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16. Abstract

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This study evaluated different CR-modified mixture designs to address design and performance concerns. Additionally, the study assessed the volumetric and mechanical properties of DG, SMA, and OGFC mixtures prepared with unmodified and Styrene-Butadiene-Styrene-modified asphalt binders as well as crumb rubber from five different sources. Superpave volumetric parameters were evaluated to ascertain the impact of CR modification on the design of CR-modified mixtures. Rutting and intermediate temperature cracking resistance were determined by conducting the Hamburg Loaded Wheel Tracking and Semi-Circular Bend Tests, respectively. Further, solvent extraction and ignition test methods were used to determine the asphalt binder content of the modified mixtures. The results showed that CR modification resulted in increased rutting resistance and decreased cracking resistance. The volumetric parameters were also found to be affected by CR modification. Based on the analysis of the results, it is recommended that additional asphalt content, reduced CR dosage, and polymer additives be used to enhance the cracking resistance of CR-modified asphalt mixtures. Contractors are advised to redesign mixtures if they anticipate using CR-modified asphalt binder.

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Evaluation of Crumb Rubber Modification of Louisiana Mixtures

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This study evaluated different CR-modified mixture designs to address design and performance concerns. Additionally, the study assessed the volumetric and mechanical properties of DG, SMA, and OGFC mixtures prepared with unmodified and Styrene-Butadiene-Styrene-modified asphalt binders as well as crumb rubber from five different sources. Superpave volumetric parameters were evaluated to ascertain the impact of CR modification on the design of CR-modified mixtures. Rutting and intermediate temperature cracking resistance were determined by conducting the Hamburg Loaded Wheel Tracking and Semi-Circular Bend Tests, respectively. Further, solvent extraction and ignition test methods were used to determine the asphalt binder content of the modified mixtures. The results showed that CR modification resulted in increased rutting resistance and decreased cracking resistance. The volumetric parameters were also found to be affected by CR modification. Based on the analysis of the results, it is recommended that additional asphalt content, reduced CR dosage, and polymer additives be used to enhance the cracking resistance of CR-modified asphalt mixtures. Contractors are advised to redesign mixtures if they anticipate using CR-modified asphalt binder.

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The authors acknowledge the financial support for this study by the Federal Highway Administration (FHWA), the Louisiana Department of Transportation and Development (DOTD), and the Louisiana Transportation Research Center (LTRC). The efforts of Jeremy Icenogle and Kristi Goetting at the LTRC asphalt laboratory are highly appreciated. Additional thanks to Lehigh Technologies, Inc., and Asphalt Plus, LLC, who offered rubber supplies. Special thanks to the construction contractors, Diamond B Construction Co., LLC, and Coastal Bridge Company, LLC, who provided us with CRM-modified asphalt blends. Lastly, sincere gratitude is extended to Marathon Petroleum Corporation for providing asphalt binders for this project.

IMPLEMENTATION STATEMENT

This study has provided techniques for enhancing the rutting and cracking performance of DG, SMA, and OGFC mixtures containing CR-modifiers. Recommendations have been provided for the redesign of CR-modified OGFC mixtures with a higher asphalt binder content to enhance rutting and cracking resistance. Additionally, polymer additives, lower CR dosage, and increased asphalt binder content have been recommended for enhancing the cracking resistance of CR-modified DG, SMA, and OGFC mixtures.

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BACKGROUND

With scrap tire stockpiles continually growing, the federal government has encouraged state agencies and private businesses to find environmentally friendly ways to dispose of tire waste. One way to solve this problem is by grinding or breaking tire rubber into small, crumb-like particles to be used in HMA pavements [1]. This crumb rubber material, also known as crumb rubber modifier (CRM), can be blended with HMA mixtures either by the wet or dry process. In the wet process, also known as the MacDonald process, the crumb rubber (CR) particles are heated and blended with the asphalt binder. In the dry process, the CRM is added to the aggregate to substitute for a small portion of the fine aggregates [2].

Highway engineers worldwide have investigated the use of scrap tire rubber in asphalt pavements since the 1950s. It was not until the 1960s that Charles H. MacDonald, who worked for the City of Phoenix, experimented with CR by adding it to hot liquid asphalt. He found that after thoroughly mixing CR with asphalt and allowing it to react for 45 to 60 minutes, the rubber particles absorbed the asphalt binder and swelled in size at higher temperatures, allowing for greater concentrations of liquid asphalt content in CR-modified mixtures. CR particles possess beneficial engineering characteristics that enhance their ability to stiffen asphalt binders, allowing for better performance at relatively higher temperatures. McDonald named the CR-asphalt binder blend asphalt rubber, which was first used to create “band-aids” for pothole repair and later used as a binder for chip seals [3].

To develop a comprehensive study of the performance of CRM mixtures, state agencies have carried out their own investigations and covered a wide range of applications and characteristics. In 1988, the Florida Department of Transportation (FDOT) initiated a study to assess reclaimed tire rubber applications in asphalt pavement construction. Researchers in the FDOT study recommended that tire rubber be used as an asphalt binder additive to improve the performance of friction course mixtures. Further, in the field operations, the researchers found that CRM mixtures with 5 percent (by weight of asphalt cement) of 80-mesh ground tire rubber showed similar performance as conventional friction course mixtures. The researchers in the FDOT study concluded that the rubber increased the elasticity of the CR-modified asphalt binders and mixtures, increasing their resilience and ability to recover from deformations. As part of the FDOT study, open-graded mixtures were designed with 12 percent (by weight of asphalt binder) 40-mesh ground tire rubber. Increased binder content in the open-graded mixtures containing CR-modifiers resulted in increased film thickness on the aggregate particles, which improved durability. Based on these observations, FDOT developed specifications for using ground tire rubber in friction course mixtures [4].

Following the successful use of asphalt rubber in Arizona, other state transportation agencies initiated comprehensive investigations into CRM asphalt binders, developing their own research projects pertaining to this material. Over the years, numerous research projects have been conducted to make CRM asphalt pavement more durable, cost-effective, and resistant to cracking and rutting.

In March 2007, LTRC published a research report on the long-term pavement performance of different CRM mixtures compared to control sections built with conventional asphalt mixtures. Laboratory tests, including Marshall stability and flow, indirect tensile strength (ITS) and strain, and indirect tensile resilient modulus (M_r) were conducted on field-compacted Marshall specimens from eight CRM asphalt pavement sections. Furthermore, field in-place density as well as performance data such as rut depth, cracking resistance, and international roughness index (IRI) were collected from the CRM pavement sections and compared with that of the control section. Additionally, the DYNAFLECT system was used to determine the structural number of the CRM pavement sections as compared to the control section.

The LTRC study concluded that conventional mixtures showed greater laboratory strength characteristics than the CRM mixture, while pavement sections paved with CRM exhibit improved field performance indices (rut depth, random cracks, and IRI numbers) compared to conventional sections [5]. The California Department of Transportation (Caltrans) started using scrap tires in chip seals in the 1970s and then later moved forward to use them in HMA as rubberized hot mix asphalt (RHMA) in the 1980s. Caltrans used rubberized HMA for 31% of its total HMA (approximately 1.2 million tons) production by the end of 2010. Caltrans conducted field trials to evaluate the wet (field blend) and dry processes of CR applications, which included the construction of two full-scale field experiments, five warranty projects, and an accelerated pavement section. The Caltrans experience showed that if CRM mixtures are designed and constructed properly, they can be durable and extend the service life of the pavement [6]. A significant consideration for CRM application in asphalt mixtures was determined to be the design parameters for the mixtures by several state agencies. Therefore, this study evaluated the change in design and performance properties of previously designed conventional mixtures compared to a CRM mixture with the same design parameters. The study focused on the effects of CR modification on various wearing course (WC) mixtures (OGFC, SMA, and dense-graded mixtures) in Louisiana and made necessary recommendations to address these effects.

INTRODUCTION

The Louisiana Department of Transportation and Development (DOTD) has authorized the use of CR-modified mixtures in flexible pavement construction since 2008. It was found that, initially, the performance of the roadways was satisfactory. The impact of the CR modification on the rutting resistance of CR-modified mixtures provided a performance and economic advantage to the public. In Louisiana, it is typical to use crumb rubber at a dosage rate of 10–12% by weight of binder. Typically, CR modification reduces the asphalt binder content by half a percent, so if the mixture is designed with a CRM binder, it will require a higher asphalt content than if it were designed with a conventional binder. In addition, the CR stiffens the asphalt binder, resulting in an increase in high-temperature performance grade. The reduction in asphalt binder content and increased performance grade result in mixtures with improved rutting resistance; however, the reduction in binder content may cause adverse effects on cracking and moisture susceptibility. Recently, there have been growing concerns over the durability and cracking resistance of mixtures prepared with CRM binders.

Louisiana DOTD has incorporated a balanced mix design (BMD) approach into the specifications for asphalt mixture design. The BMD approach requires asphalt mixtures to pass specified laboratory rutting and cracking criteria. Rutting is evaluated using the Hamburg Loaded Wheel Tracking Tester (HWTT). In addition to rutting resistance, using the HWTT allows for moisture resistance evaluation. Cracking resistance is evaluated by conducting the Semi-Circular Bend (SCB) Test. The evaluation of mixtures containing CRM binder has raised some concerns regarding the implementation of the BMD approach in Louisiana. Dense-graded mixtures have encountered challenges in meeting the BMD criteria for cracking. In addition, gap-graded, stone mastic asphalt (SMA), and open-graded friction course (OGFC) mixtures have exhibited a degree of sensitivity to rutting and moisture resistance as measured by the HWTT.

A source of concern has arisen from the comparison between elastomeric modified binder and CRM binder. The comparison showed that the mixtures made with modified elastomeric binders met the HWT and SCB criteria for the Louisiana BMD approach. However, the use of CR-modified mixtures raises certain concerns and uncertainties regarding cracking and rutting performance. A comprehensive experimental evaluation of the effects of CR modification on various mixtures is required to address these concerns. In order to determine the effect of CR modification on mixture performance, two studies were performed at LTRC. The current study considered the balanced design needed to address the performance concerns regarding the use of crumb rubbers in asphalt mixtures, and a parallel chemical support study determined the change in the binder chemistry after CR modification. The chemical support study included Fourier-transform infrared spectroscopy (FTIR), gel permeation chromatography (GPC), and differential thermal analysis (DTA) at the DOTD Materials lab to evaluate the effects of CR modification on the chemical properties of asphalt binders. This study aimed to assist DOTD in the evaluation of potential methods for quality control/quality assurance (QC/QA) of binders modified with crumb rubber.

OBJECTIVE

The objective of this research was to evaluate the effect of CR modification on the performance of asphalt mixtures used in Louisiana. As part of the evaluation, the effects of CR modification on design volumetric and compositional properties as well as laboratory performance in terms of resistance to rutting and cracking at intermediate temperatures were assessed. The impacts of CR modification were assessed on dense-graded and gap-graded mixtures. This research also evaluated potential methods for quality control/quality assurance (QC/QA) of asphalt mixtures modified with crumb rubber through ignition and solvent extraction methods.

SCOPE

Two types of crumb, cryogenic and ambient ground crumb rubber from five different suppliers, were used in the study. These crumb rubber particles were blended into three different types of asphalt mixtures typically used in Louisiana: dense-graded (DG), stone matrix asphalt (SMA), and open-graded friction course (OGFC) mixtures. The wet and dry processes of blending CR into asphalt mixtures were considered in the study following the suppliers' recommendation. For the dense-graded mixtures, seven CRM mixtures prepared with two types of CR particles (ambient or cryogenic) using different blending techniques (wet or dry process) and dosage rates were compared with an unmodified PG 67-22 and a modified PG 76-22 conventional HMA mixtures. For the SMA and OGFC mixtures, six CRM mixtures were prepared and compared with a polymer-modified PG-76-22 conventional HMA mixture.

The effects of CR modification on rutting and cracking performance were determined using HWTT and the SCB test, respectively. Further, solvent extraction and ignition tests were performed together with volumetric characterization to ascertain the effects of CR modification on asphalt binder content and other mix design parameters.

METHODOLOGY

To achieve the objectives of the study, the following tasks were performed:

Task 1 – Conduct a literature review;

Task 2 – Develop an experimental program;

Task 3 – Select materials and perform mixture design;

Task 4 – Perform laboratory testing;

Task 5 – Ascertain impact of aging on CRM binders (support study by LSU Chemistry Department);

Task 6 – Perform Data analyses;

Task 7 – Evaluate feasibility of quality control measures; and

Task 8 – Prepare a draft project report.

Crumb Rubber Modified Binder and Mixtures

Two CR modifier types, cryogenic and ambient ground CR, were obtained from five sources in Louisiana, comprising contractors and asphalt producers. Each CRM type is a frequently used modifier in Louisiana, and the suppliers provided LTRC with the mixing and blending procedures. Five CRM mixture types were evaluated in this research and are described below.

76CRM1

This CRM mixture category was prepared in multiple sequential steps according to instructions provided by the producer. A high-shear mixer was used for blending at temperatures ranging from 177 to 191 °C (350 to 375 °F) with a rotational speed of 3600 rpm. Initially, an SBS agent was blended with a base binder for 10 minutes. Then, the 5% (by the weight of the total binder) pellet crumb rubber was introduced to the blend and mixed for approximately 45 to 50 minutes until the blend was homogeneous. Finally, a sulfur compound was added, and the mix was blended for an additional 10 minutes. The wet blend was then mixed with aggregates to produce the 76CRM1 mixture.

76CRM2

This CRM mixture was produced using a dry process. In this process, the aggregates and cryogenic crumb rubber particles were initially combined, with the temperature of the aggregates carefully monitored to ensure it was equal to or greater than 170°C. Subsequently, liquid asphalt binder was added to the aggregate-CR blend to produce the 76CRM2 mixture.

76CRM3 and 82CRM4

For these two CRM mixture types, the CR-asphalt binder blends were prepared at the suppliers' facilities and then collected by LTRC for evaluation. The blends were made with 10% crumb rubber (by weight of total asphalt binder). Subsequently, the aforementioned blends were incorporated into the aggregates to produce the 76CRM3 and 82CRM4 mixtures, respectively.

82CRM5

The CRM binder used in preparing this mixture was produced by blending CRM particles and polymer additives at different dosage rates with the base asphalt binder. Initially, 10% (by the weight of the total binder) CR particles were gradually introduced into the base binder at temperatures ranging from 191 to 196 °C (375 to 385 °F) in five minutes and at a rotational speed of 3600 rpm. Simultaneously, the speed of the shear mixer was adjusted according to the viscosity of the blend per the supplier's recommendation. The mixing process continued for 30 minutes after the addition of the CR particles. Further, the blend was kept in an oven at 163°C. Then, a polymer additive was added to the CR-asphalt binder blend at a temperature of 190 °C, and the mix was blended for 20 minutes. Finally, the CR-asphalt binder-polymer additive blend was mixed with the selected aggregates to produce the 82CRM5 mixture.

Mixture Design

To address the asphalt paving needs of Louisiana's road infrastructure, a comprehensive investigation was undertaken to examine three distinct types of asphalt mixtures: dense-graded (DG), stone mastic asphalt (SMA), and open-grade friction course (OGFC). The aggregate distributions for the three mixture types were selected in accordance with the Louisiana Standard Specification for Roads and Bridges, 2016 edition; see Table 1. Figure 1 shows the gradation curves for the three mixtures considered in the study.

Table 1
Aggregate gradation

Sieve Size		Percent Passing for each Mixture		
US Sieve	Metric (mm)	Dense-Graded Mix	SMA	OGFC
2 in	50	100	100	100
1.5 in	37.5	100	100	100
1 in	25	100	100	100
3/4 in	19	100	100	100
1/2 in	12.5	96	96	93
3/8 in	9.5	85	79	71
No. 4	4.75	67	34	20
No. 8	2.36	49	22	10
No. 16	1.18	35	19	6
No. 30	0.6	26	18	4
No. 50	0.3	16	14	3
No. 100	0.15	9	11	2
No. 200	0.075	7	8	2

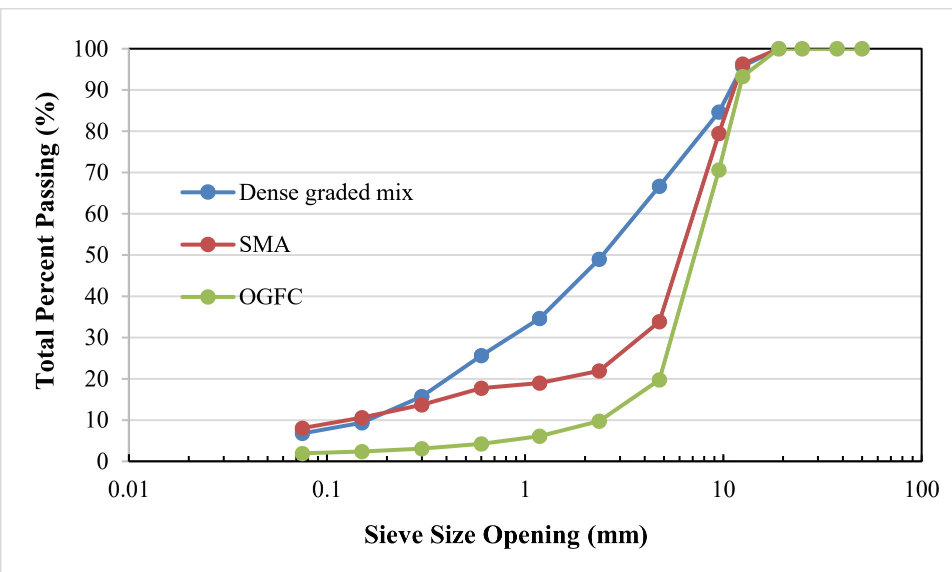

Figure 1
Mixture gradation curves

Mixture Description

A total of nine mixture types were considered in this study, seven of which were CRM mixtures; see Table 2. The remaining two were conventional HMA mixtures, 67Con and 76Con, which were prepared with unmodified PG 67-22 and SBS-modified PG 76-22 asphalt binders, respectively; see Table 2. These two aforementioned mixtures were considered control mixtures. The base binder for the CRM mixtures was unmodified PG 67-22 asphalt binder. The 76CRM1 and 76CRM1+AC mixtures were prepared by blending unmodified PG 67-22 asphalt binder with ambient ground CR particles using the wet process. The 76CRM2 mixture was prepared by blending the base binder with cryogenic CR particles using the dry process. 76CRM3 was a CRM binder sampled from a mixture facility. The aforementioned CRM binder was produced using ambient rubber through the wet process. Similarly, 82CRM4 and 82CRM4+AC were produced with ambient rubber in the wet process at an asphalt mixture facility. 82CRM5 was produced with cryogenic rubber utilizing the wet process.

The CR particles and CR-asphalt binder blends listed in Table 2 were incorporated into dense-graded (DG), stone matrix asphalt (SMA), and open-graded friction course (OGFC) aggregate structures shown in Figure 1 to produce CRM mixtures. For the DG mixtures, 67Con and 76Con control HMA mixtures were prepared and compared with seven CRM mixtures: 76CRM1, 76CRM2, 76CRM3, 82CRM4, 82CRM5, 76CRM1+AC, and 782CRM4+AC. For the SMA and OGFC mixtures, a 76con control HMA mixture was prepared and compared with six CRM mixtures: 76CRM1, 76CRM2, 76CRM3, 82CRM4, 76CRM1+AC, and 782CRM4+AC.

Table 2
Mixture type

Mixture Identification	Original Binder Grade	Final Binder Grade	Crumb Rubber Type	Mixing process	Adjustment
67Con	PG 67-22	PG 67-22	NA	Wet Blend	
76Con	PG 76-22	PG 76-22	NA	Wet Blend	
76CRM1	PG 67-22	PG 76-22	Ambient	Wet Blend	
76CRM1+AC	PG 67-22	PG 76-22	Ambient	Wet Blend	w/ additional AC
76CRM2	PG 67-22	PG 76-22	Cryogenic	Dry Blend	
76CRM3	PG 67-22	PG 76-22	Ambient	Wet Blend	
82CRM4	PG 67-22	PG 82-22	Ambient	Wet Blend	
82CRM4+AC	PG 67-22	PG 82-22	Ambient	Wet Blend	w/ additional AC
82CRM5	PG 67-22	PG 82-22	Cryogenic	Wet Blend	

Laboratory Mixture Testing

In this study, two main approaches were pursued in the testing of the control and CRM mixtures. In the first approach, ignition and solvent extraction tests were conducted to ascertain the effects of CR modification on the binder content of CRM mixtures. The second approach consisted of the conduct of a volumetric test to ascertain the effects of CRM modification on mixture design parameters, as well as an HWTT and SCB test to characterize the effects of CR modification on rutting and cracking resistance, respectively.

Ignition test

The ignition test was conducted in accordance with AASHTO T 308, "Standard Method of Test for Determining the Asphalt Binder Content of Asphalt Mixtures by the Ignition Method." A representative sample of approximately 1500 to 2000 grams was obtained by employing the splitting and quartering process. Subsequently, the specimen was placed in the baskets in the ignition oven, and the temperature was set at 538°C. The combustion process was initiated, and the built-in computer program in the furnace recorded the change in mass of the specimen every minute. The combustion process ended when the specimen mass loss did not exceed 0.01 percent of the total specimen mass for three consecutive minutes. The asphalt binder content was computed as the difference between the initial mass of the specimen and the mass of the residual aggregate. The difference was then adjusted for an asphalt binder correction factor and the moisture content.

Solvent Extraction

The solvent extraction method was conducted per AASHTO T 319, "Standard Method of Test for Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures." Approximately 1500 grams of the asphalt mixture sample were washed in a trichloroethylene (TCE) solution and then filtered using a filtration apparatus. The filtrate was then centrifuged to remove aggregate particles and subjected to vacuum distillation using a rotary evaporator (Rotavap), resulting in the retention of the extracted asphalt binder within the flask. The asphalt binder content of the mixture was determined as the difference between the original sample and the sum of recovered aggregates, the change in mass of the Rotavap flask, and the change in mass of the filter used for filtration.

Volumetric Analysis

The asphalt mixtures considered in this study were subjected to volumetric analysis according to AASHTO M323, "Standard Specification for Superpave Volumetric Mix Design." The asphalt mixture design parameters measured in this research included percent air void content, voids in mineral aggregates (VMA), and voids filled with asphalt (VFA). The aforementioned mixture design parameters were measured for control and CRM mixtures to ascertain the effects of CR modification on mixture volumetric properties.

Semi-Circular Bend (SCB) Test

The SCB test was performed in accordance with ASTM D8044, "Standard Test Method for Evaluation of Asphalt Mixture Cracking Resistance using the Semi-Circular Bend Test (SCB) at Intermediate Temperatures." This test characterizes the critical strain energy release rate, SCB J_c, a measure of the fracture resistance of asphalt mixtures at intermediate temperatures. Semi-circular test specimens with a minimum of two (25.4 and 38 mm) notch depths were tested at a temperature of 25°C. Four replicate specimens were tested for each notch depth. The semi-circular specimens were subjected to monotonic loading at a constant cross-head deformation rate of 0.5 mm/min in a three-point bending load setup; see Figure 2. The load and deformation data were continually recorded and used to compute the SCB J_c parameter. The fracture resistance of a mixture increases with increasing SCB J_c values at intermediate temperatures and, conversely, decreases with lower SCB J_c values.

Figure 2
Semi-circular bending device

Hamburg Loaded-Wheel Tester (HWTT)

The Hamburg Loaded-Wheel Test (HWT) was conducted per AASHTO T 324, "Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA)." This test was performed by rolling a 703 N (158lb) wheel on asphalt mixture samples submerged in water at a temperature of 50 °C; see Figure 3. The wheel was rolled at a rate of 52 passes per minute for 20,000 passes. Four specimens were tested for each mixture, and the average rut depth at 20,000 passes was recorded and used in the analysis.

Figure 3
Hamburg loaded-wheel tester

DISCUSSION OF RESULTS

To achieve the objectives of this project, a suite of laboratory tests were conducted on the CRM and control mixtures considered in the study. These tests were performed to evaluate the impacts of CR modification on mixture design volumetric properties, rutting resistance as measured by the HWTT, and cracking resistance as measured by the SCB test. The results of laboratory tests are presented in subsequent sections of the report.

Asphalt Cement Content by Solvent Extraction and Ignition Methods

The asphalt binder content of the mixtures was evaluated through solvent extraction and ignition test methods. Figures 4 through 6 present the results of the ignition and extraction tests. Asphalt mixture extraction and burn residues were used to determine the asphalt binder content and ascertain whether the CR particles were incorporated as a part of the binder in the mixture.

As shown in Figures 4 through 6, the ignition test yielded higher asphalt binder contents, whereas the solvent extraction test yielded lower asphalt binder contents than the target value. Some of the CR-modified OGFC mixtures (i.e., 76CRM1, 76CRM3, and 76CRM1+AC) exhibited drain-down issues, resulting in reduced asphalt binder content values in the ignition and solvent extraction tests as compared to the target asphalt binder content; see Figure 6. During the ignition process, it is common to observe a higher percent loss as fine aggregate particles are often blown out of the furnace. The aforementioned phenomenon is corrected by using a correction factor. It is typical to record a lower percent loss in the solvent extraction test for CRM mixtures. This phenomenon can be attributed to the insolubility of rubber particles in the TCE solvent, resulting in their exclusion from the calculation of the asphalt content percentage. This observation further illustrates the non-binding nature of CR-modifiers, highlighting the need for them to be accounted for during the design of CRM mixtures. The rubber particles exhibit characteristics similar to those of an aggregate rather than a binder within the composite material.

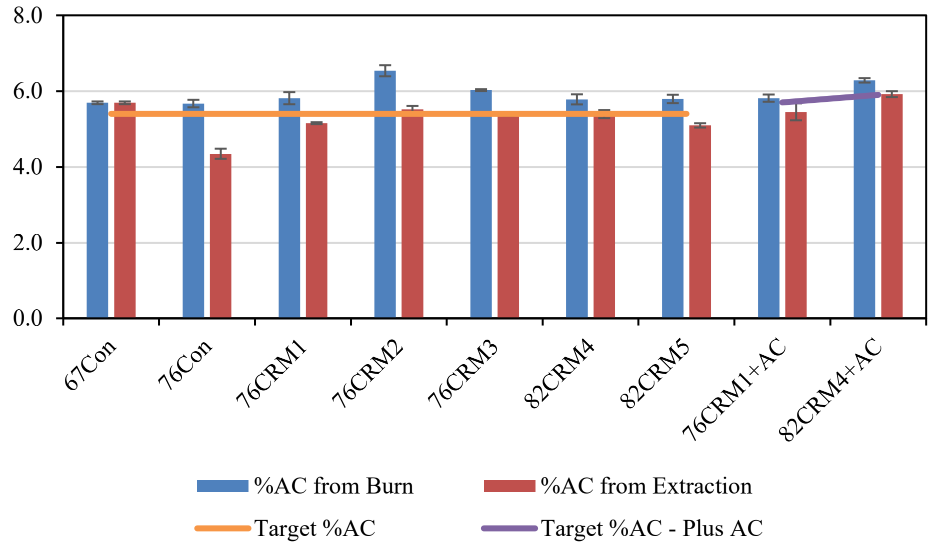

Figure 4
Percent asphalt content for dense-graded mixtures

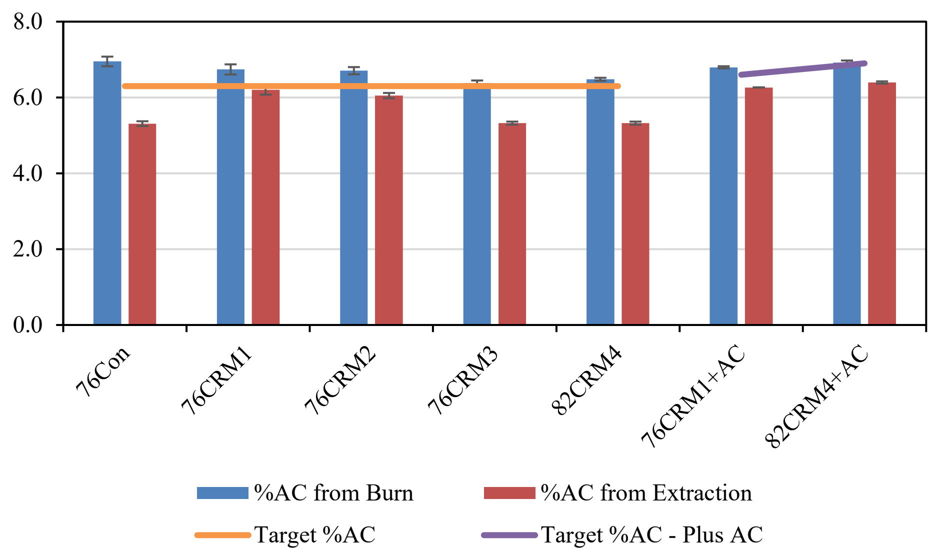

Figure 5
Percent asphalt content for SMA mixtures

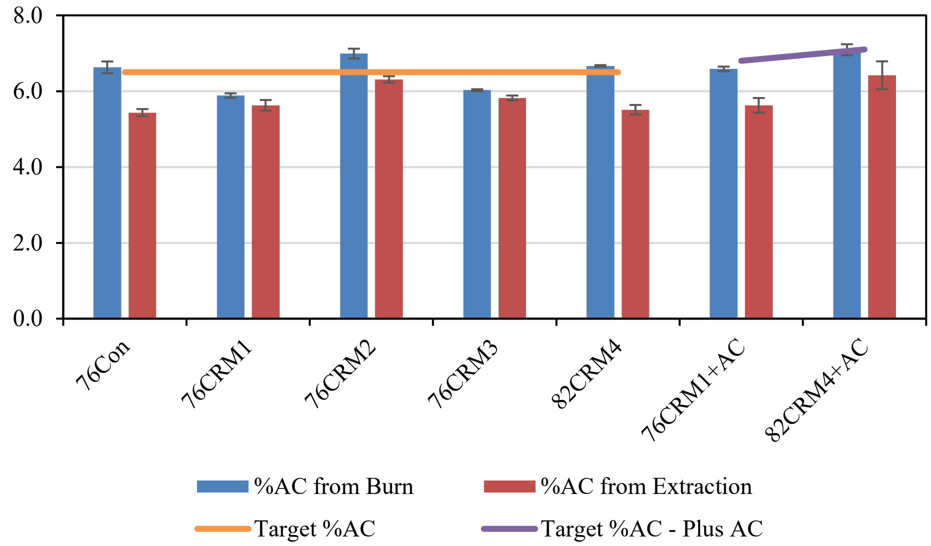

Figure 6
Percent asphalt content for OGFC mixtures

Volumetric parameters

Figure 7 presents percent air voids, voids in the mineral aggregates (VMA), and voids filled with asphalt (VFA) for the dense-graded mixtures evaluated in the study. Generally, CR modification resulted in increased air void content and VMA in the CR-modified mixtures as compared to the conventional mixtures. Furthermore, the VFA of the CR-modified mixtures was lower than that of the conventional mixtures. The trends observed in Figure 7 show that mixtures produced with CRM binders have a lower effective asphalt binder content than conventional mixtures. The CRM mixtures produced with higher asphalt binder contents mitigated the volumetric changes marginally. The reduction in effective asphalt binder content may lead to decreased mat density, increased permeability, accelerated oxidation, and premature cracking of the asphalt mixtures. Therefore, a re-design of the mixture aggregate structure may be required to ensure that volumetric properties are met when utilizing CR modifiers.

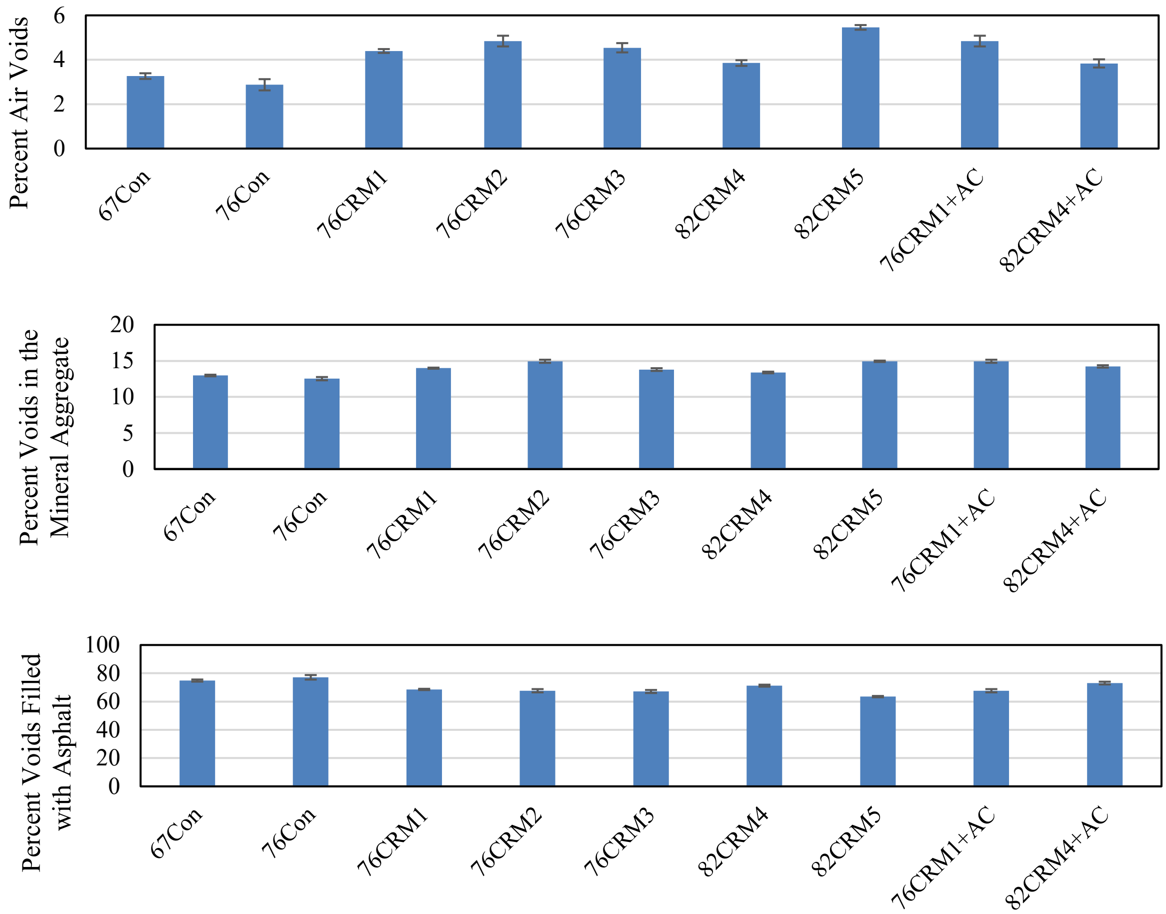

Figure 7
Volumetric properties for dense-graded mixtures

Figure 8 shows the effect of CR modification on the volumetric properties of the SMA mixtures evaluated in this study. The CR modification affected the SMA mixtures in this study differently than the dense-graded mixtures. In general, the addition of CR-modifiers resulted in decreased air void content and VMA as compared to the conventional SMA mixture. Additionally, the VFA of mixtures produced with CR-modifiers was higher as compared to the conventional mixture. This observation may be attributed to the particle size distribution of the SMA mixture. If there is enough space for the CR particles in the mixture, then the effects of the modification on the mixture's volumetric properties may be minimized.

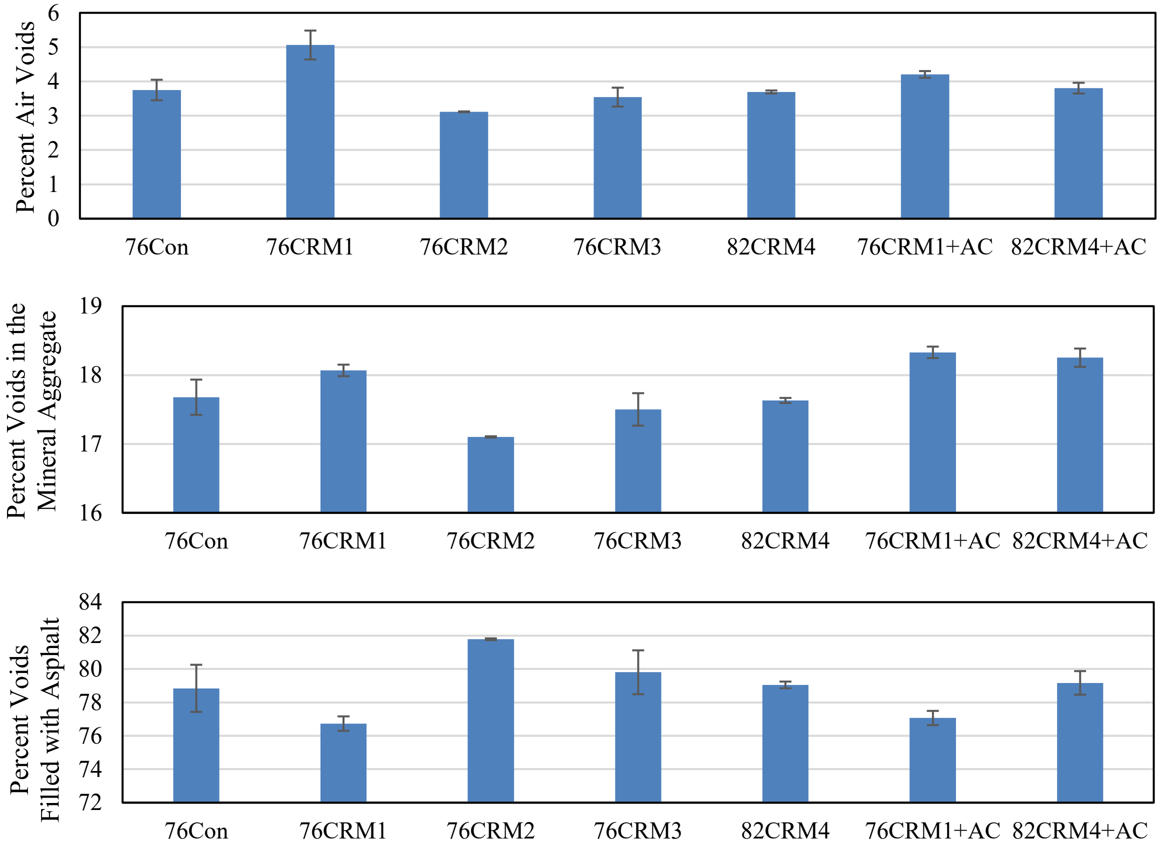

Figure 8
Volumetric properties for SMA mixture

Figure 9 presents the air void content values of the CRM and conventional OGFC mixtures evaluated in this study. Mixed trends were observed for the OGFC mixtures evaluated in this study. Similar to dense-graded mixtures, the air void content increased with CR modification, except for the 82CRM4 CR-modified mixture, which exhibited a lower air void content as compared to the conventional mixtures.

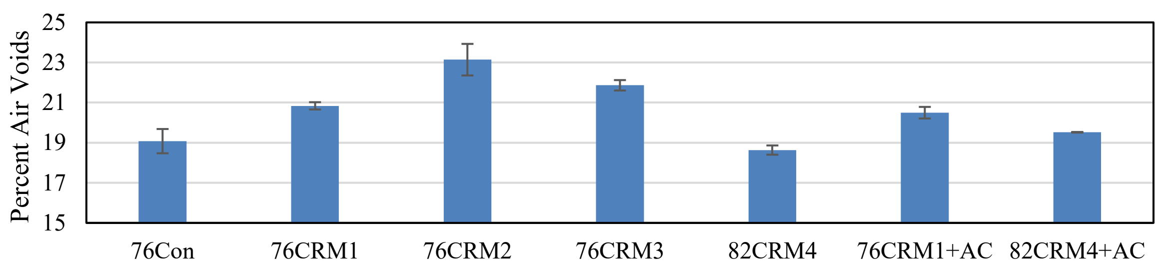

Figure 9
Volumetric properties for OGFC mixture

Loaded Wheel Tracking Test

Figures 10 to 12 show the HWT rut depth of asphalt mixtures evaluated in the study. The state of Louisiana requires all dense-graded and SMA mixtures to exhibit HWT rut depths of less than 6.0 mm at 20,000 passes. Similarly, OGFC mixtures are required to exhibit HWT rut depths of less than 12.0 mm at 5,000 passes. All mixtures in this study passed the Louisiana DOTD requirements for HWT rut depth. The dense-graded and SMA mixtures showed higher rutting resistance with CR modification. However, in the case of OGFC mixtures, the relationship between HWT rut depth and CR modification was more complex and depended on the density of the specimens. Therefore, it is evident that the samples with higher asphalt binder contents showed marginally better rutting resistance because of increased density.

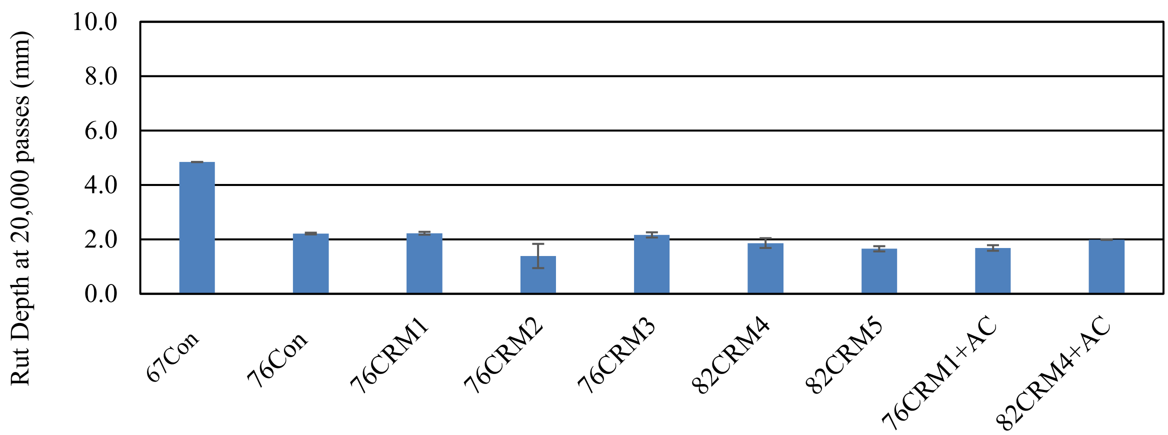

Figure 10
HWTT results for dense-graded mixtures

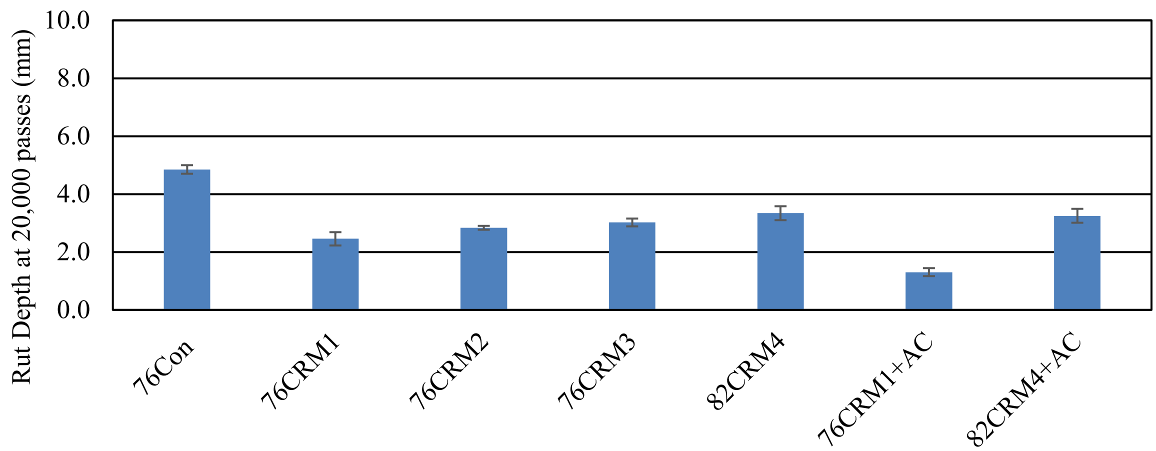

Figure 11
HWTT results for SMA mixtures

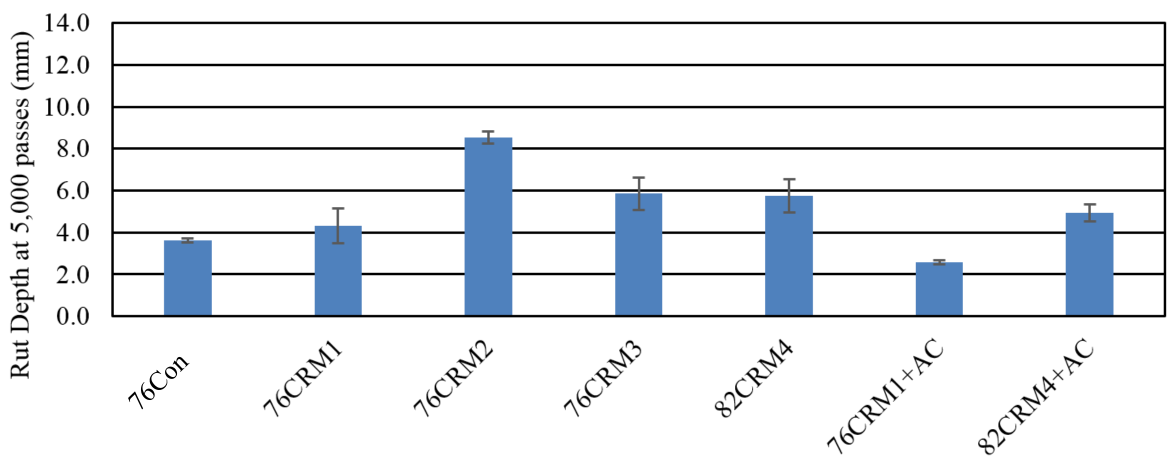

Figure 12
HWTT results for OGFC mixtures

Semi Circular Bending Test

Figures 13 and 14 present the SCB J_c values of the mixtures evaluated. A higher SCB J_c value indicates a higher resistance to fracture. The state of Louisiana adopted a minimum SCB J_c threshold of 0.50 kJ/m^2 as a failure criterion for level 1 mixtures (i.e., mixtures designed for traffic levels less than 3 million equivalent standard axle loads). For the dense-graded mixtures, the SBS-modified control HMA mixture together with two CRM mixtures (i.e., 76CRM1 and 76CRM1 + AC) exhibited SCB J_c values higher than the Louisiana DOTD recommended minimum value; see Figure 13. For the OGFC mixtures, the SBS-modified control mixture and three CRM mixtures (i.e., 76CRM1, 76CRM3, and 76CRM1 + AC) showed SCB J_c values higher than the recommended threshold value; see Figure 14. In general, the CRM mixtures showed lower SCB J_c values than the SBS-modified conventional mixtures evaluated. Therefore, if the mixtures are designed with CR-modified binder, cracking resistance may be a concern. This is likely due to the reduced effective asphalt content of the mixtures prepared with CR modifiers. Therefore, in order to increase the effective asphalt content of the CRM-modified mixtures, these mixtures should be designed with CR-modified binders. Any switch from the use of a conventional HMA to a CRM binder in mixture production should be accompanied by a redesign using the CRM mixture. The observed trends in Figures 13 and 14 confirm the premature cracking concerns reported by DOTD districts in Louisiana.

Comparisons between dense-graded and SMA mixtures indicate that SMA mixtures with relatively higher binder and coarse aggregate contents showed better cracking resistance than dense-graded mixtures. This trend can be seen in the dense-graded and SMA mixtures, which show that higher asphalt content would increase cracking performance.

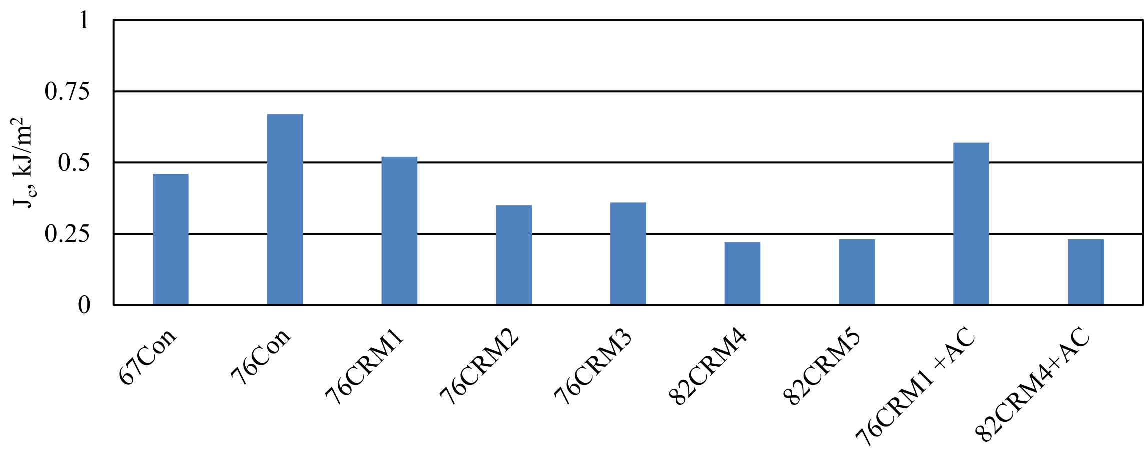

Figure 13
SCB J_c values for dense-graded mixtures

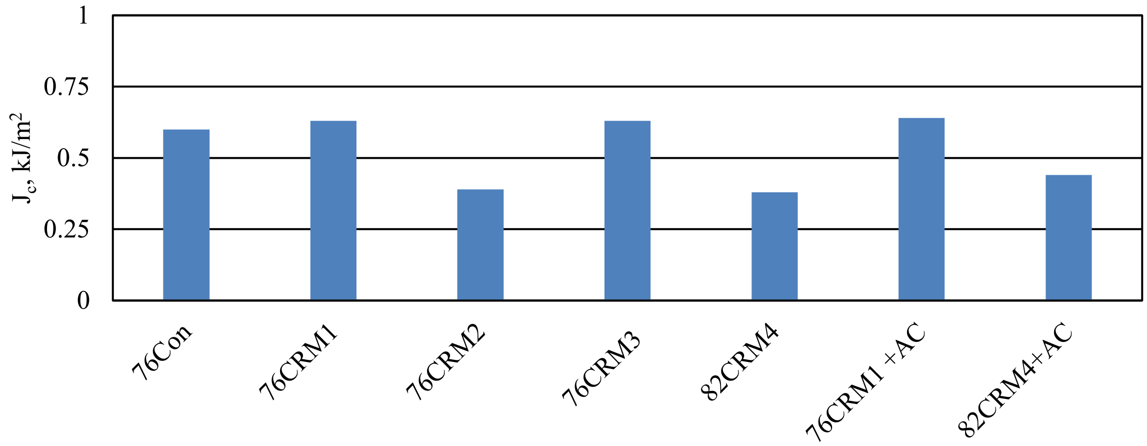

Figure 14
SCB J_c values for SMA mixtures

Statistical Analysis

A statistical analysis was performed in this project to evaluate the effects of different types of crumb rubber particles on mixture volumetric properties as well as cracking and rutting performance. The statistical analysis was used to divide the samples into groups of similar characteristics. This method was adopted to identify samples that exhibit significantly different properties when compared to the rest. The data in this study was analyzed with an ANOVA and further compared using Duncan's multiple range tests to establish statistical groupings. Statistical Analysis Software (SAS) Version 9.4 was used for the evaluation..

Dense-Graded Mixture Analysis

Table 3 shows the statistical grouping of the dense-graded mixtures based on the asphalt binder content values measured from the solvent extraction test. The CRM mixtures exhibited significantly similar asphalt binder content values as the control mixtures, except the 82CRM4+A CRM mixture, which exhibited a significantly higher asphalt binder content; see Table 3. 76CRM1 and 82CRM5 CR-modified mixtures showed the lowest asphalt binder content, as the rubber particles used in these mixtures did not dissolve during the solvent extraction process. The rubber particles in the 82CRM4 mixture fully dissolved into the asphalt binder solution during the solvent extraction process; therefore, when the asphalt content was increased to form 82CRM4+AC, the total dissolved binder content increased accordingly.

Table 3
Duncan's grouping for dense-graded mixtures (extraction test)

Duncan Grouping		Mean	N	Mix
	A	5.92	3	82CRM4+AC
B	A	5.52	2	76CRM2
B	A	5.45	3	76CRM1+AC
B		5.39	3	76CRM3
B		5.39	3	82CRM4
B		5.36	3	67Con
B		5.34	3	76Con
B		5.15	3	76CRM1
B		5.09	3	82CRM5

*N represents the number of samples

Table 4 presents the statistical grouping of the dense-graded mixtures based on the asphalt binder content values obtained from the ignition test. In the ignition method, the CR and fine aggregate particles burn with the asphalt binder. Therefore, increased asphalt binder contents were observed in most CRM mixtures. Significant differences were observed between the CRM and the control HMA mixtures. However, the majority of the data is within the specified tolerance of ±0.2%. Therefore, these differences are within practical limits.

Table 4
Duncan's grouping for dense-graded mixtures (ignition test)

Duncan Grouping		Mean	N	Mix
	A	6.53	3	76CRM2
B	A	6.28	3	82CRM4+AC
B	C	6.02	3	76CRM3
B	C	5.95	3	67Con
	C	5.81	3	76CRM1+AC
	C	5.81	4	76CRM1
	C	5.79	3	82CRM5
	C	5.78	3	82CRM4
	C	5.67	3	76Con

*N represents the number of samples

Table 5 shows the statistical groupings of the mixtures in terms of measured air void content. The conventional HMA mixtures exhibited significantly lower air void contents than the CRM mixtures. The CRM mixture prepared with cryogenic ground CR and using the wet blending process exhibited the highest air void content compared to all other mixtures. All the air voids were within the Louisiana DOTD-specified limits, except for the mixtures in statistical group A.

Table 6 presents the statistical groupings of the dense-graded mixtures, as determined from voids in mineral aggregates (VMA) measurements. The conventional samples exhibited significantly lower VMA values than most of the CRM mixtures.

Table 5
Duncan's grouping for dense-graded mixtures (Air voids)

Duncan Grouping		Mean	N	Mix
	A	5.46	2	82CRM5
B	A	4.84	3	76CRM2
B	A	4.84	3	76CRM1+AC
B	C	4.54	3	76CRM3
B	C	4.39	3	76CRM1
D	C	3.85	3	82CRM4
D	C	3.83	2	82CRM4+A
D	E	3.26	3	67Con
	E	2.87	3	76Con

*N represents the number of samples

Table 6
Duncan's grouping for dense-graded mixtures (VMA)

Duncan Grouping		Mean	N	Mix
	A	14.94	2	82CRM5
	A	14.94	3	76CRM2
	A	14.94	3	76CRM1+AC
	B	14.23	2	82CRM4+AC
C	B	13.98	3	76CRM1
C	B	13.79	3	76CRM3
C	D	13.39	3	82CRM4
E	D	12.96	3	67Con
E		12.52	3	76Con

*N represents the number of samples

Table 7 presents the statistical grouping of the VFA results for the dense-graded mixtures. Generally, the conventional HMA mixtures exhibited significantly higher VFA values than most of the CRM mixtures. The 76CRM3 and 82CRM5 CR-modified mixtures showed the lowest VFA values. The lower VFA values observed in the CRM mixtures may result in reduced cracking resistance in CRM mixtures. The reduction in VFA shows that the rubber is not a binding agent. This phenomenon was not captured in the air void measurements.

Table 7
Duncan's grouping for dense-graded mixtures (VFA)

Duncan Grouping		Mean	N	Mix
	A	77.10	3	76Con
B	A	74.80	3	67Con
B		73.00	2	82CRM4+AC
B	C	71.20	3	82CRM4
D	C	68.50	3	76CRM1
D	C	67.60	3	76CRM1+AC
D	C	67.60	3	76CRM2
D	E	67.10	3	76CRM3
	E	63.40	2	82CRM5

*N represents the number of samples

Table 8 shows the statistical groupings of the SCB J_c values for the dense-graded mixtures. The SBS-modified CRM mixtures (i.e., 76CRM1 and 76CRM1+AC) as well as the SBS-modified conventional HMA (76Con) mixtures exhibited the highest SCB J_c values compared to the other mixtures evaluated. The addition of excess asphalt binder to 76CRM1 and 82CRM4 to form 76CRM1+AC and 82CRM4+AC, respectively, did not significantly increase the SCB J_c values. The SCB J_c results are consistent with observations made from the VFA results. 76CRM1 and 76CRM+AC mixtures were prepared as a hybrid blend (i.e., CRM+SBS polymer); therefore, the cracking performance reflects the SBS modification. Statistical grouping of the HWT rut depth results is presented in Table 9. As expected, the addition of the CR-modifier improved the laboratory rutting resistance. However, the impact of crumb rubber type, polymer addition, and additional asphalt content on the rutting performance of dense-graded mixtures was not statistically significant.

Table 8
Duncan's grouping of SCB test results for dense-graded mixtures

Duncan Grouping			Mean	N*	Mix
	A		0.71	3	76CRM1+A
	A		0.67	4	76Con
B	A		0.55	3	76CRM1
B	A	C	0.45	4	67Con
B		C	0.37	3	76CRM2
B		C	0.36	4	76CRM3
		C	0.25	2	82CRM4+A
		C	0.23	2	82CRM5
		C	0.22	3	82CRM4

*N represents the number of samples

Table 9
Duncan's grouping of HWTT results for dense-graded mixtures

Duncan Grouping		Mean	N*	Mix
A		4.80	2	67Con
	B	2.20	2	76CRM1
	B	2.20	2	76Con
	B	2.10	2	76CRM3
	B	1.90	2	82CRM4+A
	B	1.80	2	82CRM4
	B	1.60	2	76CRM1+A
	B	1.60	2	82CRM5
	B	1.40	2	76CRM2

*N represents the number of samples

SMA Mixture Analysis

Table 10 presents the statistical groupings of the asphalt content values obtained from the solvent extraction test conducted on the SMA mixtures. Generally, CR modification resulted in a reduction in the extracted asphalt binder content. This result is expected because of the inability of the rubber particles to dissolve and form part of the liquid asphalt. Furthermore, the CR particles were found to be insoluble in the extraction solvent. These aforementioned observations may result in durability concerns as the CRM mixtures have lower effective binder contents than the conventional mixtures. Table 11 shows the statistical groupings of the asphalt content values obtained from the ignition tests conducted on the SMA mixtures. In these groupings, the conventional mixture exhibited significantly higher asphalt binder content than the 82CRM4 and 76CRM3 CR-modified mixtures.

Table 10
Duncan's grouping of solvent extraction result for SMA mixtures

Duncan Grouping		Mean	N	Mix
	A	6.39	3	82CRM4+A
	A	6.31	2	76Con
	A	6.20	3	76CRM1
B	A	5.98	3	76CRM2
B	A	5.69	3	76CRM1+A
B		5.32	3	76CRM3
B		5.32	3	82CRM4

*N represents the number of samples

Table 11
Duncan's grouping of ignition result for SMA mixtures

Duncan Grouping		Mean	N*	Mix
	A	6.95	2	76Con
	A	6.92	3	82CRM4+A
B	A	6.79	3	76CRM1+A
B	A	6.74	3	76CRM1
B	A	6.70	3	76CRM2
B	C	6.48	3	82CRM4
	C	6.38	3	76CRM3

*N represents the number of samples

The air void contents of SMA mixtures were analyzed and statistically grouped in Table 12. The statistical grouping shows that there was a significant difference in the air void content of the conventional mixture as compared to the majority of the CRM mixtures. A significant difference was observed between the air void content of 76CRM2 and that of 76CRM1. However, all of the mixtures met the LADOTD specification requirements.

Table 13 shows the statistical groupings of the VAM values for the SMA mixtures. The grouping shows that the majority of these mixtures exhibited significantly similar VMA values. The most significant statistical difference was observed between 76CRM2 and samples with 76CRM1+A. However, the results are practically identical..

Table 12
Duncan's grouping of air void content values for SMA mixtures

Duncan Grouping		Mean	N*	Mix
	A	4.20	3	76CRM1
	A	4.20	3	76CRM1+A
B	A	3.80	3	82CRM4+A
B	A	3.75	3	76Con
B	A	3.69	3	82CRM4
B	A	3.54	3	76CRM3
B		3.11	2	76CRM2

*N represents the number of samples

Table 13
Duncan's grouping of VMA values for SMA mixtures

Duncan Grouping			Mean	N*	Mix
	A		18.33	3	76CRM1+A
B	A		18.25	3	82CRM4+A
B	A	C	18.07	3	76CRM1
B	D	C	17.68	3	76Con
	D	C	17.63	3	82CRM4
	D	C	17.50	3	76CRM3
	D		17.10	2	76CRM2

*N represents the number of samples

Table 14 presents the statistical groupings of measured VFA values for SMA mixtures. The statistical groupings of VFA showed a similar trend as VMA, with the largest significant difference observed between 76CRM2 and 76CRM1 CR-modified asphalt mixtures.

Table 14
Duncan's grouping of VFA values for SMA mixtures

Duncan Grouping		Mean	N*	Mix
	A	81.78	2	76CRM2
B	A	79.80	3	76CRM3
B	A	79.17	3	82CRM4+A
B	A	79.05	3	82CRM4
B	A	78.84	3	76Con
B		77.06	3	76CRM1+A
B		76.73	3	76CRM1

*N represents the number of samples

Table 15 shows statistical groupings of SCB J_c values for SMA mixtures. The statistical grouping showed that there were minor differences in J_c values for the SMA mixtures evaluated. Similar to the dense-graded mixtures, CR modification negatively impacted the laboratory-measured cracking resistance of the mixtures. The CRM mixtures produced with SBS polymer (76CRM1 and 76CRM1+AC) exhibited similar cracking resistance as the conventional mixture.

Table 16 presents the statistical groupings of the HWT rut depth data for the SMA mixtures. All the mixtures passed the Louisiana DOTD criterion of 6mm HWT rut depth at 20,000 passes. The conventional mixture showed the highest HWT rut depth value compared to the CRM mixtures. The CRM-modified SMA mixture prepared with SMS polymer additive and an increased asphalt binder content (76CRM1+AC) showed the lowest HWT rut depth. CR modification resulted in improved rutting performance, which was consistent with observations made in the HWT tests conducted on the dense-graded mixtures.

Table 15
Duncan's grouping of SCB results for SMA mixtures

Duncan Grouping		Mean	N*	Mix
	A	0.65	3	76CRM1+AC
B	A	0.63	4	76CRM3
B	A	0.62	3	76CRM1
B	A	0.59	2	76Con
B	A	0.45	3	82CRM4+A
B	A	0.39	3	76CRM2
B		0.31	3	82CRM4

*N represents the number of samples

Table 16
Duncan's grouping of HWTT results for SMA mixtures

Duncan Grouping			Mean	N*	Mix
A			4.85	2	76Con
	B		3.34	2	82CRM4
	B		3.25	2	82CRM4+AC
	B		3.02	2	76CRM3
	B		2.835	2	76CRM2
	B		2.455	2	76CRM1
		C	1.305	2	76CRM1+AC

*N represents the number of samples

OGFC Mixture Analysis

Table 17 shows statistical groupings of the asphalt binder content values obtained from the solvent extraction tests conducted on the OGFC mixtures. The results indicate that the addition of CRM additives reduced the extracted binder content of the CRM mixtures. This trend is expected, as the CR additives do not entirely dissolve in the solvent used for the extraction process. The potential risk associated with this phenomenon is that mixtures produced with CR additives may not provide the minimum effective binder content to resist aggregate pop-outs. Louisiana DOTD recommends a minimum asphalt binder content of 6.5% for OGFC mixtures. All the CRM mixtures, together with the control mixture, exhibited asphalt binder content values lower than the recommended minimum value. The aforementioned observation has been a persistent concern among the research community.

Table 17
Duncan's grouping of solvent extraction test results for OGFC mixtures

Duncan Grouping		Mean	N	Mix
	A	6.43	3	76Con
	A	6.42	2	82CRM4+AC
	A	6.30	3	76CRM2
B	A	5.82	3	76CRM3
B		5.62	3	76CRM1
B		5.62	2	76CRM1+AC
B		5.51	3	82CRM4

*N represents the number of samples

Table 18 presents the statistical groupings of the asphalt binder content values measured from the ignition tests conducted on the OGFC mixtures. The results show that the ignition method did not capture the reduction in asphalt binder content values as observed in the solvent extraction test. This phenomenon is attributed to the burning of the rubber particles during the ignition process.

Table 19 shows the results of the statistical analysis of the measured air voids for the OGFC mixtures. The table shows that the air void content of 82CRM4 was significantly lower than other CRM samples. On the other hand, the conventional and CRM mixtures with increased asphalt content were grouped together with significantly similar air void contents but showed considerable differences in air void contents as compared to the 76CRM2 and 76CRM3 mixtures. The 82CRM4 CR-modified mixture exhibited significantly higher air void content than the control and the other CRM mixtures, except the 76CRM2 mixture. The incorporation of CR into OGFC mixtures generally resulted in increased air void content, which is consistent with the reduction in asphalt content observed with CRM modification.

Table 18
Duncan's grouping of ignition test results for OGFC mixtures

Duncan Grouping		Mean	N*	Mix
	A	7.09	3	82CRM4+AC
B	A	6.99	3	76CRM2
B	C	6.66	3	82CRM4
B	C	6.63	3	76Con
	C	6.58	3	76CRM1+AC
	D	6.02	3	76CRM3
	D	5.88	3	76CRM1

*N represents the number of samples

Table 19
Duncan's grouping for air void content values for OGFC mixtures

Duncan Grouping			Mean	N*	Mix
	A		23.14	3	76CRM2
B	A		21.86	3	76CRM3
B	C		20.84	3	76CRM1
B	C	D	20.49	3	76CRM1+AC
E	C	D	19.52	2	82CRM4+AC
E		D	19.08	3	76Con
E			18.63	3	82CRM4

*N represents the number of samples

Table 20 presents the statistical analysis of HWT rut depth values for the OGFC mixtures evaluated in this study. The results show that the 76CRM1+AC mixture exhibited the lowest HWT rut depth. All of the mixtures met the LADOTD HWT rut depth requirements for OGFC mixtures.

Table 20
Duncan's grouping for HWTT results for OGFC mixtures

Duncan Grouping		Mean	N*	Mix
	A	8.53	2	76CRM2
	A	7.46	2	76CRM3
	A	6.835	2	76Con
	A	6.705	2	82CRM4
B	A	5.8	2	82CRM4+AC
B	A	5.035	2	76CRM1
B		2.68	2	76CRM1+AC

*N represents the number of samples

CONCLUSIONS

Based on the analysis of the results of the tests conducted on different CRM and control mixtures, the following conclusions were made regarding the effects of CR modification on mixture volumetric properties as well as rutting and cracking performance.

- CRM modification consistently resulted in a reduction in HWT rut depth values, except for two CR-modified (i.e., 76CRM2 and 76CRM3) and OGFC mixtures, which showed increased rut depth with CR modification. CRM mixtures with increased asphalt binder content exhibited significantly similar or lower rut depth values. Nevertheless, the rutting performance of the CRM mixtures was within Louisiana DOTD allowable limits.
- The HWT test showed that both the conventional dense-graded and the SMA mixtures exhibited higher HWT rut depth than their corresponding CRM mixtures. Similar conclusions cannot be drawn for OGFC mixtures because of the high dependency of OGFC mixture properties on the air voids.
- CR modification effectively reduced the rut depth for dense-graded and SMA mixtures. Nevertheless, the addition of CR particles to asphalt mixtures resulted in reduced fracture resistance. The aforementioned trend was generally observed for all the dense-graded mixtures considered in the study. However, some inconsistencies were observed in the SMA and OGFC mixtures. The observed phenomenon is attributed to the fact that the rutting and cracking resistance of OGFC and SMA mixtures are dependent on the orientation of the aggregates in the mixture, and therefore, the performance characteristics of these mixtures are unpredictable.
- SMA and dense-graded mixtures showed similar trends in cracking resistance characteristics. The general observation was that CR modification reduced the cracking resistance of CRM mixtures. The reduction in cracking resistance was more noticeable in CRM binders with relatively higher high-temperature performance grades (PG).
- Increasing the asphalt binder content in the CRM mixtures above the optimum level resulted in increased cracking resistance. For example, when the optimum asphalt binder content of the CR-modified 76CRM1 asphalt binder was increased to produce 76CRM1+AC, the SCB J_c value of the dense-graded and SMA mixtures increased. It was observed that mixtures prepared with hybrid CRM/SBS additives exhibited better cracking resistance than those prepared with regular CR additives. The aforementioned observations imply that the use of polymer additives and increased

asphalt content should be considered to mitigate the impact of crumb rubber additives on the long-term cracking resistance of CRM mixtures.

RECOMMENDATIONS

The findings of the study indicate that CR modification is likely to enhance the resistance of asphalt mixtures to rutting. However, it is important to note that the long-term durability of these mixtures, particularly in relation to cracking resistance, may be impacted. Consequently, the following recommendations have been made for consideration:

- Additional mix design procedures should be considered and adopted for CRM mixtures. Previously, procedures used for conventional mix designs were adopted for CRM mixtures. The findings of this study indicate that CRM modification requires the development of unique design approaches for each CRM mixture type.
- CR particles had a tendency to absorb the base asphalt binder that was used to produce CRM binders. The above phenomenon reduces the effective binder content and the ability of the remaining binder to effectively bind the aggregates in hot mix asphalt. Therefore, additional asphalt content should be considered in the proposed mix design approach for CRM mixtures.
- It is recommended that hybrids of CRM and SBS additives be used to improve the cracking resistance of CRM mixtures.
- The study showed that a 10% (by the weight of the total binder) CR modification without changes to the mix design will result in a significant decrease in the cracking resistance of the asphalt mixture. Consequently, lower percentages of crumb rubber modifications should be considered.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BMD	Balanced Mix Design
CR	Crumb Rubber
CRM	Crumb Rubber Modified/Modifier(s)
DG	Dense-graded
DTA	Differential Thermal Analysis
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
ft.	foot (feet)
FTIR	Fourier-Transform Infrared Spectroscopy
GPC	Gel Permeation Chromatography
HMA	Hot Mix Asphalt
HWTT	Hamburg Wheel Tracking Test
HWT	Hamburg Wheel Tracking
in.	inch(es)
ITS	Indirect Tensile Strength
LADOTD	Louisiana Department of Transportation and Development
LTRC	Louisiana Transportation Research Center
lb.	pound(s)
m	meter(s)
M_r	Resilient Modulus
OGFC	Open-Graded Friction Course
SCB	Semi-Circular Bending test
SMA	Stone Matrix Asphalt
VMA	Voids in Mineral Aggregates
VFA	Voids Filled with Asphalt

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