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   Development of a 4.75-mm Asphalt Mixture Design

2. Author(s)

   Saman Salari, P.E.; Samuel B. Cooper III, Ph.D., P.E.

3. Performing Organization Name and Address

   Louisiana Transportation Research Center
   4101 Gourrier Ave
   Baton Rouge, LA 70808-4443

4. Sponsoring Agency Name and Address

   Louisiana Department of Transportation and Development
   P.O. Box 94245
   Baton Rouge, LA 70804-9245

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13. Abstract

The Louisiana Department of Transportation and Development (DOTD) and other agencies continually identify techniques to reduce roadway maintenance and construction costs. One common approach to this task is the introduction of asphalt mixtures with a smaller nominal maximum aggregate size (NMAS) for utilization in roadways. Excessive stockpiles of unused, smaller aggregates create an economically competitive resource that should be considered for asphalt mixtures. The objective of this study was to evaluate the economic viability of the recently developed mixture design criteria for 4.75-mm NMAS mixtures to be used in Louisiana. The 4.75-mm mixtures were prepared with four aggregate types and two binder types. A comprehensive performance evaluation was conducted through volumetric and mechanistic testing. Performance testing consisted of the Hamburg loaded wheel tracking (LWT) test to determine rutting resistance, the semi-circular bend (SCB) test to determine cracking potential, the dynamic modulus (E*) test to determine stiffness at different temperatures, and a friction test to evaluate the friction resistance of the proposed mixtures. Additionally, an economic analysis was conducted to determine the viability of 4.75-mm mixtures through life-cycle cost analysis

(LCCA) of pavement sections designed with 4.75-mm mixture overlays compared to sections designed with 9.5-mm and 12.5-mm mixtures. The Pavement Mechanistic-Empirical (ME) design software was used for the LCCA. As expected, asphalt binder grade, aggregate type, and mixture composition affected the performance of the mixtures. The gravel mixtures were susceptible to cracking, whereas the limestone mixtures were susceptible to rutting. The 4.75-mm mixtures were found to be cost-effective compared to conventional 9.5-mm and 12.5-mm NMAS mixtures.

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By
Saman Salari, P.E.
Samuel B. Cooper III, Ph.D., P.E.

Louisiana Transportation Research Center
4101 Gourrier Avenue
Baton Rouge, LA 70808

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The Louisiana Department of Transportation and Development (DOTD) and other agencies continually identify techniques to reduce roadway maintenance and construction costs. One common approach to this task is the introduction of asphalt mixtures with a smaller nominal maximum aggregate size (NMAS) for utilization in roadways. Excessive stockpiles of unused, smaller aggregates create an economically competitive resource that should be considered for asphalt mixtures. The objective of this study was to evaluate the economic viability of the recently developed mixture design criteria for 4.75-mm NMAS mixtures to be used in Louisiana. The 4.75-mm mixtures were prepared with four aggregate types and two binder types. A comprehensive performance evaluation was conducted through volumetric and mechanistic testing. Performance testing consisted of the Hamburg loaded wheel tracking (LWT) test to determine rutting resistance, the semi-circular bend (SCB) test to determine cracking potential, the dynamic modulus (E*) test to determine stiffness at different temperatures, and a friction test to evaluate the friction resistance of the proposed mixtures. Additionally, an economic analysis was conducted to determine the viability of 4.75-mm mixtures through life-cycle cost analysis (LCCA) of pavement sections designed with 4.75-mm mixture overlays compared to sections designed with 9.5-mm and 12.5-mm mixtures. The Pavement Mechanistic-Empirical (ME) design software was used for the LCCA. As expected, asphalt binder grade, aggregate type, and mixture composition affected the performance of the mixtures. The gravel mixtures were susceptible to cracking, whereas the limestone mixtures were susceptible to rutting. The 4.75-mm mixtures were found to be cost-effective compared to conventional 9.5-mm and 12.5-mm NMAS mixtures.

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Implementation Statement

The findings of this research serve as a guide for DOTD in the production of 4.75-mm NMAS mixtures. The use of 4.75-mm mixtures for overlay construction and pavement preservation will improve the quality, durability, and structural performance of pavements in Louisiana. Furthermore, the findings of this study serve as a guide for conducting field studies to verify the design and performance of 4.75-mm NMAS mixtures.

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Introduction

The Louisiana Department of Transportation and Development (DOTD) is facing budgetary challenges due to limited funding. Coupled with the fact that Federal Highway Administration (FHWA) funds have not seen significant increases in the past four years [1], the preservation of Louisiana's transportation infrastructure has been affected. DOTD has researched techniques to reduce the maintenance and construction costs of asphalt pavements [2]. The use of asphalt mixtures with a smaller nominal maximum aggregate size (NMAS) may be a viable option to increase the number of miles that a mixture can perform effectively.

In 2002, the National Center for Asphalt Technology (NCAT) completed a study to develop a Superpave mix design criteria for a 4.75-mm NMAS mixture [3]. NCAT used the permeability test (ASTM PS 121) to study different aggregate qualities that could enhance the performance of the 4.75-mm NMAS mixture. Multiple federal and state agencies, including AASHTO, Georgia Department of Transportation, Maryland Department of Transportation, and others, have included mixture design requirements for 4.75-mm NMAS mixtures in their specifications. As a result, several state highway agencies have started utilizing these recommendations for maintenance, leveling courses, and thin-lift applications to decrease construction time and provide an economical surface mix for low-volume roads.

Currently, the smallest NMAS mixture in DOTD's specifications is 12.5-mm (i.e., 1/2 inch) [4]. However, several studies [3] [5] [6] [7] have concluded that, in specific scenarios, an NMAS mix of less than 12.5-mm is more effective than mixtures that employ a larger NMAS. The DOTD is pursuing multiple goals in utilizing a lower NMAS mix: (1) decrease construction time; (2) provide an economical surface mix for low-volume roads; (3) provide smooth riding surfaces; (4) provide thin-lift asphalt overlays; (5) correct surface defects; (6) serve as a leveling material; (7) reduce permeability; and (8) reduce the fine-aggregate stockpile for contractors.

DOTD has recently implemented a balanced design framework for asphalt mixtures. Therefore, asphalt mixtures are verified by specified rutting/moisture resistance and cracking criteria. The Hamburg loaded wheel tracking test (LWT) is used to evaluate rutting and moisture resistance, whereas the semi-circular bend test (SCB) assesses intermediate temperature cracking resistance. Since the Louisiana balanced mix design (BMD) framework has been shown to be effective in relating laboratory-measured rutting and cracking performance to field performance, it is imperative that it be used to ascertain the field performance of 4.75-mm NMAS mixtures. In order to thoroughly evaluate aggregate sources commonly used for roadway construction throughout the state, several mixture and aggregate designs were developed and subjected to mechanical testing. Additionally, an economic analysis of 4.75-mm mixtures is required to ascertain their cost effectiveness compared to conventional 9.5-mm and 12.5-mm mixtures.

Objective and Scope

This study aimed to evaluate the economic viability of the recently developed mixture design criteria for 4.75-mm NMAS mixtures to be used in Louisiana. Researchers employed the data used to recommend the implementation of a 4.75-mm mixture design in DOTD specifications. The laboratory and mixture design data are included in the report. The cost analysis of the mixtures was combined with performance prediction using AASHTOWare Pavement ME to generate the LCCA. Commonly used aggregates and binders were evaluated to determine the most economical mixture for DOTD. Five mixtures were developed for the testing factorial; these mixtures employed four aggregate types from variable sources (gravel, limestone, sandstone, and 910 limestone). Asphalt binder grades used for testing included unmodified PG 67-22 and styrene-butadiene-styrene (SBS)-modified PG 76-22m. The mixture design parameters were varied to better understand the effects of aggregate and binder type on 4.75-mm NMAS mixtures' performance. The cost and performance predictions of the five 4.75-mm mixtures were compared to those of conventional 9.5-mm and 12.5-mm mixtures.

Background

Currently, the lowest nominal maximum aggregate size (NMAS) mixture allowed in Louisiana is 12.5-mm (i.e., 1/2 inch) [4]. State agencies and research labs have shown that smaller NMAS mixtures, specifically 4.75-mm NMAS mixtures, have several benefits over larger NMAS mixtures. A comparison between these two mixtures is seen in Figure 1. These benefits include a reduction in screening stockpiles, use in thin lift applications, use in leveling and patching applications, and use in low-volume road applications [5] [6] [7]. These benefits have made it a priority for state agencies such as Louisiana DOTD to evaluate the implementation of 4.75-mm NMAS mix designs into their standard specifications.

Figure 1. 12.5-mm NMAS mixture (left) next to 4.75-mm NMAS mixture (right)

The use of lower NMAS mixtures is often met with skepticism due to concerns about rutting susceptibility. These rutting issues are caused by the higher asphalt content of 4.75-mm NMAS mixtures compared to that of a standard 12.5-mm NMAS mixture. When the binder content is too high, it fills the void spaces and separates the aggregate particles, which reduces the stone-to-stone contact; as a result, the rutting resistance is decreased [8]. In 2002, Cooley Jr. et al. [5] indicated that fine mixes have no more rutting potential than coarse mixes. In later studies, Williams [7] compared 4.75-mm mixtures with 12.5-mm mixtures using two-wheel tracker tests and confirmed the same phenomenon. The studies found that 4.75-mm mixtures could be designed to resist rutting and stripping equally or more effectively than 12.5-mm mixtures. Both studies found that aggregate type, air void content, and binder grade affected rut depths. Based on the work done by Cooley Jr. et al., a 4.75-mm mixture design and criteria section were added to the Superpave mixture design specifications [5].

While aggregate selection depends on accessibility and cost, it is essential to a 4.75-mm NMAS mixture's performance and should follow the chosen limitation [6]. Studies performed by Cooley Jr. et al. [5] and Zaniewski and Diaz [6] showed that limits of 30-54% passing the 1.18-mm sieve were reasonable. Table 1 shows the gradations from different agencies and research groups. Dust content (i.e., the percent of aggregate passing the 0.075-mm sieve) has a considerable effect on VMA and rutting. As dust content increases, VMA decreases, and vice versa. According to Williams [7], for every 3% increase in dust content, optimum binder content decreases by an average of 0.5%.

Rutting is also affected by fine aggregate angularity (FAA) and natural sand. FAA and natural sand content need to be controlled in the mixture to ensure a high degree of fine aggregate internal friction [6]. Cooley Jr. et al. [5] reported that FAA should be greater than 40% for less than 0.3 million design ESALs and greater than 43% for 0.3 to 3 million design ESALs. FAA criteria help limit the quantity of rounded particles in the aggregate blend. Cooley Jr. et al. [5] suggested that natural sand should be limited to 15–20% for high-volume roadways and 20–25% for low- and medium-volume roads. There is also evidence that natural sand content above 15% can adversely affect moisture and rutting susceptibility, as well as permeability [5]. Zaniewski and Diaz [6] found that over 10% of natural sand resulted in increased rutting, and over 20% of natural sand resulted in pronounced rutting potential. Furthermore, researchers generally agreed that an excess of natural sand can cause problems in the mixture.

The design air void content has a significant impact on the mixture. Williams [7] suggested that the air void content of mixtures be restricted to 4–6%. High-volume roads typically require 4–4.5% air void content, whereas low- to medium-volume roads are compacted to 6% air void content due to their low rutting potential. Higher air void contents, such as 6%, help reduce binder content, which in turn reduces construction costs. West et al. [9] also concluded that using a design air void content range of 4-6% has little effect on the VMA. Additionally, it will allow mix designers to reduce the asphalt content for a given aggregate blend when the VMA is well above 16%, which will improve the resistance of 4.75-mm mixtures to permanent deformation.

Both AASHTO and Superpave criteria have a minimum VMA requirement of 16% for 4.75-mm mixtures. Williams [7] determined the critical VMA value from the relationship with dust content to be 16%, which matches AASHTO and Superpave criteria. Zaniewski and Diaz [6] suggest that mixes designed at greater than 75 gyrations should have a maximum VMA of 18% to avoid excessive optimum binder. They stated that no maximum VMA criteria should be used for mixtures compacted at 50 gyrations. If the air void content is 4% on a low-volume road, a VMA range of 16–18% may be used since low-volume roads can tolerate higher VMA values. If the air void content and VMA are controlled, VFA is implied and not necessary. The gradation and design criteria from various studies and state agencies for 4.75-mm NMAS mixtures are demonstrated in Table 1.

Historically, pavement design relied on empirical methods developed by the American Association of State Highway and Transportation Officials (AASHTO) in the 1950s. However, the empirical approach is limited, as it does not account for different climate conditions, detailed traffic information, or variability in material properties. In order to overcome these limitations, the mechanistic-empirical (ME) design method was developed [10]. The mechanistic-empirical pavement design approach has been adopted to enable pavement engineers to design pavement structures with more comprehensive knowledge. The pavement's mechanistic responses are calculated based on the inputs of traffic, climate, structures, and material properties. By utilizing the empirical response-distress relationship, the various distresses of pavement can be predicted. This approach can establish the fundamental relationship between material properties and their consequent distresses. This method can simulate pavement structure with more accurate and reliable inputs such as detailed climate and traffic data, material properties, and various construction procedures.

Table 1. Design criteria of state agencies and research of 4.75-mm NMAS mixtures

Source	**AASHTO [3]**	**Georgia**	**Maryland**	**Williams (2006) [7]**	**NCAT (2011) [7]**
Gradations (Percent Passing)					
12.5 mm (1/2 in.)	95 - 100	90 - 100	100	100	95 - 100
9.5 mm (3/8 in.)	90 - 100	75 – 95	80 - 100	95 - 100	90 - 100
4.75 mm (No. 4)	-	60 – 65	36 - 76	90 - 100	-
2.36 mm (No. 8)	30 - 60	-	-	-	30 - 55
1.18 mm (No. 16)	-	-	-	30 - 60	-
0.3 mm (No. 50)	-	20 – 50	-	-	-
0.15 mm (No. 100)	-	-	-	-	-
0.075 mm (No. 200)	6.0 - 12	4.0 - 12	2.0 - 12	6.0 - 12	6.0 - 13
Design Criteria					
Asphalt Content (%)	-	6.0 - 7.5	5.0 - 8.0	-	-
Air Voids (%)	4.0	4.0 - 7.0	4.0	4.5 – 6.0	4.0
VMA (%)*	16 min.	-	-	18 - 20	-
VFA (%)**	75 - 78	50 - 80	-	71.9 - 75	-
DP (Percent Dust)	0.9 - 2.0	-	-	0.9 - 2.0	-

* Voids in mineral aggregates; **Voids filled with asphalt

A life-cycle analysis of mixtures must be considered so that performance and durability can be compared to the costs of mixtures with different components. Son et al. [11] considered cost-benefit analysis to define the advantages of 4.75-mm SMA mixtures. By incorporating both field and laboratory performance data into their analysis, they were able to effectively compare the mixtures across various aspects.

Methodology

Aggregate Blends and Mixture Description

Aggregate types that are commonly used on Louisiana roads were selected for this study. Four aggregate types were chosen: gravel, limestone, sandstone, and 910LS (910 represents the size, and LS is the aggregate type). Multiple aggregate blends were designed with one or two aggregate types that satisfied the 4.75-mm NMAS aggregate criteria established by AASHTO. The four aggregate sources were combined with two different binder types, resulting in eight total mixtures for this study, as described below. Table 2 presents the mixture naming convention used throughout this study.

Table 2. Mixture types

Mixture Identification	Aggregate type	Binder PG Grade	Additive
67-Gr	Gravel	67-22	
76-Gr		76-22m	
M7 Gr		67-22	M7
67-Ls	Limestone	67-22	
76-Ls		76-22m	
M7 Ls		67-22	M7
67-Gr+Ls	Gravel + LS	67-22	
76-Gr+Ls		76-22m	
M7 Gr+Ls		67-22	M7
67-910	910 LS	67-22	
M7-910		67-22	M7
67-St	Sandstones	67-22	
M7-St		67-22	M7
9.5 Gr	9.5 mm Gravel	67-22	
12.5 Gr	12.5 mm Gravel	67-22	

67-Gr and 76-Gr

These mixtures contained gravels with the same gradation but differed in the type of asphalt binder used. The 67-Gr mixture used an unmodified PG 67-22 asphalt binder, whereas the 76-Gr incorporated a polymer-modified PG76-22m (SBS) asphalt binder.

67-Ls and 76-Ls

These mixtures were produced with the same limestone aggregate structure and blended with an unmodified PG 67-22 for the 67-Ls mixture and a polymer-modified PG76-22m (SBS) asphalt binder for the 76-Ls mixture.

67-Gr+Ls and 76-Gr+Ls

These mixtures were prepared with a uniform blend of gravel and limestone aggregates. The gravel-limestone aggregate blends were combined with an unmodified PG 67-22 asphalt binder to produce the Gr+Ls-67 mixture and a polymer-modified PG 76-22m (SBS) binder to produce the Gr+Ls-76 mixture.

67-910 and 67-St

Two aggregate sources were used to prepare the 67-910 and 67-St mixtures: 910LS and sandstone. The 910LS and sandstone aggregates were blended with unmodified PG 67-22 asphalt binder to produce 67-910 and 67-St, respectively.

9.5-mm and 12.5-mm Gravel

For a comprehensive evaluation of the 4.75-mm mixtures, two conventional mixtures (i.e., 9.5-mm and 12.5-mm NMAS) were prepared with gravel and unmodified PG 67-22 asphalt binder for comparison.

It should be noted that some selected mixtures in Table 2 were modified with a crumb rubber additive (i.e., M7) to ascertain the effects of crumb rubber modification on 4.75-mm mixtures.

Laboratory Testing

Laboratory tests were conducted to determine the effectiveness of the aggregate designs, the effect of binder type, and the various mixtures' overall performance. The laboratory evaluation methods utilized in this research are presented below.

Ignition Test

The ignition test was conducted following the AASHTO T-308 procedure for verification. A sample of approximately 1,500 to 2,000 grams of the mixture was collected through quartering. The sample is placed in a high-temperature oven that burns off the asphalt binder at 530°C. The oven continuously burns and weighs the sample every minute. The test is complete when the weight remains constant, indicating that the entirety of the asphalt binder burned off. Simple calculations of the pre- and post-ignition weight determine the asphalt weight. In addition to the asphalt weight, the remaining aggregate is collected for gradation analysis based on AASHTO T-30.

Volumetric Analysis

To gain a comprehensive understanding of the various aspects of the 4.75-mm NMAS mix design, volumetric analysis was conducted. This analysis was used to determine the optimum asphalt content for all mixes. AASHTO M-323 was used to obtain the volumetric properties. The verified volumetric properties consisted of air voids (Va), voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), and dust to asphalt proportion (DP).

Semi-Circular Bend (SCB) Test

The SCB test was performed in accordance with ASTM D8044, "Standard Test Method for Evaluation of Asphalt Mixture Cracking Resistance using the Semi-Circular Bend Test (SCB) at Intermediate Temperatures." This test characterizes the critical strain energy release rate, SCB J_c, a measure of the fracture resistance of asphalt mixtures at intermediate temperatures. Semi-circular samples were prepared with two different notch depths: 25.4 mm and 38 mm. The test was conducted at a moderate, controlled temperature of 25°C. Four replicates were tested for each notch depth to ensure reliable results. The specimens were subjected to a steadily increasing load (i.e., monotonic loading) at a constant speed of 0.5 millimeters per minute in a three-point bending setup; see Figure 2. Throughout the test, the load and deformation of the samples were continuously recorded. The recorded data was used to calculate the SCB J_c for each sample. By comparing the SCB J_c values of different mixtures, the intermediate cracking resistance of the asphalt mixture can be assessed. The fracture resistance of a mixture increases with increasing SCB J_c values at intermediate temperatures and, conversely, decreases with lower SCB J_c values.

Figure 2. Semi-circular bend (SCB) test

Hamburg Loaded-Wheel Tester (LWT)

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

Figure 3. Hamburg Loaded-Wheel Tester (LWT)

Friction Tests (DFT and CTM)

To ensure the safety of roads utilizing finer aggregate mixtures, LTRC conducted sophisticated friction tests. These tests included the Dynamic Friction Test (DFT) and the Circular Track Meter (CTM) test. The DFT was performed following ASTM E1911-19, “Standard Test Method for Measuring Surface Frictional Properties Using the Dynamic Friction Tester.” The DFT machine has three rubber sliders at the bottom. These sliders are spring-mounted on a disk with a diameter of 350 millimeters. During testing, the disk remains above the slab surface until the sliders reach a tangential speed of 90 km/h. At this point, the disc is separated from the driving motor and lowered onto the surface of the slab while introducing water to the surface. The three rubber sliders touch the surface, and the friction force is measured by a transducer as the disk spins down. The DFT system measures different frictions in the range of 0 to 90 km/h. This device is used to determine the micro-texture properties of the slabs; see Figure 4.

Figure 4. Dynamic Friction Test (DFT) setup

The macro-texture characteristics of the mixtures were evaluated using the Circular Texture Meter (CTM). The CTM is a laser-based measuring device with a measuring area of a circle that is 284 millimeters in diameter. CTM reports its results as mean profile depth (MPD). This test was conducted based on ASTM E2157-15, “Standard Test Method for Measuring Pavement Macro-texture Properties Using the Circular Track Meter.” Figure 5 shows the setup of the CTM device.

Figure 5. Circular Track Meter (CTM) test setup

Further strengthening safety assessments, the World Road Association’s Permanent International Association of Road Congresses (PIARC) developed the International Friction Index (IFI). This index combines the friction parameters obtained from both the DFT and CTM test, providing a comprehensive evaluation of a pavement's grip.

To understand the friction changes due to tire passage, lab-made slabs were prepared using the different mixture types developed for this project; after production of the slabs, the DFT and CTM tests were performed. In the next step, the slabs were treated with the Three Wheel Polisher, which simulates the effect of tire passage on the slab’s surface. The Three Wheel Polisher was developed in the late 1980s by the National Center for Asphalt Technology (NCAT) in Auburn, Alabama, as shown in Figure 6. It has three abrasive wheels mounted on a rotating carriage. The wheels grind across the surface of an asphalt slab, mimicking the polishing effect of traffic tires. In this project, 10,000 passes were chosen, while the tire pressure was routinely checked and kept constant. Another round of DFT and CTM testing was then performed on polished slabs. The comparison between friction parameters before and after polishing evaluates the performance of mixtures as a result of polishing by tires.

Figure 6. Three wheel polisher and polished slab

Dynamic Elastic Modulus (E*)

Dynamic Elastic Modulus was conducted to determine the stiffness of 4.75-mm NMAS mixtures at a wide range of temperatures and frequencies, as compared to 12.5-mm NMAS mixtures. This test was performed to evaluate the stiffness of the mixtures being subjected to cyclic loading; it was conducted according to AASHTO T342. The data obtained from the dynamic modulus test was used for the Pavement ME analysis.

Pavement Performance Evaluation using AASHTOWare Pavement ME Software

In order to relate pavement structure and mixture properties such as layer thickness, modulus, and volumetric properties to the pavement response and performance, AASHTO-Ware Pavement ME was employed to compare the lifetime durability of smaller aggregate size mixtures (i.e., 4.75-mm NMAS) to conventional mixtures (i.e., 12.5-mm or 9.5-mm NMAS). This software requires a series of inputs to evaluate the pavement design, including traffic information, climate data for the target region, local calibration factors for various distresses, and the properties of materials used in the layers. Asphalt pavement performance is predicted for major distresses such as the International Roughness Index (IRI), top-down and bottom-up fatigue cracking, asphalt layer rutting, total rutting, and thermal cracking. A 95% reliability level was considered for all distress types with a relatively conservative design. A new asphalt pavement was analyzed with a design life of 20 years, considering the inputs below.

Traffic Inputs

A high traffic level with an average annual daily truck traffic (AADTT) of 4,000 was assumed. Although a 4.75-mm NMAS mixture was considered for low-traffic cases, a high traffic level was assumed as the worst-case scenario. In this research, AASHTOWare

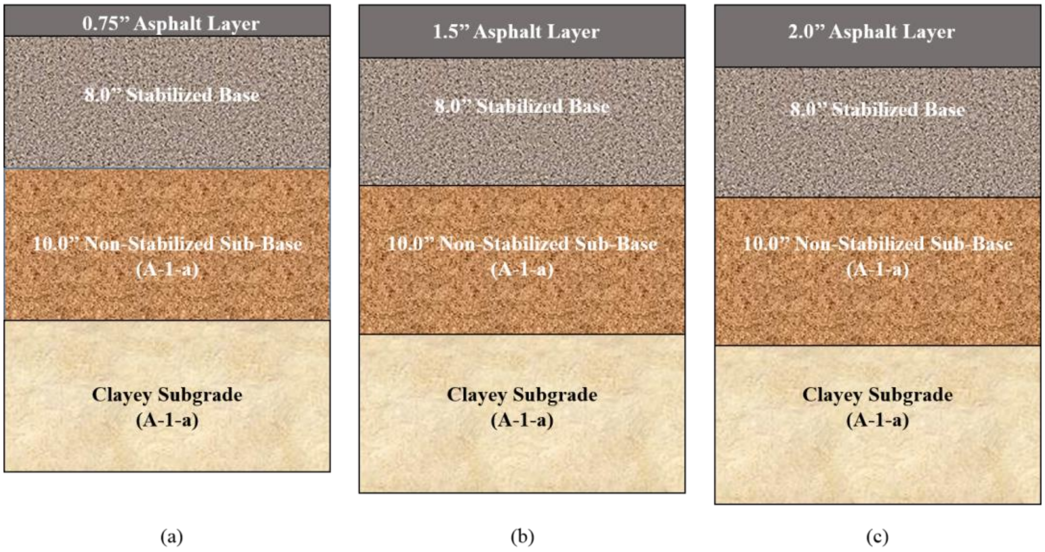
Pavement ME default traffic was used. Based on the developed truck axle load spectra in the software, the normalized axle load distributions for single, tandem, tridem, and quad-axle types for vehicle classes 4 through 13 were used. A monthly distribution factor of 1 was considered. In terms of axle configuration, 8.5 feet was used for average axle width, while 51.5 inches, 49.2 inches, and 49.2 inches were used as tandem, tridem, and quad-axle spacing, respectively. Furthermore, the mean wheel location was considered to be 18 inches, and the traffic wander standard deviation was assumed to be 10 inches.

Based on previous research, the Louisiana pavement mechanistic-empirical design's local calibration coefficients were implemented following the proposed guideline [12].

Materials and Pavement Structure

A total of three aggregate structures with an NMAS of 4.75-mm, 9.5-mm, and 12.5-mm were selected for evaluation; see Figure 7. An asphalt layer with a thickness of 0.75 inches was used for the 4.75-mm mixture. Asphalt layers for the 9.5-mm and 12.5-mm mixtures were assumed to be 1.5 inches and 2.0 inches, respectively. For the 4.75-mm and 12.5-mm mixtures, level 1 inputs were considered for the dynamic modulus and binder performance grade data. A level 3 dynamic modulus input was considered for the 9.5-mm mixture. An 8-inch stabilized base layer with a resilient modulus of 80 ksi was assumed. Additionally, a 10-inch non-stabilized layer with a resilient modulus of 27 ksi was considered for the sub-base layer. The subgrade was assumed to be a semi-infinite clayey layer with a resilient modulus of 16 ksi.

Figure 7. Pavement structures for (a) 4.75-mm mixture, (b) 9.5-mm mixture, (c) 12.5-mm mixture



Discussion of Results

A series of laboratory tests was performed to fulfill the objective of this study. These tests were designed to evaluate the performance of the 4.75-mm NMAS mixtures with different aggregate combinations and compare them with 9.5-mm and 12.5-mm NMAS mixtures. These tests compared the behavior of the finer aggregate mixtures by evaluating four key properties: mixture design volumetric properties, rutting performance using Hamburg Loaded Wheel Tracking (LWT), cracking performance using the Semi-Circular Bend (SCB) test, and friction performance. The results of the laboratory testing are presented in subsequent sections of this report. Details of the design and development of the mixtures evaluated in this study are provided in previous work [13].

Mixture Design

Table 3 presents the design properties of the mixtures evaluated in this study. Five aggregate structures were considered for evaluation. Three of the aggregate structures were combined with two asphalt binder grades (PG 67-22 and PG 76-22), whereas the two remaining aggregate structures were combined with PG 67-22 asphalt binder, resulting in eight total mixtures for assessment.

Table 3. Mixture design

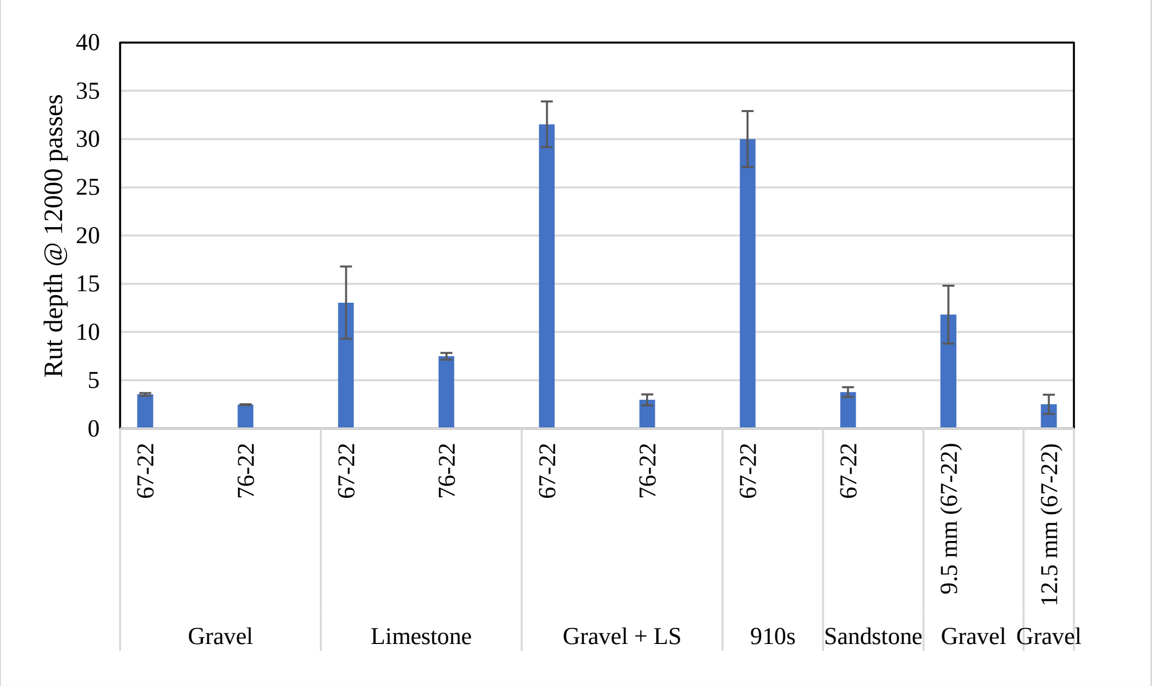
	Limestone	**Gravel**	**Sandstone**	**Gravel+ Limestone**	**910LS**	**9.5 mm Gravel**	**12.5 mm Gravel**
Gradations (Percent Passing)							
12.5 mm (1/2 in.)	100	100	100	100	100	100	97
9.5 mm (3/8 in.)	97	100	100	100	100	95	86
4.75 mm (No. 4)	92	97	93	100	100	85	66
2.36 mm (No. 8)	73	59	62	67	70	56	47
1.18 mm (No. 16)	53	38	40	40	46	41	35
0.6 mm (No.)	38	26	28	24	33	31	27
0.3 mm (No. 50)	25	15	22	15	21	20	16
0.15 mm (No. 100)	14	9	15	10	14	12	9
0.075 mm (No. 200)	9	6	9	7	11	8	6
Design Criteria							
Asphalt Content (%)	7.0	8.2	7.2	7.8	7.1	7	6.5
Air Voids (%)	3.2	3.5	3.4	4.2	3.8	3.5	4
VMA (%)*	17	15	14	18	17	14	14
VFA (%)**	82	78	76	77	82	50	44
DP (Percent Dust)	1.6	1.7	2.0	1.5	1.6	2.6	2.1

*VMA: Voids in mineral aggregates, **VFA: Voids filled with asphalt

Hamburg Loaded Wheel Tracking Test

Permanent deformation is a significant concern for mixtures containing small aggregates; therefore, LWT was selected to characterize the behavior of the mixtures in response to cyclic rolling loads. The LWT rut depth values for each mixture are presented in Figure 8. The DOTD specifications for thin-lift asphalt mixtures (Section 501) require dense mixtures to exhibit rut depth values less than 12 millimeters after 12,000 passes. Among the 4.75-mm mixtures evaluated, the gravel and sandstone mixtures showed rut depth values comparable to that of the 12.5-mm mixture, which also met the DOTD-specified threshold. Additionally, all 4.75-mm mixtures containing PG 76-22 asphalt binder exhibited rut depth values lower than the specified threshold. It is worth noting that DOTD does not require the use of PG 76-22 binder in dense-graded mixtures used for thin-overlay applications. The remaining 4.75-mm mixtures prepared with PG 67-22 asphalt binder and limestone, gravel-limestone blends, or 910 LS showed rut depth values that exceeded the recommended maximum value of 12 millimeters at 12,000 passes. These observations suggest that the use of gravel and sandstone aggregates in 4.75-mm mixtures can provide better aggregate interlock to enhance rutting resistance. The 9.5-mm mixture exhibited rut depth values higher than the recommended value, whereas the 12.5-mm mixtures showed rut depth values below the DOTD-specified threshold.

Figure 8. Hamburg Loaded Wheel Tracking test results, 50°C, wet

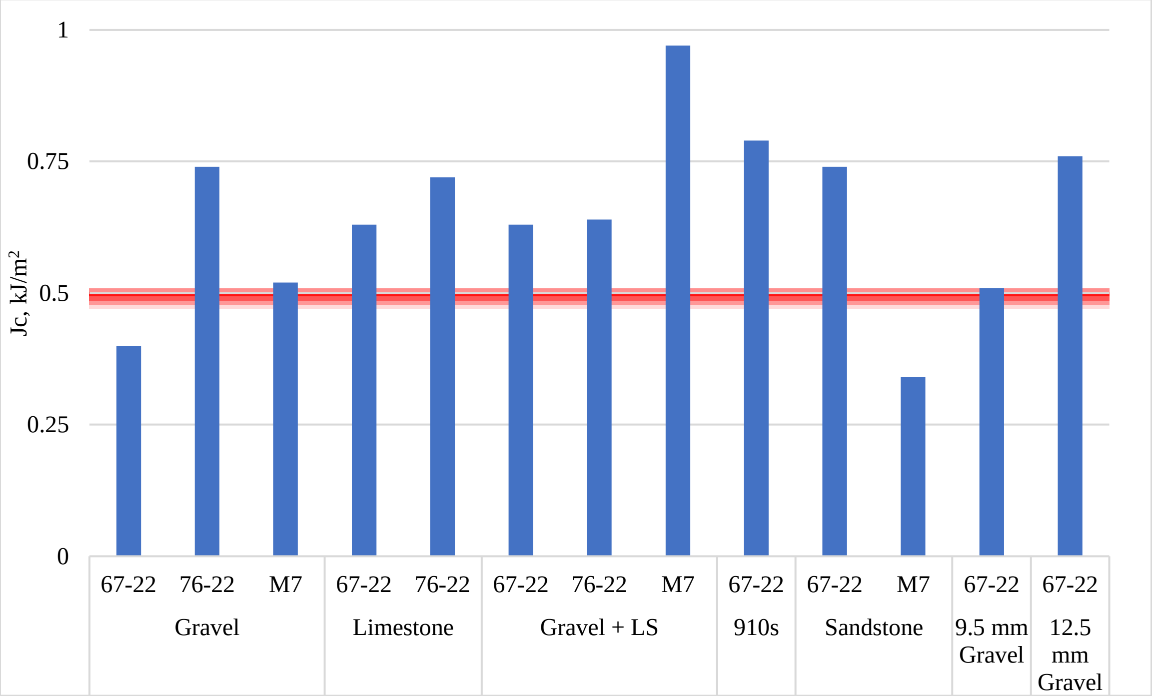


Semi-Circular Bend (SCB) Test

Cracking sensitivity was determined using the Semi-Circular Bend test (SCB) at an intermediate temperature. The SCB J_c values of the mixtures are presented in Figure 9. The state of Louisiana specified the criteria for acceptable cracking resistance (J_c) to be greater than or equal to 0.5 kJ/m^2 for low-volume roadways and greater than or equal to 0.6 kJ/m^2 for high-volume roadways. All of the mixtures passed the minimum J_c threshold of 0.50 kJ/m^2, with the exception of two 4.75-mm mixtures: PG 67-22 gravel mix and sandstone mix modified with crumb rubber additive. Therefore, the mixtures developed in this study should not have concerns regarding premature intermediate temperature cracking. This result is consistent with other researchers' observations regarding small NMAS mixtures [14]. Higher asphalt content results in increased durability, as long as permanent deformation is not present.

The use of a polymer-modified binder consistently increased the evaluated J_c values. Again, this finding is expected due to the increased durability observed by using SBS polymer modification. Gravel was the most susceptible to cracking, while limestone and limestone plus gravel performed similarly.

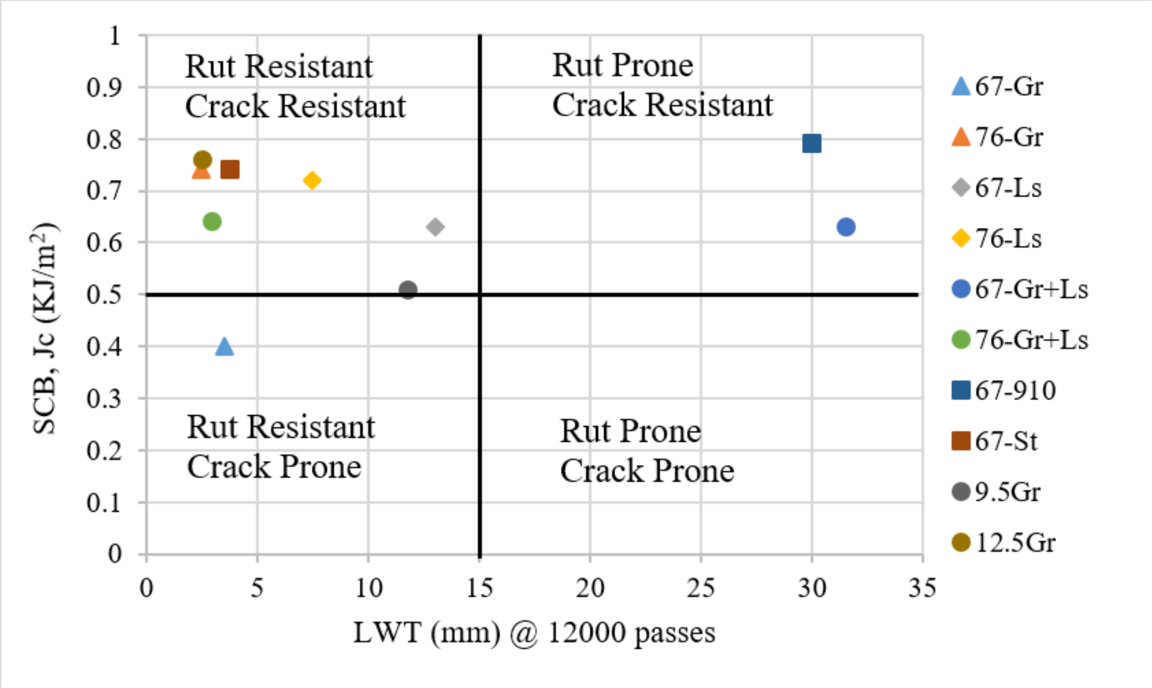
Figure 9. J_c values from SCB test



Balanced Performance Comparison

Figure 10 presents a BMD plot for SCB J_c and LWT rut depth values. These comparisons included Louisiana state specification restrictions for balanced mixture design and thin-lift mixture criteria. The objective is to have the mixture results appear in the top left portion of the graph. These samples will be rut- and crack-resistant. A total of four 4.75-mm mixtures met the proposed requirements for a balanced mixture together with the conventional mixtures (i.e., 9.5-mm and 12.5-mm): 67-St, 76-Ls, 76-Gr, and 76-Gr+Ls. These mixtures contained PG 76-22m asphalt binder, with the exception of the sandstone mixture. Three 4.75-mm mixtures were found to be rut-prone but crack-resistant: 67-Ls, 67-Gr+Ls, and 67-910Ls. The 67-Gr mixture was found to be rut-resistant but prone to cracking. These results indicate that using a polymer-modified binder can enhance the cracking or rutting resistance of the 4.75-mm NMAS mixtures.

Figure 10. Balanced performance for mixtures



Friction Tests (DFT and CTM)

Asphalt pavement friction testing is essential for ensuring safe driving conditions. It measures the resistance to skidding offered by the pavement surface, which directly impacts vehicle stopping distances and braking performance. Table 4 presents the aggregate friction ratings used in this study. Several other methods exist for friction consideration; the Circular Texture Meter (CTM) and Dynamic Friction Tester (DFT) are two of the most common.

Table 4. Aggregate friction ratings

Mixture identification	Aggregate type	Aggregate friction rating
67-Gr	Gravel	III
76-Gr	Gravel	III
M7 Gr	Gravel	III
67-Ls	Limestone	IV
76-Ls	Limestone	IV
M7 Ls	Limestone	IV
67-910	910 LS	III
M7-910	910 LS	III
67-St	Sandstone	I
M7-St	Sandstone	I
9.5 Gr	9.5 mm Gravel	III
12.5 Gr	12.5 mm Gravel	III
12.5 Ls	12.5 mm Limestone	IV

CTM Test

The CTM measures the macro texture of the pavement surface, which refers to the larger-scale texture features like grooves, bumps, and voids. The resulting mean profile depth (MPD) values are presented in Table 5.

Table 5. MPD results of slabs

MPD	Unpolished	Polished	Difference
Gravel	0.29	0.46	-0.17
Limestone	0.37	0.34	0.03
Grav+LS	0.41	0.41	0.00
Sandstone	0.57	0.51	0.06
9s&910s	0.55	0.54	0.01
M7 Gravel	0.27	0.42	-0.15
M7 Limestone	0.28	0.33	-0.05
M7 Grav+LS	0.34	0.34	0.00
M7 Sandstone	0.36	0.42	-0.06
12.5 Gravel	0.36	0.47	-0.11
12.5 Limestone	1.53	1.41	0.12

DFT Test

The DFT measures the dynamic friction between the pavement and a standard tire traveling at various speeds. This provides an insight into the micro-texture characteristics of the pavement, which refer to the finer-scale surface irregularities. In the NCHRP 1-43 study, researchers utilized DFT at 20 km/h for friction evaluation. Therefore, DFT_{20} has been adopted for this study as well. The DFT_{20} results are presented in Table 6.

Table 6. DFT_{20} results of slabs

DFT_{20}	**Unpolished**	**Polished**	**Difference**
Gravel	0.77	0.43	0.34
Limestone	0.48	0.39	0.09
Grav+LS	0.76	0.42	0.34
Sandstone	0.49	0.49	0.00
9s&910s	0.56	0.45	0.11
M7 Gravel	0.53	0.48	0.05
M7 Limestone	0.44	0.43	0.01
M7 Grav+LS	0.55	0.43	0.12
M7 Sandstone	0.60	0.48	0.12
12.5 Gravel	0.63	0.48	0.15
12.5 Limestone	0.59	0.39	0.20

International Friction Index (IFI) or F_{60}

The IFI, also known as F_{60}, is a standardized index used to compare the skid resistance of different pavement surfaces. It is calculated using the following equations:

$$S_p = 14.2 + (89.7 * MPD) \tag{1}$$

$$F_{60} = 0.081 + (0.732 * DFT_{20} * e\hat{}(-\frac{40}{S_p}) \tag{2}$$

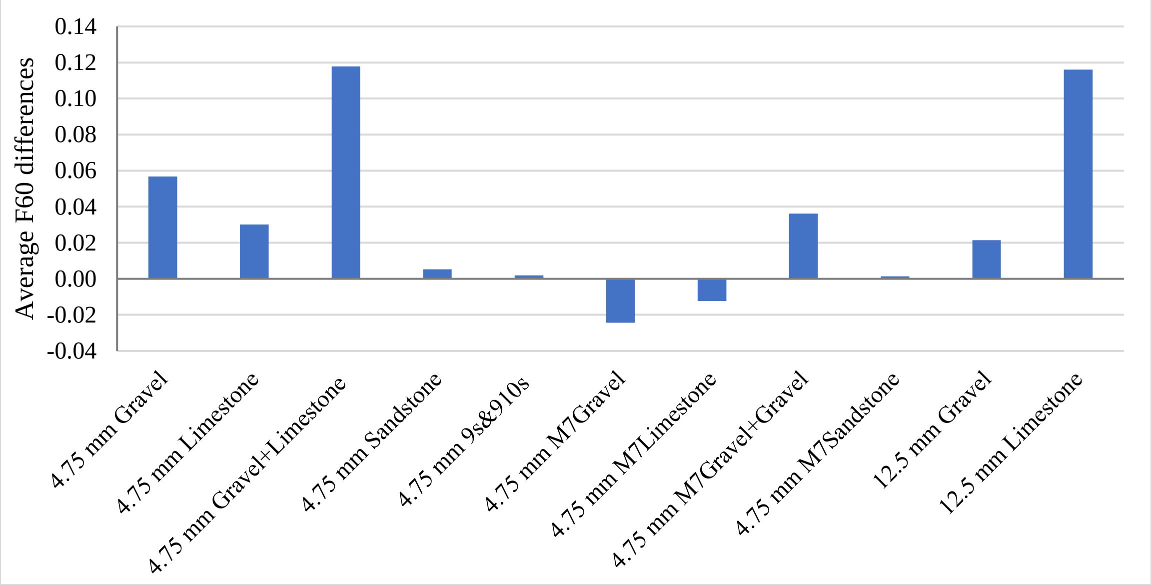
Where,

Sp and F_{60} are calculated on the average values of MPD and DFT_{20} from slabs; and
MTD is the Mean Texture Depth measured by the CTM test.

By combining both macro- and micro-texture information, the IFI provides a more comprehensive assessment of pavement friction and facilitates better comparisons across different test locations and conditions.

Figure 11 shows the results from different 4.75-mm NMAS mixtures compared to those of the 12.5-mm NMAS mixtures.

Figure 11. Average F_{60} differences between unpolished and polished slabs



As Figure 11 demonstrates, almost all mixtures experience the normal friction reduction after the polishing procedure. However, crumb rubber-modified samples (M7) showed increased friction after polishing. This phenomenon has been observed in other mixtures by Wu and King [15]. According to Wu and King [15], F_{60} values in asphalt mixtures tend to increase initially, but then decrease with continued polishing. The rise and fall of F_{60} values depends on the mixture type. The above results determined that crumb rubber-modified samples exhibit higher F_{60} values after 10,000 polishing cycles and can be recommended for delaying friction reduction.

All of the 4.75-mm NMAS mixtures showed lower or similar friction (F_{60}) performance as the 12.5-mm NMAS mixtures. Limestone samples are more sensitive to polishing, therefore demonstrating a higher friction reduction after polishing. This performance can be adjusted by using different mixture designs or crumb rubber modifiers.

Dynamic Modulus Test

Dynamic modulus test was performed in accordance with AASHTO T342 to characterize the stiffness of the 4.75-mm NMAS mixtures for pavement design purposes. This test was performed to determine the stiffness of the asphalt mixtures subjected to cyclic compressive loads. Master curves of performance have been established and shown in Figure 12.

Figure 12. Dynamic modulus test results for mixtures

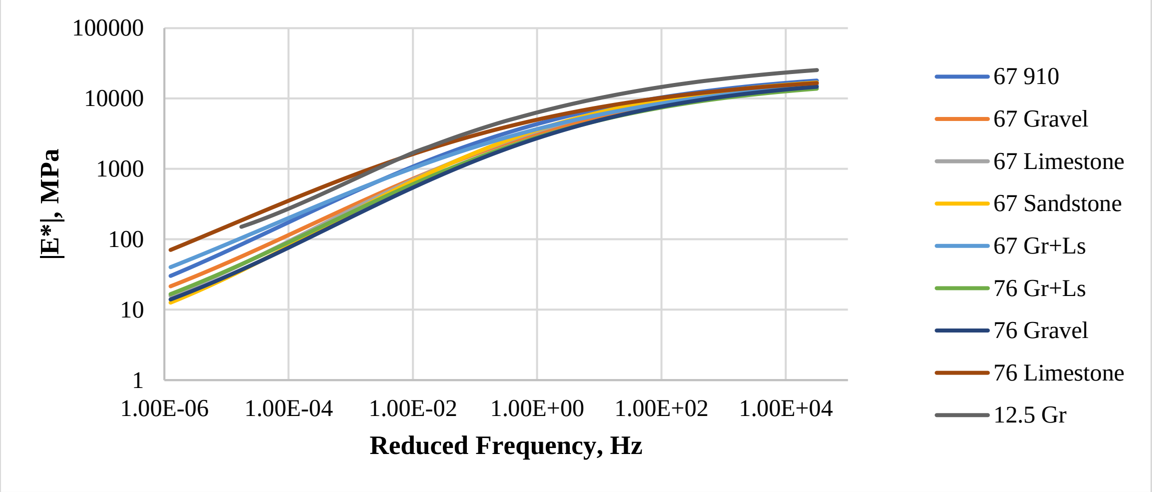


Figure 12 shows that the mixtures perform similarly at low temperatures, with minor variations. However, high-temperature properties show significant differences depending on the specific aggregate structure used. Although mixtures with higher PG binder grades are generally expected to be stiffer, Figure 11 highlights that the type and design of the aggregate play a critical role in the elastic response of mixtures containing finer aggregates. The information developed by this testing will be used by the DOTD pavement design group to assign structural components, if any are needed, to the new mixture design.

Cost-Benefit Analysis

DOTD's mix design specification was developed to ensure the quality of mixtures. However, economic analysis is also needed for a comprehensive evaluation. Therefore, a cost-benefit analysis was conducted to ascertain the cost-effectiveness of constructing asphalt mixtures with various NMAS and designs. Table 7 shows the costs per ton for each mixture while considering only one binder (PG 67-22) for all types. The average price to produce the stockpile throughout the state was considered for cost analysis. This assumption, along with the tendency of fine aggregate mixtures to require higher binder content to satisfy volumetric and performance constraints, caused the cost per ton of the 4.75-mm NMAS mixtures to be slightly higher than that of the 9.5-mm and 12.5-mm mixtures.

Table 7. Production costs comparison per ton (materials only)

NMAS	Gravel	Limestone	Gravel + LS	Sandstone	910s
4.75 mm	$44.29	$58.10	$54.63	$48.72	$61.24
9.5 mm	$39.26	$57.19	-	-	-
12.5 mm	$37.18	$55.69	-	-	-

Although the price per ton of the 4.75-mm NMAS mixtures is usually higher than that of the conventional mixtures, they are typically placed on the roadway as a thin lift (i.e., < 3/4 in.). The analysis in Table 8 indicates a significant reduction in cost for 1 lane mile (i.e., 12 ft. wide) construction for the fine aggregate mixtures. The yield for all of the mixtures is constant (i.e., 110 lb-sy-in.), due to similar design density.

Table 8. Comparison of mixture costs per lane mile

NMAS	Thickness	Gravel	Limestone	Gravel + LS	Sandstone	910s
4.75 mm	3/4 in.	$12,862	$16,872	$15,865	$14,148	$17,784
4.75 mm	1 in.	$17,149	$22,496	$21,153	$18,864	$23,712
9.5 mm	1.5 in.	$22,802	$33,216	-	-	-
12.5 mm	2 in.	$28,792	$43,126	-	-	-

Pavement Performance Analysis Results

Figure 13 presents the pavement service life values determined using the AASHTOWare Pavement ME regarding the time required to reach the performance threshold for top-down cracking distress. Note that top-down cracking was considered the evaluating distress since it was the most dominant distress among all types. Figure 13 shows the pavement life, considering top-down cracking. A total of 10 asphalt pavements with various NMAS, including 4.75-mm, 9.5-mm, and 12.5-mm, as well as different aggregate types (i.e. gravel, limestone, sandstone, 910 limestone, and gravel+limestone), were considered for the analysis. It is noted that two different binder sources (i.e., B1 and B2) were used in the mixtures. Also, asphalt pavements with similar aggregate types were considered for the comparison.

In general, mixtures with higher dynamic modulus values showed lower service lives. Comparing B1-LS and B2-LS pavements, mixtures containing binder type 2 yielded lower fatigue life, indicating the adverse effect of stiffer material on pavement performance. Similarly, the gravel and gravel-limestone blend mixtures with lower dynamic modulus values showed higher pavement service lives as measured by top-down cracking parameter. Furthermore, 9.5-mm and 12.5-mm pavements showed comparable fatigue lives compared to 4.75-mm mixtures. Although these pavements had higher thicknesses, a similar performance with gravel-limestone blend mixtures was observed.

Figure 13. Pavement life results based on top-down cracking

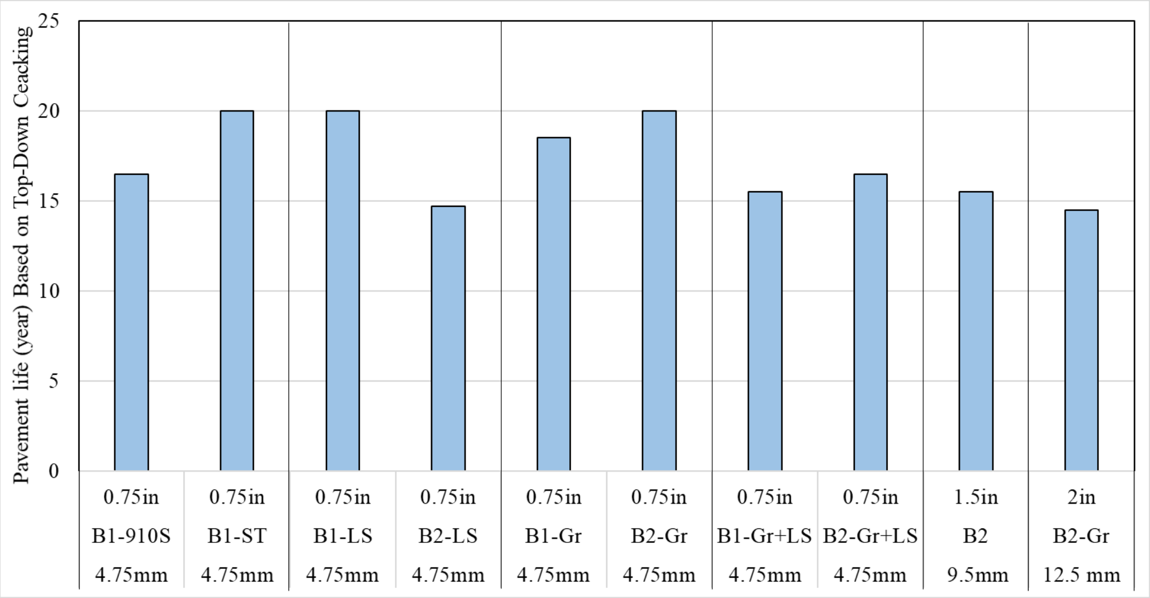


Table 9 shows the cost-effectiveness ratio, or the cost per lane mile of each mixture divided by the service life, determined from the Pavement ME analysis. This information compares different mixtures' costs and their respective performance lives. Mixtures with lower cost-effective ratio values are assumed to be cost-effective and economically viable. It is noticeable that thicker mixtures cost more (i.e., are less cost-effective) than 4.75-mm NMAS mixtures due to similar durability performance. Among the 4.75-mm NMAS mixtures, the gravel and sandstone mixtures were the most cost-effective mixtures.

Table 9. Cost-effective ratio for asphalt mixtures

4.75 mm NMAS					**9.5 mm NMAS**	**12.5 mm NMAS**
Gravel	Limestone	Gravel + LS	Sandstone	910s	Gravel	Gravel
$695	$844	$1024	$707	$1078	$1471	$1986

Conclusion

Based on the laboratory evaluation of the test results for different 4.75-mm NMAS mixtures and the mechanistic-empirical design of pavements, the following conclusions were made regarding the effects of aggregate and binder types on the performance of these mixtures.

- 4.75-mm NMAS mixtures generally exhibited acceptable SCB and LWT performance. All of the mixtures except 67-LS, 67-Gravel+LS, and 67-910s passed the DOTD requirement for rutting. These results indicate that using a polymer-modified binder can enhance the cracking or rutting resistance of 4.75-mm NMAS mixtures.
- While higher-PG-grade mixtures are expected to exhibit higher stiffness values in the dynamic modulus test, it was observed that aggregate type and gradation have a major effect on the elastic performances of fine aggregate mixtures. For pavement design practices, the department will need to develop a range of acceptable stiffness values.
- Mechanistic-empirical analysis results revealed that asphalt mixtures with higher dynamic modulus values resulted in pavements with lower fatigue lives.
- 4.75-mm NMAS pavements (Gr+LS) showed comparable fatigue lives to 9.5-mm and 12.5-mm NMAS pavements.
- The cost analysis of the mixtures showed a considerable advantage of using 4.75-mm NMAS mixtures due to their lower application thickness. This is a compelling outcome, as the laboratory testing and mechanistic-empirical simulation showed comparable performance between fine aggregate mixtures and conventional mixtures.
- The comparison between years of performance and cost per lane mile determined gravel and sandstone mixtures to be most cost-effective among the 4.75-mm mixtures.

Friction results of 4.75-mm mixtures showed lower or similar friction tolerances as compared to conventional (i.e., 12.5-mm NMAS) mixtures after being polished with the three wheel polisher. Crumb rubber-modified mixtures showed enhanced aggregate coating properties, which delayed the polishing of the aggregates and therefore increased the friction resistance after polishing. These results show that the reduction in friction of the 4.75-mm mixture associated with polishing is not significantly different from that of 12.5-mm NMAS mixtures.

Recommendations

DOTD Specification Recommendation

Based on the findings of this study, the recommended design parameters for a 4.75-mm NMAS mixture are presented in Table 10. While the results show no differences in friction properties between 4.75-mm and 12.5-mm NMAS mixtures, changing the mix design and adding crumb rubber modifiers can be considered if friction is a concern.

Table 10. DOTD 4.75-mm specification recommendation

Gradations	**Percent Passing**
12.5 mm (1/2 in.)	100
9.5 mm (3/8 in.)	96-100
4.75 mm (No. 4)	90-96
2.36 mm (No. 8)	
1.18 mm (No. 16)	40-55
0.6 mm (No.)	
0.3 mm (No. 50)	
0.15 mm (No. 100)	
0.075 mm (No. 200)	6-12
Design Criteria	
Air Voids (%)	2.5-4.5
VMA (%)	>16
VFA (%)	>74
DP	1.0-2.0
Performance Criteria	
LWT, rut depth, mm, 50°C, wet	12mm max @ 12,000 passes
SCB, J_c, 25°C kJ/m^2	0.5 min

Acronyms, Abbreviations, and Symbols

Term	**Description**
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BMD	Balanced mix design
cm	centimeter(s)
CTM	Circular Track Meter
DFT	Dynamic Friction Test
DFT_{20}	Friction at 20 km/h
DOTD	Louisiana Department of Transportation and Development
DP	Dust to asphalt proportion
F_{60}	Friction number at 60 km/h
FAA	Fine aggregate angularity
FHWA	Federal Highway Administration
IFI	International Friction Index
ksi	Kilopound per square inch
LCCA	Life-Cycle Cost Analysis
LTRC	Louisiana Transportation Research Center
LWT	Loaded Wheel Tracking
ME	Mechanistic-Empirical
MPD	Mean profile depth
NMAS	Nominal maximum aggregate size
PIARC	Permanent International Association of Road Congresses
SBS	Styrene-Butadiene-Styrene
SCB	Semi-Circular Bending
SMA	Stone matrix asphalt
Sp	Speed parameter
Va	Air voids

Term	**Description**
VFA	Voids filled with asphalt
VMA	Voids in the mineral aggregate

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