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Assessment of Long-Term Performance of Louisiana Asphalt Pavements

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13. Abstract
This study investigated the effectiveness of various enhanced asphalt mixture designs and construction techniques used in Louisiana since 1994, evaluating to what degree they improved long-term performance. 24 field projects were evaluated, focusing on how these enhancements impacted rutting, cracking, ride quality, and overall pavement performance. Additionally, the cost-effectiveness and ability of laboratory testing to predict field performance were assessed.

Generally, pavement sections constructed with crumb rubber-modified mixtures exhibited similar or better resistance to rutting and cracking compared to conventional mixtures. This improvement is attributed to crumb rubber enhancing the binder's viscosity and acting as a filler to improve rutting resistance, while the natural rubber component improves crack resistance. However, the higher initial

cost of CRM often results in less cost-effective projects. Limited laboratory tests were not effective in predicting field performance for CRM sections. Further, the effects of warm mix asphalt (WMA) on long-term performance were evaluated, and WMA pavement sections generally showed similar or better cracking resistance than their corresponding conventional hot mix asphalt (HMA) sections. WMA test sections also showed inconsistent results for transverse cracking, with some sections exhibiting better resistance due to factors unrelated to WMA itself. Importantly, all WMA sections met the Louisiana Department of Transportation and Development (DOTD) rutting depth criteria after five to eight years of service. As part of this study, the Hamburg wheel track (HWT) rut depth and Semi-Circular Bend (SCB) strain energy release rate (J_c) values used in the Louisiana BMD framework were validated. The HWT rut depth and SCB J_c thresholds established in the Louisiana BMD framework were successfully validated for Level 1 and 2 pavement sections with service ranging from eight to 18 years. The maximum HWT rut depths of 10 mm and 6 mm for Levels 1 and 2 asphalt mixtures, respectively, were effective parameters for assessing the field rutting performance. Similarly, the minimum SCB J_c thresholds of 0.5 and 0.6 kJ/m^2 instituted in the Louisiana BMD framework for Levels 1 and 2 asphalt mixtures, respectively, were effective for assessing field random and alligator cracking performance.

Regarding the use of improved construction techniques on in-place field density and long-term performance, techniques such as Evotherm WMA and Plus AC were effective in improving rutting and cracking resistance, particularly transverse cracking, compared to control sections. Further, the temperature-segregation minimization technique assessed as part of this study was effective in enhancing the rutting and cracking performance, as well as the ride quality, of the pavement sections evaluated. Additionally, all of the increased in-place density techniques, including Evotherm WMA, Plus AC, and temperature-segregation minimization, increased the overall Pavement Condition Index (PCI) rating of the pavement sections evaluated. The minimum initial shear strength (ISS) value of 40 *psi* evaluated was also found to be effective in creating pavements with good bonding between layers. Sections constructed with this minimum ISS did not exhibit any significant cracking, rutting, or roughness values after seven to eight years of service.

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Implementation Statement

Asphalt mixture materials, as well as construction technologies and practices, have been recommended in this report for implementation. Implementing these recommendations will improve the durability and long-term performance of Louisiana asphalt pavements.

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Introduction

The construction of road infrastructure is a capital-intensive endeavor. Therefore, roads must be built to achieve long-term performance to justify the construction cost. Title 23 of the U.S. Federal Regulations, Chapter I, Subchapter G, Part 626.3 mandates that the design of pavements meet current and projected traffic demands in a manner that is safe, durable, and cost-effective. However, state highway agencies (SHAs) face challenges in constructing durable pavements to resist distresses such as cracking and rutting under the prevailing traffic and environmental conditions. To address pavement durability issues, SHAs have implemented various techniques, including using warm mix asphalt (WMA) to improve compaction, varying air void and asphalt contents, and creating a balanced mix design to achieve the expected lifespan [1, 2]. Consequently, the Louisiana Transportation Research Center (LTRC) has investigated how different factors affect flexible pavement performance. LTRC research studies aimed to improve the durability of the flexible pavement by suggesting modifications in asphalt mixture design methods and implementing improved construction techniques. For example, LTRC researchers demonstrated improved resistance to cracking and rutting compared to conventional methods by employing different approaches: using warm mix asphalt (WMA) additives, preventing temperature-segregation within mixtures, increasing asphalt content above the optimum level, and more [3, 4, 5]. Other researchers have modified mixture design methods by using different component materials and changing mixture design criteria to enhance performance. Asphalt mixture component materials such as polymer additives, anti-strip additives, and fibers have been shown to improve the overall performance of asphalt mixtures [6]. Additionally, there has been a growing emphasis on incorporating sustainable materials such as warm mix asphalt (WMA) additives, crumb rubber (CR) particles, and reclaimed asphalt pavement (RAP) into asphalt mixtures to conserve resources and protect the environment [7].

Recently, WMA technology usage has increased in the U.S. due to its ability to reduce asphalt binder viscosity and improve mixture compaction at lower temperatures compared to conventional hot mix asphalt (HMA) [8, 9]. The reduced production and compaction temperatures in WMA mixtures results in reduced energy consumption during mixing and paving, leading to lower greenhouse gas emissions. Despite the environmental benefits obtained from WMA production, there is also a trade off; mixing and laying WMA at lower temperatures can result in the incomplete drying of aggregates, which can lead to poor bonding between the asphalt binder and the aggregates, increasing the risk of moisture damage and stripping [10]. Goh [11] reported that WMA mixtures have lower air voids compared to HMA, resulting in better resistance to oxidative aging and cracking. However, Mogawer et al. [12] indicated that WMA may have lower rutting resistance due to reduced aging and a less stiff binder at lower mixing temperatures. Despite the role of WMA technologies in ensuring sustainable pavement construction, research on the long-term performance of WMA asphalt pavements is limited [9]. Crumb rubber (CR), a sustainable material, has been used for asphalt mixture production since the 1840s due to its natural rubber content, which enhances the resistance of asphalt mixtures to cracking [13, 14]. Crumb rubber is produced from recycled waste tires, and using recycled products helps protect the environment from pollution and significantly contributes to sustainability. Researchers have conducted several studies to evaluate the impact of crumb rubber on the performance of asphalt mixtures. Reported benefits of using a crumb rubber-modified asphalt mixture include improved rutting, cracking resistance, and noise reduction [13, 14, 15, 16].

State highway agencies (SHAs) continuously explore different techniques for improving the durability of asphalt mixtures. Over time, these agencies have enhanced mixture durability through a combination of well-defined mixture design criteria and high-quality component materials. Previously, SHAs relied on method-based specifications, but the industry has shifted towards performance-based specifications to enhance performance and durability [17]. This trend reflects the positive impact of improved mixture designs on pavement quality, as demonstrated in different research studies [18]. Balanced mixture design (BMD) is an example of a performance-based method that is gaining popularity among SHAs. According to the Federal Highway Administration (FHWA), BMD is “an asphalt mix design using performance tests on appropriately conditioned specimens that addresses multiple modes of distress, taking into consideration mix, aging, traffic, climate, and location within the pavement structure” [19]. The BMD approach focuses on identifying typical pavement distresses and selecting suitable mechanical or performance tests to address these distresses. Typical distresses considered in the BMD approach include rutting, moisture damage, and cracking. West et al. reported successful implementations of the BMD in six states: California, Louisiana, New Jersey, Texas, Iowa, and Illinois [19].

Beyond the use of mix design methods to improve performance, emerging construction techniques also play a significant role in influencing the durability of asphalt pavements. The asphalt industry is continuously improving its equipment and processes. Contractors and road agencies typically leverage various innovative technologies to enhance the in-place density and overall performance of asphalt pavements [1, 2]. A recent FHWA study concluded that increasing flexible pavement density can improve rutting and fatigue resistance [1]. In the aforementioned study, researchers used WMA additives, intelligent compaction technology, paver-mounted thermal profiling (PMTP) equipment, and material transfer vehicles (MTV) to achieve higher in-place density in flexible pavements. Laboratory analysis of field cores from the aforementioned study suggests that these techniques enhance flexible pavement performance in terms of rutting and cracking resistance [1, 2, 4]. Notably, researchers have demonstrated that a 1% increase in density above the recommended 93% relative density value can extend pavement lifespan by 20% [1, 2].

A key factor influencing the performance of flexible pavements is interlayer shear strength (ISS). In an effort to enhance ISS, researchers have explored the effects of various tack coat types, application rates, and techniques on performance [20]. For this purpose, the AASHTO TP 114 test, "Standard Method of Test for Determining the Interlayer Shear Strength," was created through the National Cooperative Highway Research Program (NCHRP). Based on a one-year field study, the NCHRP study recommended a minimum ISS of 40 *psi* for satisfactory pavement performance [20]. However, to validate this recommendation, further monitoring of these test sections is required.

The utilization of enhanced asphalt mixture design and construction techniques has resulted in enhanced pavement performance, as indicated by the findings of laboratory experiments and short-term field investigations. There are limited long-term studies assessing the impacts of these enhanced asphalt mixture design procedures and construction practices on performance. Therefore, it is necessary to assess the durability of flexible pavements constructed using advanced construction techniques and enhanced asphalt mixture design methods in order to confirm the results obtained from laboratory and short-term studies. The long-term in-service performance data obtained from this study will provide valuable guidance to state agencies in enhancing the implementation of novel technologies and methodologies for asphalt pavement construction.

Literature Review

This chapter presents a review of existing literature regarding factors influencing the durability and sustainability of flexible pavements. The review is divided into two parts to study (1) the effects of modified asphalt mixture design methods and (2) improved construction techniques on pavement performance.

Asphalt Mixture Design Methods

Regarding the effects of asphalt mixture design methods on long-term performance, this study considered two factors: mixture component materials and mixture design criteria. Further, this research focused on three primary aspects of mixture design factors: (1) the use of a rubber-modified asphalt mixture as a component material for sustainability, (2) the use of WMA additives for sustainable mixture production, and (3) the evaluation of the balanced mixture design approach as an asphalt mixture design criteria.

Use of Crumb Rubber-Modified Asphalt Mixture (CRM) for Sustainable Mixture Production

Waste recycling enhances the sustainable use of scarce natural resources and protects the environment from pollution. According to the U.S. Environmental Protection Agency (EPA), recycling is an integral part of the U.S. economy, which creates jobs and contributes to tax revenues. In 2012, recycling and reuse activities in the U.S. accounted for 681,000 jobs, an equivalent of 1.17 jobs per 1,000 tons of materials recycled, $37.8 billion in wages, and $5.5 billion in tax revenues [21]. Recycled materials typically used in the production of asphalt mixtures include recycled asphalt pavements and shingles (RAP and RAS), crumb rubber (CR), steel and blast furnace slag, foundry sand, and waste plastics [7]. According to the U.S. Tire Manufacturers Association (USTMA), waste tire is among the most recycled materials in the U.S., and its recycling plays a significant role in achieving a sustainable circular economy. In 2021, 1.4 million tons of the 3.6 million tons of recycled tire rubbers produced in the U.S. were ground into crumb rubber for different uses. Approximately 10% (0.14 million tons) of the crumb rubber produced in 2021 was used for asphalt mixture production [22]. Approximately 0.7 million tons of scrap tires were disposed into landfills across the U.S., which accounted for a 7.7% increase in landfill disposal from 2019. To curb the menace posed by waste tires to the environment, the U.S. Congress passed the Intermodal Surface

Transportation Efficiency Act of 1991 (ISTEA), which mandated that all state highway agencies (SHAs) use crumb rubber additives in hot mix asphalt (HMA) paving on federal aid highway projects [23]. Consistent with this mandate, the Louisiana Department of Transportation and Development (DOTD) initiated a research study to evaluate the effects of crumb rubber modification on long-term performance [24]. ISTEA was later modified, and the mandate for the inclusion of crumb rubber in every federal project was suspended; however, the passage of the act reduced waste tire stockpiles in the U.S. from one billion tons in 1990 to 50 million tons in 2021 [22, 23]. Despite the achievement of this milestone, a significant number of scrap tires are still being disposed in landfills across the U.S.

Crumb rubber has been shown to be an important additive in hot mix asphalt (HMA) [25]. A typical crumb rubber material consists of synthetic polymers, carbon black, natural rubber, extender oils, and other additives. Natural rubber has been shown to be a major component of crumb rubber, which improves cracking resistance [14]. The use of natural rubber (i.e., latex) as an asphalt binder modifier started in the 1840s [24]. There are different techniques for incorporating crumb rubber into asphalt mixture depending on mixture type (dense, gap, or open grade HMA). These techniques are broadly classified under the dry and wet processes. In the dry process, the crumb rubber is added to the aggregate before mixing with the asphalt binder. The typical size of the crumb rubber used in the dry process ranges from 600 to 420 μm. A major advantage of the dry process over the wet process is that the dry process requires shorter material processing and handling time since it does not require the blending of the crumb rubber with asphalt binder at higher temperatures [13, 15, 16]. Standard methods of incorporating crumb rubber into asphalt mixtures through the dry process include PlusRide, developed in Sweden in the 1960s; generic dry process, developed in Kansas, U.S., in the 1990s; and Asphalt Plus SmartMix, developed in Georgia, U.S., in the 2010s. In the wet blending process, finely ground crumb rubber (maximum particle size of 1.5 mm) is mixed with the asphalt binder at high temperatures (175 – 190˚C) for 30 to 60 min. before mixing with the aggregate. Techniques typically used in the wet process include the McDonald process, developed in Arizona, U.S., in the 1960s; the continuous blend process developed in Florida, U.S., in 1989; and the terminal blend, developed in Arizona, U.S., in 1992.

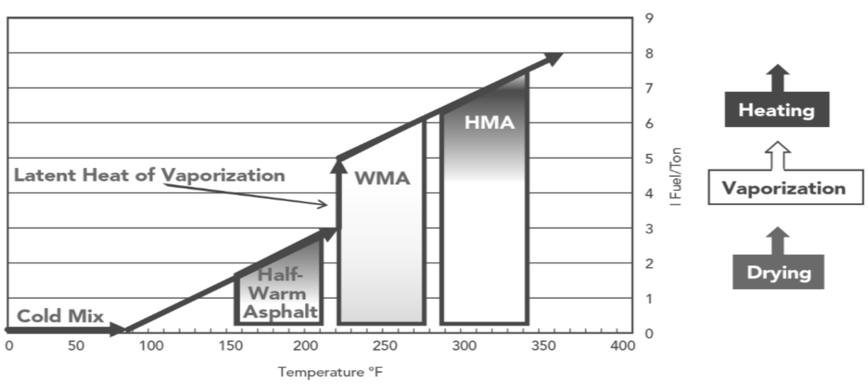
Several research studies have been conducted over the years to assess the effect of crumb rubber additives on mixture performance [13, 26]. Reported benefits of crumb rubber additives in asphalt mixture production include improved rutting resistance, ride quality, noise reduction, thermal cracking, and fatigue cracking resistance [15, 16]. Huang et al. evaluated the wet and dry processes of blending crumb rubber into Louisiana mixtures and reported that crumb rubber-modified sections showed better performance than conventional sections, including improved ride quality, rutting, and cracking resistance [27]. In a related study, Cao evaluated the dry process of using crumb rubber additives in asphalt mixtures in the laboratory and reported improved rutting and cracking (low and intermediate temperature cracking) resistance associated with crumb rubber modification [28]. Other researchers have demonstrated that crumb rubber modification increases the high-temperature grade of an asphalt binder by at least one level, which accounts for the improved rutting performance of crumb rubber-modified mixtures [29, 30, 31]. Several researchers have demonstrated through field evaluation that the wet process of incorporating crumb rubber into asphalt mixtures is effective in mitigating cracking compared to the dry process [32, 33]. However, Shen et al. [34] demonstrated in a related laboratory study that crumb rubber-modified (CRM) mixtures produced using the wet and dry processes have similar fatigue life. Nazzal et al. reported that the crumb rubber-modified sections with ten years of service life performed similarly to that of polymer-modified mixtures [35]. The researchers further demonstrated that crumb rubber sections had higher life cycle costs compared to their corresponding polymer-modified section and attributed this observation to the higher initial cost of producing the crumb rubber sections [35, 36]. Other researchers have demonstrated in a related study that crumb sections are more expensive to construct compared to conventional HMA sections [36]. It is noted that these researchers [35, 36] did not account for the added economic and environmental benefits gained from utilizing waste tires that may have been placed in landfills. However, a recent study showed that there are other environmental benefits associated with CRM use that may offset the added cost of producing CRM mixtures [37].

Due to the benefits obtained from crumb rubber usage, Louisiana DOTD permits the use of CR particles as a mixture additive in accordance with its 2016 standard specifications document. Following a study conducted by the Louisiana Transportation Research Center (LTRC), DOTD specified that a maximum of 10% crumb rubber by the weight of the asphalt binder be used in asphalt mixtures [38, 39]. This recommendation was based on the findings of the aforementioned research studies, which indicated that asphalt binder-CR blends with CR dosages exceeding 10% exhibited instability and a tendency to separate from the blend when exposed to high temperatures [38, 39]. Because CR-modified mixtures play a significant role in sustainable pavement technology, it is imperative to continuously evaluate the field performance of CR-modified pavement sections over longer periods to ascertain their cost-effectiveness and improve the state-of-practice of CR modification.

Use of Warm Mix Asphalt (WMA) Additives for Sustainable Pavement Construction

Various environmentally sustainable techniques have been employed to reduce the placement and production temperature of hot mix asphalt (HMA). All techniques that reduce the production and placement temperature of HMAs can be classified as warm mix asphalt (WMA) technologies. The key difference between WMA and HMA is the production temperature. Figure 1 presents the classification of asphalt mixtures based on the temperature of production [40]. Mixtures produced at temperatures less than 90°F (32°C) are termed cold mixtures. If the production temperature of the mix is between 155°F (68°C) and 212°F (100°C), the mix is described as half-warm asphalt. If the production temperature of the mix is between 212°F (100°C) and 280°F (138°C), the mix is classified as warm mix asphalt. Hot mix asphalt refers to mixtures produced at temperatures ranging from 290°F (143°C) to 340°F (171°C). A high temperature of production corresponds to high fuel consumption. Therefore, lower production temperatures are desirable for environmental sustainability. The production temperature of WMA is generally 25°F to 90°F (14°C to 50°C) below that of HMA. The magnitude of temperature reduction is determined by the type of warm-mix technology used [41].

Figure 1. Asphalt mixture types based on production temperature [40]



Three primary categories of WMA technologies are currently available: organic additives, chemical additives, and foaming techniques. This classification is based on the material used and/or the process used to reduce the production temperature of conventional HMA. Generally, organic additives consist of waxes or fatty acid amides. These are typically long-chain hydrocarbon compounds. Organic additives are added to asphalt binders to reduce the viscosity and improve the stiffness of the mix [3, 11, 42]. Waxes have melting points lower than typical asphalt mixing temperatures. When the mix is heated, the melted wax reduces viscosity, and upon cooling down, the stiffness of the mix increases. Common waxes on the market include Sasobit®, Licomont BS-100®, and Asphaltan-B®. Chemical additives generally combine surfactants, anti-strip, and emulsifiers to produce mixtures with enhanced compaction, adhesion, coating, and workability properties [11, 40, 43]. Surfactants, which refer to substances that decrease the surface tension of liquids after dissolution, are used to reduce frictional forces at the interface of aggregates and binder to enhance mixing and compaction at low temperatures (85°C to 140°C). Cecabase® RT, Rediset WMX®, and Evotherm® are examples of chemical additives. Various chemical additives are used in the production of WMA based on the desired performance for a specific mix.

Among the WMA technologies used in the U.S., foaming techniques are predominant. Foaming is cost-effective because water, the primary component for viscosity and temperature reduction, is readily available. Foaming requires the addition of water to the asphalt binder during the mixing stage. The evaporation of water causes steam to be dispersed through the binder; the steam is temporarily entrapped, leading to the formation of foam. The foam causes an increase in the volume of binder and a temporal reduction in viscosity, which is ideal for aggregate coating and workability [3, 11, 42]. Foaming techniques can be broadly classified into two categories based on the process of adding water to the binder: water-based and water-bearing. Water-bearing techniques refer to the use of hydrophilic materials such as zeolite, which releases crystallized water into the binder to form foam. Examples of water-bearing techniques include Aspha-min and ADVERA. For water-based techniques, water is applied directly into the binder through a nozzle or series of nozzles to generate the foam. Water-based equipment available on the market includes Aquablack and Standsteel from Maxam Equipment Incorporated and the Double Barrel Green System from Astec Industries [3, 42, 43]. WMA is cost-effective and improves environmental sustainability. However, at lower mixing and production temperatures, aging is reduced, and aggregates may not be completely dried. This can lead to the development of pavement distresses such as rutting, cracking, and potholes. Rutting is a major cause of pavement distress, which reduces ride comfort and poses a safety hazard for road users. Rutting is caused by a plethora of factors, including poor compaction, inadequate pavement structure, high binder content, and an excessive proportion of fines in an asphalt mix. WMA technology focuses on the reduction of asphalt mixing and compaction temperatures while increasing workability through a reduction of viscosity. This causes a reduction in the short-term aging of binder, which has the potential to make WMA susceptible to rutting [44]. As a result, several studies have been conducted to compare the rutting performance of WMA to that of traditional HMA.

Bairgi et al. [44] evaluated the performance of WMA technologies (Cecabase, Evotherm®, and Foamed WMA) and a companion control HMA section on overlay test sections on I-40 in New Mexico. The researchers conducted laboratory and field experiments. Laboratory evaluation by the Hamburg Wheel Tracking (HWT) test showed that Cecabase, Evotherm®, and foamed WMA-modified mixtures exhibited higher rutting compared to conventional HMA mixtures. This observation was attributed to binder softening by foaming and the addition of additives. The field experiment was conducted in two phases. The first phase involved a laser-based automated collection of pavement distress data (rutting, cracking, and raveling) using the Mandli pavement profile scanner (PPS) developed by Phoenix Scientific Inc. An individual distress index (IDI), which refers to a numerical score assigned based on the severity and extent of distress, was computed for rutting. IDI values ranged from 0 to 100, where 0 denotes the worst condition and 100 a perfect condition (i.e., no existing distress). After four years in service, all WMA and HMA sections satisfied the state rutting criteria (< 5 mm). However, the rutting values were slightly higher for WMA sections compared to HMA sections. For rutting IDI, all sections exhibited values greater than 91, which implies good rutting performance. However, Cecabase, Evotherm®, and WMA with foaming technologies reported slightly lower rutting IDI values compared to conventional HMA. In related research, Mohammad et al. [3] conducted a comprehensive study on the performance of WMA in Louisiana. 11 plant-produced, laboratory-compacted WMA mixtures and companion conventional HMA mixtures were evaluated in this study. A series of laboratory tests, including HWT, indirect tensile (IDT) strength, Semi-Circular Bend (SCB), thermal strain restrained specimen (TSRS), dynamic modulus, Modified Lottman, and flow number tests, were conducted. Flow number, HWT rut depth, and rut factor were used to evaluate the rutting performance. For rutting performance, no statistical difference was reported for WMA mixtures and HMA mixtures. Bower et al. [45] evaluated the early-age performance of four WMA technologies and their corresponding conventional HMA mixtures in Washington State. The WMA technologies used in this study were Sasobit®, Gencor®, AquaBlackTM, and ALmix water injection. A suite of laboratory tests was conducted on field cores to characterize and compare the moisture susceptibility, fatigue, thermal cracking resistance, and rutting of WMA and conventional HMA mixtures. There was no statistically significant difference in rut depth values for Sasobit® and AquaBlack and their companion HMA mixtures. However, Gencor and ALmix water injection WMA-modified mixtures showed significantly higher rut depths compared to their companion HMA mixtures. The higher rut depth values were attributed to a reduction in binder aging since Gencor® and ALmix water injection were produced at relatively lower production temperatures (< 130°C) than Sasobit® and AquaBlack (> 130°C). The field performance of the aforementioned study was assessed by extracting and analyzing pavement distress data from the Washington State pavement management system in 2012. Data were only analyzed for test sections where HMA and WMA cores were taken. Similar early-age rutting performance was reported for both the HMA and WMA test sections.

WMA technology is designed to reduce production and compaction temperatures. At low temperatures, asphalt aging is reduced. As a result, pavements constructed using WMA technologies are expected to have adequate cracking resistance. The common approach followed by most researchers in the literature to evaluate the fatigue and thermal cracking performance of WMA and companion HMA mixtures is laboratory performance testing and early-age field experiments. Bower et al. [45] conducted laboratory and field experiments on four WMA projects consisting of Sasobit®, Gencor, AquaBlack, and ALmix water injection, as well as a control HMA section, across Washington State. The authors evaluated cracking performance using the IDT fracture and thermal cracking tests. For fatigue cracking, no statistical difference was reported for Gencor, AquaBlack, and ALmix water injection technologies compared to conventional HMA mixtures. However, Sasobit® showed lower fracture work than control HMA, which indicates lower bottom-up fatigue cracking resistance. The thermal cracking results indicated no statistical difference between the WMA mixtures and the control HMA mixtures. The authors obtained field performance data (transverse and longitudinal cracking) from the Washington State pavement management system and analyzed it using dual criteria of actual measured crack length and a mechanistic-empirical pavement design guide (MEPDG) threshold value for cracking. Per the dual criteria, all WMA sections had comparable transverse and longitudinal cracking resistance to HMA, except for Sasobit®, which has better transverse cracking resistance compared to HMA. It must be noted that cracking may not entirely be a result of construction technology such as HMA or WMA but can originate from the propagation of cracks due to underlying conditions [46].

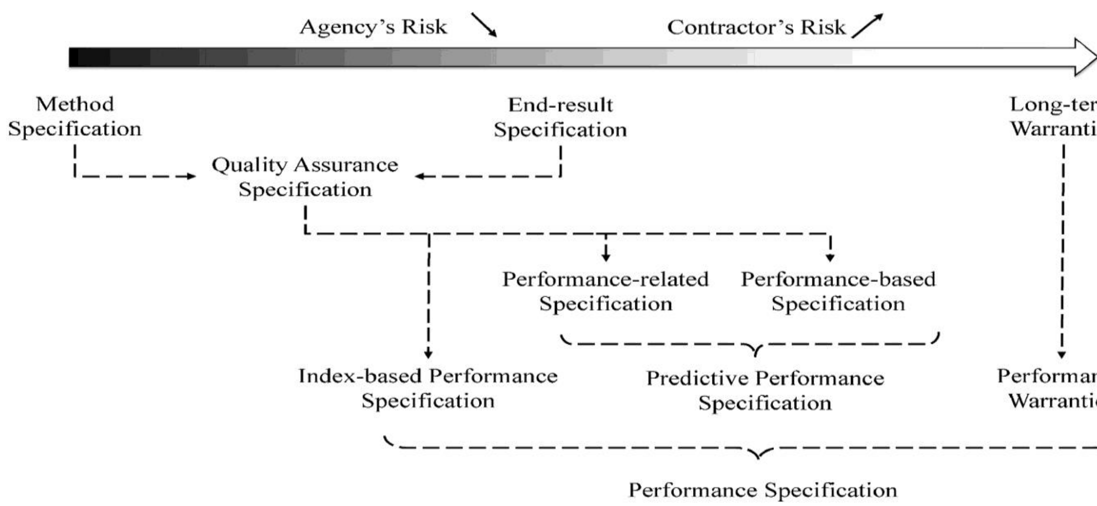
WMA technologies have been used extensively in Europe. To implement the best practices from Europe in the United States, D'Angelo et al. [40] assessed and evaluated various WMA technologies used in Germany, Norway, and France. Field and laboratory performance data obtained from the three countries indicate that WMA technologies such as Sasobit®, Asphaltan-B, and Aspha-min® exhibit similar or better fatigue cracking performance than HMA [40]. A study by Hurley and Prowell [47] corroborated these findings as well. The researchers discovered that the reduction in mixing, compaction, and placing temperature of WMA technologies leads to a decrease in early-stage aging of the binder, resulting in better cracking resistance. Wu et al. [48] evaluated the top-down fatigue cracking of 28 pavement sections, including sections constructed with WMA technologies and their companion HMA sections, which had been in service for four to ten years across the United States. Field core samples were taken from test sections that exhibited longitudinal wheel-path cracking with different traffic loading, pavement characteristics, and climatic zones. To characterize fatigue cracking resistance in the field, the authors conducted an IDT fracture test and reported parameters such as fracture work density, vertical failure deformation, and horizontal failure strain. The top-down cracking performance for HMA-WMA pairs was ranked statistically using a T-test at a significance level of 0.05. Generally, HMA and WMA test sections evaluated in this study showed comparable top-down fatigue cracking performance in the field.

Shen et al. [9] conducted a comprehensive evaluation of WMA technologies to determine their effect on long-term field performance. The researchers observed that the current MEPDG program had limited capability in predicting the long-term performance of WMA and HMA pavements and therefore developed a statistically-based predictive model to identify critical factors influencing field cracking and rutting performance. Three WMA technologies were utilized in this study (chemical additive, organic additive, and foaming WMA technology) and compared to conventional HMA technology. The researchers compared cracking distresses (transverse cracking and longitudinal wheel-path cracking) observed on WMA test sections to those observed on HMA control sections subjected to similar traffic and environmental conditions. They performed a manual measurement of distress on 200-ft. pavement test sections following the Long-Term Pavement Performance (LTPP) Distress Survey Manual. Further, field cores were obtained for laboratory evaluations. Among the pavement test sections evaluated, the WMA test sections were found to exhibit similar long-term performance in terms of transverse cracking and longitudinal wheel-path cracking compared to the HMA test sections. The short-term performance of the three WMA technologies (chemical, organic, and foaming additives) was also found to be similar. However, the long-term cracking performance of chemical and foaming WMA pavements appeared to be better than that of the organically modified WMA pavements. Further, higher fracture work density values measured from the indirect tensile (IDT) test at 57° C (14° F) were found to correlate with lower transverse cracking in the field.

Balanced Asphalt Mixture Design Approach as an Asphalt Mix Design Criteria

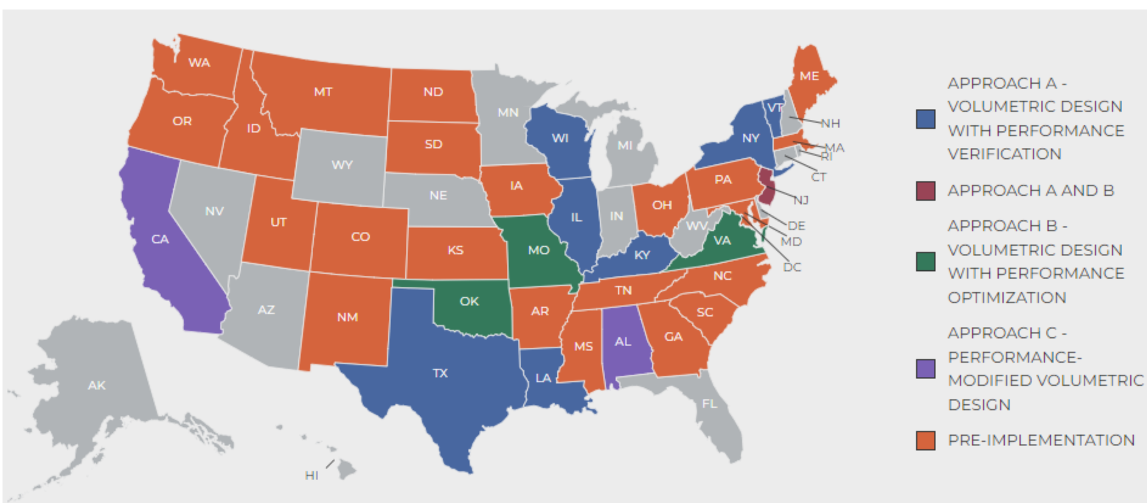
Over the years, state highway agencies (SHAs) have used various construction specification procedures to measure whether a durable flexible pavement is produced. These construction specification techniques have evolved from method-based specifications into performance-based specifications through continuous research and improvements [49]. The method-based specification considered the volumetric properties of an asphalt mixture as a critical factor for ensuring the stability and durability of the mixture. As a result, contractors received specific asphalt mix design instructions from road agencies in order to achieve the specified mix properties. These contractors were responsible for following specific mix design requirements; however, they had limited responsibility regarding the finished product's performance, provided they followed the specified methods. The introduction of performance-based specifications for road construction resulted in shared responsibility between contractors and road agencies regarding the performance of the constructed flexible pavements [17, 49] . This change encouraged cooperation, innovation, and improved pavement quality. Figure 2 shows the construction specifications over time adopted by the SHAs. This demonstrates the risk of the construction project shifting from SHAs toward contractors [17].

Figure 2. Construction specifications [17]



The asphalt mixture design concept started with the Marshall and Hveem mixture design in the 1930s. Later, in the 1990s, the Superpave asphalt mixture design method was implemented to improve the rutting resistance of asphalt mixtures and address the limitations of the Marshall and Hveem mixture design methods. Rutting resistance was enhanced in the Superpave mix design method using relatively lower asphalt binder content, stiffer binders, and a coarser aggregate structure. These mixture design modifications resulted in asphalt mixtures with reduced cracking resistance and durability and lowered workability during mixing. Further, the recent adoption of different asphalt binder modifiers (e.g., polymer, warm mix asphalt, and anti-strip additives) and sustainable materials (e.g., recycled asphalt, crumb rubber, rejuvenating agents) has limited the capability of the volumetric mixture design to effectively capture the performance of asphalt mixtures both in the field and in the laboratory [50, 51]. Therefore, the balanced mix design (BMD) approach was implemented by SHAs to complement the volumetric mix design method. According to the Transportation Research Circular E-C280, BMD is defined as "asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress taking into consideration mix aging, traffic, climate, and location within the pavement structure" [52]. West et al. conducted a research study to develop a framework for implementing a BMD procedure incorporating mixture performance testing criteria. The study described a step-by-step approach from the selection to implementation of mechanical/performance tests by different highway agencies. A survey conducted as part of the study showed that 24 state agencies considered rutting tests in their BMD approach, whereas eight state agencies included cracking tests in their BMD approach. Further, West et al. reported that six states (California, Louisiana, New Jersey, Texas, Iowa, and Illinois) have successfully implemented the BMD approach in constructing flexible pavements. Figure 3 shows the summary of BMD implementation progress by SHAs, as reported by National Asphalt Pavement Association (NAPA) [53].

Figure 3. BMD implementation progress



The BMD approach focuses on identifying typical pavement distresses and selecting appropriate mechanical/performance tests to address these distresses. Distresses typically considered in the BMD approach include rutting, moisture damage, and cracking (fatigue, reflection, and thermal cracking) [19, 54]. West et al. reported that 10 and 11 SHAs use the HWT device and flexible pavement analyzer (APA), respectively, for characterizing the rutting resistance and moisture susceptibility [19]. Among the six states that have successfully implemented the BMD approach, five use the HWT test to characterize rutting moisture damage resistance because of its ability to simulate field rutting and moisture damage resistance. These SHAs select HWT test rut depth or stripping (i.e., moisture damage) criteria depending on the design traffic level or mixture type [19, 54, 55, 56]. In a related study, Zhou et al. identified seven cracking tests typically used for characterizing cracking resistance (thermal, reflection, bottom-up, and top-down cracking) in different U.S. states [57]. Subsequent research studies were conducted to assess the ruggedness of the eight identified cracking tests, one being the newly developed Ideal CT cracking test. Table 1 summarizes the cracking tests that were evaluated for their ruggedness [58].

Table 1. Cracking tests summary

Test designation	Standard test method
ASTM D7313	Standard Test Method for Determining Fracture Energy of Asphalt-Aggregate Mixtures Using the Disk-Shaped Compact Tension Geometry (or DCT)
AASHTO TP 105	Standard Method of Test for Determining the Fracture Energy of Asphalt Mixtures Using the Semicircular Bend Geometry (SCB)
AASHTO TP 124	Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using the Flexibility Index Test (IFIT)
ASTM D8044	Standard Test Method for Evaluation of Asphalt Mixture Cracking Resistance Using the Semi-Circular Bend Test (SCB) at Intermediate Temperatures
ASTM D8225	Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature (or IDEAL-CT)
Tex-248-F	Overlay Test (or OT)
AASHTO T 321	Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending (or BBF)
Florida IDT Test	Standard Method of Test for Tensile Resilient Modulus of Asphalt Mixtures Using the Superpave Indirect Tension (IDT) Test

The researchers considered factors such as simplicity, cost of equipment, variability, lab-to-field correlation, etc. in assessing the ruggedness of these tests. Among the eight cracking tests evaluated for their ruggedness, two were found to be rugged, which included the SCB test (ASTM D8044) [58]. The SCB-J_c parameter captures the fracture energy of the mixture in terms of critical strain energy rate (J_c). Higher J_c values indicate higher cracking resistance in asphalt mixtures. The SCB test has been shown to be a simple and reliable method to characterize the cracking resistance of asphalt mixtures [59, 60, 61, 62, 63]. A study conducted by Oklahoma DOT identified the SCB test as an effective tool for characterizing the cracking resistance of asphalt mixtures [63].

The Louisiana DOTD BMD framework was implemented in 2016 and is comprised of the use of the HWT rut depth and SCB J_c for characterizing rutting and intermediate-temperature cracking resistance, respectively [64]. Louisiana DOTD conducted a study in 2016 to select the appropriate HWT rut depth and SCB J_c thresholds for mixture design. A total of nine field projects, including 21 asphalt mixtures, were considered in the study. For each field project, field performance data were obtained from the Louisiana PMS and compared with Louisiana DOTD field performance thresholds and laboratory measured HWT rut depth and SCB J_c values [64, 65]. Based on the findings of the study, Mohammad et al. established a BMD framework, which requires maximum HWT rut depths of 10 mm and 6 mm and minimum SCB J_c values of 0.5 and 0.6 kJ/m^2 for Levels 1 (< 3 million, equivalent single axle loads, ESALs) and 2 (i.e, > 3 million ESALs) traffic, respectively. The developed BMD framework was implemented in Section 502 of the 2016 Louisiana Standard Specification for Roads and Bridges [64, 65]. A subsequent study by Cooper et al. evaluated 51 different Louisiana asphalt mixtures and validated the BMD criteria for HWT rut depth and SCB J_c [66, 67]. In the 2016 Louisiana Standard Specification for Roads and Bridges, the effective asphalt content of the asphalt mixture was increased as part of the new BMD framework to improve mixture durability. The pavement sections used in establishing the BMD framework ranged from three to eight years of service [65, 66, 67] . Because the BMD framework has shown promise in improving the rutting and cracking resistance of asphalt mixtures in Louisiana, it is imperative to continuously monitor pavement sections constructed using these standards for longer service periods (i.e., eight years and beyond) to validate the BMD criteria.

Improved Construction Techniques

Contractors and road agencies frequently utilize advanced technology and equipment to enhance the durability and long-term performance of flexible pavements during construction [1]. For improved construction techniques, this study focused on techniques for enhancing in-place field density and the use of tack coat materials to improve interlayer shear strength (ISS) and performance. The following section presents a comprehensive literature review on enhanced in-place density techniques and optimal methods of using tack coats to improve ISS and performance.

Techniques for Enhancing In-Place Field Density

During the construction of flexible pavements, field density is considered a significant parameter for assessing the performance of the constructed pavement [68]. An in-place density of 92-93% of theoretical maximum specific gravity (G_{mm}) is commonly specified by SHAs for the construction of flexible pavement [1]. Increasing the in-place density of pavement by 1% can improve its rutting and fatigue performance by an average of 7-8%, respectively, thus extending the pavement life by 20% [69]. Inadequate or improper compaction and asphalt mixture design can also lead to premature pavement failure, including rutting and cracking, leading to costly maintenance treatments. With the aim of achieving higher in-place density and improving pavement durability, the Federal Highway Administration (FHWA) funded field demonstration projects across the U.S. to assess the use of different types of construction technologies and techniques for enhancing the in-place field density of asphalt pavements. The improved density techniques considered in the FHWA study for the construction of the pavement sections included the use of warm mix asphalt (WMA) additives, technology, or intelligent compaction (IC) technology. Additionally, equipment such as the paver-mounted thermal profiler (PMTP), spray paver, material transfer vehicle (MTV), etc. were evaluated to assess their ability to enhance in-place field density. Furthermore, asphalt mixture design parameters such as the optimal asphalt binder content and compaction efforts (i.e., desired number of gyrations) were evaluated to determine their effects on in-place field density. Density measurements were performed by using in-situ density measurement devices (i.e., nuclear and non-nuclear density gauges) and collecting field cores. The study concluded that the use of the aforementioned densification techniques was effective in improving the in-place field density of asphalt pavements. Further, the study also helped SHAs improve their in-place field density specifications by varying the minimum density requirements for flexible pavement construction [1].

Warm mix asphalt (WMA) is one of the construction technologies that can be used to achieve the increased in-place density of flexible pavements. Various researchers have explored the possibility of exploiting the lower compaction temperatures of WMA to achieve higher in-place density in laboratory and field studies. For laboratory research findings, Hurley and Prowell observed an overall reduction in air voids (i.e., improved densification) at compaction temperatures as low as 190° F [48]. They evaluated three WMA additives in the laboratory: Aspha-min®, Sasobit®, and Evotherm®. Further, Mohammad et al. reported in a related field study that WMA asphalt layers required only five roller passes to achieve the minimum density requirements, whereas HMA layers required nine passes of roller passes, suggesting improved densification rates from WMA usage [8]. The aforementioned study evaluated two WMA technologies, water-based foaming techniques (Astec Double Barrel Green and Accu-Shear) and chemical additives (Evotherm®, Rediset, and Sasobit), and included six field rehabilitation projects in Louisiana. Along with improved densification, researchers have also reported that WMA mixtures exhibit similar or better rutting and cracking performance compared to conventional HMA mixtures [8, 70, 71]. It is noted that most WMA studies focus on achieving similar densification in WMA pavement sections as conventional HMA pavement sections at relatively lower temperatures. Therefore, it is imperative to explore the benefits of using WMA technologies to achieve higher densification compared to conventional HMA mixtures at similar compaction temperatures and effort.

To attain higher in-place field density, engineers sometimes make modifications to asphalt mix design parameters by increasing the asphalt binder content. Increasing the asphalt content can significantly improve the fatigue life of the flexible pavement [72]. Sreedhar and Coleri reported that increasing the asphalt content and density by 0.7% and 2.0%, respectively, can improve the cracking performance of the flexible pavement, thus enhancing the pavement's service life [73]. Additionally, a research study conducted at LTRC evaluated the effects of increasing the asphalt content to a level above the optimum to enhance densification. Two variations of this technique (i.e., similar compaction effort but higher asphalt content or lower compaction effort but higher asphalt content compared to the control mixture) were used in Phase 3 of the FHWA demonstration project to achieve higher in-place field densities [1]. The LTRC study used higher asphalt content, termed as Plus AC, to achieve higher densification by increasing the asphalt content by 0.2% above the optimum level compared to the control asphalt mixture without changing the compaction effort (N_{design}). Based on the initial laboratory-mechanical evaluation of field cores, researchers at LTRC observed that the increased in-place density associated with the Plus AC mixture resulted in improved rutting and cracking resistance compared to conventional HMA mixtures [4]. Although the 0.2% increase in the asphalt binder content came at an additional cost, this technique resulted in improving rutting and cracking performance and was therefore cost-effective [4]. Since most of the aforementioned findings were based on laboratory test results, it is imperative to evaluate the effects of these densification techniques on long-term performance using field distress data.

The use of intelligent compaction techniques can improve the compaction and densification of flexible pavements. This technology enables road agencies to optimize, automate, and monitor compaction processes and parameters, resulting in higher densification and consistency. To achieve uniformity of temperature and compaction, intelligent compaction systems utilize sensors such as infrared temperature sensors, accelerometer-mounted sensors, global positioning systems (GPS), and on-board computers to monitor real-time mat density and surface temperature and make necessary adjustments [74]. Additionally, material transfer vehicles (MTVs) can be employed to attain a uniform mat temperature and prevent material-and temperature-segregation during construction. These enhanced pavement construction methods effectively improve the densification level of asphalt mats. Temperature-segregation, which refers to the uneven temperature distribution within an uncompacted asphalt mat, influences the densification level of flexible pavements. As stated in NCHRP Report 441, temperature-segregation is defined as “the result of the differential cooling of the portions of the mix on the surface of the mix in a haul truck, along the sides of the truck, and in the wings of a paver” [75]. Infrared cameras, infrared sensor bars, or paver-mounted infrared bars (PAVE IR) can detect temperature-segregated regions in an asphalt mat. Studies have shown that thermally segregated areas of flexible pavements have lower density and cracking resistance than those with uniform temperatures. Researchers have reported that the density differential caused by temperature-segregation can lead to a reduced pavement lifespan of three to seven years [74, 75, 76, 77, 78]. Kim et al. [76] found that the use of a material transfer device (MTV) for remixing helped minimize temperature-segregation. Amirkhanian and Putnam [79] reported that reducing haul time to less than 70 min. and using truck tarps to prevent the surface layer from cooling during mixture haulage limited temperature-segregation.

Tack Coat Optimization

Flexible pavements are constructed with several layers and do not possess a monolithic structure. Applying a tack coat between pavement layers allows the entire section to act as a monolithic structure and effectively distribute traffic loads. According to ASTM D8, “tack coat is an application of bituminous material to an existing relatively non-absorptive surface to provide a thorough bond between old and new surfacing” [80]. Inadequate layer bonding can lead to distresses such as slippage cracking, rutting, and alligator/fatigue cracking, decreasing overall pavement service life [81, 82, 83]. Various factors significantly influence interface bond strength, including the tack coat material type, application rate and uniformity, and pavement surface type. Environmental factors (i.e., dry and wet conditions) and construction factors (i.e., clean and dirty surfaces) can also affect the layer's bond strength [20, 84].

Materials typically used for tack coat applications include hot asphalt binder, asphalt emulsion, and cutback asphalt. Due to environmental concerns, cutback asphalt is not as commonly employed [20, 85]. Compared to hot asphalt binder or cutback asphalt, emulsions are commonly used because they can be applied at relatively lower temperatures, resulting in a more uniform, energy-efficient, and safe application [85]. Asphalt emulsions consist of asphalt binder, water, and an emulsifying agent. These emulsifying agents can either be anionic, cationic, or nonionic. An anionic emulsion carries a negative electrical charge, while a cationic emulsion carries a positive electrical charge [20]. Further, emulsions are divided into three categories: slow-setting (SS), medium-setting (MS), and rapid-setting (RS). These categories are based on setting or curing rates. Examples of slow-setting asphalt emulsions include SS-1, SS-1h, CSS-1, and CSS-1h, whereas those of rapid-setting (RS) grades include RS-1, RS-2, CRS-1, CRS-2, and CRS-2P (i.e., polymer-modified). A significant drawback of employing conventional emulsion tack coat materials is tracking. This occurs when the sticky emulsion, already applied to align tires during construction, leaves unsightly marks on the pavement. Tracking can lead to an uneven application of tack coat, resulting in cracking and premature pavement failure. While good construction methods can help minimize tracking, the use of trackless emulsion products has proven effective in addressing these issues. Among asphalt emulsions, trackless tack coat exhibits the highest interlayer shear strength. Tack coat application rate and non-uniformity significantly impact pavement performance [20, 85]. Nozzle size, spray pattern, spray bar height, distributor speed, application pressure, and tack coat temperature influence the uniformity of application [20]. Covey et al. concluded that non-uniform tack coat application resulted in lower ISS values [86]. Failure to meet the target residual application rate due to either insufficient spray or non-uniform application affects overall pavement performance [20]. Further, other researchers have demonstrated that surfaces with higher roughness exhibit greater interfacial shear strength compared to smoother surfaces at the same application rate [20, 85, 86, 87]. Based on the aforementioned findings, researchers have recommended that tack coat be applied to clean and dry surfaces for better bonding between layers [20, 88].To determine the optimum application methods and rates of tack coat, NCHRP Project 9-40, "Optimization of Tack Coat for HMA Placement," was conducted [20]. Over time, researchers have developed a range of tests, including shear, tensile, and torque tests, to assess tack coat properties [89]. Each test has specific loading conditions (shear, tensile, and torque) and failure modes (tensile or shear stress). Table 2 shows a summary of tests typically used to evaluate tack coat bond strength.

Table 2. Laboratory bonding tests [20]

Test	Loading Condition
Leutner Shear Test	Shear
Louisiana Interlayer Shear Strength Tester (LISST)	
TTI Torsional Shear Test	
Florida Direct Shear Test	
Virginia Shear Fatigue Test	
ASTRA Interface Shear Test	
Layer-Parallel Direct Shear (LPDS)	
NCAT Shear Test	
Loboratorio de Caminos de Barcelona Shear Test (LCB)	
Switzerland Pull-Off Test	Tensile
Kansas Test Method KT-78	
Tex-243-F	

NCHRP Project 9-40 recommended AASHTO T 407, "Standard Method of Test for Determining the Interlayer Shear Strength (ISS)," for characterizing tack coat performance [20]. A minimum ISS value of 40 *psi* was recommended for ensuring satisfactory pavement performance by performing mechanistic and Finite Element (FE) analysis of several pavement sections. Additionally, residual application rates were recommended for each pavement surface type to ensure a higher ISS and improved pavement performance. Table 3 shows typical residual application rates recommended for different pavement surface types [20].

Table 3. NCHRP recommended tack coat residual application rate for different surface types [20]

Surface Type	Residual application rate (*gsy*)
New asphalt mixture	0.035
Old asphalt mixture	0.055
Milled asphalt mixture	0.055
Portland cement concrete	0.045

Subsequently, NCHRP Project 09-40A, "Validation of the Louisiana Interlayer Shear Strength Test for Tack Coat," was conducted to assess and validate AASHTO TP 114. This test protocol was validated through the correlation of measured tack coat parameters with the performance of flexible pavements in field projects constructed in four different climatic zones of the U.S.: wet-freeze, wet-no-freeze, dry-freeze, and dry-no-freeze. NCHRP Project 09-40A also assessed how tack coat type, application rate, and surface texture influenced performance using the LISST device developed in NCHRP Project 9-40 by evaluating field projects [90]. Short-term (i.e., one year) field performance data was collected to validate the effectiveness of the minimum ISS value of 40 *psi* in ensuring satisfactory pavement performance. Since the minimum ISS value was validated in NCHRP Project 09-40A using one-year field performance data, it is imperative to further validate the minimum ISS criteria using field performance data obtained over periods longer than one year.

Objective

Two primary objectives were considered in the study. These included evaluating the impacts of:

1. Enhanced mix design methods on performance; and
2. Enhanced construction techniques on performance.

Specific aims for the first objective included:

- Evaluating the effects of WMA additives and technologies on the long-term performance of asphalt pavements;
- Evaluating the effects of crumb rubber additives on the long-term performance of asphalt pavements; and
- Validating the Louisiana DOTD-specified balanced mix design (BMD) criteria for Hamburg Wheel Tracking (HWT) rut depth and Semi-Circular Bend (SCB) J_c values.

Specific aims for the second objective included:

- Evaluating the effect of increased in-place density techniques on the long-term performance of asphalt pavements; and
- Validating the minimum ISS criteria recommended in NCHRP Project 9-40A using field performance data.

Scope

Field projects constructed across Louisiana since 1994 were used to assess the performance effects of enhanced asphalt mixture design methods and improved construction techniques. This study considered five previous LTRC studies, two NCHRP studies, and one FHWA demonstration project to identify and select field projects for long-term performance evaluation. These studies are listed below:

- LTRC Project 95-5B, "Evaluation of Field Projects Using Crumb Rubber-Modified Asphaltic Concrete" [24];
- LTRC Project 07-1B, "Evaluation of Warm Mix Asphalt Technology in Flexible Pavements [8]" ;
- LTRC Project 10-4B, "Development of Performance-Based Specifications for Louisiana Asphalt Mixtures" [65];
- LTRC Project 11-3B "Testing and Analysis of LWT and SCB Properties of Asphalt Concrete Mixtures" [66];
- LTRC Project 14-1B, "Effects of Temperature-Segregation on the Volumetric and Mechanistic Properties of Asphalt Mixtures" [5];
- NCHRP 9-40A, "Optimization of Tack Coat for HMA Placement" [20];
- NCHRP 9-49A, "Long-Term Field Performance of Warm Mix Asphalt Technologies" [9] ; and
- FHWA Demonstration Project, "Enhanced Durability of Asphalt Pavements through Increased In-Place Density" [1].

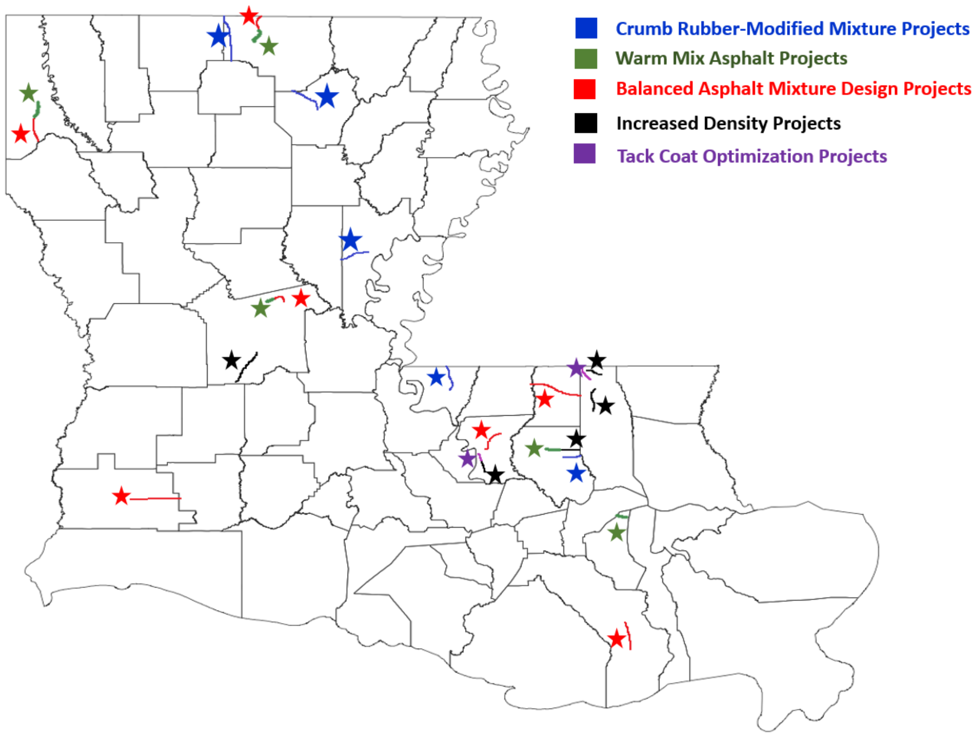
A total of 21 rehabilitation projects were considered in the research study. Field evaluations were conducted for all field projects, involving the collection of field performance indicators (rutting, roughness, and cracking) and index data from the Louisiana Pavement Management System (PMS) for analysis. The collected performance indicator data were analyzed to determine the impact of construction technology, techniques, asphalt mixture materials, and mixture design criteria on rutting, cracking (both alligator/fatigue and transverse), and ride quality performance. Performance index data were also gathered and analyzed to assess the influence of construction techniques, asphalt mixture materials, and mixture design criteria on the overall pavement performance, specifically the Pavement Condition Index (PCI). Additionally, initial laboratory performance indicator data measured during construction were analyzed to assess their ability to rank field performance and validate their predictive capability. Further, falling weight deflectometer (FWD) tests were conducted, and field cores were collected from selected projects to ascertain the effects of improved construction techniques on structural capacity. Additionally, economic analysis was conducted to determine the cost-effectiveness of these enhanced mix design methods, specifically the inclusion of CR particles in asphalt mixtures for sustainable pavement construction.

Methodology

Field Project Identification and Selection

To evaluate the performance of flexible pavements built with improved asphalt mixture design methods and construction techniques in Louisiana, specific field projects were identified. These field projects were identified based on research conducted at the Louisiana Transportation Research Center (LTRC), which explored the effectiveness of enhanced asphalt mixture design methods and construction techniques in improving field performance. Field project identification was the most crucial part of this research study. Information such as project number, control section, location (parish and district), section length (start and end log mile), traffic direction (primary and secondary), and pavement structure (construction material type) were obtained from the Louisiana PMS database. 24 field projects in Louisiana were identified and carefully chosen for comprehensive, long-term evaluation in accordance with the study's objectives. This section is divided into four sub-headings, providing detailed information about the field projects chosen to accomplish each objective. Figure 4 presents the location of the field projects considered in this study. It is noted that pavement sections at each field project location had similar structures and were subjected to the same traffic and environmental conditions over the analysis period.

Figure 4. Field project locations



Use of Crumb Rubber-Modified Asphalt Mixture (CRM) for Sustainable Mixture Production

Five field projects were considered in this project: US 61, LA 1040, US 84, LA 15, and US 167. These projects were rehabilitation projects constructed between 1994 and 1997 [24]. For each project evaluated, at least one CRM section was constructed with a companion control section; see Table 4. The pavement section service years ranged from eight to 18 years.

Table 4. Summary of crumb rubber projects

Field Projects	CR Product	Blending Process/% Blended	Test Sections	Length (miles)	Design Traffic Volume (ESALs)	Years in Service
US 61	16-mesh generic CR by ISI	Wet/17.5%	CRM Arizona Wet	4.5	844,761	11
	NA	NA	Control	1.0		
LA 1040	PlusRide™ shredded rubber	Dry/3%	CRM PlusRide Dry	3.0	1,211,947	18
	NA	NA	Control	1.7		
US 84	Neste Wright	Wet/5%	CRM Neste Wright Wet	1.9	898,143	13
	NA	NA	Control	2.1		
LA 15	Rouse-80 powder /10%	Wet/10%	CRM Rouse Wet	2.0	485,814	9
	16-mesh generic CR by ISI	Wet/17.5%	CRM Arizona Wet	2.0		
	NA	NA	Control	1.7		
US 167	Rouse-80 powder	Dry/1%	CRM Rouse Dry	2.0	829,173	8
	16-mesh generic CR by ISI	Dry/2%	CRM Generic Dry	2.0		
	NA	NA	Control	2.7		

CR: crumb rubber; CRM: crumb rubber-modified; ISI: International Surfacing Inc. NA: not applicable; ESALs: equivalent single axle loads.

US 61

US 61 is located in West Feliciana Parish, Louisiana. The project consisted of a CRM and a control section constructed in October 1992. Arizona Wet process was used in constructing the CRM asphalt section (referred to hereafter as CRM Arizona Wet), which utilized 16-mesh crumb rubber manufactured by International Surfacing Inc (ISI). AC 10 asphalt binder was blended with 17.5% by weight of asphalt binder content CR prior to mixing to construct the CRM section. The control section was constructed with a Styrene Butadiene Styrene (SBS) polymer-modified asphalt binder graded as PAC 40HG (equivalent to asphalt binder meeting Louisiana specifications for Roads and Bridges of PG 70-22) [24, 64]. These pavement sections were designed for Level 1 traffic (< 3 million ESALS). Test sections on US 61 were rehabilitated in 2006 after 11 years of service.

LA 1040

LA 1040 was constructed in February 1994 in Livingston Parish, Louisiana. The project comprised both a control and CRM asphalt section. PlusRideTM dry process (referred to hereafter as CRM Plus Ride Dry), which requires blending of 3% by total weight of mix PlusRideTM shredded rubber with aggregates, was utilized to construct the CRM section. AC 30 (equivalent to asphalt binder meeting Louisiana specifications of PG 67-22 asphalt binder) was used in both the control and CRM asphalt sections. These pavement sections were designed for Level 1 traffic (< 3 million ESALS). Rehabilitation activity was performed on the test sections in 2014 after 18 years of service [24, 64].

US 84

This project was constructed in August 1994 in Catahoula Parish, Louisiana. The project included both CRM and control sections. Neste Wright Wet process (referred to hereafter as CRM Neste Wright Wet) was used to incorporate 5% Neste Wright CR by weight of asphalt binder content into AC 30 asphalt binder to construct the CRM section. The control section was constructed with SBS polymer-modified asphalt binder graded as PAC 40HG (equivalent to PG 70-22). These pavement sections were designed for Level 1 traffic (< 3 million ESALS). These pavement sections were rehabilitated in 2010 after 13 years of service [24, 64].

LA 15

This project was constructed in October 1995 in Ouachita Parish, Louisiana. Three test sections were considered in this project: a CRM section constructed using Arizona Wet process, referred to as CRM Arizona Wet, that included 17.5% 16-mesh crumb rubber by weight of asphalt binder; a CRM section constructed using the Rouse Wet process, referred to as CRM Rouse Wet, that used 10% 80-mesh crumb rubber by weight of asphalt binder; and a control section constructed with PAC 40HG polymer-modified binder (equivalent to PG 70-22). AC 10 and AC 30 asphalt binders were used in the Arizona and Rouse Wet processes, respectively. These pavement sections were designed for Level 1 traffic (< 3 million ESALS). Rehabilitation activities were conducted in 2006 after nine years of service [24, 64].

US 167

US 167 pavement sections were constructed in May 1996 in Union Parish, Louisiana. Three experimental sections were evaluated. Two CRM sections were constructed utilizing the Rouse and Generic Dry processes and a control section. A total of 1% and 2% of CR by weight of the total asphalt mixture were used in the Rouse (referred to as CRM Rouse Dry) and Generic (referred to as CRM Generic Dry) Dry processes, respectively. A PAC 40HG (equivalent to PG 70-22) asphalt binder was used to construct the CRM and control sections. These pavement sections were designed for Level 1 traffic (< 3 million ESALS). The test sections were rehabilitated in 2006 after eight years of service [24, 64].

Use of Warm Mix Asphalt (WMA) Additives for Sustainable Pavement Construction

To assess the long-term performance of pavement sections constructed using different WMA technologies, four field projects were considered: LA 3121, US 61, US 171, and US 90. Each project consisted of a conventional asphalt pavement test section and a companion WMA test section. Table 5 shows a summary of the properties of the pavement sections evaluated to assess the effects WMA technology on field performance. A brief description of each pavement section is provided below [3].

Table 5. Summary of WMA projects

Route	Section Length (mi.)	Mixture Type	Pavement Structure/ Thickness (in.)	Year of Construction	Service Years	Design Traffic Volume (ESALS)	Thickness of Asphalt Overlay
LA 3121	2.3	Conventional HMA + 15% RAP	ACC / 2	2009	8	80,000	2 in.
	1.5	Evotherm WMA + 15% RAP	CTB / 4				
	0.7	Evotherm WMA + 30% RAP	Red Sand				
US 61	2.9	Conventional HMA + Granite Agg. + 15% RAP	ACC / 12	2012	5	12,000,000	
	2.4	Sasobit WMA + Granite + Agg. + 15% RAP	PCC / 10				
	2.7	Foamed WMA + Sandstone Agg. + 15% RAP	Grey Fat Clay				
US 171	0.8	Conventional HMA + 15% RAP	ACC / 12	2010	7	2,500,000	
	1.4	Rediset WMA + 15% RAP	PCC / 10				
	3.0	Foamed WMA + 15% RAP	Grey Fat Clay				
	1.3	Foamed WMA + 30% RAP					
US 90	0.3	Conventional HMA + 15% RAP	ACC / 10	2012	5	2,8000,00	
	1.3	Evotherm WMA + 30% RAP	PCC /13				
			Tan Lean Clay				

mi: mile(s); HMA: hot mix asphalt; WMA: warm mix asphalt; Agg.: aggregate; RAP: recycled asphalt pavement; ACC: asphalt cement concrete; CTB: cement treated base; PCC: Portland cement concrete; ESALs: equivalent single axle loads.

LA 3121

The pavement sections on LA 3121 were constructed in 2009 in Union Parish, Louisiana. Three experimental sections were constructed that comprised a conventional HMA mixture with 15% RAP, Evotherm WMA mixture with 15% RAP, and Evotherm WMA mixture containing 30% RAP. The pavement structure is a flexible one and consisted of a two-in. asphalt layer placed over a four-in. cement-treated base. The design traffic volume for each direction was approximately 80,000 equivalent single axle loads (ESALs).

US 61

This project was constructed in 2012 in St. Charles Parish, Louisiana. Three test sections were evaluated in this field project: a conventional HMA mixture containing 15% RAP and granite aggregates; a Sasobit WMA mixture with 15% RAP and granite aggregates; and a foamed WMA mixture containing 15% RAP and sandstone aggregates. The pavement structure is composite with a grey-fat-clay subgrade and a 12-in. asphalt layer placed on a 10-in. PCC layer. The design traffic volume for each direction was approximately 12 million ESALs.

US 171

US 171 was constructed in 2010 in Caddo Parish, Louisiana. Four test sections were evaluated in this project: a conventional HMA mixture containing 15% RAP; a Rediset WMA mixture with 15% RAP; a Foamed WMA mixture with 15% RAP; and a Foamed WMA mixture with 30% RAP. The pavement structure is a composite consisting of a clay subgrade and a 12-in. asphalt layer placed over 10-in. Portland cement concrete. The design traffic volume for each direction was approximately 2.5 million ESALs.

US 90

These sections were constructed in 2012 in St Charles Parish, Louisiana. This project consisted of two test sections that included conventional HMA with 15% RAP and Evotherm WMA with 15% RAP. The pavement structure is composite and consisted of a lean clay subgrade and 10-in. asphalt layer placed over 13-in. concrete layer. The design traffic for each direction was approximately 2.8 million ESALs.

Balanced Asphalt Mixture Design Approach as an Asphalt Mix Design Criteria

Seven field projects located throughout Louisiana were included in this study. These field projects were constructed between 2005 and 2013 [65]. The field projects included 13 pavement sections that were designed for Level 1 (< 3 million ESALs) and Level 2 traffic (> 3 million ESALs). Among the 13 pavement sections considered in the study, 11 were designed for Level 1 traffic, including six HMA sections and five WMA sections. Pavement sections designed for Level 1 traffic ranged from eight to 12 years of service. Further, two pavement sections were designed for Level 2 traffic, both of which were HMA sections. The Level 2 pavement sections ranged from 16 to 18 years of service [65, 66]. Table 6 presents a detailed summary of the projects evaluated in the balanced mixture design project.

Table 6. Summary of balanced mix design projects

Field Project	Mixture Type	Design Traffic Level	Pavement Structure / Thickness, in.	Asphalt Binder Grade	NMAS, mm	Service Years	Pavement Section Length, mi.
LA 116	WMA	1 (< 3 million ESALS)	ACC/5	PG 70-22M	12.5	11	1.3
	HMA		CSB/8				1.7
			Sand				
LA 3121	HMA		ACC/2	PG 70-22M	12.5	12	1.9
	WMA1		CTB/4				1.9
	WMA2		Red Sand				1.6
US 171	HMA		ACC/12	PG 70-22M	12.5	11	1.0
	WMA1		PCC/10				2.2
	WMA2		Clay				0.5
LA 10	HMA		ACC/7	PG 70-22RM	12.5	9	3.1
			PCC/7				
			Clay				
LA 3235	HMA1		ACC/9	PG 70-22M	12.5	8	4.1
	HMA2		Granular Base/12				4.1
			Sand				
I-10	HMA	2 (< 3 million ESALS)	ACC/9	PG 76-22M	12.5	18	2.7
			PCC/8				
			Clay				
LA 964	HMA		ACC/6	PG 76-22M	19	16	3.1
			CSB/8				
			Silt				

HMA: hot mix asphalt; WMA: warm mix asphalt; ESALs: equivalent single axle loads; mi.: miles; NMAS: Nominal Maximum aggregate size; ACC: asphalt cement concrete; CTB: cement treated base; PCC: Portland cement concrete; PG: performance grade; M: styrene butadiene styrene polymer-modified binder; RM: crumb rubber-modified.

LA 116

The pavement sections in this project were constructed in 2010 in Rapides Parish, Louisiana. Two pavement sections were constructed and evaluated in this project: WMA and HMA sections. These pavement sections were designed for Level 1 traffic (< 3 million ESALS). PG 70-22M asphalt binder was used to construct the pavement sections. These pavement sections have been in service for 11 years.

LA 3121

The pavement sections on LA 3121 were constructed in 2009 in Union Parish, Louisiana. Three pavement sections were evaluated as part of this project: HMA, WMA1, and WMA2 sections. These pavement sections were designed for Level 1 traffic (< 3 million ESALS). A PG 70-22M asphalt binder was used to construct the pavement sections. These pavement sections have been in service for 12 years.

US 171

The pavement sections in this field project were constructed in 2010 in Caddo Parish, Louisiana. Three pavement sections were considered in this project: HMA, WMA1 and WMA2 sections. These pavement sections were designed for Level 1 traffic (< 3 million ESALS). A PG 70-22M asphalt binder was used for the construction of the pavement sections. These pavement sections have been in service for 11 years.

LA 10

The pavement section on LA 10 was constructed in 2012 in St. Helena Parish, Louisiana. A conventional HMA mixture was used for this project. This pavement section was designed for Level 1 traffic (< 3 million ESALS). A PG 70-22RM asphalt binder was used to construct the pavement section. This pavement section has been in service for nine years.

LA 3235

The LA 3235 pavement sections were constructed in 2013 in Lafourche Parish, Louisiana. Two conventional HMA sections, HMA1 and HMA2, were constructed for this field project. These pavement sections were designed for Level 1 traffic (< 3 million ESALS). A PG 70-22M asphalt binder was used for the construction of the pavement sections. These pavement sections have been in service for eight years.

I-10

The pavement section on this field project was constructed in 2003 in Calcasieu Parish, Louisiana. A conventional HMA mixture was used to construct the section. This pavement section was designed for Level 2 traffic (< 3 million ESALS). A PG 76-22M asphalt binder was used to construct the pavement sections. This pavement section has been in service for 18 years.

LA 964

The LA 964 pavement section was constructed in in 2005 in East Baton Rouge Parish, Louisiana. A conventional HMA mixture was used to construct the pavement section. The pavement section was designed for Level 2 traffic (< 3 million ESALS). A PG 76-22M asphalt binder was used to construct the pavement section. This pavement section has been in service for 19 years.

Techniques for Enhancing In-Place Field Density

Two field projects were evaluated to assess the techniques for enhancing the in-place density of asphalt pavements. The first field project consisted of three test sections constructed in 2018 as part of the FHWA demonstration project on enhanced durability through increased in-place density [1]. Three test sections—a control section, a WMA section, and an increased asphalt content section—were constructed on US 190 in Louisiana to assess techniques for enhancing in-place field density. Similarly, the second field project comprised test sections constructed from 2015 to 2016 as part of a Louisiana DOTD-sponsored project to assess the effects of thermal segregation in constructed asphalt mats on mixture volumetric and mechanistic properties [5]. Four routes were evaluated: LA 30, US 165, LA 1058, and LA 1053. To monitor the extent of temperature-segregation in each pavement section, a paver-mounted infrared bar was used. Based on the degree of thermal segregation, each pavement section was categorized into two experimental sections: a control section without thermal segregation (i.e., spots with temperature-differentials lower than 14˚C (25˚F) compared to the specified compaction temperature) and a thermally segregated section (i.e., colder spots with temperature-differentials higher than 14˚C (25˚F) compared to the specified compaction temperature). Table 7 presents a detailed summary of the projects evaluated.

Table 7. Summary of enhanced in-place density projects

Route	Placement Temperature (˚F)	Mixture Type	Test Section	Average In-Place Density (% G_{mm})	Year of Construction	Service Years
Field Project 1						
US 190	300	WMA	Evotherm WMA	96.5	2018	5
		HMA	Plus AC	96.9		
			Control HMA	95.6		
Field Project 2						
LA 30	300	HMA	Control	91.5	2015	7
			Temp. Segregated	88.4		
US 165	300		Control	94.0	2016	6
			Temp. Segregated	93.0		
LA 1058	275		Control	95.0	2016	6
			Temp. Segregated	93.3		
LA 1053	300		Control	93.2	2016	6
			Temp. Segregated	92.1		

in.: inch; NA: not available; AC: asphalt content; WMA: warm mix asphalt; HMA: hot mix asphalt; %G_{mm}: percent theoretical maximum specific gravity.

US 190

The US 190 pavement sections were constructed in 2018 in Livingston Parish, Louisiana. Three pavement sections were considered as part of this project: control section, WMA section, and an increased asphalt content section. These sections were constructed as part of the FHWA demonstration project on enhanced durability through increased in-place density [1]. These pavement sections were designed for Level 1 traffic. These pavement sections have been in service for five years.

LA 30

The pavement sections on LA 30 in East Baton Rouge Parish, Louisiana, were constructed in 2015. This project included two pavement sections: a control section and a temperature-segregated section, both designed for Level 2 traffic. The pavement structure consists of a 2-in. wearing course placed on an existing 10-in. thick asphalt layer, after 2 in. of cold planing. Beneath the binder course is a 14-in. cement-treated base. The 20-year design traffic for this pavement section was 2,447,372 Equivalent Standard Axle Loads (ESALs). A PG 76-22M binder was used for the wearing course mixture. These pavement sections have been in service for seven years.

US 165

The pavement sections on US 165 in Rapides Parish, Louisiana, were constructed in 2016. This project also included a control section and a temperature-segregated section. The construction involved milling a 3.5-in. existing asphalt layer, which was originally 10.5 in. thick, followed by the placement of a 2-in. Level 2 binder course and a 1.5-in. Level 2F wearing course. The wearing course layer was constructed with a PG 70-22M asphalt binder. The 20-year design traffic was estimated at 4,225,656 ESALs. The existing base material consisted of a 7-in. cement-treated soil. These pavement sections have been in service for six years.

LA 1058

The pavement sections on LA 1058 in Tangipahoa Parish, Louisiana, were constructed in 2016. This project comprised a control section and a temperature-segregated section. Construction involved milling 2 in. from an existing asphalt layer, followed by the placement of a 2-in. Level 1 binder course and a 1.5-in. Level 1 wearing course. The wearing course layer was constructed with a PG 70-22M asphalt binder. The existing asphalt layer is underlain by a 12-in. cement-treated base. The 20-year design traffic for this pavement section was 507,591 ESALs. These pavement sections have been in service for six years.

LA 1053

These pavement sections were constructed in 2016 in Tangipahoa Parish, Louisiana, and include a control section and a temperature-segregated section. The construction process involved cold planing an existing asphalt layer, which was originally 5 in. thick, by 2 in., followed by the placement of a 2-in. Level 1 binder course and a 1.5-in. Level 1 wearing course. The wearing course layer was constructed with a PG 82-22RM asphalt binder. The existing asphalt layer is underlain by a 12-in. cement-treated base. The 20-year design traffic was calculated to be 151,244 ESALs. These pavement sections have been in service for six years.

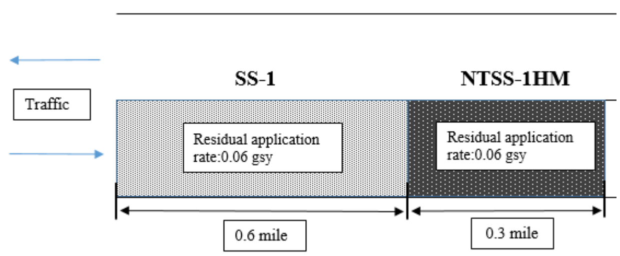
Tack Coat Optimization

Two field rehabilitation projects with seven to eight service years were investigated in NCHRP Project 9-40A, "Validation of the Louisiana Interlayer Shear Strength Test for Tack Coat" [90]. The field projects assessed in the aforementioned study consisted of a total of ten pavement sections. Various types of tack coat materials, including SS and RS and non-tracking asphalt emulsions, were applied at different residual application rates, ranging from 0.01 *gsy* to 0.06 *gsy*. The rehabilitation projects evaluated in this part of the study are described in detail below.

LA 30

This rehabilitation project was constructed in 2014 on LA 30 in East Baton Rouge Parish, Louisiana. Two pavement sections were constructed using two tack coat types at a residual application rate of 0.06 *gsy*; see Figure 5. The wet pavement sections were milled prior to the application of the tack coat material. After the tack coat application, a 1.5-in. wearing course was placed on the two sections. The wearing course mix was prepared with a 12.5 mm nominal maximum aggregate size (NMAS) Superpave asphalt mixture and SBS-modified PG 76-22 asphalt binder. The two tack coat types utilized on the two pavement sections included a slow setting (SS-1) and a non-tracking rapid setting (NTSS-1HM) tack coat material.

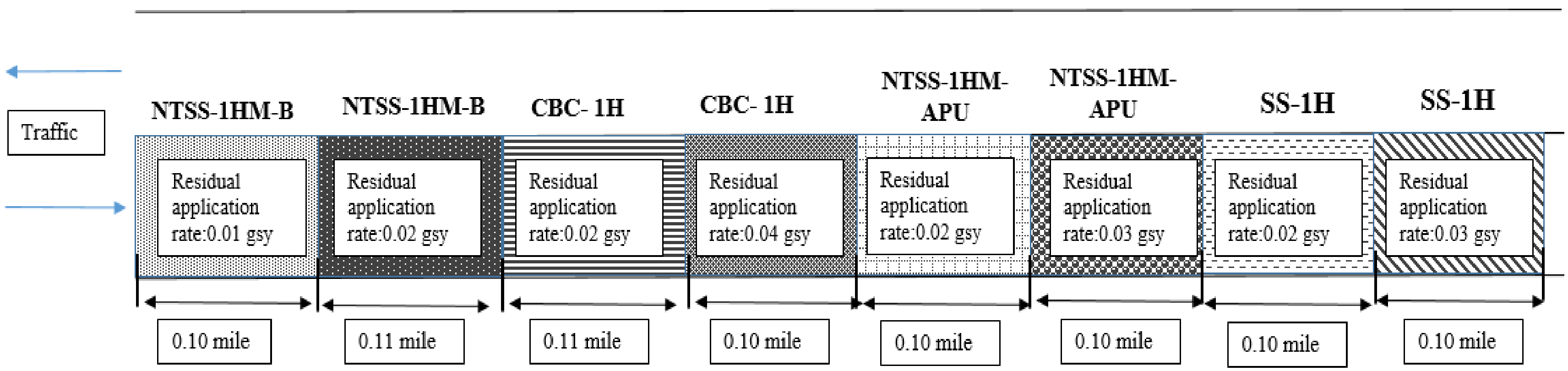
Figure 5. Layout of LA 30



LA 1053

This rehabilitation project was constructed in 2015 on LA 1053 in Tangipahoa Parish, Louisiana. Eight pavement sections were constructed using four tack coat types at two different residual application rates ranging from 0.01 to 0.04 *gsy*; see Figure 6. There were eight combinations of tack coat types and residual application rates, one for each pavement section. There was no milling performed on the surface of the pavement sections prior to the application of tack coat material. After the tack coat application, a 1.5-in. wearing course layer was placed on the eight sections. The wearing course mix was prepared with a 12.5 mm NMAS Superpave mixture along with 14.3% RAP and a PG 64-22 asphalt binder. One slow setting (SS-1H) and three trackless rapid settings (two NTSS-1HM and one CBC-1H) tack coat materials were utilized on the eight pavement sections.

Figure 6. Layout of LA 1053



Laboratory Mechanical Evaluation

As part of this study, results obtained from different mechanical tests performed on plant-produced and laboratory-compacted specimens during the construction of selected field projects were compiled for analysis. For the crumb rubber study, results from laboratory mechanical tests performed on plant-produced and laboratory-compacted specimens during construction were compiled and analyzed to ascertain the effectiveness of these tests in ranking field performance. It is noted that these tests were performed based on the state of the practice and the equipment available at the time of construction in the 1990s [24]. These mechanical tests included Marshall Flow at 60˚C (AASHTO T 245), indirect tensile strength at 25˚C (AASHTO 245), and resilient modulus at 25˚C (ASTM D4123). Performance parameters considered from these tests included Marshall Flow for rutting resistance, IDT strength for cracking resistance, and resilient modulus (*Mr*) for cracking resistance characterization.

Furthermore, laboratory mechanical tests performed during the construction of pavement sections and used to assess the effects of WMA technology on field performance were compiled for analysis. Table 8 presents a summary of asphalt mixture laboratory experiments performed as part of the WMA study. All tests were performed on plant-produced mixtures obtained at the time of construction and compacted in the laboratory. Samples were compacted at air void levels of 7.0 ±0.5%. It is noted that this air void range was within the range of air void content values recorded in field compacted specimens from the test sections evaluated. Further, it is noted that WMA and control HMA specimens utilized in the flow number test were compacted in the laboratory following AASHTO T 378 specification for compacting WMA and HMA specimens for flow number test, respectively [8].

Table 8. Laboratory mechanical tests for WMA study

Test/Temperature	Test Protocol	Engineering Properties Measured	Test Replicates
HWTT, 50°C	AASHTO T 324	Rutting and moisture susceptibility	4
Flow Number, 54°C	AASHTO T 378	Rutting susceptibility	3
SCB, 25°C	ASTM D8044	Intermediate temperature/fatigue cracking resistance	4
Dissipated Creep Strain Energy, 10°C	Florida IDT Test [91]	Intermediate temperature/fatigue cracking resistance	3

HWTT: Hamburg wheel tracking test; SCB: Semi-Circular Bend test; IDT: indirect tensile.

For the balanced mixture design study, HWT rut depth and SCB J_c values obtained from mechanical tests performed on plant-produced and laboratory-compacted specimens were compiled for analysis. The HWT test was conducted per AASHTO T 324, "Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)." The test involves rolling a steel wheel with a weight of 158 lbs. over cylindrical asphalt specimens that are 150 mm in diameter and 60 mm thick and submerged in hot water (50°C) for 20,000 passes at 56 passes per min. The rut depth of the specimens is measured at regular intervals throughout the test. Four replicates were used in the HWT test.

The SCB test was conducted following ASTM D8044, "Standard Test Method for Evaluation of Asphalt Mixture Cracking Resistance Using the Semi-Circular Bend Test (SCB) at Intermediate Temperatures." The test assesses the fracture resistance of asphalt mixtures by employing principles of fracture mechanics and the critical strain energy release rate, also known as the critical value of J-integral, or J_c. Semi-circular specimens are tested at three different notch depths (25.4 mm, 31.8 mm, and 38 mm) to determine the critical value of J-integral (J_c). The test entails loading the semi-circular specimens in a three-point bending load configuration at a deformation rate of 0.5 mm/min. until failure. Four SCB test replicates were employed. The critical value of J-integral (J_c) is determined using the following equation:

$$Jc = \left(\frac{U_1}{b_1} - \frac{U_2}{b_2}\right) \frac{1}{a_2 - a_1} \qquad [1]$$

where,
J_c = critical strain energy release rate (kJ/m^2);
b = sample thickness (m);
a = notch depth (m); and
U = strain energy to failure (kJ).

Table 9 shows a summary of HWT rut depth and SCB J_c values for the wearing course of the pavement sections evaluated.

Table 9. HWT rut depth and SCB J_c test results

Field Projects	Mixture Type	Design Traffic Level	HWT Rut Depth, mm	HWT Rut Depth Criteria	SCB J_c kJ/m^2	SCB J_c Criteria
LA 116	WMA	1 (< 3 million ESALS)	3.2	10 mm – Level 1	0.7	0.5 kJ/m^2 – Level 1
	HMA		1.7		0.8	
LA 3121	HMA		3.1		0.7	
	WMA1		4.5		0.9	
	WMA2		4.8		0.6	
US 171	HMA		6.7		0.5	
	WMA1		4.3		0.7	
	WMA2		4.8		0.6	
LA 10	HMA		3.7		0.5	
LA 3235	HMA1		4.6		0.6	
	HMA2		4.6		0.6	
I-10	HMA	2 (> 3 million ESALS)	2.7	6 mm – Level 2	0.9	0.6 kJ/m^2 – Level 2
LA 964	HMA		4.1		0.3	

HMA: hot mix asphalt; WMA: warm mix asphalt; ESALs: equivalent single axle loads; HWT: Hamburg wheel tracking ; SCB J_c : Semicircular bending test strain energy release rate.

In the tack coat optimization study, results for Louisiana Interlayer Shear Strength Tests (LISST) performed on field cores obtained from the proposed pavement sections immediately after construction were compiled for analysis [20, 90]. Table 10 summarizes ISS values measured using the LISST device for the pavement sections evaluated in the study.

Table 10. Summary of ISS values [20, 90]

Field Project / Surface Texture	Tack Coat Type	Target Residual Application Rate	Measured Residual Application Rate, *gsy*	Residual Application Rate Recommendation	Years in Service	ISS, *psi*
LA 1053 (New Surface)	NTSS-1HM-B	0.022	0.010	DOTD	6	55
		0.035	0.020	NCHRP		80
	CBC-1H	0.019	0.020	DOTD		41
		0.035	0.040	NCHRP		66
	NTSS-1HM-APU	0.017	0.020	DOTD		68
		0.035	0.030	NCHRP		76
	SS-1H	0.017	0.020	DOTD		52
		0.035	0.030	NCHRP		58
LA 30 (Milled Surface)	SS-1	0.055	0.060	DOTD/NCHRP	7	38
	NTSS-1HM					80

DOTD: Louisiana Department of Transportation and Development; NCHRP: National Cooperative Highway Research Program; ISS: Interlayer shear strength; *gsy*: gallons per square yard.

PMS Data Acquisition and Analysis

Field performance or distress data were acquired from the Louisiana Pavement Management System (PMS) for all field projects considered in the study. Louisiana DOTD collects and stores performance indicators (rutting, roughness, and cracking) and indexes (rutting, roughness, alligator, and random) in the PMS, which is a web-based application referred to as iVision5. The iVision5 system stores performance or distress data alongside images of the road and right-of-way. Louisiana DOTD conducts annual surveys of its road network in the national highway system (NHS) and biennial surveys for all other highways. The distress data are collected using the Automatic Road Analyzer (ARAN); see Figure 7 [65, 92].

Figure 7. Automatic road analyzer (ARAN) van

The ARAN employs the transverse laser profiler at a van's rear end to measure rutting. This apparatus gathers 1,280 measurements across the lane's width to calculate the mean transverse rut depth at specific positions. Transverse rut depth is continuously assessed while the vehicle is in motion at typical highway speeds. Subsequently, the average rut depth is computed for each 528-ft. (0.1 mi.) pavement segment and utilized in subsequent analyses. Further, the ARAN has a high-speed profiler for longitudinal profile and roughness measurements. Pavement cracks are evaluated using a 3-D laser scanning measuring system (LCMS) integrated at the rear of the ARAN van. This system captures planar-view images of the pavement surface at 25-ft. (0.004 mi.) intervals while the van travels at designated highway speeds. These images undergo processing, after which cracks are categorized based on severity, following the Louisiana Cracking and Patching Protocol for Asphalt Surface Pavements. The Louisiana PMS documents various types of cracking, including alligator, transverse, longitudinal, block, and random, with different levels of severity (low, moderate, and high). Alligator cracks and random cracks are frequently observed within the Louisiana PMS database. Notably, "random crack" encompasses the cumulative occurrence of transverse and longitudinal non-wheel path cracks. Louisiana DOTD uses a distress index to ascertain the condition of its pavement network, make maintenance decisions, and assign treatment costs. The index values range from 1 to 100, with 100 being in perfect condition. The rutting and cracking index values were computed as shown in Equations 2 and 3 [92].

$$Rutting\ Index = -80(rut\ depth, inches) + 110 \quad [2]$$

$$Cracking\ Index = 100 - [(CD)_L + (CD)_M + (CD)_H] \quad [3]$$

where,
$(CD)_L$ = deduct value for a low-severity crack;
$(CD)_M$ = deduct value for a medium-severity crack; and
$(CD)_H$ = deduct value for a high-severity crack.

Elsewhere, researchers have detailed the characterization of low, medium, and high-severity random and alligator cracks, along with the determination of their respective deduct values [92, 93]. Louisiana DOTD uses these index values to trigger maintenance decisions and assign treatment costs. For example, rutting index values below 80 on any interstate highway in Louisiana will trigger a thin overlay treatment decision [93, 94].

Further, Pavement Condition Index (PCI), a measure of the overall pavement condition of pavement sections, is computed using the performance index values obtained. Similar to the performance index ratings, PCI ratings ranged from 0 to 100 index values, where 100 represents road in excellent condition. After downloading field performance data for the selected projects from iVision5, the data was organized in a Microsoft Excel document. The iVision5 system provides two types of files: segment and distress data files. The segment data file contains distress information for every 0.1 mi. reported according to the classification defined by Louisiana DOTD. These segment data files were utilized for obtaining performance data for all pavement sections. Similarly, the distress data file provides more detailed information related to cracking and patching. In the distress data file, data is reported for every 0.004 mi. of pavement. For each field project considered, detailed cracking data was obtained from the distress data file to separate the load (transverse, alligator, and longitudinal) and non-load-associated or construction-related cracks (random edge cracks) for detailed analyses. It is noted that only load-associated cracks were considered in the analysis. The Deighton Total Infrastructure Management System (DTiMs) was also utilized to obtain ground-penetrating radar (GPR) and field core data to characterize the structure of the pavement sections considered in the study. Additionally, index plot data for each pavement section collected over several years was obtained from DTiMs.

Statistical Analyses of Performance Data

Statistical analysis was performed to determine the significance of the performance difference between the control sections and sections constructed using enhanced asphalt mixture design methods and construction techniques. For the crumb rubber-modified asphalt mixture project, a t-test with 95% confidence compared the average performance indicator and PCI values of each CRM section to its control section. This test aimed to determine if the CRM mixture performed significantly different from the conventional HMA mixture. To establish the significance of performance differences between WMA pavement test sections and their corresponding control test sections in the WMA study, an Analysis of Variance (ANOVA) was conducted first, followed by a Tukey's multiple comparison test. This two-step process was conducted to identify statistically significant differences in performance among the WMA test sections and their controls, all at a 95% confidence level. The analysis focused on the average values of chosen performance parameters. For the balanced mixture design project, statistical analysis was not performed for any pavement sections. Similar to the CRM study, a t-test was used to compare the average performance of increased density sections to their corresponding control section. This test aimed to identify if the increased density techniques resulted in a statistically significant improvement in performance. For the tack coat optimization project used in the validation of the 40 *psi* ISS criterion, no statistical analysis was performed. The statistical results were ranked and presented with letters (A, B, C) assigned to different performance levels (A for best rutting resistance, C for worst). It is noted that the statistical analysis and ranking were conducted on pavement sections located on the same route, as the test sections on each route were exposed to similar factors such as pavement structure, traffic, etc. Furthermore, the statistical analyses were performed using the t-test and analysis of variance procedures provided in the Statistical Analysis System (SAS) 9.4 program.

Field Performance Prediction

The study aimed to identify the service life of selected pavement sections considered in the study, which refers to the time it takes for these pavements to achieve a specific minimum performance threshold specified by Louisiana DOTD. This threshold indicates when maintenance or rehabilitation work is needed. However, the majority of these pavement sections were neither approaching the end of their lifespan nor had performance index values above the minimum required for rehabilitation treatment. Therefore, a prediction technique was utilized to ascertain the service life of certain pavement sections. Louisiana DOTD's sigmoidal model was used to predict the index values of these pavement sections to determine their service lives, because pavement distress severity plots have been shown to follow a sigmoidal model with upper and lower asymptotes [94, 95, 96, 97]. The performance index values were predicted using Equation 4.

$$Performance\ index = Max - C_1 * e^{\left(-\left(\frac{C2}{t}\right)^{C3}\right)} \quad [4]$$

where,

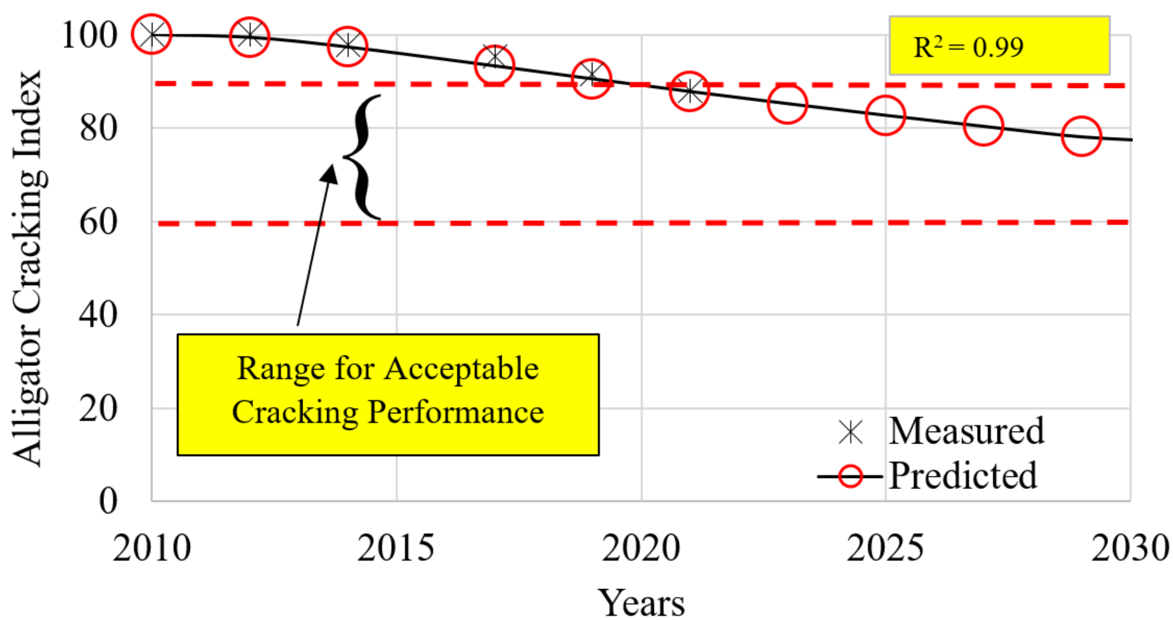
Max = the initial performance index value;

t = elapsed time, years; and

C_1, C_2, and C_3 are regression coefficients

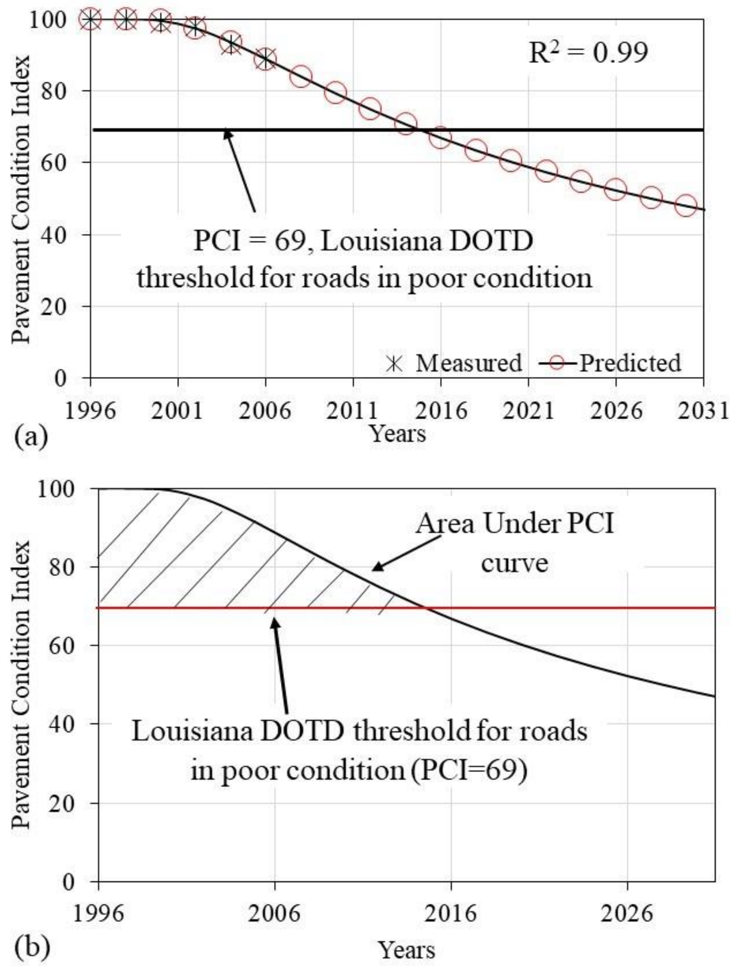
Field performance prediction was performed for the crumb rubber-modified asphalt mixture and BMD projects. Figure 8 shows a sample plot for the measured and predicted alligator cracking index for pavement sections evaluated in the BMD project.

Figure 8. Measured and predicted alligator cracking index



Further, for the crumb rubber-modified asphalt mixture project, the PCI values recorded over several years were used to predict PCI values over extended service periods until the values reached a terminal threshold where treatment is required. The area under the PCI plots from the time of initial construction until the time the PCI reached a terminal point of 69 was computed graphically. Figure 9 presents sample plots for measured and predicted PCI values and the area under the PCI curve. The area under the PCI curve is assumed to measure the effectiveness of CR modification or otherwise in enhancing the overall pavement condition [98, 99]. The area under the PCI curve for CRM sections was compared with that of their corresponding control sections.

Figure 9. (a) Measured and predicted PCI (b) area under PCI curve



Life Cycle Cost Analysis

Life cycle cost analysis (LCCA) was performed for the crumb rubber-modified asphalt project. LCCA was conducted to ascertain the cost-effectiveness of CR modification in flexible pavement construction. For each field project, the average cost-effectiveness (CE) and the equivalent uniform annual cost (EUAC) were computed and analyzed. A detailed description of the computation of CE and EUAC are provided below.

Cost-Effectiveness (CE)

A cost-effective analysis was performed based on the predicted PCI values of pavement sections. The analysis considered the initial cost (cost per ton of asphalt mixture) for each pavement section and the expected performance (time taken for the PCI to reach the terminal threshold); see Equation 5 [100, 101, 102, 103].

$$CE_i = \frac{C_i}{E_i} \quad [5]$$

where,
CE_i = average cost-effectiveness of each overlay construction technique (control or CRM);
C_i = initial unit cost of pavement section (cost/ton); and
E_i= time required to reach the terminal threshold (i.e., time to trigger a medium overlay treatment).

The value of E_i varied across different pavement sections due to different environmental and traffic conditions experienced by each field project. Even within the same field project, the test sections exhibited varying rates of deterioration. A lower CE value is desirable as it indicates the cost-effectiveness of specific pavement [100, 101, 102, 103].

Equivalent Uniform Annual Cost (EUAC)

For each field project, the EUAC was computed to determine the annual cost for owning, operating, and maintaining a CRM asphalt section compared to a control section. The analysis period for the five projects ranged from 20-26 years and were selected based on time taken for the specified distress indices (rutting, roughness, cracking, and patching) to trigger a medium overlay treatment. Recorded routine maintenance activities on each section were applied to the EUAC analysis over the years. The EUAC was determined as shown in the following equations [104, 105]:

$$= IC + \sum_{k=1}^{n} PMC_k \left(\frac{1}{(1 + i)^k}\right) \quad [6]$$

$$EUAC = NPV \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \quad [7]$$

where,
NPV = net present value;
IC = initial cost;
i = discount rate;
k = year of expenditure;
PMC_k = maintenance treatment cost at year k; and
n = analysis period.

A lower EUAC value is preferred as it signifies a lower cost for owning, maintaining, and operating a pavement section [104, 105].

Field Structural Evaluation

For the enhanced in-place field density project, the structural condition of the pavement sections was evaluated using the falling weight deflectometer (FWD). Field Project 1 was selected to assess the effect of WMA and increased asphalt content (referred to as Plus AC) techniques on the structural capacity of the wearing course. The FWD test was performed at 200-ft. intervals along the test sections to determine the deflection basin area, which measures the pavement's structural condition. Further, the deflection basin area data was used to compute the effective structural number (SN_{eff}) of each pavement section. Additionally, a back-calculation analysis was conducted to determine the modulus of the asphalt layers for each pavement section [106, 107].

Discussion of Results

This chapter presents the results and analysis of the study. This section is divided into five sub-sections to evaluate the effects of enhanced asphalt mixture design methods (asphalt mixture component material and mixture design criteria) and construction techniques. Crumb rubber-modified and warm mix asphalt mixtures were assessed as component materials, while the BMD approach was assessed as a mix design approach. Additionally, enhanced construction techniques were considered, focusing on techniques for achieving higher in-place density and tack coat optimization to improve ISS.

Use of Crumb Rubber-Modified Asphalt Mixture (CRM) for Sustainable Mixture Production

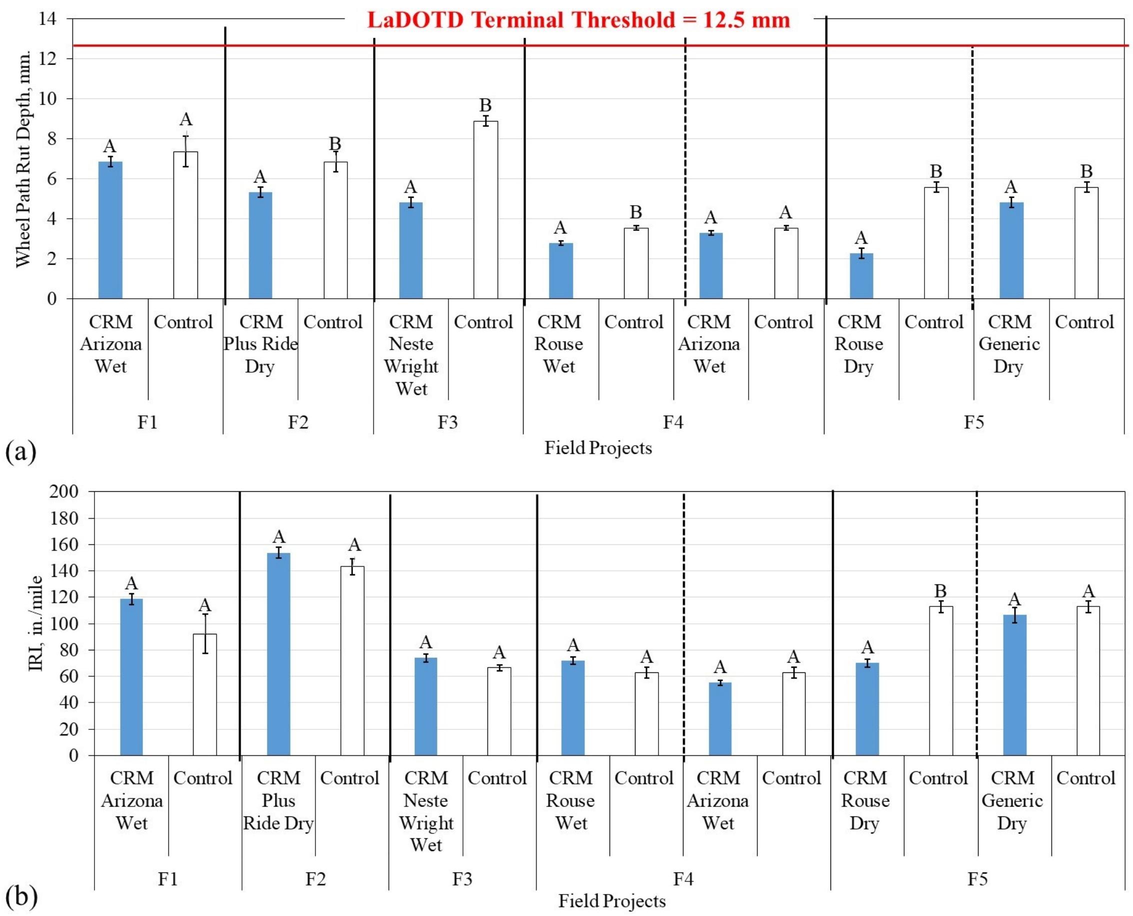
The crumb rubber-modified asphalt mixture project assessed the effects of CR modification on rutting, roughness, transverse cracking, and alligator cracking performance. Moreover, it involved a comparison between the overall performance (PCI) of CR-modified pavement sections and that of their corresponding control sections subjected to similar traffic and environmental conditions. Additionally, the ability of initially measured laboratory mechanical parameters to rank field performance was assessed and evaluated. Finally, a life cycle cost analysis was conducted to ascertain the cost-effectiveness of CR modification.

Effects of Crumb Rubber Modification on Rutting and Roughness Performance

Figure 10 shows the average wheel path rut depth and international roughness index (IRI) values for the pavement sections evaluated. CRM sections exhibited significantly similar or higher rutting resistance than their corresponding control sections; see Figure 10a. For CRM mixtures produced using the wet process, the increased rutting resistance is attributed to the increased viscosity associated with the CR modification. In the dry process, CR particles enhance rutting resistance by acting as fillers in the asphalt mixture [14, 27, 28, 30, 108]. It is worth noting that all of the sections evaluated had rut depths lower than the Louisiana DOTD-specified maximum value of 12.5 mm prior to rehabilitation.

The CRM asphalt sections showed similar ride quality as the control sections, except for Field Project 5, where the CRM section constructed utilizing the Rouse Dry process exhibited significantly better ride quality than its corresponding control section; see Figure 10b. This observation demonstrates that CRM asphalt sections can exhibit better or comparable ride quality as conventional sections, which is consistent with observations made by other researchers [32, 109]. Volle evaluated CRM sections constructed using dry and wet processes and concluded that there was no substantial difference in ride qualities between the CRM and control sections [32]. Further, Buttlar and Rath stated in a “state of the knowledge” report that CR modifiers have the capability of significantly enhancing the ride quality of asphalt pavements [109]. However, it is noted that the ride quality of asphalt pavements is primarily influenced by construction quality and the stability of the underlying pavement and is not dependent on the presence of a CR additive in the mix [110].

Figure 10. (a) Average wheel path rut depth and (b) international roughness index values

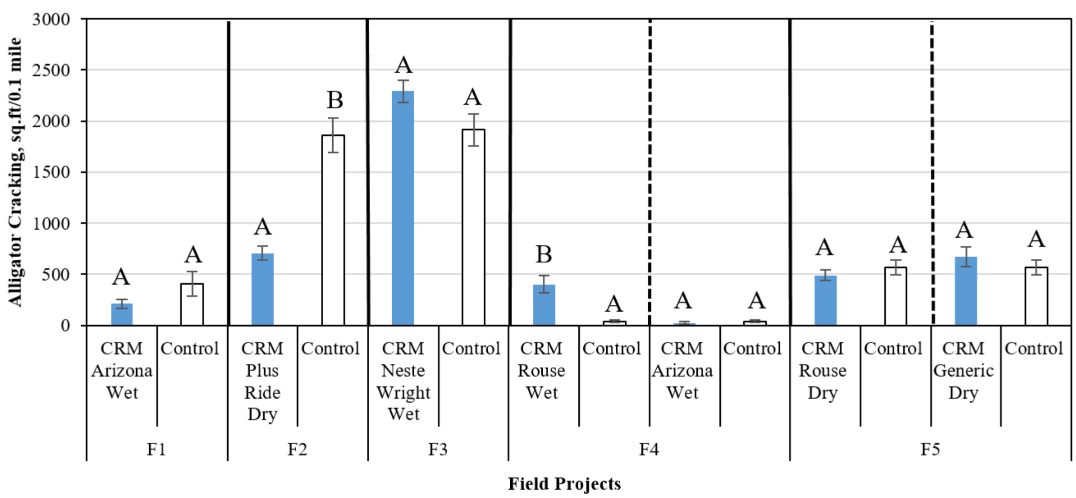


Effects of Crumb Rubber Modification on Alligator Cracking Resistance

Figure 11 presents the average alligator cracking values for the pavement sections evaluated. CRM asphalt sections showed significantly similar or higher alligator cracking resistance compared to their corresponding control sections, except for Field Project 4 (F4), where the

Rouse Wet CRM section exhibited significantly lower alligator cracking resistance than its corresponding control section. It is noted that the CRM section in Field Project 3 (F3) showed substantially lower cracking resistance than its corresponding control section, though this was not significant. Further, it is worth noting that AC 10 and AC 30 viscosity-graded binders were used in producing the Arizona and Rouse Wet CRM asphalt sections, respectively, in F4, whereas AC 30 binder was used for the Neste Wright section in F3. The higher viscosity of the AC 30 base binder may have resulted in a Rouse Wet CRM asphalt section in F4 with exceptionally higher rutting resistance compared to the corresponding control or Arizona Wet CRM section; see Figure 10a. Therefore, the low cracking resistance exhibited by the Neste Wright and Rouse Wet CRM asphalt sections may be attributed to the high viscosity of the AC 30 base binder, which may have minimized the ability of the mixture to absorb induced stresses without cracking. The control sections in F3 and F4 were constructed with SBS-modified asphalt binders, which have been shown to exhibit better cracking resistance properties [111].

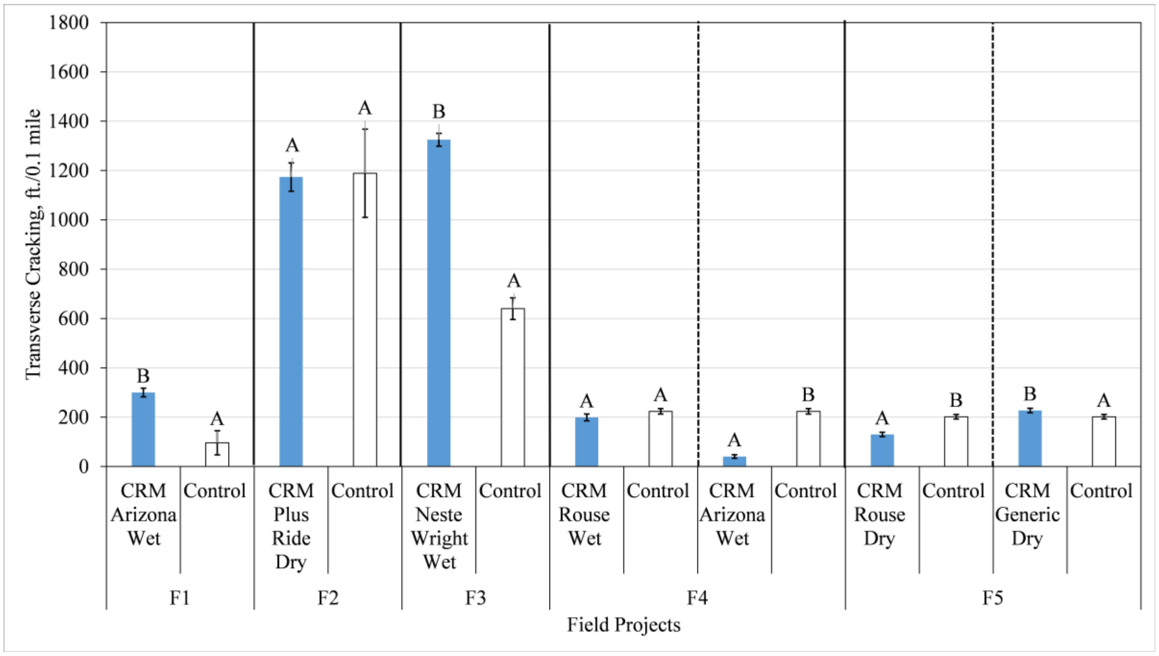
Figure 11. Average alligator cracking values



Effects of Crumb Rubber Modification on Transverse Cracking

Figure 12 shows the average transverse cracking values for the pavement sections evaluated. For the field projects evaluated, CRM sections on Field Projects 1, 3, and 5 showed significantly lower transverse cracking resistance, while those on Field Projects 2 and 4 showed significantly similar or higher cracking resistance. For Field Projects 1, 3, and 5, the Arizona Wet, Neste Wright Wet, and Generic Dry CRM sections showed significantly lower transverse cracking resistance than their corresponding control sections. The SBS-modified binder used in the construction of the control sections in Field Projects 1, 3, and 5 enhanced their ability to relax induced stresses and exhibit superior transverse cracking resistance properties compared to their corresponding CRM sections [112, 113].

Figure 12. Average transverse cracking values



Effects of Crumb Rubber Modification on Overall Pavement Condition

Figure 13 shows the average PCI of all pavement sections prior to rehabilitation, with Louisiana DOTD PCI rating thresholds indicated. CRM asphalt sections showed similar or higher overall performance than their corresponding control sections. The PCI values reported in Figure 13 are single-year values reported before the rehabilitation and do not capture pavement performance over extended periods. Therefore, the areas under the predicted PCI curves were computed graphically up to a point where a terminal PCI threshold of 69 (PCI for roads in poor condition) is reached. Figure 14 shows the area under the PCI curve for CR-modified sections compared with their corresponding control sections. Generally, CR modification was effective in improving the overall pavement condition of CRM sections compared to their corresponding control sections over the pavement's service life. The only exception was Field Project 5, where the Generic Dry CRM asphalt section exhibited a lower area under the performance curve than its corresponding control section.

Figure 13. Pavement Condition Index (PCI)

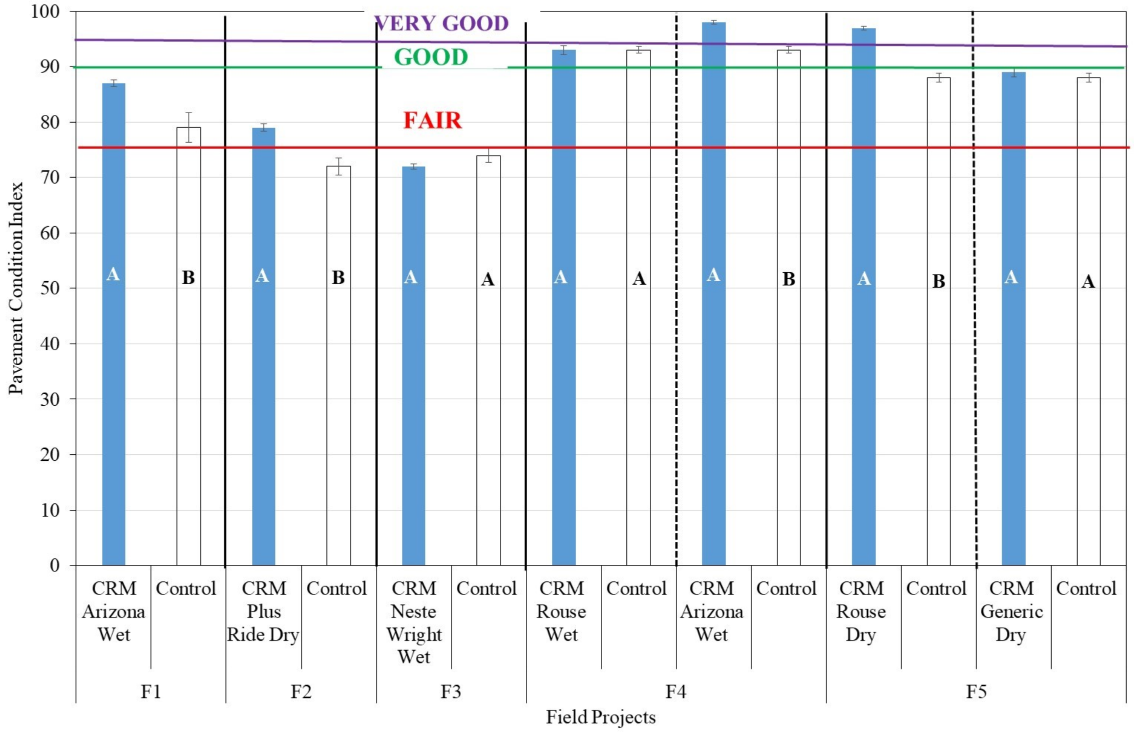


Figure 14. Area under the PCI curve

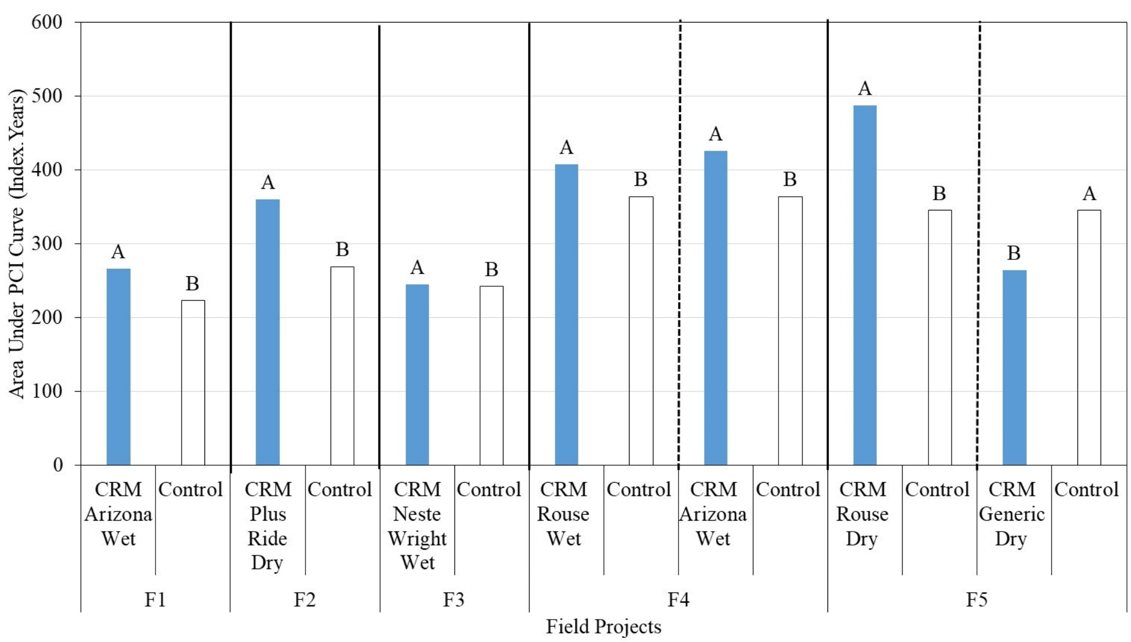
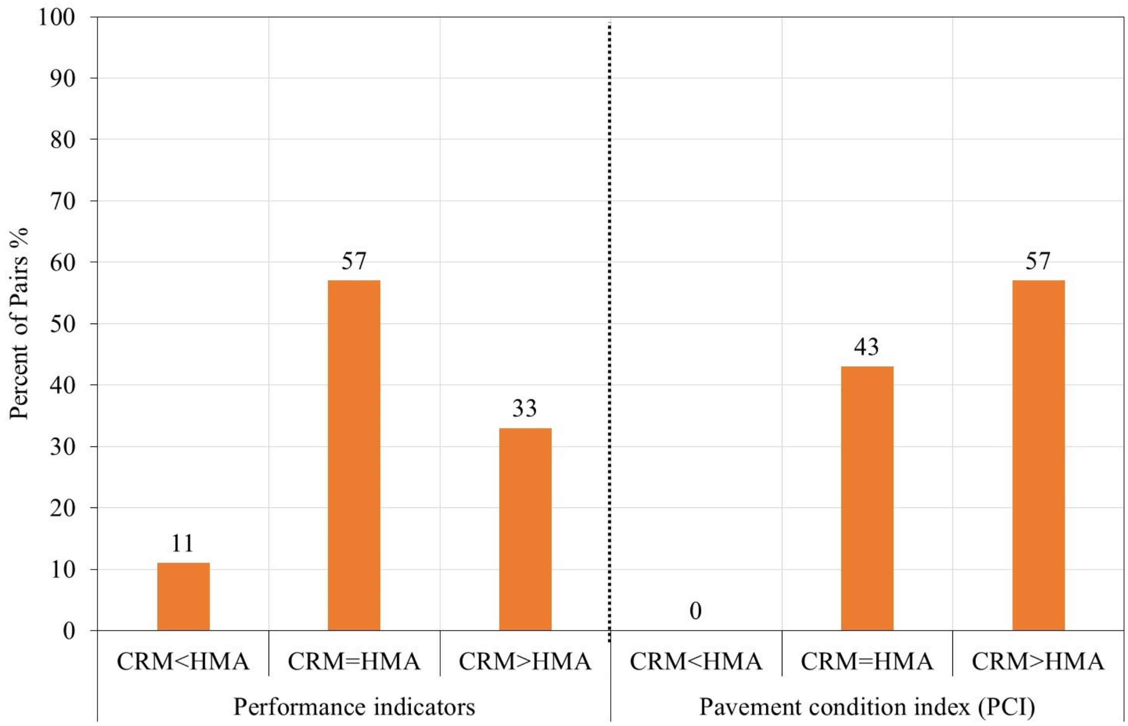


Figure 15 presents t-test comparisons of the pavement performance parameters (performance indicators and PCI) recorded on the CRM and control pavement sections evaluated in this study. The sections were ranked with the terms CRM < HMA, CRM = HMA, and CRM > HMA, which denote that CRM asphalt sections had lower, similar, and better performance than the control section, respectively. Performance indicators were ranked separately and included rutting, IRI, alligator cracking, and transverse cracking. Among the 35 pairs of performance indicators evaluated, CRM sections exhibited comparable or better performance than the control section in 90% of the comparisons; see Figure 15. On the other hand, CRM asphalt sections showed comparable or better overall performance (higher PCI) than the control section in 100% of the comparisons; see Figure 15.

Figure 15. Comparison of pavement performance indicators and Pavement Condition Index



Ranking Between Laboratory Measured Mechanical Properties and Field Performance

Tables 11 and 12 show the average values of the laboratory performance indicators (Marshall Flow, IDT strength, and resilient modulus, M_r) and their respective ranking compared with the field performance indicators (wheel path rut depth and alligator cracking). For field rutting performance, the Marshall Flow parameter could correctly rank 36% of the test sections evaluated. The IDT strength and M_r laboratory cracking parameters correctly ranked

40% of the test sections regarding alligator cracking performance. These observations underscore the limitations of these previously used mechanical tests to characterize asphalt mixtures, highlighting the subsequent development of different mechanical tests for rutting and cracking performance characterization [19, 50, 58]. For example, mechanical devices such as the Hamburg Wheel-Tracking device and asphalt pavement analyzer have been shown to be effective in characterizing the rutting resistance of asphalt mixtures. Other researchers have also found that mechanical tests like the Illinois Flexibility Index Test (IFIT), the Semi-Circular Bend (SCB) test at intermediate temperatures, and the indirect tensile cracking test at intermediate temperatures (IDEAL-CT) are effective tools for ascertaining the cracking resistance of asphalt mixtures [19, 50, 58].

Table 11. Average field rut depth and Marshall Flow values

Field Project	Mixture Type	Field Rut Depth, in.	Field Rut Depth Ranking	Marshall Flow	Marshall Flow Ranking
F1	CRM Arizona Wet	0.27	A	15	B
	Control	0.29	B	9	A
F2	CRM PlusRide Dry	0.21	A	26	B
	Control	0.27	B	10	A
F3	CRM Neste Wright Wet	0.19	A	10	A
	Control	0.35	B	10	A
F4	CRM Rouse Wet	0.11	A	9	A
	Control	0.14	B	11	B
	CRM Arizona Wet	0.13	A	17	B
	Control	0.14	B	11	A
F5	CRM Rouse Dry	0.09	A	10	A
	Control	0.22	B	11	B
	CRM Generic Dry	0.19	A	16	B
	Control	0.22	B	11	A

CRM: crumb rubber modified; in.: inch; A, B: Statistical ranking, where A is the best.

Table 12. Average alligator cracking, ITS, and M_r values

Field Project	Mixture Type	Alligator cracking, sq. ft./0.1 mi.	Alligator Cracking Ranking	ITS, *psi*	ITS Ranking	M_r (10^5), *psi*	M_r Ranking
F1	CRM Arizona Wet	211	A	95	B	2.53	B
	Control	405	B	220	A	5.97	A
F2	CRM PlusRide Dry	776	A	129	B	4.00	B
	Control	1862	B	173	A	4.39	A
F3	CRM Neste Wright Wet	2291	B	140	B	3.17	B
	Control	1914	A	153	A	3.97	A
F4	CRM Rouse Wet	403	B	184	B	4.19	B
	Control	41	A	227	A	6.40	A
	CRM Arizona Wet	23	A	89	B	3.61	B
	Control	41	B	227	A	6.40	A

CRM: crumb rubber-modified; sq. ft.: square feet; *psi*: pound per square inch; ITS: indirect tensile strength; M_r.: Resilient Modulus; A, B: Statistical ranking, where A is the best.

Results of Life Cycle Cost Analysis

Table 13 presents the unit cost, CE, and EUAC values for the pavement sections evaluated. It is noted that the unit cost for CRM sections was higher than the control section, except for the Rouse Wet CRM section in Field Project 4, which had a similar unit cost as the control section. In some cases, the unit cost of the CRM section was twice as much as that of the corresponding control section. Such high unit costs are likely to affect the cost-effectiveness of CRM sections if the improved performance benefits are not enough to offset the increased cost of producing the CRM mixture [35]. Generally, the CRM sections showed higher CE values than their corresponding control sections, except the Rouse Wet section in Field Project 4; see Table 13. The Rouse Wet CRM section was found to be more cost-effective than its corresponding control section. This observation is attributed to the lower unit cost of the Rouse section. Similarly, the CRM sections exhibited higher EUAC values than their corresponding control sections, except for the Rouse Wet section. The higher cost of constructing the CRM asphalt sections can be attributed to the experimental nature of the field projects, which necessitated the utilization of specialized equipment for the modification of the asphalt binders and mixtures. However, the control sections required the use of asphalt binders that were readily available in Louisiana and therefore had a lower initial cost [24]. Recent advances in CRM mixture production can help agencies produce CRM asphalts with a relatively lower initial cost than polymer-modified pavements. Additionally, other researchers have reported that reducing the design thickness of CRM asphalts can result in similar field performance as compared to conventional HMA sections over the same service life, resulting in cost savings [109, 114, 115].

Table 13. Cost-benefit analyses data

Field Project	Test Section	Unit Cost, $/ton of mix	CRM Cost / Control Cost	CE	EUAC. $/mile
F1	CRM Arizona Wet	69	2.0	3.1	8258
	Control	34	N/A	2.1	6020
F2	CRM PlusRide Dry	70	2.1	2.7	8248
	Control	34	N/A	2.1	5734
F3	CRM Neste Wright Wet	40	1.2	2.4	7307
	Control	34	N/A	2.3	6861
F4	CRM Rouse Wet	34	1.0	1.5	5667
	CRM Arizona Wet	68	2.0	3.4	8611
	Control	34	N/A	1.9	5866
F5	CRM Rouse Dry	40	1.2	1.5	6962
	CRM Generic Dry	47	1.4	3.1	5907
	Control	34	N/A	1.5	5557

CE: Cost effectiveness; EUAC: Equivalent Uniform Annual Cost.

Use of Warm Mix Asphalt (WMA) Additives for Sustainable Pavement Construction

Field distress data (performance indicators, performance indices, and Pavement Condition Index) obtained from the Louisiana PMS database were analyzed. The significance of performance differences between various experimental pavement sections and corresponding control test sections was determined. Statistical analyses were performed using the analysis of variance (ANOVA) procedure provided in the Statistical Analysis System (SAS) 9.4 program [116]. Multiple comparison test procedures with a confidence level of 95% were performed on the means. The groupings represent the mean for distresses reported by the control or WMA test section. Results of the statistical grouping are reported with letters A, B, C, and so forth, representing statistically distinct performance (longitudinal wheel path cracking, rutting, roughness, etc.) from best to worst. Further, the laboratory performance indicator data were analyzed to establish the capability of laboratory performance properties to rank field performance. It is noted that statistical analyses and rankings were performed on pavement sections on the same route because these test sections were subjected to similar factors (pavement structure, traffic, etc.), with the exception of the construction technology.

Effects of WMA Technology on Pavement Performance Indicators

For each project (LA 3121, US 61, US 171, and US 90), pavement performance indicators (rutting, roughness, longitudinal wheel path cracking, transverse cracking, fatigue/alligator cracking) were analyzed to determine the significance of the differences in performance of WMA test sections compared to the corresponding HMA control section. Table 14 presents average wheel path rut depth and international roughness index (IRI) values for the test sections evaluated.

Rutting

Generally, WMA test sections showed statistically similar field rut depths compared to their companion control HMA sections; see Table 14. This observation is consistent with results reported by other researchers [9, 19, 117, 118]. Further, an increase in RAP content from 15% to 30% in WMA test sections on LA 3121 and US 171 resulted in a minimal, though not significant, increase in field rut depth, see Table 14. This observation is counterintuitive since increased RAP content was expected to improve rutting resistance. The discrepancy is likely attributed to the improper application of cement treatment to the base layer at sections of LA 3121 with high RAP content [119]. Further, the reduction in rutting resistance on US 171 associated with increased RAP content may be attributed to underlying issues in the Portland cement concrete (PCC) layer. It is noted that all HMA control and WMA test sections exhibited rut depths lower than the Louisiana DOTD specified maximum of 12.5 mm (0.5 in.) after they have been in service for five to eight years.

Roughness

For US 171 and US 90 routes, WMA test sections showed statistically similar IRI values compared to their corresponding control HMA sections; see Table 14. Additionally, WMA test sections on LA 3121 and US 61 exhibited statistically similar or higher IRI values compared to the control HMA sections. It is noted that an increase in RAP content from 15% to 30% resulted in a significant increase in IRI for the WMA test sections on LA 3121 and a slight reduction in IRI for the WMA sections on US 171. The reduction in IRI on US 171 associated with increased RAP content was likely caused by underlying issues with the PCC layer underneath the asphalt mixture. Table 15 presents the average cracking values for the test sections evaluated.

Table 14. Average wheel path rut depth and IRI values

Route	Mixture Type	Service Years	Wheel Path Rut Depth, mm	Statistical Ranking	DOTD Specified Maximum
LA 3121	Conventional HMA + 15% RAP	8	3.0	A	12.5 mm
	Evotherm WMA + 15% RAP		3.0	A	
	Evotherm WMA + 30% RAP		3.9	A	
US 61	Conventional HMA + Granite Agg. + 15% RAP	5	4.8	A	
	Sasobit WMA + Granite + Agg. + 15% RAP		3.1	A	
	Foamed WMA + Sandstone Agg. + 15% RAP		4.3	A	
US 171	Conventional HMA + 15% RAP	7	7.8	A	
	Rediset WMA + 15% RAP		7.6	A	
	Foamed WMA + 15% RAP		8.3	A	
	Foamed WMA + 30% RAP		9.2	A	
US 90	Conventional HMA + 15% RAP	5	4.7	A	
	Evotherm WMA + 30% RAP		4.0	A	
Route	**Mixture Type**	**Service Years**	**IRI, in./mi.**	**Statistical Ranking**	
LA 3121	Conventional HMA + 15% RAP	8	96	A	
	Evotherm WMA + 15% RAP		92	A	
	Evotherm WMA + 30% RAP		123	B	
US 61	Conventional HMA + Granite Agg. + 15% RAP	5	62	A	
	Sasobit WMA + Granite + Agg. + 15% RAP		70	B	
	Foamed WMA + Sandstone Agg. + 15% RAP		82	C	
US 171	Conventional HMA + 15% RAP	7	78	A	
	Rediset WMA + 15% RAP		59	A	
	Foamed WMA + 15% RAP		90	A	
	Foamed WMA + 30% RAP		63	A	
US 90	Conventional HMA + 15% RAP	5	50	A	
	Evotherm WMA + 30% RAP		63	A	

HMA: hot mix asphalt; WMA: warm mix asphalt; Agg.: aggregate; RAP: recycled asphalt pavement; IRI: International Roughness Values.

Table 15. Average longitudinal wheel path, transverse, and fatigue cracks

Route	Mixture Type	Service Years	Longitudinal Wheel Path Cracking, ft./0.1 mi.				Statistical Ranking
			L	M	H	T	
LA 3121	Conventional HMA + 15% RAP	8	6.6	12.2	0.0	18.8	A
	Evotherm WMA + 15% RAP		26.6	59.2	2.9	88.7	B
	Evotherm WMA + 30% RAP		37.7	118.1	18.9	174.7	C
US 61	Conventional HMA + Granite Agg. + 15% RAP	5	9.0	0.5	0.0	9.5	A
	Sasobit WMA + Granite + Agg. + 15% RAP		21.9	7.3	0.0	29.2	A
	Foamed WMA + Sandstone Agg. + 15% RAP		168.8	66.9	0.0	235.7	B
US 171	Conventional HMA + 15% RAP	7	73.4	0.0	0.0	73.4	B
	Rediset WMA + 15% RAP		0.0	0.0	0.0	0.0	A
	Foamed WMA + 15% RAP		9.4	0.4	0.0	9.8	A
	Foamed WMA + 30% RAP		9.4	0.0	0.0	9.4	A
US 90	Conventional HMA + 15% RAP	5	51.6	0.0	0.0	51.6	A
	Evotherm WMA + 30% RAP		59.2	9.6	0.0	68.8	A
Route	**Mixture Type**	**Service Years**	**Transverse Cracking, ft./0.1 mi.**				**Statistical Ranking**
			L	**M**	**H**	**T**	
LA 3121	Conventional HMA + 15% RAP	8	95.3	28.2	0.0	123.5	B
	Evotherm WMA + 15% RAP		142.2	47.0	0.9	190.1	B
	Evotherm WMA + 30% RAP		84.8	31.6	0.4	116.8	A
US 61	Conventional HMA + Granite Agg. + 15% RAP	5	57.4	7.4	0.1	64.9	A
	Sasobit WMA + Granite + Agg. + 15% RAP		32.1	2.5	0.0	34.6	A
	Foamed WMA + Sandstone Agg. + 15% RAP		126.9	34.1	0.0	161.0	B
US 171	Conventional HMA + 15% RAP	7	19.3	0.2	0.0	19.5	A
	Rediset WMA + 15% RAP		0.0	0.0	0.0	0.0	A
	Foamed WMA + 15% RAP		42.8	20.1	0.0	62.9	B
	Foamed WMA + 30% RAP		1.8	0.3	0.0	2.1	A
US 90	Conventional HMA + 15% RAP	5	150.1	61.3	0.0	211.4	B
	Evotherm WMA + 30% RAP		19.6	1.3	0.0	20.9	A
Route	**Mixture Type**	**Service Years**	**Fatigue/Alligator Cracking, ft^2/0.1 mi.**				**Statistical Ranking**
			L	**M**	**H**	**T**	
LA 3121	Conventional HMA + 15% RAP	8	19.8	36.6	0.0	56.4	A
	Evotherm WMA + 15% RAP		79.7	177.6	8.8	266.1	B
	Evotherm WMA + 30% RAP		113.2	354.2	56.8	524.2	C

HMA: hot mix asphalt; WMA: warm mix asphalt; Agg.: aggregate; RAP: recycled asphalt pavement; L: low; M: medium; H: high; T: total crack severity.

Longitudinal Wheel Path Cracking

For test sections on US 171 and US 90, WMA sections showed statistically similar or higher longitudinal wheel path cracking performance compared to their companion control sections; see Table 15. The improvement in cracking resistance associated with WMA technologies is consistent with observations made by West et al. [41] using AASHTOWare for performance prediction. However, WMA test sections on LA 3121 and US 61 showed similar or lower cracking performance compared to their companion control sections. An increase in RAP content from 15% to 30% resulted in a significant increase and no significant change in longitudinal wheel path cracking performance in WMA sections on LA 3121 and US 171, respectively.

Transverse Cracking

For US 90, the WMA test section showed significantly higher transverse cracking resistance compared to the companion control HMA section; see Table 15. However, no consistent trend was observed on the effect of WMA technology on the transverse cracking performance of WMA test sections on LA 3121, US 61, and US 171. It is noted that an increase in RAP content from 15% to 30% resulted in higher transverse cracking resistance in the WMA sections on LA 3121 and US 171. It is also noted that this observation is counterintuitive, as increased RAP content is expected to cause decreased level of transverse cracking resistance. For LA 3121, the higher transverse cracking resistance associated with increased RAP content is attributed to the improper application of cement treatment to the base layer at sections of the pavement. Chen et al. reported that two primary factors contribute to the development of premature transverse cracks in asphalt pavements with cement-treated base (CTB) layer: (1) higher amount of cement in the CTB and (2) higher moisture content in CTB during compaction [119]. Additionally, higher transverse cracking performance values observed in US 171 for WMA mixtures with higher RAP content may be attributed to reflective cracking from the underlying Portland cement concrete pavement on sections of the pavement with lower RAP content [96].

Fatigue/Alligator Cracking

It is noted that fatigue crack values were not reported for US 61, US 171, and US 90 because they have composite structures; see Table 15 [92, 93]. Generally, WMA test sections showed lower fatigue cracking performance than the companion control HMA section. It is also noted that an increase in RAP content resulted in a significant decrease in fatigue cracking resistance in the WMA test section.

Effects of WMA Technology on Pavement Performance Indices

Pavement performance indices (rutting index, roughness index, random cracking, fatigue cracking index, pavement condition index) for each project were analyzed to evaluate the effect of WMA technology on field performance compared to conventional HMA technology. It is worth noting that Louisiana DOTD uses performance index values to trigger a maintenance action (e.g., micro-surfacing, thin overlay, structural overlay, polymer surface treatment, and the like) on a deteriorating pavement. For example, rutting index values less than 90 but greater than 80 are trigger values for micro-surfacing on interstate highways [92]. Table 16 shows average rutting and roughness indices for test sections evaluated.

Table 16. Average rutting and roughness index values

Route	Mixture Type	Service Years	Rutting Index	Statistical Ranking	DOTD Trigger Value for Micro-Surfacing
LA 3121	Conventional HMA + 15% RAP	8	100	A	90 Max.
	Evotherm WMA + 15% RAP		100	A	
	Evotherm WMA + 30% RAP		98	A	
US 61	Conventional HMA + Granite Agg. + 15% RAP	5	95	C	
	Sasobit WMA + Granite + Agg. + 15% RAP		100	A	
	Foamed WMA + Sandstone Agg. + 15% RAP		97	B	
US 171	Conventional HMA + 15% RAP	7	85	A	
	Rediset WMA + 15% RAP		86	A	
	Foamed WMA + 15% RAP		84	A	
	Foamed WMA + 30% RAP		81	A	
US 90	Conventional HMA + 15% RAP	5	95	A	
	Evotherm WMA + 30% RAP		98	A	
Route	**Mixture Type**	**Service Years**	**Roughness Index**	**Statistical Ranking**	**DOTD Trigger Value for Micro-Surfacing**
LA 3121	Conventional HMA + 15% RAP	8	91	A	80 Max.
	Evotherm WMA + 15% RAP		92	A	
	Evotherm WMA + 30% RAP		85	B	
US 61	Conventional HMA + Granite Agg. + 15% RAP	5	98	A	
	Sasobit WMA + Granite + Agg. + 15% RAP		96	B	
	Foamed WMA + Sandstone Agg. + 15% RAP		94	C	
US 171	Conventional HMA + 15% RAP	7	94	A	
	Rediset WMA + 15% RAP		98	A	
	Foamed WMA + 15% RAP		92	A	
	Foamed WMA + 30% RAP		97	A	
US 90	Conventional HMA + 15% RAP	5	100	A	
	Evotherm WMA + 30% RAP		97	A	

Rutting Index

For the routes evaluated, WMA test sections exhibited statistically similar or higher rutting index values (improved rutting performance) than their companion control HMA sections; see Table 16. Further, an increase in RAP contents in WMA sections on LA 3121 and US 171 resulted in a reduction in rutting index. Among the routes evaluated, test sections on US 171 showed rutting index values lower than the Louisiana DOTD trigger value for micro-surfacing after seven years in service [92, 93].

Roughness Index

WMA test sections on US 171 and US 90 exhibited significantly similar roughness index values compared to their companion control HMA sections; see Table 16. However, WMA sections on LA 3121 and US 61 showed significantly similar or lower roughness index values than their companion control sections. An increase in RAP content resulted in a significant reduction in roughness index in the WMA section on LA 3121 and a slight increase in roughness index in the WMA section on US 171. Further, all test sections exhibited rutting index values higher than the Louisiana DOTD trigger value for micro-surfacing pavement rehabilitation treatment [92, 93].

Table 17 presents the average cracking and Pavement Condition Index values for sections evaluated.

Random Cracking (Longitudinal + Transverse Cracking) Index

It is noted that construction-related cracks such as joint and edge cracks were excluded from the analysis; see Table 16. For US 171 and US 90, WMA test sections showed similar random cracking index values compared to their corresponding control HMA sections. Further, WMA sections on LA 3121 and US 61 exhibited significantly similar or lower random cracking index values than their companion HMA sections. It is noted that an increase in RAP content resulted in a significant reduction in the random cracking index in the WMA section on LA 3121 but had no significant effect on the WMA section on US 171. Generally, most test sections evaluated exhibited random cracking index values greater than Louisiana DOTD’s recommended trigger value for micro-surfacing pavement rehabilitation treatment [92, 93].

Table 17. Average random cracking, fatigue cracking, and Pavement Condition Index

Route	Mixture Type	Service Years	Random Cracking Index	Statistical Ranking	DOTD Trigger Value for Micro-Surfacing
LA 3121	Conventional HMA + 15% RAP	8	97	A	95 Max.
	Evotherm WMA + 15% RAP		96	A	
	Evotherm WMA + 30% RAP		91	B	
US 61	Conventional HMA + Granite Agg. + 15% RAP	5	99	A	
	Sasobit WMA + Granite + Agg. + 15% RAP		99	A	
	Foamed WMA + Sandstone Agg. + 15% RAP		93	B	
US 171	Conventional HMA + 15% RAP	7	99	A	
	Rediset WMA + 15% RAP		100	A	
	Foamed WMA + 15% RAP		100	A	
	Foamed WMA + 30% RAP		100	A	
US 90	Conventional HMA + 15% RAP	5	96	A	
	Evotherm WMA + 30% RAP		99	A	
Route	**Mixture Type**	**Service Years**	**Fatigue Cracking Index**	**Statistical Ranking**	**DOTD Trigger Value for Micro-Surfacing**
LA 3121	Conventional HMA + 15% RAP	8	100	A	95 Max.
	Evotherm WMA + 15% RAP		93	B	
	Evotherm WMA + 30% RAP		86	C	
Route	**Mixture Type**	**Service Years**	**Pavement Condition Index**	**Statistical Ranking**	**DOTD Trigger Value for Micro-Surfacing**
LA 3121	Conventional HMA + 15% RAP	8	94	A	NA
	Evotherm WMA + 15% RAP		92	A	
	Evotherm WMA + 30% RAP		86	B	
US 61	Conventional HMA + Granite Agg. + 15% RAP	5	96	A	
	Sasobit WMA + Granite + Agg. + 15% RAP		97	A	
	Foamed WMA + Sandstone Agg. + 15% RAP		94	B	
US 171	Conventional HMA + 15% RAP	7	90	A	
	Rediset WMA + 15% RAP		91	A	
	Foamed WMA + 15% RAP		88	A	
	Foamed WMA + 30% RAP		88	A	
US 90	Conventional HMA + 15% RAP	5	96	A	
	Evotherm WMA + 30% RAP		98	A	

HMA: hot mix asphalt; WMA: warm mix asphalt; Agg.: aggregate; RAP: recycled asphalt pavement; Max.: maximum; NA: not applicable; Columns with letters A, B, C, represent statistically distinct groups from best to worst.

Fatigue Cracking Index

WMA test sections showed a significantly lower fatigue cracking index than the control HMA test section. Further, an increase in RAP content in the WMA test section resulted in a significant reduction in the fatigue cracking index. WMA test sections exhibited fatigue cracking index values lower than the Louisiana DOTD recommended trigger value for micro-surfacing pavement rehabilitation treatment [92, 93].

Pavement Condition Index (PCI)

PCI measures the overall performance of the pavements evaluated and includes random cracking (longitudinal + transverse), fatigue cracking for flexible pavements, patching, roughness, and rutting indices [92, 93]. WMA test sections on US 171 and US 90 exhibited similar PCI values compared to their corresponding control HMA sections; see Table 17. For LA 3121 and US 61, WMA test sections exhibited similar or lower PCI values compared to their companion HMA sections. Further, an increase in RAP content resulted in a significant reduction in PCI values for the WMA section on LA 3121 but had no effect on the WMA test section on US 171.

Table 18 presents paired t-test comparisons of performance parameters (performance indicators, performance indices, and pavement condition indices) recorded on control HMA and WMA test sections. The terms WMA < HMA, WMA = HMA, and WMA > HMA denote that the WMA section has significantly lower, comparable, and better performance than the control HMA section, respectively. It is noted that higher performance is represented by a lower performance indicator or a higher performance or Pavement Condition Index. Among the 34 pairs of performance indicators evaluated, WMA sections exhibited comparable or better performance (higher performance indicator) than the control HMA in 71% of the comparisons; see Table 18. For the performance indices evaluated, WMA sections showed comparable or better performance (higher performance index) than the control HMA section in 73% of the comparisons; see Table 18. It is noted that regarding the overall performance of the sections, indicated by PCI, the WMA section exhibited similar or better performance than the control HMA section in 75% of the comparisons; see Table 18.

Table 18. Paired comparison of average performance indicators, performance indices, and Pavement Condition Index

Parameter	Ranking	Number of Pairs	Percent of Pairs (%)
Performance Indicators	WMA < HMA	10	29
	WMA = HMA	19	56
	WMA > HMA	5	15
Performance Indices	WMA < HMA	7	27
	WMA = HMA	17	65
	WMA > HMA	2	8
Pavement Condition Indices	WMA < HMA	2	25
	WMA = HMA	6	75
	WMA > HMA	0	0

Ranking between Laboratory Measured Mechanical Properties and Field Performance

Tables 19 and 20 present average values of mechanical performance indicators (HWT rut depth, Flow Number, SCB J_c, and dissipated creep strain energy, DCSE) and their respective statistical rankings compared with that of field performance indicators (wheel path rut depth and cracking).

Table 19. Average HWT rut depth, flow number, and field rut depth values

Route	Mixture Type	HWT Rut Depth, mm	HWT Rut Depth Ranking	Flow Number	Flow Number Ranking	WP Rut Depth, mm	WP Rut Depth Ranking
LA 3121	Conventional HMA + 15% RAP	4.9	A	2232	A	3.0	A
	Evotherm WMA + 15% RAP	5.6	A	2536	A	3.0	A
	Evotherm WMA + 30% RAP	5.7	A	1699	A	3.9	A
US 61	Conventional HMA + Granite Agg. + 15% RAP	4.0	A	2170	B	4.8	A
	Sasobit WMA + Granite + Agg. + 15% RAP	3.2	A	5079	B	3.1	A
	Foamed WMA + Sandstone Agg. + 15% RAP	3.1	A	5107	A	4.3	A
US 171	Conventional HMA + 15% RAP	6.3	A	454	B	7.8	A
	Rediset WMA + 15% RAP	6.3	A	486	B/A	7.6	A
	Foamed WMA + 15% RAP	8.4	A	359	B	8.3	A
	Foamed WMA + 30% RAP	6.1	A	791	A	9.2	A
US 90	Conventional HMA + 15% RAP	3.5	A	2680	A	4.7	A
	Evotherm WMA + 30% RAP	4.4	A	174	B	4.0	A

HMA: hot mix asphalt; WMA: warm mix asphalt; Agg.: aggregate; RAP: recycled asphalt pavement; Columns with letters A, B, C, represent statistically distinct groups from best to worst; HWT: Hamburg wheel tracking; WP: wheel path.

Table 20. Average SCB J_c, DCSE, longitudinal wheel path, and fatigue cracking values

Route	Mixture Type	SCB J_c, kJ/m^2	SCB J_c Ranking	DCSE, kJ/m^3	DCSE Ranking	Total LWP Crack, ft./0.1mi.	LWP Crack Ranking
LA 3121	Conventional HMA + 15% RAP	0.8	A	1.94	A	18.8	A
	Evotherm WMA + 15% RAP	0.5	B	2.49	A	88.7	B
	Evotherm WMA + 30% RAP	0.2	C	2.24	A	174.7	C
US 61	Conventional HMA + Granite Agg. + 15% RAP	0.4	A	2.87	A	9.5	A
	Sasobit WMA + Granite + Agg. + 15% RAP	0.5	A	2.43	A	29.2	A
	Foamed WMA + Sandstone Agg. + 15% RAP	0.5	A	3.06	A	235.7	B
US 171	Conventional HMA + 15% RAP	0.5	A	2.75	A	73.4	B
	Rediset WMA + 15% RAP	0.6	A	1.86	A	0.0	A
	Foamed WMA + 15% RAP	0.3	A	1.67	A	9.8	A
	Foamed WMA + 30% RAP	0.4	A	2.92	A	9.4	A
US 90	Conventional HMA + 15% RAP	0.4	A	0.89	A	51.6	A
	Evotherm WMA + 30% RAP	0.5	A	1.24	A	68.8	A
Route	**Mixture Type**	**SCB J_c (kJ/m^2)**	**SCB J_c Ranking**	**DCSE (kJ/m^3)**	**DCSE Ranking**	**Total Fatigue Crack (ft^2/0.1 mi)**	**Fatigue Crack Ranking**
LA 3121	Conventional HMA + 15% RAP	0.8	A	1.94	A	56.4	A
	Evotherm WMA + 15% RAP	0.5	B	2.49	A	266.1	B
	Evotherm WMA + 30% RAP	0.2	C	2.24	A	524.2	C

HMA: hot mix asphalt; WMA: warm mix asphalt; Agg.: aggregate; RAP: recycled asphalt pavement; Columns with letters A, B, C, represent statistically distinct groups from best to worst; SCB J_c: Semi-Circular Bend test strain energy release rate; DCSE: dissipated creep strain energy; LWP: longitudinal wheel path crack; mi: mile.

Table 21 shows percent field rutting and cracking (longitudinal wheel path and fatigue cracking) performance indicators correctly ranked by laboratory mechanical performance indicators (HWT rut depth, Flow Number, SCB J_c, and DCSE). For field rutting performance indicators, the HWT rut depth parameter was able to correctly rank 100% of the test sections compared to 58% of test sections correctly ranked by the flow number parameter. It is noted that despite its ability to correctly rank field performance, the HWT test showed a reduction in rutting performance after increased RAP content in the WMA section on US 171, which was counterintuitive. However, the flow number value increased with increased RAP content in the WMA section on US 171. A future study is recommended to further address these discrepancies. Further, it is noted that the Evotherm WMA mixture on US 90 recorded an extremely low flow number value despite exhibiting lower HWT and field rut depth values. This extremely low flow number value is attributed to testing errors in the laboratory experiment. The SCB J_c was able to correctly rank 87% percent of the field cracking indicators, whereas the DCSE parameter correctly ranked 60% of the field cracking indicators. This observation suggests that HWT rut depth and SCB J_c are better indicators of field rutting and cracking performances, respectively.

Table 21. Ranking of field rutting and cracking performance indicators using measured laboratory performance indicators

Laboratory Test Parameter	**Percent Field Rutting Indicator Correctly Ranked (%)**
Rutting	
HWT Rut Depth	100
Flow Number	58
Laboratory Test Parameter	Percent Field Cracking Indicator (Longitudinal Wheel Path and Fatigue Cracking) Correctly Ranked (%)
Cracking	
SCB J_c	87
DCSE	60

Balanced Asphalt Mixture Design Approach as an Asphalt Mix Design Criteria

The validation of the Louisiana DOTD balanced mixture design criteria included an assessment of HWT rut depth and SCB J_c parameter. Initially measured laboratory performance data, specifically HWT and SCB test results, were obtained and analyzed. Comparisons were made between HWT rut depth and SCB J_c from the laboratory with the field rut depth and cracking data, respectively. Further, predictions for field performance of pavement sections designed for traffic Level 1 up to year 15 were conducted to evaluate and validate HWT rut depth and SCB J_c criteria.

Laboratory Mechanical Properties

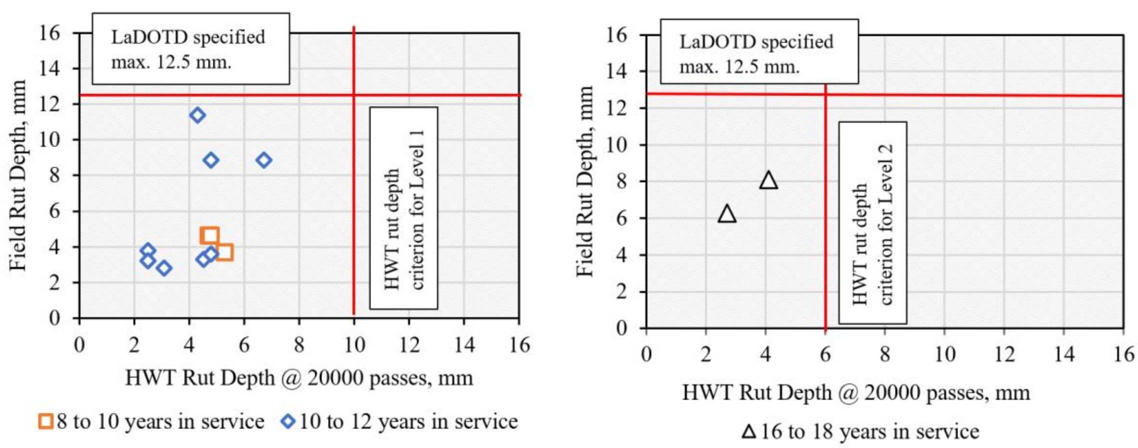
The HWT rut depth and SCB J_c values for the wearing course of pavement sections considered in this part of the study were presented previously in the methodology section; see Table 9. The HWT rut depth and SCB J_c values were obtained from laboratory tests conducted on plant-produced mixture samples collected from the pavement sections during construction. All 13 pavement sections evaluated in this study exhibited HWT rut depth values lower than the maximum threshold specified in the Louisiana BMD framework for Level 1 and 2 mixtures; see Table 9 [64, 65]. The 11 Level 1 pavement sections considered in this study showed SCB J_c values higher than the minimum threshold specified in the Louisiana BMD framework. Among the two Level 2 pavement sections evaluated in this study, the pavement section on I-10 exhibited a higher SCB J_c value, whereas LA 964 showed a lower SCB J_c value than the minimum threshold specified in the Louisiana BMD framework. It is noted that factors such as mixture aging, traffic, climate, and location within the pavement structure can influence the rutting and cracking performance, as measured by HWT and SCB, respectively. However, the HWT and SCB tests considered in this study do include the effect of aging and traffic volume [65].

Validation of HWT Rut Depth Maximum Threshold

Figure 16 shows plots of HWT rut depth versus field rut depth for the Level 1 and 2 pavement sections. The field rut depth values of the Level 1 sections were collected after eight to 12 years in service, whereas those of the Level 2 pavement sections were collected after 16 to 18 years in service. All of the Level 1 pavement sections exhibited HWT and field rut depth values below the maximum HWT rut depth threshold (10 mm) specified in the Louisiana BMD framework and the Louisiana DOTD specified maximum field rut depth of 12.5 mm; see Figure 16a. Similarly, the Level 2 pavement sections showed HWT and field rut depth values lower than the specified Louisiana DOTD maximum BMD and field rut depth thresholds, respectively; see Figure 16b. These observations imply that the Levels 1 and 2 pavement sections with service years ranging from eight to 18 exhibited field rut depth values that validated the maximum HWT rut depth values specified in the BMD framework. Therefore, the maximum HWT rut depth criteria of 10 mm and 6 mm for Level 1 and 2 mixtures, respectively, are effective for assessing the rutting performance [75, 77].

Because the Level 1 pavement sections had service years that ranged from eight to 12 years, rut depth data for these pavement sections was collected from the time of construction until 2021 and used to predict the rutting performance for 15 years, following Louisiana DOTD's sigmoidal model shown in Equation 4 [92, 96, 97]. The predicted data were then analyzed to assess the capability of the maximum HWT rut depth criteria in assessing the rutting performance of Level 1 pavement sections for 15 years.

Figure 16. (a) HWT rut depth versus field rut depth for Level 1 pavement sections (b) HWT rut depth versus field rut depth for Level 2 pavement sections



(a) **(b)**

Validation of SCB J_c Minimum Threshold

Figure 17 presents plots of the random cracking index versus the SCB J_c values for Levels 1 and 2 pavement sections evaluated. Generally, all of the Level 1 pavement sections exhibited SCB J_c values higher than the specified threshold of 0.5kJ/m^2 and field random cracking index values that met and exceeded the field cracking performance threshold; see Figure 17a. Further, the Level 2 pavement section on I-10 showed SCB J_c values higher than 0.6kJ/m^2 and field random cracking index values that met and exceeded the field cracking performance threshold; see Figure 17b. However, the Level 2 pavement section on LA 964 exhibited an SCB J_c value lower than the Louisiana DOTD-specified minimum value of 0.6 kJ/m^2 and lower field random cracking index values that did not meet the field random cracking performance threshold. These observations show that the Level 1 and 2 pavement sections with service years ranging from eight to 18 exhibited field random cracking (longitudinal and transverse) index values that validated the minimum SCB J_c values specified in the Louisiana BMD framework. Pavement sections with SCB J_c values that met the specified BMD criteria also met the required field random cracking performance threshold; the opposite was true for sections that did not meet the specified minimum SCB J_c criteria [64, 65]. Therefore, the SCB J_c is an effective parameter for assessing the field transverse and longitudinal cracking performance of pavement sections with eight to 18 service years.

Figure 17. Random cracking index versus SCB J_c for Level 1 pavement sections (b) random cracking index versus SCB J_c for Level 2 pavement sections

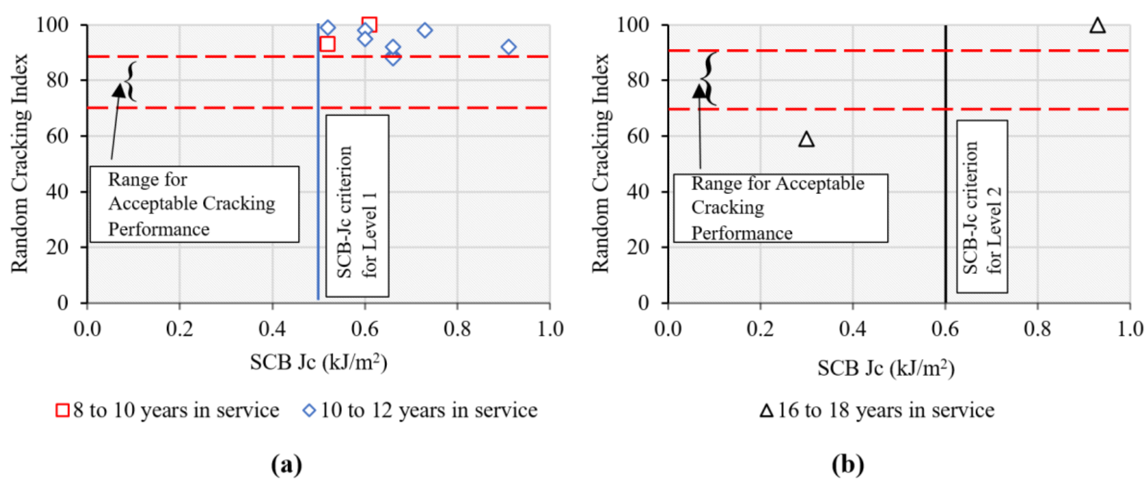
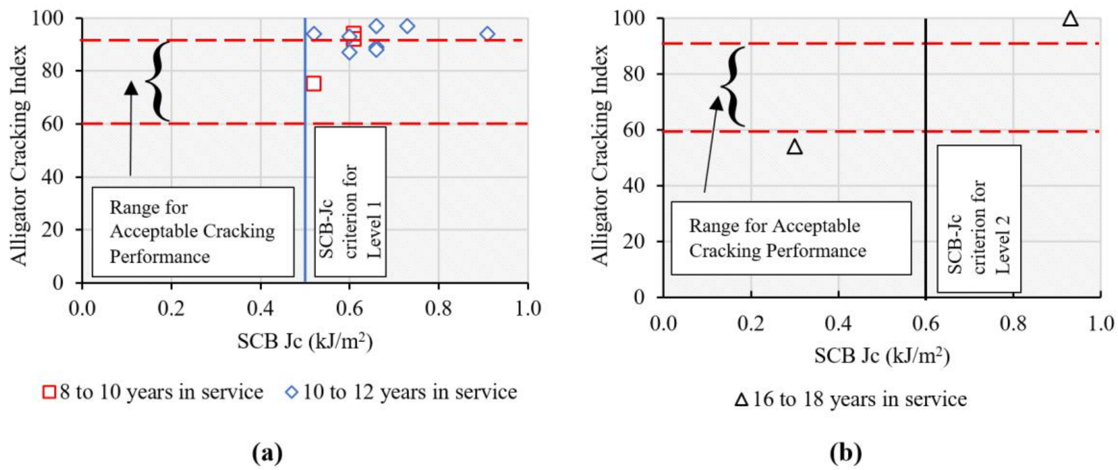


Figure 18 presents plots of the alligator cracking index versus SCB J_c values for pavement sections evaluated. The Level 1 pavement sections showed SCB J_c values greater than the minimum Louisiana BMD threshold of 0.5 kJ/m^2 and field alligator cracking values that met the required performance threshold. For the Level 2 pavement sections, I-10 exhibited SCB J_c values higher than the minimum BMD threshold of 0.6 kJ/m^2 and field alligator cracking index values that met the performance threshold. However, the Level 2 mixture on LA 964 showed SCB J_c values lower than the minimum BMD threshold and field alligator cracking index values that did not meet the specified threshold. It can be inferred from the above observations that the Level 1 and 2 pavement sections with service years ranging from eight to 12 years and 16 to 18 years, respectively, exhibited field alligator cracking index values that validated the minimum SCB J_c values specified in the Louisiana BMD framework. Pavement sections with SCB J_c values that met the specified BMD criteria had comparatively lower alligator cracking in the field. Conversely, pavement sections that did not meet the specified minimum SCB

J_c criteria had relatively higher alligator cracking in the field [64, 65]. Therefore, the SCB J_c is an effective parameter for evaluating field alligator cracking performance of pavement sections with service years ranging from eight to 18.

Figure 18. Alligator cracking index versus SCB J_c for (a) Level 1 pavement sections (b) alligator cracking index versus SCB J_c for Level 2 pavement sections



Summary of HWT Rut Depth and SCB J_c Validation

Figure 19a shows a BMD plot for the HWT rut depth and the SCB J_c values measured during construction. In contrast, Figure 19b presents the corresponding BMD plot for field rutting and alligator cracking index values for the Level 1 pavement section with service years ranging from eight to 12. Each pavement section was plotted with a different symbol or color to allow for a one-to-one comparison of the location of each section in any of the four quadrants in Figures 19a and 19b. Pavement sections located in the top left quadrant in Figures 19a and 19b are considered to be constructed with balanced mixtures (crack and rut resistant) [41, 50]. The Level 1 pavement sections were found in the top left quadrant (rut and crack resistant) in both the laboratory and field instituted BMD criteria. This observation further validates the HWT rut depth and SCB J_c parameters for designing balanced mixtures for Louisiana's Level 1 (< 3 million ESALs) pavements.

Figure 19. Level 1 BMD plot for (a) laboratory measured performance parameters (b) field measured performance parameters

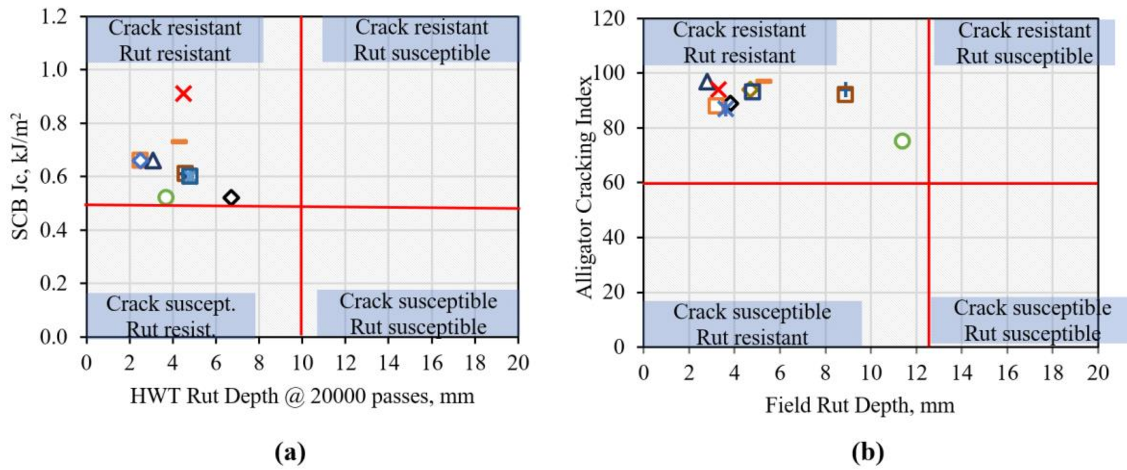
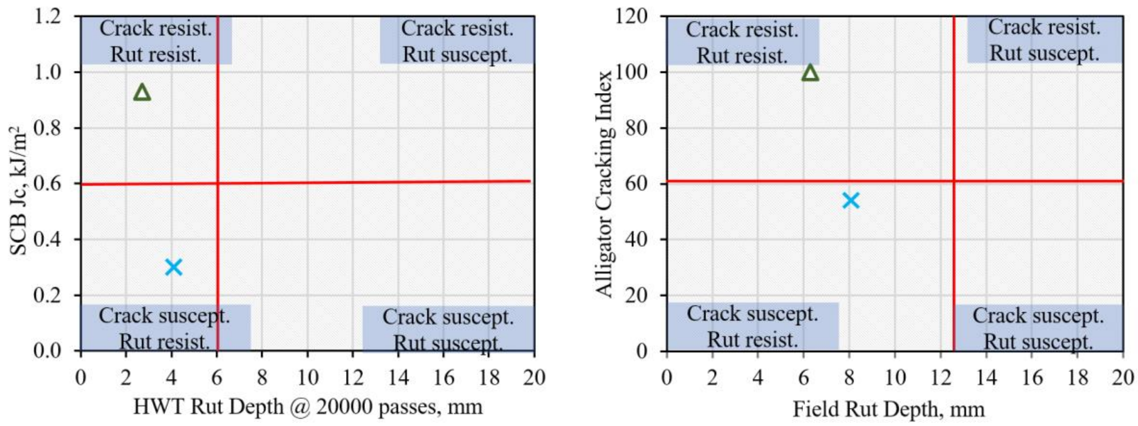


Figure 20a presents a BMD plot for the HWT rut depth and the SCB J_c values measured during construction, and Figure 20b shows the corresponding BMD plot for field rutting and alligator cracking index values for Level 2 pavement sections with service years ranging from 16 to 18. Similar to the Level 1 pavement sections, each section in Figure 20 was plotted with a different symbol or color to allow for a one-to-one comparison of the location of each section in the respective quadrants in Figures 20a and 20b. The Level pavement section on I-10 was found in the top left quadrant of Figures 20a and 20b, indicating the use of a balanced mixture to construct the pavement section. However, the Level 2 pavement section on LA 964 was located in the bottom left quadrant, suggesting the use of an unbalanced (rut resistant and crack susceptible) mixture in constructing the pavement section. Since the two pavement sections were found in similar quadrants in Figures 20a and 20b, it can be inferred that HWT rut depth and SCB J_c are effective parameters for selecting balanced mixtures for Level 2 (> 3 million ESALs) pavements in Louisiana, based on the limited field data evaluated [41, 50].

Figure 20. Level 2 BMD plot for (a) laboratory measured performance parameters (b) field measured performance parameters



(a) **(b)**

Table 22 shows the validation results for the maximum HWT rut depth and minimum SCB J_c values specified in the Louisiana DOTD BMD framework for pavement sections with 15 years of service. All the pavement sections evaluated in this study showed HWT and field rut depth values lower than the Louisiana DOTD BMD and field rutting performance thresholds, respectively. This observation further validates the capability of the specified maximum HWT rut depth value in the Louisiana BMD framework to assess the rutting performance of Levels 1 and 2 pavement sections with 15 years of service. Among the 13 pavement sections evaluated, 12 exhibited SCB J_c values higher than the Louisiana BMD threshold and field cracking (random and alligator) index values that met the Louisiana performance thresholds. The Level 2 pavement section on LA 964 showed SCB J_c and cracking (random and alligator) index values lower than Louisiana DOTD BMD and field cracking performance thresholds, respectively. These observations validate the SCB J_c as an effective parameter for assessing the cracking performance of Level 1 and 2 pavement sections with 15 years of service. Although the Louisiana BMD framework was validated in all pavement sections, the data for LA 964 was recorded in red and bold font to show that the pavement section in LA 964 failed to meet the Louisiana BMD SCB J_c criteria as well as the field cracking performance thresholds [92, 96, 97, 95].

Table 22. Field performance validation results

Field Projects	Mixture Type	Distress/ Indices		
		Field Rut Depth	RCI	ACI
LA 116	WMA	✓	✓	✓
	HMA	✓	✓	✓
LA 3121	HMA	✓	✓	✓
	WMA1	✓	✓	✓
	WMA2	✓	✓	✓
US 171	HMA	✓	✓	✓
	WMA1	✓	✓	✓
	WMA2	✓	✓	✓
LA 10	HMA	✓	✓	✓
LA 3235	HMA1	✓	✓	✓
	HMA2	✓	✓	✓
I-10	HMA	✓	✓	✓
LA 964	**HMA**	✓	✓	✓

RCI: random cracking index; ACI: alligator cracking index; HMA: hot mix asphalt; WMA: warm mix asphalt; ✓ : field performance validated laboratory test results.

Techniques for Enhancing In-Place Field Density

Field performance data were analyzed to investigate the effects of enhanced in-place density techniques on performance for the two field projects considered in this part of the study. Field performance data included performance indicators, performance indices, and overall PCI. Performance indicators included rutting, roughness, longitudinal wheel path cracking, transverse cracking, and alligator cracking. Furthermore, an evaluation of pavement structure was conducted for Field Project 1 to assess the effects of enhanced in-place density on pavement structural condition.

Effects of Enhanced In-Place Density Techniques on Pavement Performance Indicators

For each field project, pavement performance indicators (rutting, roughness, longitudinal wheel path cracking, transverse cracking, and alligator cracking) were analyzed for all test sections to ascertain the significance of performance difference between test sections with increased in-place density techniques and control sections. Tables 23 and 24 present the average performance indicator values (rutting, roughness, longitudinal wheel path cracking, transverse cracking, and alligator cracking) for the test sections considered. For Field Project 1, performance indicator values were determined at 528 ft. (0.1 mi.) intervals and averaged for each experimental section. Further, performance indicator values for Field Project 2 were determined at 25 ft. (0.005 mi.) intervals and averaged to represent each control or thermally segregated section.

Table 23. Pavement performance indicators for Field Project 1—US 190

Test Section	Service Years	Wheel Path Rut Depth, mm				Statistical Ranking	DOTD Terminal Threshold
Ev. WMA	5	5.7				A	12.5 mm
Cont. HMA		5.8				B	
Plus AC		6.1				A	
Cont. HMA		6.4				B	
Test Section		**IRI, in./0.1 mi.**				**Statistical Ranking**	**DOTD Terminal Threshold**
Ev. WMA		76				A	N/A
Cont. HMA		74				A	
Plus AC		64				A	
Cont. HMA		74				B	
Test Section		**Longitudinal wheel path cracking, ft./0.1 mi.**				**Statistical Ranking**	**DOTD Terminal Threshold**
		High	Medium	Low	Total		
Ev. WMA		0	0.2	0.3	0.5	A	N/A
Cont. HMA		0	0	0.7	0.7	A	
Plus AC		0	0	0	0	A	
Cont. HMA		0	0	0.7	0.7	A	
Test Section		**Transverse cracking, ft./0.1 mi.**				**Statistical Ranking**	**DOTD Terminal Threshold**
		High	Medium	Low	Total		
Ev. WMA		0	0.9	0.4	1.3	A	N/A
Cont. HMA		0	6.7	24	30.7	B	
Plus AC		0	4.1	0.2	4.3	A	
Cont. HMA		0	6.7	24	30.7	B	
Test Section		**Alligator cracking, sq. ft./ 0.1mi.**				**Statistical Ranking**	**DOTD Terminal Threshold**
		High	Medium	Low	Total		
Ev. WMA		0	0.5	0.8	1.3	A	N/A
Cont. HMA		0	0	2.1	2.1	A	
Plus AC		0	0	0	0	A	
Cont. HMA		0	0	2.1	2.1	A	

Ev: Evotherm; Cont. = control; WMA: warm mix asphalt; HMA: hot mix asphalt; AC: asphalt content; in.: inch, IRI: International Roughness Index; A, B: statistical ranking, where A is the best.

Rutting

For Field Project 1, test sections with improved in-place density techniques (Evotherm WMA and Plus AC) exhibited significantly better rutting performance than the control section; see Table 23. The Evotherm WMA test section showed the highest rutting resistance followed by the Plus AC section. This observation is consistent with results obtained from the Hamburg Wheel-Tracking (HWT) test conducted on field cores retrieved from the pavement sections during construction [4].

Temperature-segregated sections on Field Project 2 did not exhibit significantly different rutting resistance compared to their corresponding control sections; see Table 24. Generally, the temperature-segregated sections in Field Project 2 showed slightly lower rutting resistance than their corresponding control sections; see Table 24. For the two field projects, sections with increased in-place density techniques and their corresponding control sections exhibited rut depths lower than Louisiana DOTD's specified maximum of 12.5 mm after being in service for five to seven years. This observation implies that the pavement sections considered in the field projects need additional service years and traffic loads for the differences in the rutting performance of sections with increased in-place density techniques and their corresponding control sections to become apparent.

Roughness

For Field Project 1, the increased in-place density sections exhibited similar rutting performance as the control section; see Table 23. The Plus AC test section of Field Project 1 showed the lowest IRI value, followed by the control and Evotherm sections, respectively; see Table 23.

For Field Project 2, temperature-segregated sections on LA 30 and LA 1053 exhibited similar roughness values compared to their corresponding control test sections; see Table 24. However, temperature-segregated test sections on US 165 and LA 1058 showed significantly higher roughness values compared to their corresponding control sections; see Table 24. The higher roughness values observed on temperature-segregated sections is consistent with observations made by Stroup-Gardiner et al. [78]. Stroup-Gardiner et al. reported that pavement sections constructed with strategies to minimize temperature-segregation (e.g., using consistently available haul trucks with very short stop times and material transfer vehicles) exhibited lower initial IRI values compared to sections constructed without those strategies [78].

Table 24. Pavement performance indicators for Field Project 2

Route	Test Sect.	Service Years	Wheel Path Rut Depth, in.				Statistical Ranking	DOTD Terminal Threshold
LA 30	Control	7	6.6				A	12.0 mm
	T-S		6.9				A	
US 165	Control	6	4.3				A	
	T-S		4.8				A	
LA 1058	Control	6	3.0				A	
	T-S		3.0				A	
LA 1053	Control	6	3.8				A	
	T-S		3.6				A	
Route	**Test Sect.**	**Service Years**	**IRI, in./mi.**				**Statistical Ranking**	**DOTD Terminal Threshold**
LA 30	Control	7	67.5				A	N/A
	T-S		78.8				A	
US 165	Control	6	64.3				A	
	T-S		85.4				B	
LA 1058	Control	6	51.8				A	
	T-S		62.0				B	
LA 1053	Control	6	84.4				A	
	T-S		91.5				A	
Route	**Test Sect.**	**Service Years**	**Longitudinal wheel path cracking, ft./0.1 mi.**				**Statistical Ranking**	**DOTD Terminal Threshold**
			H	**M**	**L**	**Total**		
LA 30	Control	7	14.6	20.3	9.5	44.4	A	N/A
	T-S		2.2	34.6	34.0	70.8	A	
US 165	Control	6	0.0	0.0	0.4	0.4	A	
	T-S		0.0	0.0	2.1	2.1	A	
LA 1058	Control	6	2.0	9.2	32.8	42.1	A	
	T-S		0.0	22.5	86.2	108.8	A	
LA 1053	Control	6	0.0	16.9	30.6	47.6	A	
	T-S		0.0	38.0	35.0	73.0	A	
Route	**Test Sect.**	**Service Years**	**Transverse cracking, ft./0.1 mi.**				**Statistical Ranking**	**DOTD Terminal Threshold**
			H	**M**	**L**	**Total**		
LA 30	Control	7	0.0	11.2	21.2	32.4	A	N/A
	T-S		0.0	23.1	52.5	75.6	B	
US 165	Control	6	0.0	6.7	6.5	13.2	A	
	T-S		0.0	27.7	15.6	43.2	B	
LA 1058	Control	6	0.0	27.4	50.8	78.2	A	
	T-S		10.1	64.0	106.3	180.5	B	
LA 1053	Control	6	2.9	335.9	125.1	463.9	A	
	T-S		0.0	379.0	90.2	469.2	A	
Route	**Test Sect.**	**Service Years**	**Alligator cracking, sq. ft./0.1 mi.**				**Statistical Ranking**	**DOTD Terminal Threshold**
			H	**M**	**L**	**Total**		
LA 30	Control	7	43.8	61.0	28.4	133.2	A	N/A
	T-S		6.6	103.9	102.0	212.5	A	
US 165	Control	6	0.0	0.0	1.1	1.1	A	
	T-S		0.0	0.0	6.4	6.4	A	
LA 1058	Control	6	0.0	27.7	98.5	126.2	A	
	T-S		0.0	67.6	258.7	326.3	A	
LA 1053	Control	6	0.1	50.7	91.9	142.7	A	
	T-S		0.0	113.9	105.1	219.1	A	

Sect.: section; T-S: temperature-segregated; H: high; M: medium; L: low.

Longitudinal Wheel Path Cracking

For Field Project 1, longitudinal wheel path crack values recorded on sections with increased in-place density techniques as well as the control section were very low and insignificant; see Table 23. After five years in service, the total accumulated level of traffic was not sufficient to develop any significant amount of longitudinal wheel path cracks among the three experimental test sections. Continuous monitoring of the pavement sections for the development of longitudinal wheel path cracks is required.

Temperature-segregated pavement sections on Field Project 2 did not exhibit significantly different longitudinal wheel path cracks compared to their corresponding control sections; see Table 24. It is noted that temperature-segregated sections showed slightly higher longitudinal wheel-path crack values than their corresponding control sections; see Table 24. The lower cracking resistance exhibited by the temperature-segregated pavement sections in Field Project 2 is consistent with results reported from the Semi-Circular Bend test (SCB) conducted on field cores retrieved from these test sections during construction [76].

Transverse Cracking

Although transverse cracks levels observed on Field Project 1 were low, sections with increased in-place density techniques (Evotherm WMA and Plus AC) exhibited significantly lower transverse cracks than the control section; see Table 23.

For Field Project 2, temperature-segregated sections on LA 30, US 165, and LA 1058 routes showed significantly lower transverse crack resistance compared to their corresponding control sections; see Table 24. The lower in-place field density values associated with the temperature-segregation phenomenon may have resulted in a reduction in transverse crack resistance on these pavement sections. Gong et al. [120] reported that asphalt mixtures with higher density and indirect tensile (IDT) strength showed higher transverse crack resistance; the opposite was true for mixtures with lower density and IDT strength. It is noted that the higher levels of transverse cracks observed in Field Project 2 compared to longitudinal and alligator cracks may be attributed to underlying base or subgrade issues [119]. Additionally, LA 1053 exhibited unusually high levels of low and medium severity transverse cracks when compared to LA 30, US 165, and LA 1058, despite having lower design traffic; see Table 23. This could be due to the improper application of cement treatment to the original base layer. Previous research indicates that two primary factors contribute to premature transverse cracking in asphalt pavements with a cement-treated base (CTB) layer: a higher amount of cement in the CTB, and higher moisture content in the CTB during compaction [119].

Alligator Cracking
For Field Project 1, alligator cracks observed among sections with increased in-place density techniques, as well as the control section, were very low and insignificant; see Table 23.

Further, temperature-segregated sections in Field Project 2 did not show significantly different alligator cracking resistance compared to their corresponding control section; see Table 24. However, for each temperature-segregated section considered in Field Project 2, the observed alligator cracking resistance was slightly lower than that of their corresponding control sections. The lower cracking resistance observed on the temperature-segregated sections is attributed to the lower in-place density reported during construction [76]. Further, the slightly lower alligator cracking resistance values recorded on the temperature-segregated sections compared to the control sections is consistent with results obtained from SCB test conducted on field cores retrieved during construction [76].

Effects of Enhanced In-Place Density Techniques on Pavement Performance Indices

Pavement performance indices (rutting index, roughness index, alligator cracking index) were analyzed for all test sections to determine the effects of the improved density techniques on the field performance. Tables 25 and 26 present average rutting, roughness, alligator cracking, and Pavement Condition Index values for pavement sections evaluated. It is noted that the performance index values for Field Project 1 were determined at 528 ft. (0.1 mi.) intervals and averaged for each experimental section. For Field Project 2, the performance index values were determined at 25 ft. (0.005 mi.) intervals and averaged to represent each control or thermally segregated section.

Rutting Index
For Field Project 1, the WMA and Plus AC section showed significantly higher rutting index values than the control section; see Table 25. The two increased density techniques (WMA and Plus AC) were effective in increasing the rutting index values to levels above the Louisiana DOTD terminal threshold for micro-surfacing after five years in service.

Temperature-segregated sections in Field Project 2 did not exhibit significantly different rutting index values compared to their corresponding control sections; see Table 26. For Field Project 2, all test sections except those on LA 30 showed rutting index values higher than the Louisiana DOTD terminal threshold for micro-surfacing; see Table 26 [93]. For the two test sections on LA 30 that exhibited rutting index values lower than the

Louisiana DOTD trigger value, the control section showed a slightly higher rutting index value than the temperature-segregated section.

Roughness Index

The increased density techniques utilized in Field Project 1 resulted in significantly higher and similar roughness index values in the Plus AC and WMA section, respectively, compared to the control section; see Table 25.

For Field Project 2, the temperature-segregated sections on US 165 and LA 1058 exhibited significantly lower roughness index values than their corresponding control sections; see Table 26. This observation is attributed to lower density values recorded on the temperature-segregated sections during construction [76, 78]. It is noted that temperature-segregated sections on LA 30 and LA 1053 did not show statistically different roughness index values compared to their corresponding control sections. However, the roughness index values observed on the control sections of these routes were slightly higher than their corresponding temperature segregated section, indicating a lower ride quality on the temperature-segregated sections of these roads. All test sections for the two field projects considered showed roughness index values greater than Louisiana DOTD terminal threshold for micro-surfacing [93].

Alligator Cracking Index

All three pavement test sections considered in Field Project 1 showed excellent alligator cracking index values (i.e., new pavement in excellent condition); see Table 25. This observation shows that the three pavement sections have not been subjected to sufficient traffic volume to cause any noticeable damage. Additional monitoring is required to ascertain the differences in performance between the three test sections.

For Field Project 2, temperature-segregated sections did not show significantly different alligator cracking index values compared to their corresponding control sections; see Table 26. It is noted that for most routes in Field Project 2, including LA 30, LA 1058, and LA 1053, the temperature-segregated sections showed slightly lower alligator cracking index values than their corresponding control sections; see Table 26. The reduced in-place field density associated with the temperature-segregation phenomenon may have contributed to the slight reduction in alligator cracking resistance [76, 78]. Except for the temperature-segregated section on LA 1058 in Field Project 2, all test sections considered in the two field projects exhibited alligator cracking index values higher than the specified Louisiana DOTD terminal threshold for micro-surfacing [93].

Table 25. Pavement performance indices for Field Project 1—US 190

Test Section	Service Years	Rutting Index	Statistical Ranking	DOTD Terminal Threshold for Micro-Surfacing
Ev. WMA	5	92	A	90
Plus AC		91	A/B	
Cont. HMA		90	B	
Test Section	**Service Years**	**Roughness Index**	**Statistical Ranking**	**DOTD Terminal Threshold for Micro-Surfacing**
Ev. WMA	5	95	B	80
Plus AC		97	A	
Cont. HMA		95	A/B	
Test Section	**Service Years**	**Alligator Cracking Index**	**Statistical Ranking**	**DOTD Terminal Threshold for Micro-Surfacing**
Ev. WMA	5	100	A	95
Plus AC		100	A	
Cont. HMA		100	A	
Test Section	**Service Years**	**Pavement Condition Index**	**Statistical Ranking**	**DOTD PCI Rating**
Ev. WMA	5	95	A/B	Very Good
Plus AC		95	A	
Cont. HMA		93	B	Good

Table 26. Pavement performance indices for Field Project 2

Route	Test Section	Service Years	Rutting Index	Statistical Ranking	DOTD Terminal Threshold for Micro-Surfacing
LA 30	Control	7	89	A	90
	Temp. Segregated		88	A	
US 165	Control	6	96	A	
	Temp. Segregated		95	A	
LA 1058	Control	6	100	A	
	Temp. Segregated		100	A	
LA 1053	Control	6	98	A	
	Temp. Segregated		98	A	
Route	**Test Section**	**Service Years**	**Roughness Index**	**Statistical Ranking**	**DOTD Terminal Threshold for Micro-Surfacing**
LA 30	Control	7	96	A	80
	Temp. Segregated		94	A	
US 165	Control	6	97	A	
	Temp. Segregated		93	B	
LA 1058	Control	6	99	A	
	Temp. Segregated		97	B	
LA 1053	Control	6	93	A	
	Temp. Segregated		92	A	
Route	**Test Section**	**Service Years**	**Alligator Cracking Index**	**Statistical Ranking**	**DOTD Terminal Threshold for Micro-Surfacing**
LA 30	Control	7	96	A	95
	Temp. Segregated		95	A	
US 165	Control	6	100	A	
	Temp. Segregated		100	A	
LA 1058	Control	6	97	A	
	Temp. Segregated		93	A	
LA 1053	Control	6	97	A	
	Temp. Segregated		95	A	
Route	**Test Section**	**Service Years**	**Pavement Condition Index**	**Statistical Ranking**	**DOTD PCI Rating**
LA 30	Control	7	92	A	Good
	Temp. Segregated		90	A	
US 165	Control	6	96	A	Very Good
	Temp. Segregated		93	B	Good
LA 1058	Control	6	98	A	Very Good
	Temp. Segregated		93	B	Good
LA 1053	Control	6	88	A	Good
	Temp. Segregated		88	A	

WMA: warm mix asphalt; HMA: hot mix asphalt; AC: asphalt content; A, B: statistical ranking, where A is the best; Temp.: temperature; DOTD: Louisiana Department of Transportation and Development.

Pavement Condition Index (PCI)

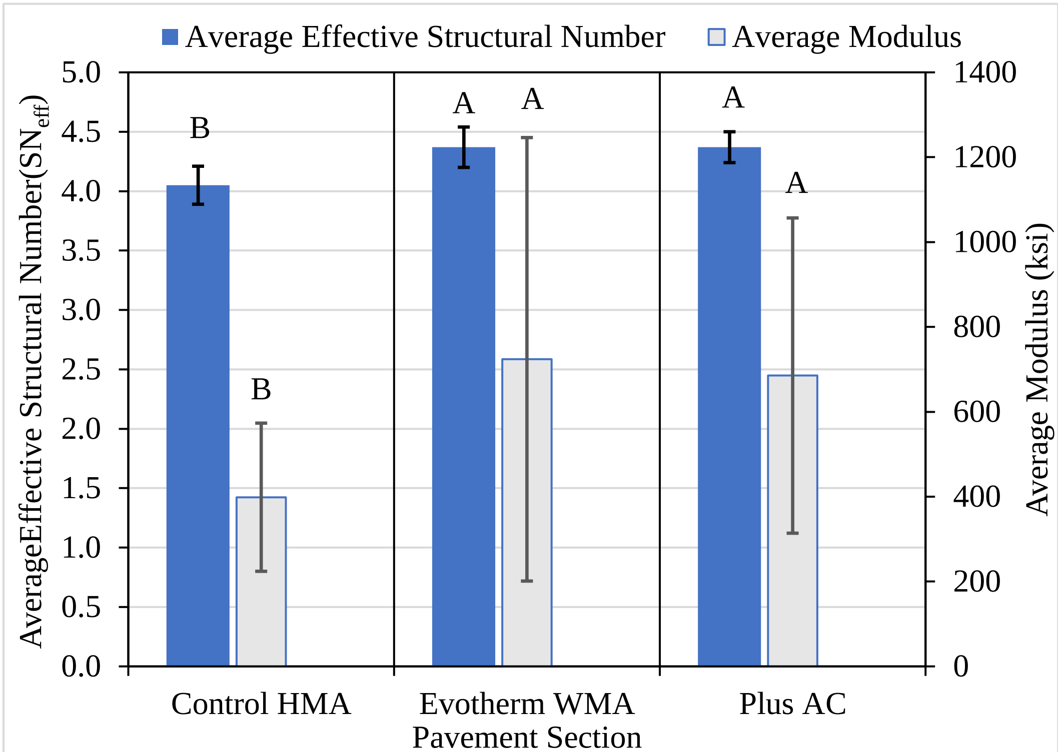
PCI values were computed to characterize the overall condition of the pavement sections considered. For Field Project 1, pavement section with increased in-place density techniques showed significantly similar or higher PCI values than the control section; see Table 25. The PCI of pavement sections with the two increased in-place density techniques (Evotherm WMA and Plus AC) was 95, an indication of a pavement section in "very good" condition, whereas that of the control section was 93, which represented a pavement section in "good" condition [93]. This observation implies that the two in-place density techniques were effective in improving the overall condition of the pavement section from "good" to "very good" after five years in service.

For Field Project 2, the temperature-segregation phenomenon on US 165 and LA 1058 were effective in significantly reducing the PCI rating from "very good" to "good" on the temperature-segregated test sections compared to their corresponding control test section after six years in service; see Table 26. It is noted that the temperature-segregation phenomenon resulted in a slight reduction in PCI value for the temperature-segregated section on LA 30 compared to its corresponding control section, however, the reduction was not significant enough to change the PCI rating. The control and temperature-segregated sections on LA 1053 of Field Project 2 exhibited significantly similar PCI values and ratings [93].

Effects of Enhanced In-Place Density Techniques on Pavement Structural Condition

Figure 21 presents the average effective structural number and moduli for the wearing course of the pavement sections constructed in Field Project 1. The increased density techniques utilized in Field Project 1 resulted in a significant increase in the SN_{eff} and moduli of the WMA and Plus AC sections compared to the control section. The improved SN_{eff} and moduli values is an indication of enhanced structural capacity and therefore may lead to improved field performance of the WMA and Plus AC sections, as observed in the performance indicator and index values reported in Tables 23 and 25 [106].

Figure 21. Average effective structural number and moduli values



Tack Coat Optimization

The validation of the minimum ISS value recommended in NCHRP Project 09-40 was conducted by assessing the field performance of pavement sections constructed with different tack coat materials at different application rates. Interfacial Shear Strength (ISS) data during the execution of NCHRP Project 09-40 was obtained and analyzed; see Table 10. These ISS values were then compared with field performance data, including rutting, roughness, and cracking performance. Additionally, a pavement surface assessment was completed to identify the presence of any potholes, slippage cracking, or other forms of distress associated with an inadequate interface shear bond.

Laboratory Mechanical Properties

The LISST test data compiled in Table 10 indicated that all pavement sections on LA 1053 exhibited ISS values that met the minimum NCHRP-specified criteria of 40 *psi* [90]. However, the SS-1 section on LA 30 exhibited an ISS value that was below the specified criterion.

Distress Survey

A windshield survey was first conducted, followed by a preliminary evaluation of cracking data from the Louisiana PMS database. The pavement surface was visually examined to detect any noticeable signs of distress attributable to inadequate bonding. According to researchers [20, 85, 88], noticeable distresses associated with poor interlayer bonding in asphalt mixtures include slippage cracking, potholes, shoving, and blowups. It is noted that slippage cracking, potholes, or shoving were not observed on the pavement sections for both field projects considered in the tack coat optimization study. Figure 22 shows the sample images collected from the windshield survey.

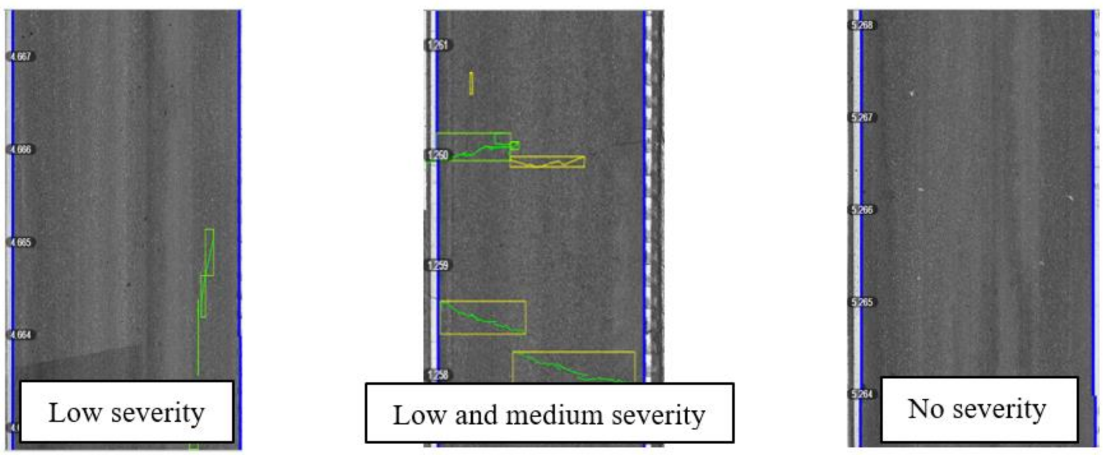
Figure 22. Windshield survey images for LA 30

Pavement cracking data was collected to assess ascertain the presence of any noticeable cracking distresses associated with inadequate bonding. This data included both severity levels and images of the cracks themselves. The Louisiana PMS database classifies cracking into four categories: no cracking, low-severity, medium-severity, and high-severity. Crack width determines the severity level [92]. Table 27 details these classifications for the Louisiana PMS database. It is important to note that some cracking is expected over time due to normal wear and tear from traffic, weather, and environmental factors, especially since these pavements have been in service for seven to eight years. Therefore, the evaluation focused on high-severity cracks and ignored low- and medium-severity alligator cracks, as well as random cracks, both transverse and longitudinal. A visual inspection was conducted using 3-D pavement images captured at 0.001-mi. intervals within the PMS database. These images use a color scheme to represent crack severity: green for low, yellow for medium, and red for high. It is noted that no high-severity cracks were found on the pavement sections examined. Based on the absence of noticeable or high-severity cracks, it appears that the minimum ISS value used was effective in improving field cracking resistance. Figure 23 presents sample 3-D pavement surface images from the two field projects evaluated in the tack coat optimization study.

Table 27. Pavement distress severity [102]

Distress	Severity/Width of Measured Crack		
	Low, in.	Medium, in.	High, in.
Alligator Cracking	N/A	≤ 0.25	≥ 0.25
Random Cracking	≤ 0.25	≥ 0.25, ≤ 0.50	≥ 0.50

Figure 23. Sample PMS images



Validation of ISS Criterion Recommended by NCHRP Project 9-40A

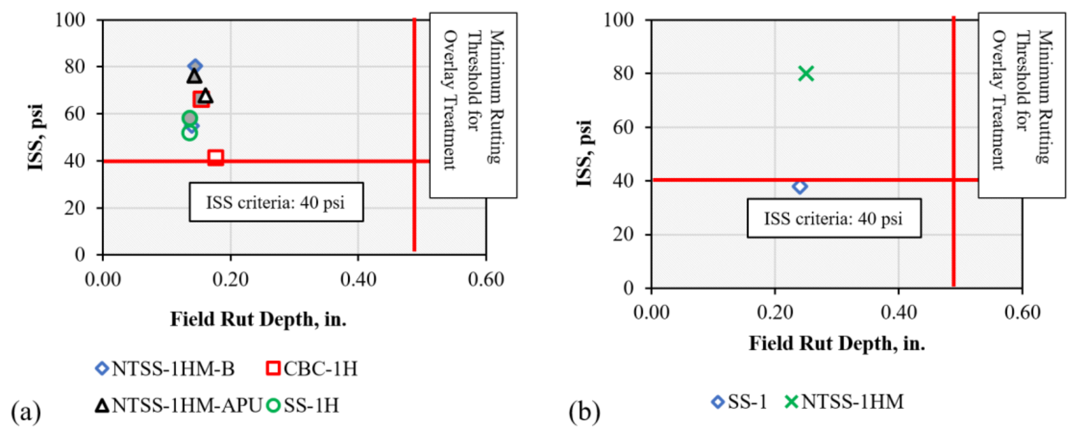
Pavement performance indicator and index (rutting, roughness, longitudinal wheel path cracking, transverse cracking, and alligator cracking) values were collected and analyzed for all test sections to validate the minimum ISS criteria recommended in NCHRP Project 09-40A [90]. PCI values were also computed from the respective distress index values to characterize overall pavement performance. For each pavement section and distress type, the measured ISS value was plotted on the y-axis against the measured field distress data on the x-axis. Additionally, the minimum ISS threshold value was delineated together with the recommended Louisiana DOTD terminal distress (rutting, roughness, or cracking) threshold values, requiring maintenance treatment. For example, Louisiana DOTD recommends overlay treatment for all pavement sections with rut values greater than 0.5 in. [92]. Pavement sections that exhibit ISS values greater than or equal to 40 *psi* are required to exhibit field distress values lower than the minimum threshold values requiring maintenance treatment; the opposite is true for those that exhibit ISS values lower than 40 *psi*. It is noted that high-severity cracks were considered in the analysis, as low- and medium-severity cracks could be attributed to the degradation of the pavement surface over time due to environmental and traffic conditions.

Rutting

Figure 24 shows plots of ISS versus field rut depth for the LA 1053 and LA 30 pavement sections evaluated. The field rut depth values of the LA 1053 pavement sections were collected in 2021 after seven years in service, whereas those of the LA 30 pavement sections were collected in 2022 after eight years in service. For the LA 1053 graph in Figure 24a, filled markers indicate sections with a high residual application rate for the respective tack coat type, and unfilled markers show sections with a lower residual application rate. All of the LA 1053 pavement sections exhibited ISS values above the minimum ISS threshold (40 *psi*) specified in NCHRP Project 09-40A and rut depth values below the Louisiana DOTD specified minimum value of 0.50 in.; see Figure 24a. [93]

The LA 30 pavement sections showed rut depth values lower than the terminal threshold for overlay treatment, irrespective of whether the section exhibited an ISS value greater or lower than the minimum threshold; see Figure 24b. Although the SS-1 section on LA 30 exhibited an ISS value of 38 *psi,* which is lower than the recommended minimum value, the SS-1 section showed rut values lower than the terminal value for overlay treatment. The 38 *psi* ISS value may be within the margin of error for the measurement method. These observations imply that the LA 1053 and LA 30 pavement sections, with service years ranging from seven to eight years, exhibited field rut depth values that validated the minimum ISS criterion specified in NCHRP Project 09-40A for adequate bonding between asphalt pavement layers [90].

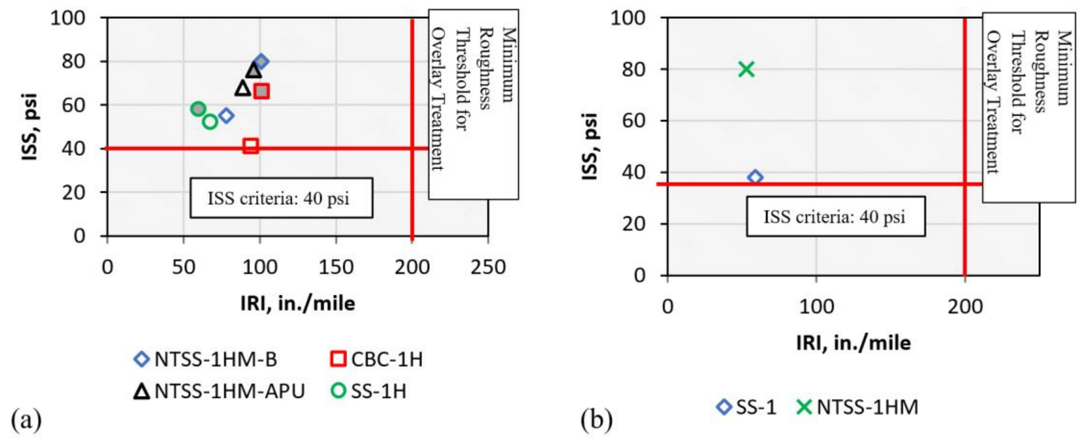
Figure 24. ISS versus field rut depth for (a) LA 1053 (b) LA 30



Roughness

Figure 25 shows plots of ISS versus international roughness index (IRI) values for the LA 1053 and LA 30 pavement sections evaluated. The IRI values of the LA 1053 pavement sections were collected in 2021 after seven years in service, whereas those of LA 30 pavement sections were collected in 2022 after eight service years. Pavement sections on LA 1053 exhibited ISS values above the 40 *psi* recommended minimum values and IRI values below the Louisiana DOTD recommended maximum (IRI = 200 in./mi.) for overlay treatment; see Figure 25a. Similarly, the LA 30 pavement sections exhibited ISS values that met the recommended minimum threshold and ISS values lower than the Louisiana DOTD recommended minimum value of 200 in./mi. for overlay treatment; see Figure 25b. The aforementioned observations imply that the LA 1053 and LA 30 pavement sections with service years ranging from seven to eight years exhibited IRI values that validated the minimum ISS criterion recommended in NCHRP Project 09-40A [90].

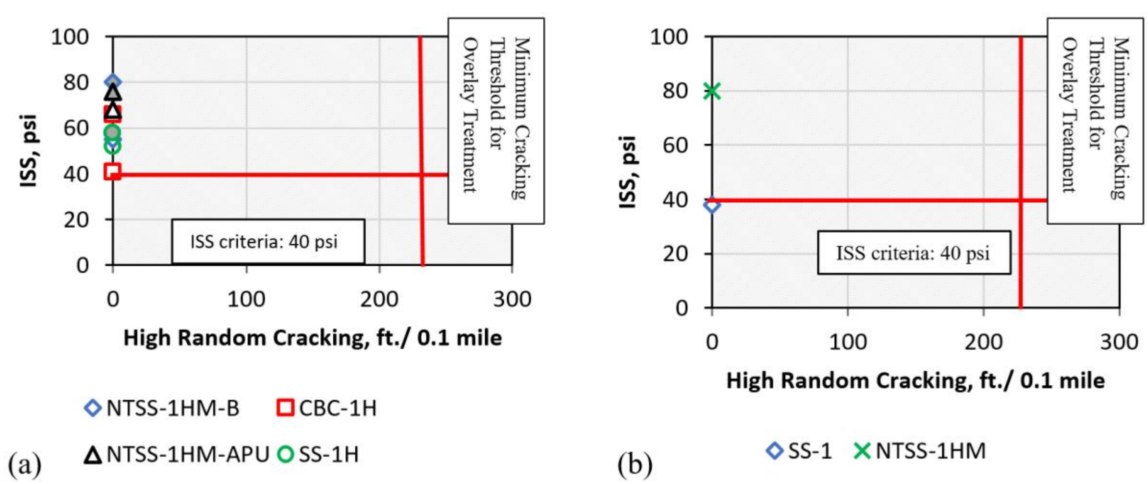
Figure 25. ISS versus IRI for (a) LA 1053 (b) LA 30



Random Cracking

Figure 26 shows plots of ISS versus random cracking (transverse and longitudinal cracking) values for the LA 1053 and LA 30 pavement sections evaluated. The random cracking values of the LA 1053 pavement sections were collected in 2021 after seven years in service, whereas those for the LA 30 pavement sections were collected in 2022 after eight years in service. None of the pavement sections considered in LA 1053 and LA 30 showed any high-severity cracks after being in service for seven to eight years. The LA 1053 and LA 30 pavement sections with service years ranging from seven to eight years exhibited high random cracking values that validated the minimum ISS criterion measured by the LISST device as specified in NCHRP Project 09-40A [90].

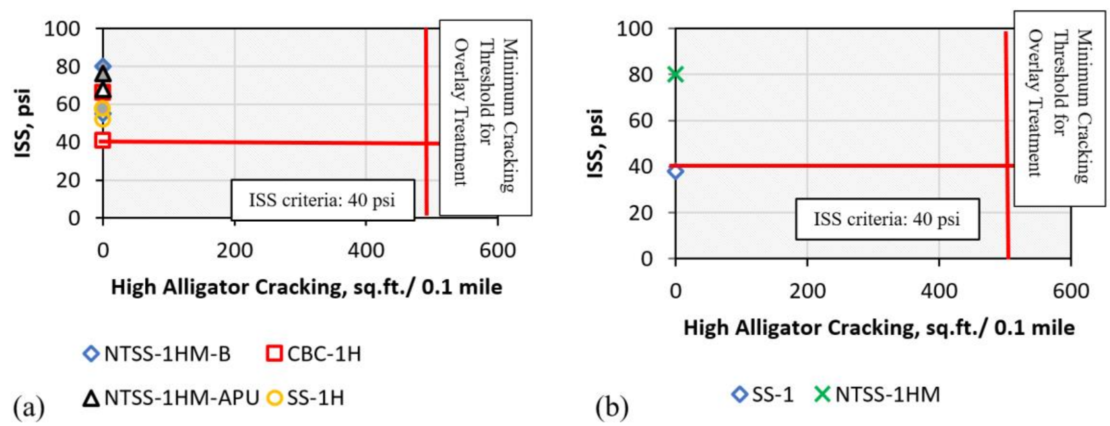
Figure 26. ISS versus high random cracking for (a) LA 1053 (b) LA 30



Alligator Cracking

Figure 27 shows plots of ISS versus high alligator cracking for the LA 1053 and LA 30 pavement sections evaluated. The alligator cracking values of the LA 1053 pavement sections were collected in 2021 after seven years in service, whereas those for the LA 30 pavement sections were collected in 2022 after eight service years. None of the pavement sections considered in LA 1053 and LA 30 had high-severity cracks after being in service for seven to eight years. The LA 1053 and LA 30 pavement sections with service years ranging from seven to eight years exhibited high alligator cracking values that validated the minimum ISS criterion measured by the LISST device as specified by NCHRP Project 09-40A [90].

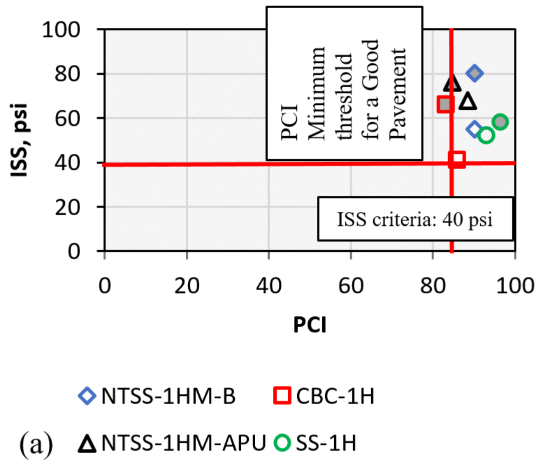
Figure 27. ISS versus high alligator cracking for (a) LA 1053 (b) LA 30



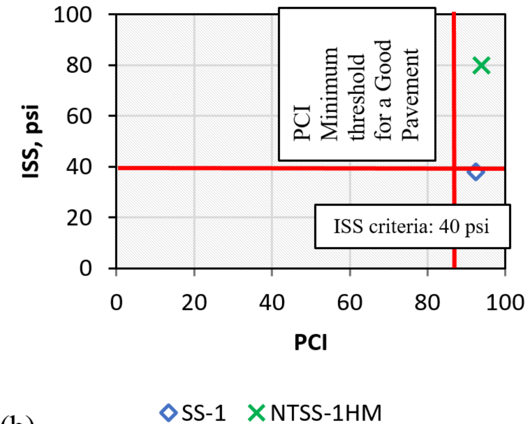
Pavement Condition Index

Figure 28 shows plots of ISS versus Pavement Condition Index (PCI) for the LA 1053 and LA 30 pavement sections evaluated. PCI represents the overall condition of the pavement sections evaluated in the study. For each field project considered, the minimum ISS and the recommended PCI rating for a pavement section in good condition (PCI = 85) were delineated in Figure 28. The PCI of the LA 1053 pavement sections was computed using the distress data collected in 2021 after seven years of service, whereas those of the LA 30 pavement sections were computed using the distress data collected in 2022 after eight service years. Among the eight pavement sections on LA 1053 that showed ISS values greater than 40 *psi*, seven exhibited a good PCI rating, whereas one showed a fair PCI rating; see Figure 28a. All of the LA 30 pavement sections were rated as good, even though the SS-1 section had an ISS value slightly lower than the recommended minimum value of 40 *psi;* see Figure 28b. These observations indicate that the recommended minimum ISS value can be used to construct pavement sections that exhibit good PCI ratings after seven to eight years of service [93].

Figure 28. ISS versus PCI for (a) LA 1053 (b) LA 30



(a)



(b)

Conclusions

The study aimed to evaluate the long-term field performance of flexible pavements constructed across Louisiana using enhanced asphalt mixture design methods and construction techniques. 24 field projects constructed in the state since 1994 were examined. Field evaluations were conducted for all projects; these evaluations involved the collection and analysis of field performance data, including performance indicators and indices, from the Louisiana PMS. The collected performance indicator data were analyzed to determine the effects of construction techniques, asphalt mixture component materials, and mixture design criteria on rutting, cracking (alligator/fatigue and transverse), and ride quality performance. Additionally, performance index data were gathered and analyzed to assess the overall pavement performance, measured by the Pavement Condition Index (PCI). The initial laboratory performance indicators measured during construction were also analyzed to evaluate their ability to rank field performance and validate their predictive capability. Further, FWD tests were conducted on selected projects to assess the effects of mixture components on structural conditions. An economic analysis was conducted to determine the cost-effectiveness of utilizing CR particles as a sustainable material in mixture production. The following sections present specific observations for each considered field project.

Asphalt Mixture Design Methods

Use of Crumb Rubber-Modified (CRM) Asphalt Mixture for Sustainable Mixture Production

- CRM asphalt sections generally performed similar to or better than their corresponding control sections in ride quality, cracking, and rutting resistance.
- Improved rutting resistance is due to crumb rubber enhancing binder viscosity and acting as a filler.
- The natural rubber component of the CR additive enhanced the crack resistance of CRM.
- In some cases, the SBS polymer modifier was effective in enhancing alligator and transverse crack resistance compared to the CR modifier.

- Due to their high initial unit costs, CRM sections generally exhibited higher CE and EUAC values than their corresponding control sections.
- The Rouse Wet CRM asphalt section in Field Project 4, which had a relatively lower unit cost compared to its corresponding control section, showed a lower EUAC value than its control section.
- The limited laboratory mechanical parameters (Marshall Flow, ITS, and M_r) considered were ineffective in correctly ranking the field performance indicators (rutting and cracking).
- CRM asphalt sections showed similar or better overall performance than their corresponding control sections.

Use of Warm Mix Asphalt (WMA) Additives for Sustainable Pavement Construction

- Generally, WMA test sections were found to exhibit similar or better rutting and cracking (longitudinal, transverse, and fatigue) performance compared to their companion control HMA sections.
- HWT rut depth was found to be a better indicator of field rutting performance than the flow number parameter.
- SCB J_c parameter was found to correctly rank more field cracking indicators than the DCSE parameter and therefore may be a better indicator of field cracking performance than the DCSE parameter.
- An increase in RAP contents in WMA test sections from 15% to 30% resulted in minimal increase in field rut depth on LA 3121 and US 171. It is noted that these counterintuitive results are attributed to the improper application of cement-treated base on LA 3121 and existing issues with the underlying PCC layer on US 171.
- All HMA control and WMA test sections exhibited rut depths lower than the Louisiana DOTD specified maximum of 12.5 mm (0.5 in.) after they have been in service for five to eight years.
- An increase in RAP content from 15% to 30 resulted in higher transverse cracking resistance in the WMA sections on LA 3121 and US 171. The increased transverse cracking resistance associated with increased RAP content is attributed to improper application of cement-treated base on LA 3121 and reflective cracking from the underlying PCC on US 171.

- WMA test sections showed lower fatigue cracking resistance than the companion control HMA sections.
- An increase in RAP content resulted in a decrease in fatigue cracking resistance in the WMA test sections.

Balanced Asphalt Mixture Design Approach as an Asphalt Mix Design Criteria

- All of the pavement sections designed for Levels 1 and 2 traffic had an HWT rut depth lower than the maximum HWT rut depth criteria established in the Louisiana BMD framework.
- All of the pavement sections considered in this study had lower field rut depth values than the Louisiana DOTD minimum specified maintenance trigger values (12.5 mm).
- The Level 1 and 2 pavement sections that showed SCB J_c values higher than the minimum Louisiana BMD threshold also showed the field cracking (alligator and random) values that met the required field cracking (alligator and random) performance threshold.
- The Level 2 mixture on LA 964 showed a SCB J_c value lower than the minimum BMD threshold of 0.6 kJ/m^2 and field cracking (alligator and random) index values that did not meet the specified field cracking (alligator and random) threshold.
- The study successfully validated the HWT rut depth and SCB J_c performance criteria selected within the Louisiana DOTD BMD framework for asphalt mixtures.

Improved Construction Techniques

Techniques for Enhancing In-Place Field Density

- The increased in-place density techniques utilized in Field Project 1 were effective in improving the structural capacity of the WMA and Plus AC sections compared to the control section.
- Generally, the Evotherm WMA and Plus AC techniques utilized in this study resulted in a similar or better rutting resistance in the increased density sections compared to the control section.
- After five years of service on Field Project 1, the traffic volume on the test sections was not high enough to significantly increase longitudinal or alligator cracking on any

of the three pavement sections (Evotherm WMA, Plus AC, and control). However, sections constructed with increased density techniques showed much better resistance to transverse cracking compared to the control section.

- Generally, the temperature-segregation phenomenon resulted in similar or lower rutting and cracking performance, as well as ride quality, in the temperature-segregated sections compared to their corresponding control sections.
- The Evotherm WMA and Plus AC techniques utilized to improve in-place field density were effective in increasing the overall PCI rating from “good” to “very good.”
- Temperature-segregation phenomenon was found to reduce the overall PCI rating of 50% of the temperature-segregated sections in Field Project 2 from “very good” to “good” compared to their corresponding control sections
- The increased in-place density techniques utilized in Field Project 1 was effective in improving the structural capacity of the WMA and Plus AC sections compared to the control section.

Tack Coat Optimization

- The windshield survey did not show any noticeable distresses attributable to inadequate bonding, indicating the 40 *psi* ISS value as an effective criteria for constructing pavement layers with adequate bonding.
- The pavement sections constructed with the minimum ISS value of 40 *psi* did not exhibit any high-severity cracks.
- Pavement sections with service years ranging from seven to eight years exhibited field rut depth, roughness, and cracking values that validated the minimum ISS criterion specified in NCHRP Project 09-40 for adequate bonding between asphalt pavement layers.
- The recommended minimum ISS value can be used to construct pavement sections that exhibit good PCI ratings after seven to eight years of service.

Recommendations

Based on the findings of the study, it is recommended that the pavement sections considered in the study be continuously monitored until their end of life to further validate the conclusions of this study. The following specific recommendations were made for each component of the study evaluated.

Asphalt Mixture Design Methods

The field performance of pavement sections modified with different dosage rates of CR particles showed similar or better performance than their respective control sections. Further, previous research studies conducted by LTRC have shown that CR dosage rates exceeding 10% by weight of asphalt binder exhibit instability and phase separation when exposed to high temperatures. Therefore, a maximum dosage rate of 10% was recommended for Louisiana mixes [39, 40]. Therefore, it is recommended that the Louisiana DOTD-specified maximum CR dosage of 10% be continuously used for CR-modified mixture production. Additionally, it is recommended that LCCA and life cycle analysis be performed on CR-modified pavement sections constructed with current CR blending techniques to ascertain their cost-effectiveness and environmental benefits.

For the WMA study, additional studies are recommended to continually monitor and evaluate the test sections together with recently constructed WMA pavement sections to ascertain the exact cause of the discrepancy in field performance associated with increased RAP content. Further, the balanced asphalt mix design study was limited to assessing one poor-performing road. Therefore, it is recommended that additional poor-performing roads be identified across the state of Louisiana to further validate the HWT rut depth and the SCB J_c criteria recommended in the Louisiana BMD framework. Louisiana DOTD currently conducts quality assurance checks on pavement production, focusing primarily on density and smoothness. Tests such as the Hamburg Wheel-Tracking (HWT) test for rutting and the Semi-Circular Bend (SCB) test for cracking, typically performed during the design phase to verify performance, should also be integrated into the production phase for quality control.

Improved Construction Techniques

The improved density techniques, such as WMA and Plus AC, along with temperature-segregation minimization technologies, were effective in achieving the increased in-place density (93.5% of G_{mm}) and enhancing pavement performance (rutting, roughness, and cracking). Therefore, it is recommended that Louisiana DOTD encourage or incentivize contractors in the state to use these techniques to enhance in-place field density and improve pavement performance.

For the tack coat optimization project, the minimum 40 *psi* criterion recommended in NCHRP Project 9-40 for tack coat application was found to be effective in enhancing pavement performance by improving rutting, roughness, and cracking resistance. Therefore, it is recommended that Louisiana DOTD adopt 40 *psi* ISS criteria for tack coat application in asphalt pavement construction.

Acronyms, Abbreviations, and Symbols

Term	Description
˚C	degrees Celsius
˚F	degrees Fahrenheit
µm	micrometer(s)
AASHTO	American Association of State Highway and Transportation Officials
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
BMD	Balanced Mixture Design
CE	Cost-Effectiveness
cm	centimeter(s)
CR	Crumb Rubber
CRM	Crumb Rubber-Modified
DCSE	Dissipated Creep Strain Energy
DOTD	Louisiana Department of Transportation and Development
DTiMs	Deighton Total Infrastructure Management System
EPA	Environmental Protection Agency
ESAL	Equivalent Single Axle Load
EUAC	Equivalent Uniform Annual Cost
FHWA	Federal Highway Administration
ISS	Interlayer Shear Strength
ISTEA	Intermodal Surface Transportation Efficiency Act
kJ	kilojoule
lb.	pound(s)
LCCA	Life Cycle Cost Analysis
LISST	Louisiana Interlayer Shear Strength Tester
LTPP	Long-Term Pavement Performance
LTRC	Louisiana Transportation Research Center
m	meter(s)
MEPDG	Mechanistic-Empirical Pavement Design Guide

Term	**Description**
mi.	mile(s)
mm	millimeter(s)
M_r	Resilient Modulus
MS	medium-setting
MTV	Material Transfer Vehicles
NAPA	National Asphalt Pavement Association
NCHRP	National Cooperative Highway Research Program
PCC	Portland cement concrete
SCB	Semi-Circular Bend
SHAs	State Highway Agencies
SS	slow-setting
TSRS	Thermal Strain Restrained Specimen
USTMA	U.S. Tire Manufacturers Association

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Appendix

Appendix A: Pavement Distress Survey Overview

Louisiana DOTD surveys its highway network using the automatic road analyzer (ARAN) every two years and records distress data in the Louisiana PMS database. A detailed description of how various pavement distresses are reported are discussed below [92].

Pavement Distress Characterization

Louisiana PMS distresses are reported according to terminology provided in the Louisiana DOTD Distress Identification Protocols for Asphalt and Composite Pavements [93]. Pavement distresses surveyed and characterized include rutting, roughness, cracking (longitudinal, transverse, alligator, or fatigue), potholes, patching, etc. Characterization terminology for different distresses are discussed below.

Rutting

ARAN uses a transverse laser profiler mounted at the back of the van to measure rutting; see Figure 29. This system captures 1,280 measurements across the width of the lane to compute the average transverse rut depth at a given location. The transverse rut depth is continuously measured at a highway driving speed. The data is further processed using a software based on AASHTO R 87. The average rut depth for every 0.16 km (0.1 mi.) pavement section is reported and used in pavement analysis.

Figure 29. ARAN rutting measurement

Roughness

Roughness is the deviation of a pavement surface from a true planar surface with a characteristic longitudinal profile that affects vehicle dynamics and ride quality [121]. Roughness data is obtained from the ARAN using a laser South Dakota Profiler (SDP) mounted in front of the ARAN van; see Figure 30. The longitudinal profile of the surface is obtained according to ASTM E950 "Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference." The profile data is then processed with the ProVal software to determine the International Roughness Index (IRI) according to AASHTO R43, "Standard Practice for Quantifying Roughness of Pavements."

Figure 30. ARAN roughness measurement

Pothole

A pothole is a bowl-shaped hole in a flexible pavement surface with a diameter greater than 4 in. (100 mm) and depth more than 1 in. (25 mm) [121]. PMS pothole data is collected by the ARAN according to AASHTO R 86, "Standard Practice for Collecting Images of Pavement Surfaces for Distress Detection." The image data is further processed to determine the pothole area using the software.

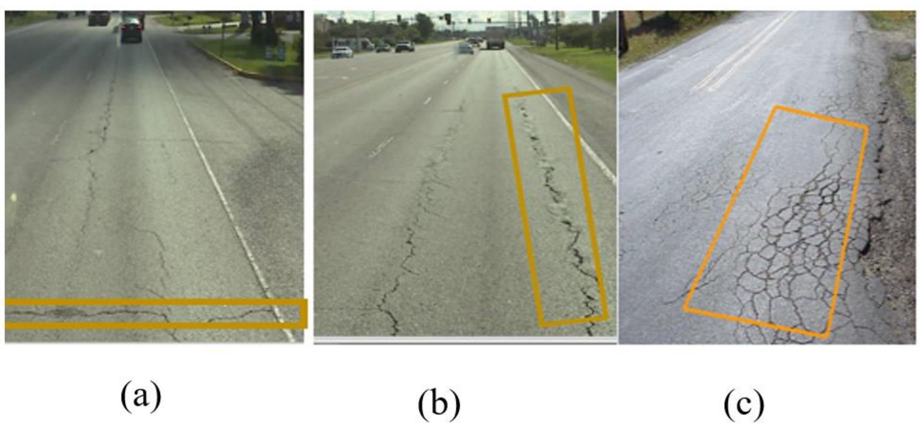
Patching

Patching is an area of pavement surface that has been repaired with the addition of new material to correct an irregularity in the pavement surface [121]. PMS patching data are collected by the ARAN according to AASHTO R 86, "Standard Practice for Collecting Images of Pavement Surfaces for Distress Detection." The image data is further processed to determine the patching area using a proprietary software.

Cracking

Cracks in pavements represent a fissure or discontinuity of the pavement surface that may extend through the entire thickness of the pavement [121]. PMS cracking data is collected using a 3-D laser scanning measuring system (LCMS) integrated at the rear of the ARAN van and according to AASHTO R 86, “Standard Practice for Collecting Images of Pavement Surfaces for Distress Detection.” The LCMS collects 3-D images of the pavement, which are then processed to determine the type and severity of cracks according to AASHTO R 85, “Standard Practice for Quantifying Cracks in Asphalt Pavement Surfaces from Collected Pavement Images Utilizing Automated Methods.” Crack types reported in PMS include transverse, longitudinal, and fatigue cracks; see Figure 31. These cracks are reported in low, medium, and high severity levels depending on the extent of the crack.

Figure 31. Typical field (a) transverse, (b) longitudinal, and (c) fatigue cracks



Description of different crack types are presented below:

Transverse Crack: These cracks are predominantly perpendicular to the direction of traffic. The unit of measurement is ft./mi.

Longitudinal Crack: These cracks are predominantly parallel to the direction of traffic and can occur both in the wheel path and outside the wheel path. The unit of measurement is ft./mi. Longitudinal cracks occurring in the right and left wheel path are denoted Long_RWP and Long_LWP, respectively. Random_C represents longitudinal cracks that occur in-between wheel paths. Random_LE and Random_RE refer to longitudinal cracks that appear at the left and right edge of the lane, respectively.

Random Crack: For composite asphalt pavements, random crack is the sum of longitudinal and transverse cracks. In flexible pavements, random crack is the sum of longitudinal and transverse cracks outside the wheel path. The unit of measurement is ft./mi.

Fatigue (Alligator) Crack: Alligator or fatigue crack is the combination of both longitudinal and transverse cracks in a mesh-like form found within each 36-in. wheel path on asphalt pavements. The unit of measurement is ft^2/mi. Fatigue_RWP and Fatigue_LWP represent mesh-like or fatigue cracks that occur in the right and left wheel paths, respectively.

Computation of Pavement Performance Indices

Louisiana DOTD quantifies the performance of each pavement section by using a distress index. Pavement distress index is a value ranging from 0 to 100 assigned to a pavement based on its condition. 0 denotes the worst condition possible and 100 refers to a new pavement in perfect condition. Pavement index is computed by subtracting a deduct value from 100 based on the magnitude, severity, and extent of pavement distress. DOTD recommends tentative treatment for pavements based on distress indices. This is done using a trigger value system, which refers to an established index value that triggers a treatment when it is reached or exceeded. In this study, alligator cracking, random cracking, rutting, and roughness indices were computed. Rutting and roughness index values are determined based on the values provided in Tables 28 and 29.

Table 28. Rutting index conversion table

Average Rut Depth, in.	Rutting Index
0.000	100
0.125	100
0.250	90
0.500	70
0.750	50
1.000	30
1.250	10
1.375	0

Table 29. Roughness index conversion table

Average IRI, in./mi.	Roughness Index
0	100
50	100
100	90
150	80
200	70
250	60
300	50
350	40
400	30
450	20
500	10

Alligator index is a measure of the severity of the of alligator cracks, which are mesh-like cracks caused by fatigue, moisture damage or variability in construction. It is computed by subtracting deduct values obtained based on severity and extent of alligator cracks from 100. Table 30 shows the Louisiana DOTD specified deduct value ranges for different severities (low, medium and high) of alligator cracks observed on flexible pavements. Equation 8 illustrates how alligator index values are computed from deduct values determined from Table 30, based on the severity of the alligator cracks observed.

$$\mathrm{ACI} = 100 - \mathrm{AD_L} - \mathrm{AD_M} - \mathrm{AD_H} \quad [8]$$

where
ACI = alligator cracking index;
$\mathrm{AD_L}$ = alligator cracking deduct for low severity;
$\mathrm{AD_M}$ = alligator cracking deduct for medium severity; and
$\mathrm{AD_H}$ = alligator cracking deduct for high severity.

Table 30. Deduct values for alligator cracks

Severity	Measured Alligator Cracks, sq. ft.					
	0-51	**51-701**	**701-1301**	**1301-2401**	**2401-3168**	**3168-9999.99**
Low	0	1-16	16-21	21-25	25-28	28
Medium	0	1-21	21-29	29-36	36-49	49
High	0	1-29	29-43	43-50	50-61	61

Random crack is a sum of all longitudinal and transverse cracks in a composite pavement. For asphalt pavements, random cracks refer to all cracks occurring outside the wheel path. The deduct values used for computing random cracking index values for flexible and composite pavements are shown in Tables 31 and 32, respectively. Random crack index values are computed using Equation 9.

$$\mathrm{RCI} = 100 - \mathrm{RD_L} - \mathrm{RD_M} - \mathrm{RD_H} \qquad [9]$$

where
RCI = random cracking index;
RD_L = random cracking deduct for low severity;
RD_M = random cracking deduct for medium severity; and
RD_H = random cracking deduct for high severity.

Table 31. Deduct values for random cracking index (flexible pavement)

Severity	Measured Random Crack Extent, linear ft.					
	0-31	**31-301**	**301-1601**	**1601-5001**	**5001-6001**	**6001-9999.99**
Low	0	1-3	3-16	16-18	18-20	20
Medium	0	1-16	16-21	21-30	30	30
High	0	1-26	26-28	28-42	42-48	48

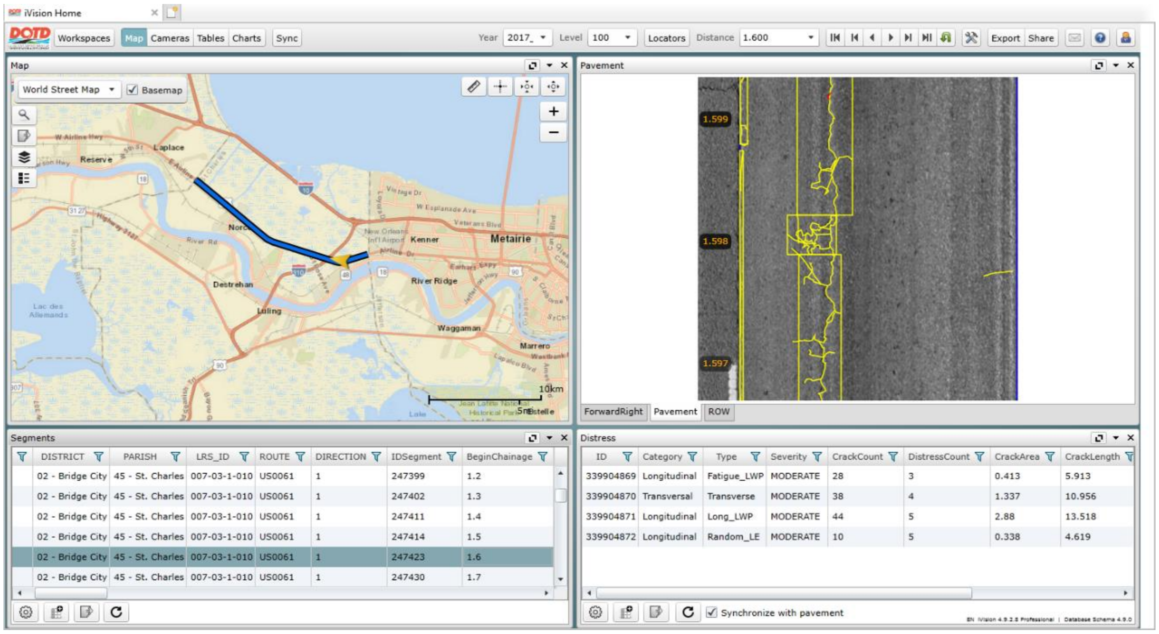
Table 32. Deduct values for random cracking index (composite pavement)

Severity	Measured Random Crack Extent, linear ft.					
	0-51	**51-326**	**326-901**	**901-2001**	**2001-6001**	**6001-9999.99**
Low	0	1-3	3-5	5-16	16-33	33
Medium	0	1-16	16-26	26-35	35-46	46
High	0	1-32	32-40	40-55	55-70	70

PMS Data Acquisition

Louisiana DOTD's Pavement Management System stores analyzed pavement distress data and images on a web-based application called iVision; see Figure 32. The pavement distress data can be accessed when connected to the DOTD intranet. In this study, field performance indicators (rutting, cracking, and roughness) and performance indices (alligator, rutting, random, and roughness) were acquired from iVision. To obtain network level data from iVision, project location data such as parish name, route name, and LRS ID is keyed into the iVision locator, and Excel files of distress data and segment data are generated. Data and images of field cores was also obtained from Deighton total infrastructure management system (DTiMs) to determine the pavement structure.

Figure 32. Typical layout of iVision



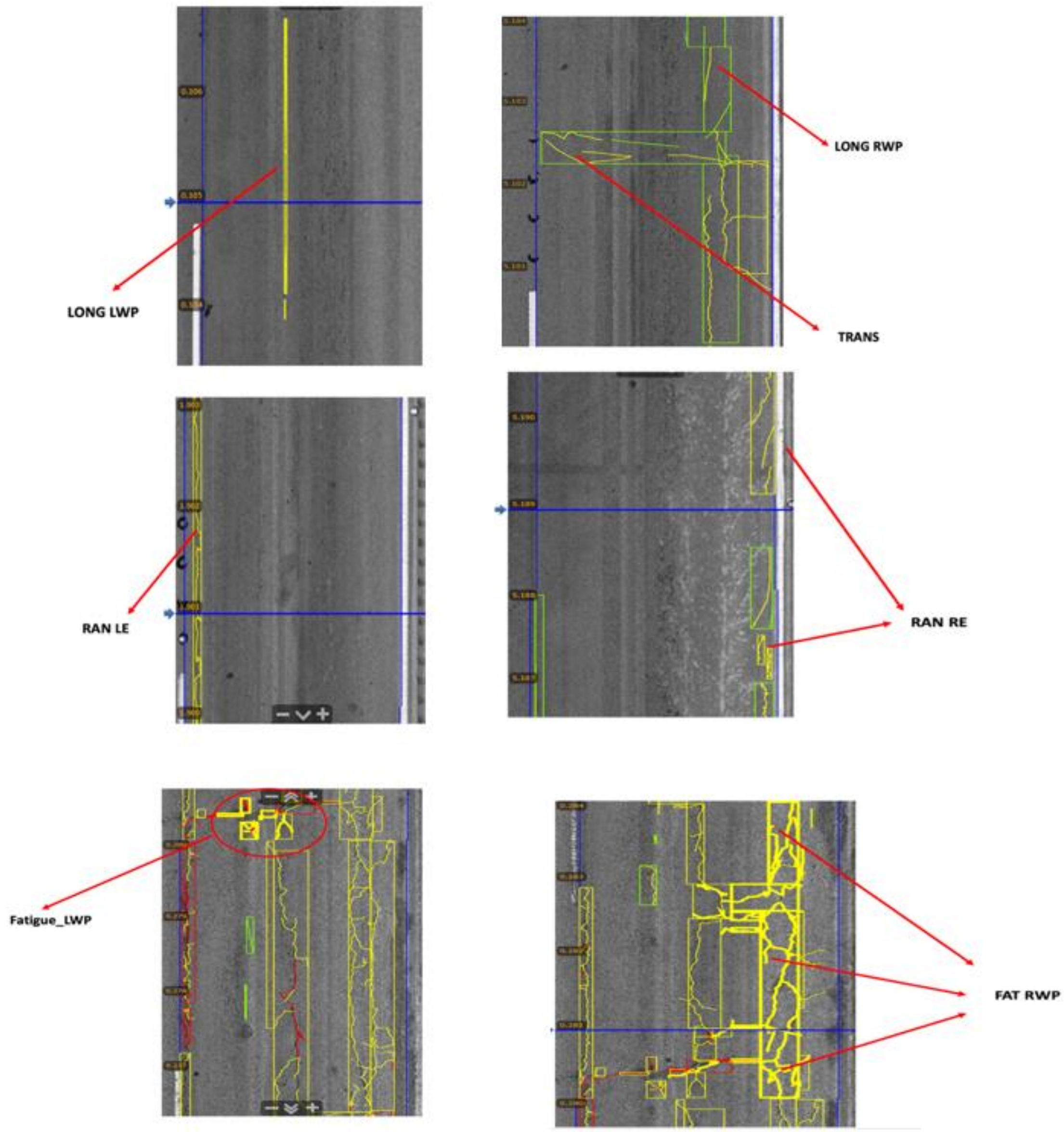
PMS Segment Data

PMS segment data refers to a summary of distress and indices data compiled based on DOTD definitions. Segment data is reported at 0.1 mi. intervals. In this study, all indices data used were acquired for PMS segment data. The rut depth and international roughness index values were also obtained from form PMS segment data. Though cracking data is reported under segment data, the cracking data used for the study was obtained from detailed distress data since segment data combines load related and non-load related cracking data. Segment data was acquired from iVision by exporting distress data, and the output is an Excel file with summary data of distresses and indices.

PMS Detailed Distress Data

The detailed distress data contains disaggregate data for cracking and patching. It is reported at 0.004 mi. intervals and shows a detailed categorization of cracks based on their geometry and position relative to the wheel path and edge of the pavement. It is advantageous to use detailed crack data because cracks can be separated into load associated and non-load associated cracks for further analyses. Figure 33 shows typical detailed cracks used in the PMS database.

Figure 33. Typical PMS detailed crack data



The detailed distress data are categorized as follows:

- Longitudinal cracks occurring in the right and left wheel path are denoted as Long_RWP and Long_LWP, respectively;
- Fatigue_RWP and Fatigue_LWP represent mesh-like or fatigue cracks that occur in the right and left wheel paths, respectively;
- Random_C represents longitudinal cracks that occur in-between wheel paths;

- Random_LE and Random_RE refer to longitudinal cracks that appear at the left and right edge of the lane
- Transverse cracks are simply labeled transverse.

Detailed data is generated by clicking “export” on the distress panel of iVision: the output is an Excel file with detail data of cracking and patching. Detailed distress data is reported for the entire length of the route without log mile location indicators every 0.1 mi. To analyze the results, the entire detailed distress for each route was extracted in an Excel file. The distress ID, which occurs at the beginning of the log mile and end of log mile, was used to filter the cracks for each 0.1 mi. using Excel programming.

To understand the effect of loading on cracking, construction related cracks like edge cracks (Random_LE and Random_RE; see Figure 33) were separated from random cracks. In asphalt pavements, random cracks which are construction related are reported as the sum of Random_LE, and Random_RE, whereas those that are load related are reported as the sum of Random_C and transverse cracks. In composite pavements, construction related random cracks are computed as the sum of Random_LE and Random_RE. Load related random cracks in composite pavements are reported as the sum of Long_RWP, Long_LWP, Random_C, and transverse cracks.

Validation of PMS Distress Data

All distress data obtained from DOTD PMS were evaluated to validate the accuracy of the data before data was used in analyses. The validation process was a two-fold approach which consisted of a virtual pavement distress survey and computation of distress values based on DOTD formulae to corroborate the values extracted from the PMS. Louisiana DOTD PMS has recorded videos of right of way and shoulders for routes surveyed. The virtual survey was conducted by entering project location data such as parish name, route name, and the desired log mile location of the test sections used in the study. The condition of the distresses as shown in the video was compared to the distress values reported at that section on the PMS. For example, a section with rutting and cracking indices of 100 on the PMS is expected to show no signs of rutting or cracking in the video. From the virtual survey it was observed that the PMS data was representative of the distress severity, as shown in the video. In sections where there was a difference in PMS data and distress in video, an analysis was performed on the 0.004 mi. PMS picture frames to address the discrepancy. In some cases, it was discovered that the disparity was due to a shift in log mile location for the video data. However, this does not affect the accuracy of distress data from the PMS. This is because PMS data is reported per 0.1 mi., while the shift in image data is approximately 0.004 mi.; therefore, the overall output is not affected. The second part of the validation process comprised of obtaining raw distress data such as cracking, rutting and roughness. The raw data served as input for index computation based on equations stipulated by DOTD. The computed indices were compared to the indices reported on the PMS. It was observed that both indices were the same.