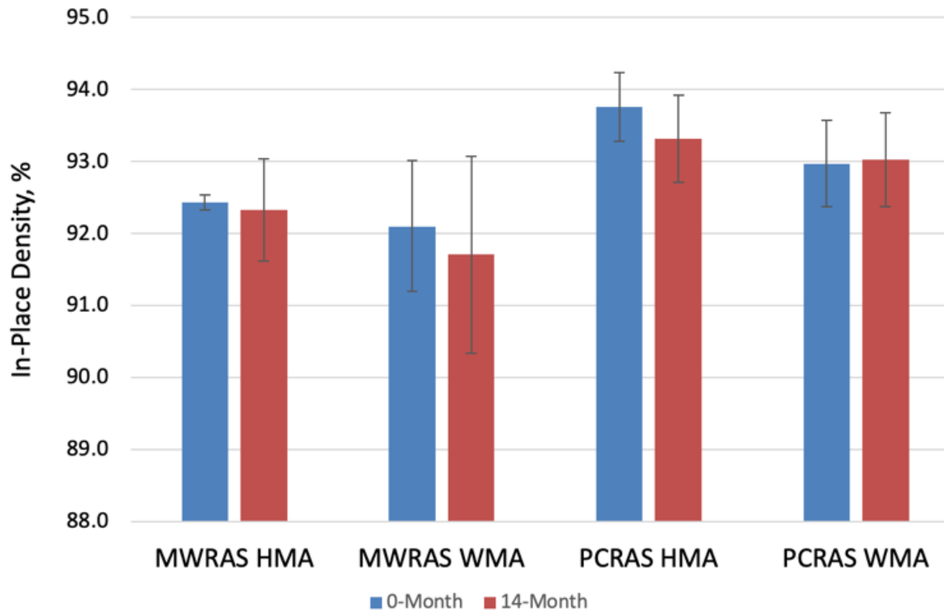

Figure 18. In-place Densities Based on Cores

Table 20 shows the results of the ANOVA to evaluate how the mix type (HMA, WMA, MW RAS, and PC RAS), the age of the pavement, and the interaction between these two factors affected the in-place density. As can be seen, only mix type had a significant effect (p-value = 0.012) on the in-place density for this project. Table 20 also shows the results of the Tukey's test of multiple comparisons. The MW RAS WMA had a statistically lower density than the two PC RAS sections. A similar trend was observed for the in-place densities based on cores at construction in Wilson, North Carolina (Figure 5).

Table 20. Density ANOVA Analysis

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix Type	3	11.52	3.84	4.52	0.012
Age	1	0.94	0.94	1.11	0.303
Mix Type × Age	3	0.81	0.27	0.32	0.813
Error	24	20.38	0.85		
Total	31	34.62			
Statistical Grouping					
Mix Type	N	Mean	Grouping		
PC RAS HMA	8	93.4	A		
PC RAS WMA	8	93.1	A		
MW RAS HMA	8	92.4	A B		
MW RAS WMA	8	91.8	B		

8 CONCLUSIONS

The type of RAS affects the overall stiffness of the binder: The high temperature continuous grade of the post-consumer RAS binder is higher in comparison with manufacturer-waste RAS binder. An explanation for this behavior relates to the post-consumer RAS binders being oxidized after an in-service period (i.e., binder from roofing shingles that have experienced years of field aging).

The use of warm mix technology allowed production of the MW RAS mixture at approximately 21°F lower than the HMA mixtures. The PC RAS WMA production temperature was approximately 28°F lower than the PC RAS HMA production temperature. No problems were encountered during production and construction of the WMA sections and no significant change in the rolling pattern was needed to adjust for the use of the WMA technology.

The Hamburg Wheel-Tracking results showed the WMA mixes to have statistically higher rut depths than the HMA mixes. However, none of the mixes came close to failing based on the Texas Hamburg criteria. RAS type (MW RAS versus PC RAS) did not impact the Hamburg results.

Two intermediate temperature tests, the Overlay Tester (OT) and the Illinois Flexibility Index Test (I-FIT), were used to assess mixture cracking susceptibility. The results for both tests showed comparable relative rankings. In each test, the MW RAS WMA was the mixture with the greatest cracking resistance, while the MW RAS HMA was the mixture with the lowest cracking resistance. The poor cracking resistance of the MW RAS HMA may be partially explained by the higher air voids relative to the other three mixes.

Indirect tension (IDT) creep compliance and strength testing was performed to assess the low temperature cracking resistance of these mixes. The results showed comparable low temperature performance for all four of the test mixes. Based on ΔTc results, post-consumer RAS binder showed higher susceptibility to cracking than the manufacturer-waste RAS binder. It can also be seen from the ΔTc results that the binder modification with WMA allows a lower cracking potential, regardless of the type of RAS binder used (i.e., post-consumer or manufacturer-waste RAS binder).

At the time of the 14-month project inspection, all four mixes exhibited similar field performance with no signs of negative effect due to the use of WMA technologies.

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APPENDIX

A.1. MW RAS HMA QC Data Summary from Contractor

QC-1 (SP)

04/08/2003 ncdot

4/27/2005 AHM

NORTH CAROLINA DEPARTMENT OF TRANSPORTATION
HOT MIX ASPALT QUALITY CONTROL CERTIFICATION

CONTRACTOR S.T.WOOTEN CORP

PLANT LOCATION SIMS

PLANT CERT. NO. AS-187

SAMPLING INFORMATION AND TONNAGES							DATE SAMPLED			06/15/15
PROJECT NO.	TYPE MIX	JMF NO.	QC SAMPLE NO.	TONS AT SAMPLE TIME	TIME FROM TICKET	INVOICE NO.	PROJECT TONNAGES PREVIOUS	TODAY	TOTAL	SAMPLE TAKEN BY
4CR.10981.25	RS 9.5B	12-1161-122	15-24	189.41	9:45	102067	0.00	1666.33	1,666.33	David
			15-25	578.15	12:18	102116			0.00	
			15-26	1560.21	17:17	102220			0.00	
									0.00	

I CERTIFY THAT THE ABOVE LISTED MIX TONNAGE WAS PRODUCED THIS DATE FROM THIS PLANT AND FURNISHED TO THE ABOVE PROJECTS. I FURTHER CERTIFY THAT ALL APPROPRIATE SAMPLES WERE TAKEN THIS DATE.

David Tyson 50997
PRINT QC TECHNICIANS NAMES AND HICAMS #

QC TECHNICIANS SIGNATURE

MIX TEST RESULTS										DATE TESTED			06/15/15		
QC SAMPLE NO.	Gmb at Ndes (PILLS)	Gmm (RICE)	VTM at Ndes	VMA at Ndes	VFA at Ndes	%Gmm at Nini	25 mm	19 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm	0.075 mm	% BINDER CONTROL	DUST / BINDER RATION
15-24	2.326	2.440	4.7	16.2	71	90.0			99	96	75	59	5.9	5.2	1.2
15-25	2.337	2.435	4.0	15.8	75	90.6			99	95	73	58	5.9	5.3	1.2
15-26	2.340	2.436	3.9	15.7	75	90.6			99	95	73	58	6.0	5.3	1.2
0-															

REMARKS 15-24/307 - 15-25/305 -15-26/302

David Tyson 50997
PRINT QC TECHNICIANS NAMES AND HICAMS #

I CERTIFY THAT ALL QUALITY CONRTOL TESTS WERE PERFORMED ON THIS MIX AND THE RESULTS LISTED ABOVE ARE CORRECT.

QC TECHNICIANS SIGNATURE

* BY PROVIDING THIS DATA UNDER MY SIGNAATURE AND/OR HICAMS NUMBER, I ATTEST TO THE ACCURACY AND VALIDITY OF THE DATA CONTAINED ON TIS FORM AND CERTIFY THAT NO DELIBERATE MISREPRESENTATION OF TEST RESULTS, IN ANY MANNER, HAS OCCURRED.

A.2. MW RAS WMA QC Data Summary from Contractor

QC-1 (SP)

04/08/2003 ncdot
4/27/2005 AHM

NORTH CAROLINA DEPARTMENT OF TRANSPORTATION
HOT MIX ASPALT QUALITY CONTROL CERTIFICATION

CONTRACTOR S.T.WOOTEN CORP

PLANT LOCATION SIMS

PLANT CERT. NO. ~~AS-187~~

SAMPLING INFORMATION AND TONNAGES

DATE SAMPLED: Tuesday, June 16, 2015

PROJECT NO.	TYPE MIX	JMF NO.	QC SAMPLE NO.	TONS AT SAMPLE TIME	TIME FROM TICKET	INVOICE NO.	PROJECT TONNAGES PREVIOUS	PROJECT TONNAGES TODAY	PROJECT TONNAGES TOTAL	~~SAMPLE TAKEN BY~~
4CR.10981.122	RS9.5B	12-1162-122	15-33	529.77	11:28	102314	0.00	1724.73	1,724.73	David
			15-34	1109.94	13:29	102365			0.00	
									0.00	
									0.00	

I CERTIFY THAT THE ABOVE LISTED MIX TONNAGE WAS PRODUCED THIS DATE FROM THIS PLANT AND FURNISHED TO THE ABOVE PROJECTS. I FURTHER CERTIFY THAT ALL APPROPRIATE SAMPLES WERE TAKEN THIS DATE.

David Tyson 50997
PRINT QC TECHNICIANS NAMES AND HICAMS #

QC TECHNICIANS SIGNATURE

MIX TEST RESULTS

DATE TESTED 06/16/15

QC SAMPLE NO.	Gmb at Ndes (PILLS)	Gmm (RICE)	VTM at Ndes	VMA at Ndes	VFA at Ndes	%Gmm at Nini	25 mm	19 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm	0.075 mm	% BINDER CONTROL	DUST / BINDER RATION
15-33	2.353	2.435	3.4	15.2	78	91.2			99	93	71	56	5.7	5.3	1.1
15-34	2.333	2.431	4.0	16.0	75	90.6			99	95	74	59	5.7	5.4	1.1
0-															
0-															

REMARKS 15-33/283 -15-34/281

I CERTIFY THAT ALL QUALITY CONRTOL TESTS WERE PERFORMED ON THIS ~~MIX AND THE~~ RESULTS LISTED ABOVE ARE CORRECT.

David Tyson 50997
PRINT QC TECHNICIANS NAMES AND HICAMS #

QC TECHNICIANS SIGNATURE

* BY PROVIDING THIS DATA UNDER MY SIGNAATURE AND/OR HICAMS NUMBER, I ATTEST TO THE ACCURACY AND VALIDITY OF THE DATA CONTAINED ON TIS FORM AND CERTIFY THAT NO DELIBERATE MISREPRESENTATION OF TEST RESULTS, IN ANY MANNER, HAS OCCURRED.

A.3. PC RAS HMA QC Data Summary from Contractor

QC-1 (SP)

04/08/2003 ncdot
4/27/2005 AHM

NORTH CAROLINA DEPARTMENT OF TRANSPORTATION
HOT MIX ASPALT QUALITY CONTROL CERTIFICATION

CONTRACTOR S.T.WOOTEN CORP

PLANT LOCATION SIMS

PLANT CERT. NO. AS-187

SAMPLING INFORMATION AND TONNAGES							DATE SAMPLED			06/17/15
							PROJECT TONNAGES			
PROJECT NO.	TYPE MIX	JMF NO.	QC SAMPLE NO.	TONS AT SAMPLE TIME	TIME FROM TICKET	INVOICE NO.	PREVIOUS	TODAY	TOTAL	SAMPLE TAKEN BY
4CR.10961.25	RS 9.5B	14-0527-121	15-01	74.02	7:57	102436	0.00	1847.33	1,847.33	David
			15-02	916.38	12:02	102526			0.00	
			15-03	1506.35	14:07	102576			0.00	
									0.00	

I CERTIFY THAT THE ABOVE LISTED MIX TONNAGE WAS PRODUCED THIS DATE FROM THIS PLANT AND FURNISHED TO THE ABOVE PROJECTS. I FURTHER CERTIFY THAT ALL APPROPRIATE SAMPLES WERE TAKEN THIS DATE.

David Tyson 50997
PRINT QC TECHNICIANS NAMES AND HICAMS #

QC TECHNICIANS SIGNATURE

MIX TEST RESULTS										DATE TESTED			06/17/15		
QC SAMPLE NO.	Gmb at Ndes (PILLS)	Gmm (RICE)	VTM at Ndes	VMA at Ndes	VFA at Ndes	%Gmm at Nini	25 mm	19 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm	0.075 mm	% BINDER CONTROL	DUST / BINDER RATION
15-01	2.347	2.439	3.8	15.8	76	90.8			99	95	74	58	6.1	5.4	1.2
15-02	2.348	2.433	3.5	15.8	78	90.9			99	96	75	58	5.9	5.5	1.1
15-03	2.351	2.438	3.6	15.6	77	90.9			100	96	74	58	6.1	5.4	1.2
0-															

REMARKS 15-1/308-15-2/304 -15-3/304

I CERTIFY THAT ALL QUALITY CONRTOL TESTS WERE PERFORMED ON THIS MIX AND THE RESULTS LISTED ABOVE ARE CORRECT.

David Tyson 50997
PRINT QC TECHNICIANS NAMES AND HICAMS #

QC TECHNICIANS SIGNATURE

* BY PROVIDING THIS DATA UNDER MY SIGNAATURE AND/OR HICAMS NUMBER, I ATTEST TO THE ACCURACY AND VALIDITY OF THE DATA CONTAINED ON TIS FORM AND CERTIFY THAT NO DELIBERATE MISREPRESENTATION OF TEST RESULTS, IN ANY MANNER, HAS OCCURRED.

A.4. PC RAS WMA QC Data Summary from Contractor

QC-1 (SP)

04/08/2003 ncdot
4/27/2005 AHM

NORTH CAROLINA DEPARTMENT OF TRANSPORTATION
HOT MIX ASPALT QUALITY CONTROL CERTIFICATION

CONTRACTOR S.T.WOOTEN CORP

PLANT LOCATION SIMS

PLANT CERT. NO. AS-187

SAMPLING INFORMATION AND TONNAGES							DATE SAMPLED			06/18/15
PROJECT NO.	TYPE MIX	JMF NO.	QC SAMPLE NO.	TONS AT SAMPLE TIME	TIME FROM TICKET	INVOICE NO.	PROJECT TONNAGES PREVIOUS	TODAY	TOTAL	SAMPLE TAKEN BY
4CR.10961.25	RS 9.5B	14-0528-121	15-01	306.10	10:40	102690	0.00	1580.02	1,580.02	David
			15-02	953.04	13:32	102764			0.00	
									0.00	
									0.00	

I CERTIFY THAT THE ABOVE LISTED MIX TONNAGE WAS PRODUCED THIS DATE FROM THIS PLANT AND FURNISHED TO THE ABOVE PROJECTS. I FURTHER CERTIFY THAT ALL APPROPRIATE SAMPLES WERE TAKEN THIS DATE.

David Tyson 50997
PRINT QC TECHNICIANS NAMES AND HICAMS #

QC TECHNICIANS SIGNATURE

MIX TEST RESULTS										DATE TESTED				06/18/15	
QC SAMPLE NO.	Gmb at Ndes (PILLS)	Gmm (RICE)	VTM at Ndes	VMA at Ndes	VFA at Ndes	%Gmm at Nini	25 mm	19 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm	0.075 mm	% BINDER CONTROL	DUST / BINDER RATION
15-01	2.347	2.437	3.7	15.7	76	90.8			99	95	74	58	6.3	5.4	1.2
15-02	2.337	2.427	3.7	15.7	76	90.9			99	95	73	58	6.0	5.4	1.1
0-															
0-															

REMARKS Test 15-1/279(pulled early per Gary Q.A.)15-2/281

I CERTIFY THAT ALL QUALITY CONRTOL TESTS WERE PERFORMED ON THIS MIX AND THE RESULTS LISTED ABOVE ARE CORRECT.

David Tyson 50997
PRINT QC TECHNICIANS NAMES AND HICAMS #

QC TECHNICIANS SIGNATURE

* BY PROVIDING THIS DATA UNDER MY SIGNAATURE AND/OR HICAMS NUMBER, I ATTEST TO THE ACCURACY AND VALIDITY OF THE DATA CONTAINED ON TIS FORM AND CERTIFY THAT NO DELIBERATE MISREPRESENTATION OF TEST RESULTS, IN ANY MANNER, HAS OCCURRED.

A5. Hamburg Results – Individual Specimens – NC RAS-WMA Project

Mix ID	Sample ID	Sample 1 Air Voids (%)	Sample 2 Air Voids (%)	Passes to 12.5 mm Rut Depth	Minimum Rut Depth (mm) @ 20,000 passes	SIP (passes)
MW RAS HMA	33,32	6.9	6.7	20,000+	-1.47	20,000+
MW RAS HMA	36,37	7.1	6.8	20,000+	-1.90	20,000+
MW RAS HMA	34,35	7.0	7.0	20,000+	-1.67	20,000+
MW RAS WMA	130,131	7.1	7.2	20,000+	-2.98	20,000+
MW RAS WMA	132,133	7.1	7.2	20,000+	-2.66	20,000+
MW RAS WMA	134,136	7.5	7.1	20,000+	-3.06	20,000+
PC RAS HMA	230,231	6.8	6.8	20,000+	-1.67	20,000+
PC RAS HMA	232,235	6.9	6.8	20,000+	-1.65	20,000+
PC RAS HMA	236,237	6.8	6.9	20,000+	-1.55	20,000+
PC RAS WMA	332,333	7.2	7.1	20,000+	-2.94	20,000+
PC RAS WMA	335,336	7.2	7.1	20,000+	-2.14	20,000+
PC RAS WMA	337,338	7.0	7.0	20,000+	-2.53	20,000+

A6. I-FIT Results – Individual Specimens – NC RAS-WMA Project

Mix ID	Specimen ID	Specimen Air Voids (%)	Peak Load (kN)	Disp. at Peak Load (mm)	Fracture Energy (J/m2)	Flexibility Index (FI)
NC HMA MW RAS	1101A	6.9	4.938	0.700	1,482	1.26
NC HMA MW RAS	1103A	6.6	4.412	0.703	1,590	2.30
NC HMA MW RAS	1103B	6.8	4.052	0.628	1,388	1.96
NC HMA MW RAS	1104B	7.0	4.830	0.691	1,406	1.27
NC HMA MW RAS	1104C	7.0	4.851	0.724	1,520	1.30
NC HMA MW RAS	1104D	6.7	4.542	0.627	1,543	2.50
NC WMA MW RAS	1201A	7.2	3.309	1.034	2,217	7.65
NC WMA MW RAS	1201B	7.5	3.126	1.094	2,120	8.12
NC WMA MW RAS	1201D	6.9	3.178	0.941	1,861	7.05
NC WMA MW RAS	1203C	6.9	3.429	0.961	1,895	6.47
NC WMA MW RAS	1203D	6.5	3.578	1.029	2,035	7.14
NC WMA MW RAS	1204D	6.9	3.519	1.031	2,125	7.40
NC HMA PC RAS	1301C	7.0	4.130	0.761	1,676	3.37
NC HMA PC RAS	1303A	6.8	4.820	0.613	1,718	2.79
NC HMA PC RAS	1303B	7.2	4.234	0.940	1,843	3.69
NC HMA PC RAS	1303D	6.9	4.452	0.694	1,751	3.04
NC HMA PC RAS	1304A	7.0	4.050	0.671	1,812	4.95
NC HMA PC RAS	1304B	7.2	4.175	0.714	1,751	4.29
NC WMA PC RAS	1401D	7.0	3.649	0.896	1,837	4.86
NC WMA PC RAS	1403A	7.0	3.642	0.853	1,637	4.10
NC WMA PC RAS	1430B	7.2	3.032	0.857	1,559	5.27
NC WMA PC RAS	1404A	6.6	3.879	0.786	1,888	4.90
NC WMA PC RAS	1404B	7.3	3.437	0.788	1,615	4.94
NC WMA PC RAS	1404C	7.0	3.744	0.798	1,542	3.96

A7. OT Results – Individual Specimens – NC RAS-WMA Project

Mix ID	Sample ID	Sample Air Voids (%)	Maximum On-Specimen Displacement (in)	Test Temperature (°C)	Peak Load (lb)	Load Reduction - Cycles to Failure
MW RAS HMA	6.8	0.025	25	708	70	6.8
MW RAS HMA	6.8	0.025	25	685	62	6.8
MW RAS HMA	6.9	0.025	25	705	135	6.9
MW RAS HMA	6.6	0.025	25	733	232	6.6
MW RAS WMA	7.4	0.025	25	532	641	7.4
MW RAS WMA	7.2	0.025	25	524	543	7.2
MW RAS WMA	7.2	0.025	25	515	735	7.2
MW RAS WMA	7.3	0.025	25	512	558	7.3
PC RAS HMA	6.5	0.025	25	713	175	6.5
PC RAS HMA	6.9	0.025	25	720	293	6.9
PC RAS HMA	7.1	0.025	25	674	178	7.1
PC RAS HMA	6.9	0.025	25	679	214	6.9
PC RAS WMA	6.9	0.025	25	591	491	6.9
PC RAS WMA	7.3	0.025	25	574	247	7.3
PC RAS WMA	6.9	0.025	25	572	409	6.9
PC RAS WMA	7.3	0.025	25	551	183	7.3