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DEVELOPMENT OF AN ECONOMICAL, THIN, QUIET, LONG-LASTING, AND HIGH FRICTION SURFACE LAYER

VOLUME 2: FIELD CONSTRUCTION, FIELD TESTING, AND ENGINEERING BENEFIT ANALYSIS

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A Report of the Findings of
ICT-R27-42
Development of a Thin, Quiet, Long-Lasting, High Friction Surface Layer for Economical Use in Illinois

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16. Abstract

This project provides techniques to improve hot-mix asphalt (HMA) overlays specifically through the use of special additives and innovative surfacing technologies with aggregates that are locally available in Illinois. The ultimate goal is to improve pavement performance through optimized materials while also controlling cost by efficiently using local materials. Therefore, the proposed new mixes use locally available aggregates when possible. The project also considered the use of alternative aggregates such as steel slag to increase the friction quality of the HMA and therefore improve pavement performance. To evaluate the newly developed wearing course mixtures and evaluate their performance under actual traffic loading, test pavements were constructed, including control mixtures, between August and November 2010 in northern Illinois. The newly proposed mixtures include fine dense-graded HMA and stone matrix asphalt (SMA). The fine dense-graded HMA was designed using the Bailey method and developed with the hope of improved compactability for thinner asphalt layers. The SMA contained a 4.75-mm nominal maximum aggregate size (NMAS) that allows for layers as thin as 0.75 in. On-site performance tests were conducted at 4-month intervals following construction; the tests include noise, friction, rutting, and texture profiling. An engineering benefit analysis was performed to evaluate the new mixes' cost effectiveness. New HMAs are proposed, along with alternative cross-sections that improve pavement performance while controlling costs.

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EXECUTIVE SUMMARY

As oil prices continue their instability in the United States, the Illinois Department of Transportation (IDOT) had an immediate need to develop innovative hot-mix asphalt (HMA) and wearing surface alternatives to cost effectively overlay roads. Since the 1980s, significant improvements have been made to HMA pavements regarding mix design, material selection, and construction technology, such as stone matrix asphalt (SMA) and ultrathin overlays with special construction equipment, which promise better performance for HMA pavements. However, to achieve this improved performance, most of these mixtures require a highly modified asphalt binder, expensive or imported aggregates, or special equipment for construction.

This project developed four potentially cost-effective wearing surface mixtures and efficient cross-sections for wearing surfaces, specifically through use of special additives and innovative surfacing technologies that incorporate locally available aggregates, whenever possible. These new mixtures include a quartzite mix, sprinkle mix, slag/fiber mix, and 4.75-mm SMA. Two conventional HMAs, a 9.5-mm coarse dense-graded mix and a 12.5-mm SMA, were selected for the control sections. The Bailey design method was used to ensure proper aggregate structure of the fine dense-graded mixture gradation, thereby allowing a reduction in layer thickness. The ultimate goal was to improve pavement performance through optimized materials while controlling cost by efficiently using local materials. The study also considered the use of new and previously used aggregates such as quartzite and steel slag, respectively, to increase the friction quality of the HMA and therefore improve pavement performance. The new HMAs were developed to improve the functional condition of the asphalt pavement. Specifically, the desired improvements would ideally include the following characteristics: durability, high friction, low noise, and improved resistance to rutting and fracture. To evaluate the performance of each new HMA, five laboratory tests were conducted at the Illinois Center for Transportation (ICT). The lab-mixed and lab-compacted (LMLC) specimens were prepared for the new HMAs, and the plant-mixed and lab-compacted specimens (PMLC) were also used; those results are presented in the accompanying report (Volume 1). This volume discusses field construction, field testing and corresponding results, and engineering cost analysis.

To evaluate field performance of the considered HMAs under actual traffic loading and environmental conditions, over time in situ testing of 14 pavement sections was conducted. The results of the field performance tests showed that the new mixtures performed better and were more cost effective than the control mixes. It is expected that further cost savings can be achieved when recycled materials such as recycled asphalt shingles (RAS) and reclaimed asphalt pavement (RAP) are included in the new mixtures, while the overlay performance is maintained.

CONTENTS

CHAPTER 1 INTRODUCTION

Sustainable and cost-effective alternatives for asphalt wearing surfaces have been recently emphasized due to the continuous instability of oil prices in the United States and the increase in environmental awareness. Since the 1980s, significant improvements have been made in the performance of HMA. These improvements include modifying the mixture design, utilizing new materials, and using innovative construction technology; however, many of these new approaches increase the total cost of pavements because of better aggregate quality, binder modification, and special equipment required for construction.

The Illinois Department of Transportation (IDOT) sponsored the development of cost-effective HMA wearing surface mixtures and efficient cross-sections for wearing surfaces using locally available aggregates and innovative techniques. Researchers at the Illinois Center for Transportation (ICT) developed four new HMAs in the laboratory using local aggregates such as dolomite and natural sand, and new and previously used materials such as quartzite, steel slag, and fibers to improve pavement performance without significant cost increases. The Bailey method was used to design the aggregate structure for the HMA overlays, thereby making it possible to reduce layer thickness by using fine dense-graded HMAs.

The new mixtures were developed to improve the functional condition of flexible pavements. Specifically, the desired improvements would ideally include one or more of the following characteristics: durability, high friction, low noise, and improved resistance to rutting and fracture. Six different HMAs were placed with various thicknesses on 14 sections with various thicknesses between August and November 2010. The sections were exposed to actual traffic loadings and environmental conditions. Several performance tests, including locked-wheel friction, rut measurement, sound intensity, and laser profiling, were conducted at 4-month intervals for 1 full year after construction in order to assess pavement short-term performance; the test sections were monitored during the second year to evaluate long-term performance. Details of the mixtures used in the study can be found in Volume 1 of this report (Al-Qadi et al. 2013).

The primary purpose of the field project is to evaluate friction, noise, rutting, and ride quality of the pavement surface to identify whether any of the newly developed mixes offer economical and improved pavement performance. Engineering benefit analyses were performed to evaluate the cost effectiveness of the new asphalt overlay applications, which included various mixtures at different layer thicknesses. Conventional cost analyses focused primarily on life-cycle cost analysis (LCCA), which often uses the international roughness index (IRI) as a performance indicator. However, this study included various aspects of pavement performance to better represent each asphalt mixture's overall performance.

This report is Volume 2 of a set of two volumes. Volume 1 (Al-Qadi et al. 2013) focuses on the mix design development and laboratory testing, while this volume includes details on field construction, field testing and corresponding results, and engineering benefit analysis of new asphalt mixes compared to control mixes. The overall engineering benefit analysis identifies the optimized mixture for thin overlay applications in Illinois.

CHAPTER 2 FIELD CONSTRUCTION

A field study was performed to better understand the mechanisms of pavement failure under actual vehicular loading and environmental conditions. Fourteen sections with various asphalt mixtures and thicknesses were constructed in Hoffman Estates and Barrington, Illinois, on IL-72 from Bartlett Road to Glen Lake Road from August through November 2010. The total test project length is 6.54 miles in both the eastbound and westbound directions. Each pavement section length varied from 1,630 ft to 3,125 ft. The contractor was Curran Contracting Company from Crystal Lake, Illinois.

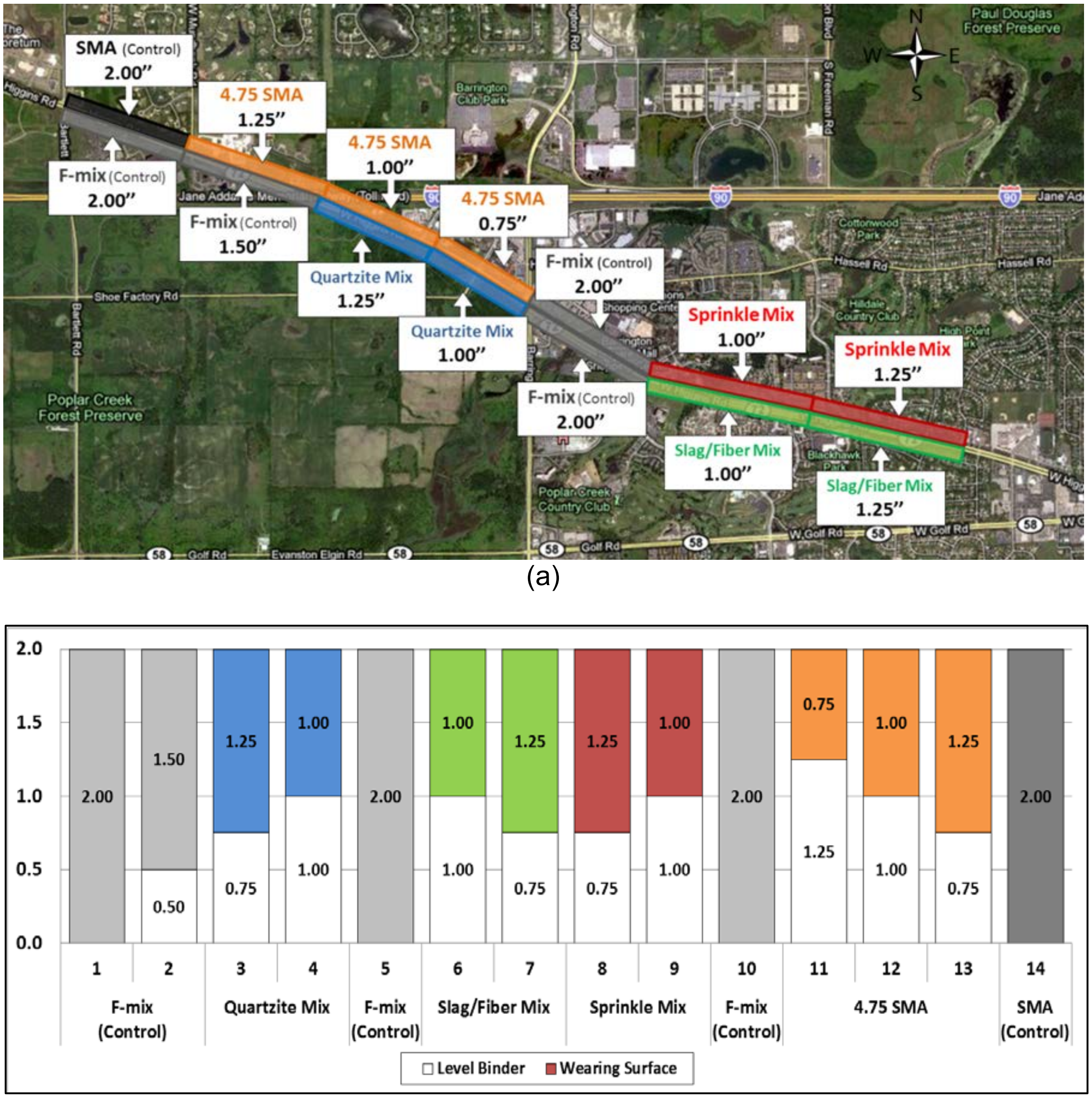
The existing pavement consists of two main lanes in each direction, in addition to shoulders, intersections, and turn lanes. The pavement was constructed with HMA overlaid jointed Portland cement concrete (JPCC). Significant reflective cracking from PCC joints was observed in the existing overlays, and longitudinal cracking existed along the lanes (Figure 1).

Figure 1. Pavement surface condition before construction.

The construction site includes four intersections. The average annual daily traffic (AADT) for each section is shown in Table 1. Although the four intersections are located along the road, the difference in traffic volume among various sections was insignificant as of 2010. Therefore, traffic loading variation among test sections can be ignored.

Six different asphalt mixes were placed in 14 sections with various layer thickness combinations that included leveling binder and wearing surface. Details of the mixtures used in the field can be found in Volume 1 of this report (Al-Qadi et al. 2013). Leveling binder was placed at various thicknesses with the wearing surface to ensure a total overlay thickness of 2 in, as seen in Figure 2. The sprinkle mix without chips was used as a leveling binder and was designed with less expensive materials. Therefore, no leveling binder was placed in the control mixture sections that have a 2-in. wearing surface.

Due to the potential difficulties of achieving the targeted compaction level for the control mixtures if used in thin layers, a 2-in wearing surface was used for the 12.5-mm SMA, and 2-in and 1.5-in wearing surfaces were used for the F-mix. All new mixtures were placed at both 1 in and 1.25 in, and a 0.75-in layer was also used for the 4.75-mm SMA. The design thickness for each layer was determined based on the minimum required thickness, which is three times the nominal maximum aggregate size (NMAS) for the dense-graded mixtures and four times the NMAS for the SMA (Vavrik et al. 2002). The 2-in F-mix sections were constructed at three locations: two in one direction, the third in the opposite direction. The two sections in the same direction were 9,000 ft apart from each other. This allows monitoring the effect of traffic within the construction site and comparing performance with various other mix designs. At least two sections with various thicknesses, not including the control SMA, were built to evaluate the effect of thickness on field performance for the new mixtures, as shown in Figure 2. Table 1 is a summary of each construction section.



(a)

(b)

Figure 2. (a) Construction sections with different mixtures and wearing surface thicknesses, and (b) design thicknesses of leveling binder and wearing surface.

Table 1. Summary of Construction Sections

Section	Station		Length (ft)	Direction	Layer Thickness (in)		AADT[*]
	Start	End			Wearing Surface	Leveling Binder	
1	19+60	45+12	2,552	Eastbound	2.00	0.00	30,700
2	45+12	70+10	2,498	Eastbound	1.50	0.50	30,700
3	75+75	97+60	2,185	Eastbound	1.25	0.75	29,100
4	97+60	119+39	2,179	Eastbound	1.00	1.00	29,100
5	132+70	149+00	1,630	Eastbound	2.00	0.00	29,600
6	157+93	189+18	3,125	Eastbound	1.00	1.00	29,600
7	189+18	220+40	3,122	Eastbound	1.25	0.75	31,700
8	220+40	189+18	3,122	Westbound	1.25	0.75	31,700
9	189+18	157+93	3,125	Westbound	1.00	1.00	29,600
10	149+00	132+70	1,630	Westbound	2.00	0.00	29,600
11	119+39	97+60	2,179	Westbound	0.75	1.25	29,100
12	97+60	77+28	2,032	Westbound	1.00	1.00	29,100
13	71+51	45+12	2,639	Westbound	1.25	0.75	30,700
14	45+12	19+60	2,552	Westbound	2.00	0.00	30,700

*www.dot.state.il.us/maps/statistical.htm

Before the new asphalt mixtures were placed, all existing pavement surfaces in need of repair were patched, then all of the sections were properly milled (2 in at the main lanes and 2.5 in at the shoulder, as shown in Figure 3). The milled surface was cleaned using a mechanical brooming device. An SS-1 tack coat was applied at a diluted rate of 0.08 to 0.10 gal/yd^2 on the milled surface and over the leveling binder to provide acceptable bonding between layers and it was allowed to cure properly.


(a) (b)

Figure 3. (a) Milling of old pavements, and (b) milled surface.

2.1 CONSTRUCTION REQUIREMENTS

The field construction consisted of the HMA wearing surface and the HMA leveling binder. The construction was in accordance with Sections 406 and 1030 of the Standard Specifications, except as modified herein (IDOT 2012).

2.1.1 Materials

Aggregates used in the mix designs are shown in Table 2.

Table 2. Aggregates Used in the Mix Designs

Material Code	Material Type	Source Number	Source Name	Source Location
032CM16	Dolomite	50312-78	Vulcan	McCook
038FM20 (951)	Crushed Dolomite Sand	50312-78	Vulcan	McCook
037FM02	Natural Sand	50970-02	Thelan	Antioch
004MF01	Mineral Filler	50312-04	Hanson	Thornton
032CM13	Quartzite	52402-25	Michels	Wisconsin
032CM13	9.5-mm and 4.75-mm Removed	52402-25	Michels	Wisconsin
FM22	4.75-mm Removed	50312-04	Hanson	Thornton

Aggregate gradations used in these mix designs were not all available in typical stockpiles. Therefore, the stockpile gradations for the quartzite and FM22 required additional screening to achieve the required gradations for the 4.75-mm SMA. The additional screening of the aggregates was performed at the quarry by the aggregate supplier. The quartzite aggregate retained on a 4.75-mm (No. 4) sieve was used as the sprinkle aggregate in the sprinkle mix. The properties of the aggregates used in the mix designs were described in Volume 1 of this report.

The fibers for the slag/fiber mix were synthetic fiber blends for HMA, manufactured by the Forta Co. The fibers were added to the HMA at a rate of 1 lb of fibers per ton of HMA. The fibers were added in the HMA batch plant after the fines collection to ensure that the fibers were not removed in the baghouse but still added before the addition of the liquid asphalt. Loose fibers were pneumatically added though a separate inlet directly into the weigh hopper above the pugmill. The addition of fiber was timed to occur during the hot aggregate charging of the hopper. Adequate mixing time was required to ensure proper blending of the aggregate and fiber additive.

PG 76-22 liquid asphalt, modified with SBS, was used for the control 12.5-mm SMA, and PG 70-22, SBS-modified asphalt, was used for all other mixes.

2.1.2 Equipment

All mixtures required, as a minimum, a silo storage plus haul time of 1.5 hr. The following was added to Article 1102.01(a) of the Standard Specifications:

“(13) For mixture IL-4.75 SMA and IL-9.5 Fine-Graded, mineral filler and collected dust (baghouse) shall be proportioned according to the following.

a. Mineral filler shall not be stored in the same silo as collected dust (baghouse).
b. Additional minus 200 material needed to meet the JMF may be entirely manufactured mineral filler.

c. Collected dust (baghouse) may be used in lieu of manufactured mineral filler according to the following:
    1. Sufficient collected dust (baghouse) is available for production of the IL-4.75 SMA and IL9.5 Fine-Graded mixtures for the entire project.
    2. A mix design was prepared based on collected dust (baghouse).

d. A combination of collected dust (baghouse) and manufactured mineral filler may be used according to the following:
    1. The amount (proportion) of each shall be established and not varied.
    2. A mix design was prepared based on the established proportions."

2.1.3 Mix Designs

Article 1030.04 was applicable to the two control mixes but was not applied in the four experimental mixtures for this special research project. The mix designs were presented in Volume 1 (Al-Qadi et al. 2013). The experimental mixtures included the following:

- IL-9.5 fine-graded fiber-reinforced steel slag mixture (slag/fiber mix)
- IL-9.5 fine-graded quartzite mixture (quartzite mix)
- IL-9.5 fine-graded mixture with sprinkle treatment (sprinkle mix).The friction aggregates should be coated with asphalt followed by spread rolling into the IL-9.5 fine-graded mix. Specialized equipment was necessary for this operation.
- IL-4.75 SMA

The IL-9.5 fine-graded mixture design was used with the sprinkle treatment and as a leveling binder for each of the four experimental mixtures and Section 2 of the control F-mix.

2.1.4 Control Limits

The control limits for the IL-9.5 fine-graded mix were the same as stated in Article 1030.05(d)(4) of the Standard Specifications (IDOT 2012).

Target job mix formula (JMF), air void (AV) content, asphalt cement (AC) content, and field voids in mineral aggregates (VMA) were provided for each mix design in Volume 1 (Al-Qadi, et al. 2013). Tables 3 (a) and (b) complement the information in Article 1030.05(d)(4) of the Standard Specifications (IDOT 2012).

Table 3 (a). Control Limits of IL-4.75 SMA

Control Limits		
Parameter	**IL-4.75 SMA Individual Test**	**IL-4.75 SMA Moving Avg. of 4**
% Passing: [1/]		
1/2 in. (12.5 mm)		
No. 4 (4.75 mm)		
No. 8 (2.36 mm)		
No. 16 (1.18 mm)	± 4 %	± 3 %
No. 30 (600 µm)	± 1.5 %	± 1.0 %
Total Dust Content No. 200 (75 µm)	± 0.3 %	± 0.2 %
Asphalt Binder Content	± 0.3 %	± 0.2 %
Voids	± 1.2 %	± 1.0 %

1/ Density shall be determined by cores or by corrected, approved thin lift nuclear gauge.

Table 3 (b). Density Control Limits

Density Control Limits			
Mixture Composition		**Parameter**	**Individual Test**
IL-4.75 SMA	Lifts < 1.25 in (32 mm)	Ndesign = 80	93.0% – 97.4 % [2/]
	Lifts ≥ 1.25 in (32 mm)	Ndesign = 80	93.0% – 97.4 % [1/]
IL-9.5 Fine-Graded	Lifts 0.75 in (19 mm)	Ndesign = 50-105	91.0% – 97.0 % [2/]
	Lift 1.0 in (25.4 mm)	Ndesign = 50-105	92.0% – 97.0 % [2/]
	Lifts ≥ 1.25 in (32 mm)	Ndesign = 50-105	93.0% – 97.0 % [1/]

1/ Density shall be determined by cores or by corrected, approved thin lift nuclear gauge.
2/ Density shall be determined by cores.

2.1.5 Placing

Each test section was placed based on the revised Article 406.06(b) of the Standard Specifications (IDOT 2012):

> "b) Placement Conditions. Placement of HMA shall be under the following conditions.
>
> - General Conditions. HMA shall be placed on a clean, dry base and when weather conditions are suitable. The leveling binder and binder courses shall be placed only when the temperature in the shade is at least 40 °F (5 °C) and the forecast is for rising temperatures. The surface course shall be placed only when the air temperature in the shade is at least 45 °F (8 °C) and the forecast is for rising temperatures.
>
>   The HMA shall be delivered at a temperature of 310 to 350 °F (155 to 175 °C).
>
>   Intermingling of different mixture compositions at any one paver will not be permitted.

- Special Conditions for mixture IL-4.75 SMA and IL-9.5 Fine-Graded.
  a. The surface shall be dry for at least 24 hours, and clean, prior to placement of the mixture.
  b. Work shall not begin when local conditions indicate rain is imminent.
  c. The mixture shall be placed only when the temperature in the shade is at least 50 °F (10 °C) and the forecast is for rising temperatures.
  d. The mixture temperature shall be 310 to 350 °F (155 to 175 °C) and shall be measured in the truck just prior to placement.
  e. When used as leveling binder, the mixture shall be overlaid within five days of being placed."

2.1.6 Compaction

Pavement compaction in this project followed the revised Table 1 of Article 406.07 of the Standard Specifications (IDOT 2012):

"Table 1- Minimum Roller Requirements for HMA [4/]

	Breakdown Roller (one of the following)	Intermediate Roller	Final Roller (one or more of the following)	Density Requirement
Level Binder: (When the density requirements of Article 406.05(c) do not apply.)	P [3/]	-	V_S, P, T_B, T_F, 3W	To the satisfaction of the Engineer
Binder and Surface [1/] Level Binder [1/]	V_D, P, T_B, 3W	P [3/]	V_S, T_B, T_F	As specified in Articles: 1030.05(d)(3), (d)(4), and (d)(7)
Bridge Decks [2/]	T_B	-	T_F	As specified in Articles: 582.05 and 582.06

1/ If the average delivery at the job site is 85 ton/hr (75 metric ton/hr) or less, any roller combination may be used provided it includes a steel wheeled roller and the required density and smoothness is obtained.
2/ One T_B roller may be used for both breakdown and final rolling on bridge decks 300 ft (90 m) or less in length, except when the air temperature is less than 60 °F (15 °C).
3/ A V_D roller may be used in lieu of the P roller on mixtures containing polymer modified asphalt binder.
4/ For mixture IL-4.75 SMA and IL-9.5 Fine-Graded, Vibratory rolling will not be permitted. Further, for breakdown compaction, a steel wheel roller 84 inches wide with 315 PLI minimum shall be used to ensure that the minimum density is obtained while the mix is still hot."

2.2 FIELD CONSTRUCTION

All mixtures except the slag/fiber mixture were produced at a drum plant. The slag/fiber mixture was mixed at a batch plant so that a small amount of fibers could be added at the proper rate during the mixing process. The sprinkle chips used in the sprinkle treatment were also produced in the batch plant; because of the small quantity of sprinkle chips, the mixture could not properly be produced in a drum plant. Figure 4 contains photos of the two plants.

(a) (b)

Figure 4. (a) Drum plant, and (b) batch plant.

Leveling binder was placed on the milled surface prior to placement of the wearing surface on all sections having a total wearing surface thickness less than 2 in. The sprinkle mix without sprinkle chips was used as a leveling binder; it was economical and contained 100% local aggregate. In addition, leveling binder may control reflective cracking that results from the milled surface. The control mixes and newly developed mixtures, except the sprinkle mix, were placed in accordance with typical construction procedures, as shown in Figure 5.

During construction of the quartzite mix at Section 3, a 1.25-in surface mix (the first section for which the newly developed mixtures were applied), mixture segregation was observed. Therefore, the number of mix discharges from the silo into the truck at the plant was increased from two drops to three to prevent any material segregation. Vibration was not applied during compaction for the quartzite mix, slag/fiber mix, and the 4.75-mm SMA due to the possibility of aggregate breakage, especially for the thinner layers. The use of pneumatic-tired rollers was not permitted. Lane 2 (the driving lane) of each section was constructed on a different day than Lane 1 (the passing lane). This allowed comparison of mixture quality against the quality control (QC) construction data from Lane 1. Adjustments were made as needed based on the QC data from Lane 1. Field testing data from Lane 2 were used in the analysis.

(a) (b)

(c) (d)

Figure 5. (a) Tack coat application, (b) paving, (c) compaction, and (d) density measurement.

The sprinkle mix consisted of properly graded non-polishing, binder-precoated aggregate chips to provide high friction quality (see Table 4 for aggregate gradation). The binder-precoated chips were applied to the HMA immediately behind the paver. Rollers embedded the chips in the overlay during the compaction process. Using imported, relatively expensive, non-polishing aggregates only in the wearing course rather than in the entire mix provides substantial savings in materials and cost. A conventional chip spreader that had been previously modified to spread the coated chips was successfully used in this operation. It allowed the chips to be spread uniformly along the 12-ft-wide lane on the newly paved, uncompacted mat. No foreign material, such as diesel or hydraulic fluid, was allowed to be applied or to leak onto any part of the pavement.

Table 4. Gradation Requirements for the Sprinkle Aggregates

Sieve Size	Percentage Passing
19.0 mm (3/4 in.)	100
12.5 mm (1/2 in.)	90–100
9.5 mm (3/8 in.)	65–85
4.75 mm (No. 4)	0-5
0.075 mm (No. 200)	1.5 max

The sprinkle aggregate was dried at a temperature of 250°F to 300°F and precoated with asphalt binder (PG 64-22) at approximately 0.75% by weight, in a batch plant. Initial asphalt binder content was designed at 1.5% by weight to precoat aggregate chips; however, it was too sticky to spread properly with a feeder. Therefore, its binder content was adjusted to 0.75%. In hindsight, a precoating rate of approximately 0.5% over the absorption rate is a good general rule for determining the precoat binder content. If a machine is designed and developed specifically for this application, 1.5% binder content could be more desirable for the coating of the aggregates. The precoating temperature was between 240°F and 275°F. Stockpiling methods that prevent segregation were utilized. To prevent sticking of the asphalt, the freshly coated aggregate was stockpiled no higher than 3 ft until sufficient cooling had occurred. The coated aggregate was turned and mixed with an end loader bucket during cooling to prevent sticking. The precoated aggregate was stored to prevent contamination. Storage for an extended period of time might require the stockpile to be covered. Wetting down the precoated aggregate and manipulating the stockpile should prevent crusting. Generally, the sprinkle aggregate should be precoated at least 1 day prior to use to allow for complete cooling.

The precoated aggregate was spread at ambient temperature and was uniformly applied to the surface of the uncompacted wearing course immediately after the HMA paver and prior to initial breakdown rolling. This was critical to the success of the treatment so that the breakdown roller could embed the chips while the mat was still hot. The application rate was initially designed to be 2.5 to 5.0 lb/yd^2, allowing adjustment up or down as needed. The application rate for the sprinkle aggregate was checked by using a portable scale at several locations and adjusted to approximately 1.6 lb/yd^2 during construction, as shown in Figure 6 (a). The gate settings that controlled the application rate were determined prior to construction and also checked during construction to establish that the correct rates were being spread. The spreader box was filled from a specially fabricated belt system by the contractor, as shown in Figure 6 (b).

Rolling began within 50 ft of the aggregate spreader with a steel wheel roller, according to the established rolling pattern. The paver, spreader, and rollers worked in unison to apply the sprinkle chips uniformly to the surface mix and to compact the two materials while the mat system was still hot. Roller vibration was applied to consolidate the chips on the wearing surface mixture. Traffic was not permitted on the surface until the pavement cooled down enough that the precoated aggregate did not ravel under traffic.

While placing slag/fiber mixes, several lumps of those mixes were found, as shown in Figure 6 (c). This made the pavement surface uneven at some locations; dragged paving surface with fiber lumps became stuck inside the paving augers. This was caused primarily by incomplete melting and dispersal of the plastic bags that originally contained the fibers. The manufacturer’s instructions were to introduce the entire plastic bag and fibers into the hot aggregates in the batch plant. The intent was for complete distribution of the fibers and melted bag into the mix. Special attention should be paid when adding fibers to asphalt mixtures to ensure better distribution of fibers. It is also recommended that fiber bags be removed before adding fibers to the mix. Manual surface finishing was necessary at several locations on the uneven surfaces prior to compaction, as shown in Figure 6 (d). Other than that, the paving process of the remaining sections went smoothly and in accordance with IDOT specifications (IDOT 2012).

The 4.75-mm SMA, 12.5-mm SMA, and quartzite mix were placed following typical construction procedures.


(a) (b) (c) (d)

Figure 6. (a) Chip spreader, (b) feeding sprinkle chips from shoulder, (c) lump of slag/fiber mixtures, and (d) material supplements on the uneven surface.

2.3 CONSTRUCTION QUALITY CONTROL

The field density data were collected using nuclear gauges during construction to achieve the target density. As part of the QC, the core densities for each section were measured in the laboratory using the saturated surface dry (SSD) method. Table 5 presents the density data for Lane 1 (L1, passing lane) and Lane 2 (L2, driving lane). Different minimum required densities were applied, depending on where the cores were sampled and whether the cores were close to a confined edge or not during construction. For example, Lane 1 was unconfined on both sides during compaction, and Lane 2 was unconfined only on the right side because Lane 1 was placed prior to Lane 2. This resulted in higher density on the confined side under the same number of compaction passes. Therefore, except for the cores taken in the middle of the lane, a different minimum density requirement was applied based on the edge confinement.

The densities of Lane 2 were used in this study because adjustments were made to material production on Lane 2 based on QC data from Lane 1, which had been paved on the previous day. In addition, performance measurements were planned for Lane 2. Although on-site densities, which were measured using a nuclear gauge, met minimum density requirements, some core density data did not meet the minimum requirement. This might have been the result of inaccuracy of the nuclear density gauge used on the site. Since the sections were not of sufficient length to perform a complete correlation of the nuclear gauge and core density measurements, its reading was higher than that of

SSD laboratory-measured density, as shown in Table 5. Another possible reason could have been the mixture itself. For the sprinkle mix, it was not easy to obtain accurate density because sprinkle chips were used on the surface. This makes the surface rough, which affects nuclear gauge- and laboratory-measured densities. For the 4.75-mm SMA, its lower density was caused primarily by smaller amount of fines (by 2.6%) and less binder content (by 0.6%) in the plant mixtures compared to the mix design (Table 6). This resulted in a lower density even after proper compaction efforts were applied.

Table 5. Density Data from On-Site Nuclear Gauge and Laboratory-Measured Cores

Section	Min. Required Density		Lane 1				Lane 2			
	Confined	Un-confined	Confined		Unconfined		Confined		Unconfined	
			Nuclear Gauge	Cores	Nuclear Gauge	Cores	Nuclear Gauge	Cores	Nuclear Gauge	Cores
1	92.5	90.0	93.8	94.0	93.9	92.3	95.3	93.6	91.1	91.0
2	92.5	90.0	94.8	93.6	93.3	93.2	92.0	92.9	92.1	89.9
3	93.0	90.0	94.6	92.7	92.1	87.4	93.7	93.0	92.7	89.4
4	93.0	90.0	91.4	88.5	91.7	90.0	93.6	92.1	94.7	90.4
5	92.5	90.0	95.1	—	94.1	—	94.5	93.9	94.6	94.8
6	92.5	90.0	94.6	95.8	93.9	94.1	92.7	94.4	94.3	90.7
7	92.5	90.0	96.8	96.6	93.4	93.5	93.9	94.7	91.9	92.2
8	93.0	90.0	93.2	92.9	91.2	91.0	94.4	92.2	91.4	91.0
9	92.0	90.0	94.2	91.9	93.5	88.9	92.5	90.5	93.6	89.6
10	92.5	90.0	94.9	94.2	93.9	93.0	93.3	91.8	93.0	92.0
11	93.0	90.0	93.1	90.5	92.7	91.8	94.3	90.5	94.2	89.8
12	93.0	90.0	95.1	92.1	93.1	88.8	94.5	89.1	94.1	87.8
13	93.0	90.0	93.3	91.9	92.0	88.9	94.6	93.2	94.4	90.2
14	93.0	90.0	94.2	95.7	93.6	94.3	93.0	94.2	91.1	93.1

Table 6. QC Data from Plant Loose Mixes

Mixture		**F-Mix (Control)**			**SMA (Control)**			**Quartzite Mix**			**Sprinkle Mix**			**Slag/Fiber Mix**			**4.75 SMA**		
		Design	**L1**	**L2**	**Design**	**L1**	**L2**	**Design**	**L1**	**L2**	**Design**	**L1**	**L2**	**Design**	**L1**	**L2**	**Design**	**L1**	**L2**
Asphalt Content (%)		5.1	5.3	5.1	6.0	5.8	5.7	5.8	5.6	5.8	6.0	5.9	6.1	5.7	6.3	5.7	7.3	7.5	6.7
N_d		90	90	90	80	80	80	90	90	90	90	90	90	90	90	90	80	80	80
G_{mm}		2.700	2.718	2.740	2.961	2.962	2.981	2.504	2.507	2.487	2.500	2.486	2.486	2.606	2.612	2.605	2.454	2.432	2.464
Voids (%)		4.0	3.8	5.1	3.5	3.9	4.4	4.0	4.8	4.0	4.0	3.8	4.4	4.0	1.0	3.2	4.0	5.7	6.3
VMA (%)		14.5	14.8	15.0	17.6	18.6	18.3	15.2	15.6	15.8	15.3	15.5	16.2	15.4	13.1	14.6	18.5	20.8	19.6
Gradation (% Passing)	**3/4"**	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	1/2"	100.0	99.0	99.0	82.0	81.8	85.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.5	99.5	100.0	100.0	100.0
	3/8"	92.0	92.0	89.5	63.0	65.3	67.8	96.0	92.5	96.5	99.0	97.5	98.0	96.0	95.3	96.5	100.0	100.0	100.0
	#4	49.0	52.0	47.0	30.0	29.5	30.5	73.0	68.0	72.5	75.0	74.5	77.5	72.0	69.0	73.5	100.0	96.7	98.0
	#8	28.0	28.0	26.0	18.0	16.5	17.5	52.0	49.5	50.5	53.0	53.5	57.5	51.0	47.3	52.0	36.0	34.0	36.7
	#16	20.0	19.0	18.0	14.0	13.5	13.8	34.0	32.5	32.5	35.0	34.0	36.5	35.0	31.3	33.0	21.0	19.0	21.3
	#30	15.0	13.0	13.0	13.0	11.5	12.0	23.0	21.0	21.0	23.0	22.0	23.0	23.0	20.3	20.5	18.0	14.7	16.3
	#50	9.0	8.0	8.5	11.0	11.0	11.5	14.0	11.0	11.0	14.0	12.0	12.0	14.0	12.0	11.0	16.0	12.7	13.7
	#100	8.0	5.0	5.5	9.0	10.0	10.8	8.0	6.0	7.0	8.0	7.0	7.0	8.0	7.8	7.0	14.0	11.3	12.0
	#200	4.1	3.8	3.7	8.3	8.5	9.0	6.0	4.0	5.0	5.8	5.2	5.3	6.2	6.2	5.5	12.3	9.7	9.7

2.4 FIELD SAMPLES

The asphalt binders, aggregates, liquid anti-strip additives, and loose plant asphalt mixtures were sampled at the plant on the second day of construction for each section, after adjustments were made to ensure the asphalt mixture was as close to the mix design as possible. Data from the plant materials were presented in Volume 1 of the project (Al-Qadi et al. 2013).

Six-in field cores were sampled from each section immediately and 4 months after construction to monitor change in density over time due to traffic and to evaluate pavement section performance in the laboratory. Six cores were sampled from each pavement section: two from each wheel path and two from the middle of the driving lane. Cores were spaced at least 3 ft from each other, and the second set of cores (obtained after 4 months) was sampled at 10-ft spacing from the first set, as shown in Figure 7. Due to the relatively thin core specimens, only fracture and rutting tests were conducted in the laboratory. Details of laboratory testing are discussed in the following section.

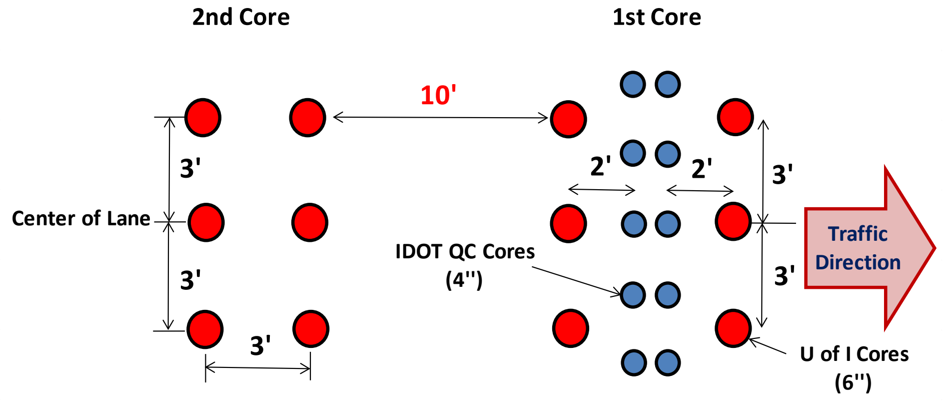


Figure 7. Field coring diagram.

2.5 LABORATORY TESTING FOR FIELD CORES

Two sets of 6-in cores were sampled during construction and 4 months later to conduct performance testing in the laboratory. From the sampled cores, the density changes during the first 4 months were obtained by measuring the air void content of the cores in the laboratory. The density of asphalt overlays significantly increased during this time due chiefly to consolidation under traffic loading. It was obvious that the air void content of the cores dropped for most of the sections 4 months after construction. Air void content under the right wheel path (R) was found to be higher than that of the cores from the center (C) and left wheel path (L) because of the unconfined edge of the asphalt materials during compaction. The density change and its effect on laboratory-measured performance are presented in the following section. The field cores were obtained to be as close to the required specimen test size as possible. The new mixture cores were 1-in thick for fracture testing and 1.25-in thick for wheel track testing, as shown in Table 7. The cores from the control mix sections were fabricated to have the same thickness as those in the new mix sections, which were 1-in thick for the fracture test and 1.25-in thick for the wheel track test to allow appropriate comparison of test results.

Table 7. Selection of Cores for Each Test

Section	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Mixture Type	**F-Mix (Ctrl)**		**Quartzite Mix**		**F-Mix (Ctrl)**	**Slag/Fiber Mix**		**Sprinkle Mix**		**F-Mix (Ctrl)**	**4.75-mm SMA**			**SMA (Ctrl)**
Wearing Surface Thickness	**2.00**	**1.50**	**1.25**	**1.00**	**2.00**	**1.00**	**1.25**	**1.25**	**1.00**	**2.00**	**0.75**	**1.00**	**1.25**	**2.00**
Fracture Test		X		X		X			X			X		X
Rutting Test	X		X				X	X					X	X

2.5.1 Fracture Tests

A semi-circular bending (SCB) test was performed to evaluate fracture resistance of the newly developed mixes in the field under actual traffic loading. The fracture energy of the control SMA was much greater than that of other mixes. This trend was also observed for the laboratory test results reported in Volume 1 of this report (Al-Qadi et al. 2013). This relatively high fracture energy could be attributed to the SMA's high content of durable steel slag, aggregate gradation, and high binder content, which may control crack propagation. The lower air void content of the control SMA section would also contribute to the high fracture resistance. In general, the newly developed mixtures had relatively lower fracture energy than the control mixes; the 4.75-mm SMA showed comparable fracture energy to that of other mixes although it has relatively high air void content (Figure 8). Therefore, if the field density could be well controlled for this mix, its fracture resistance might be improved. The relatively higher fracture energy of the slag/fiber mix section might have been attributable to the fibers, which were intended to increase the mix tensile strength and provide better resistance to crack opening in the tension mode of loading.

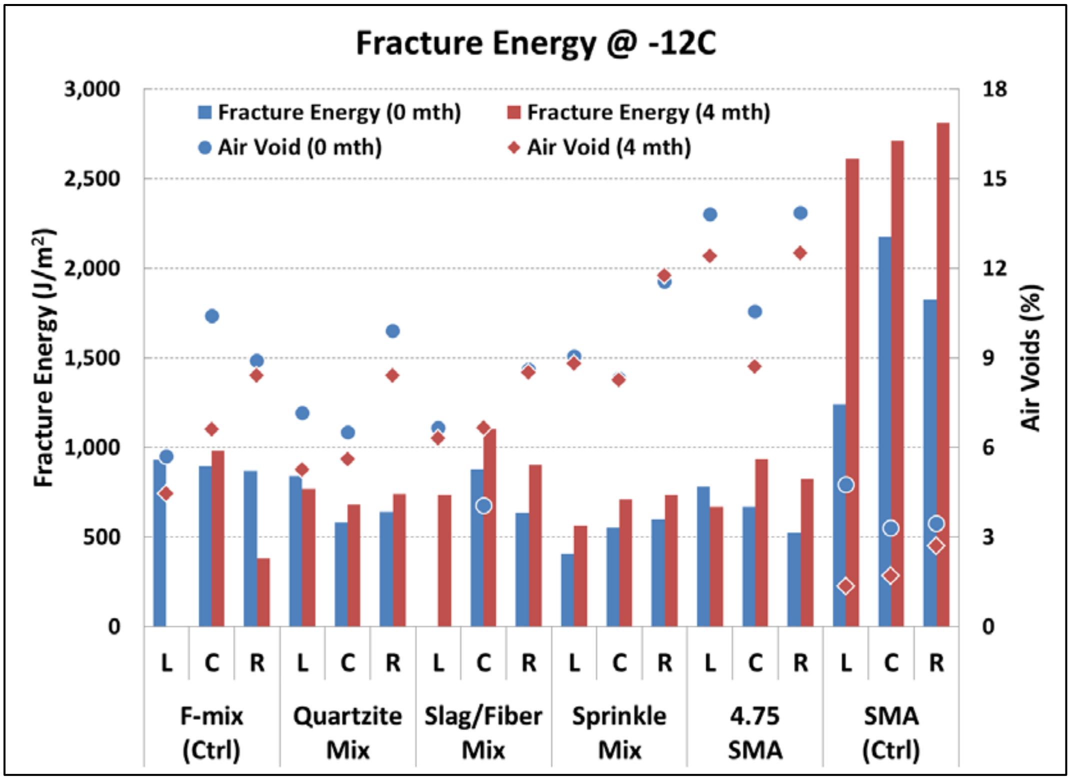
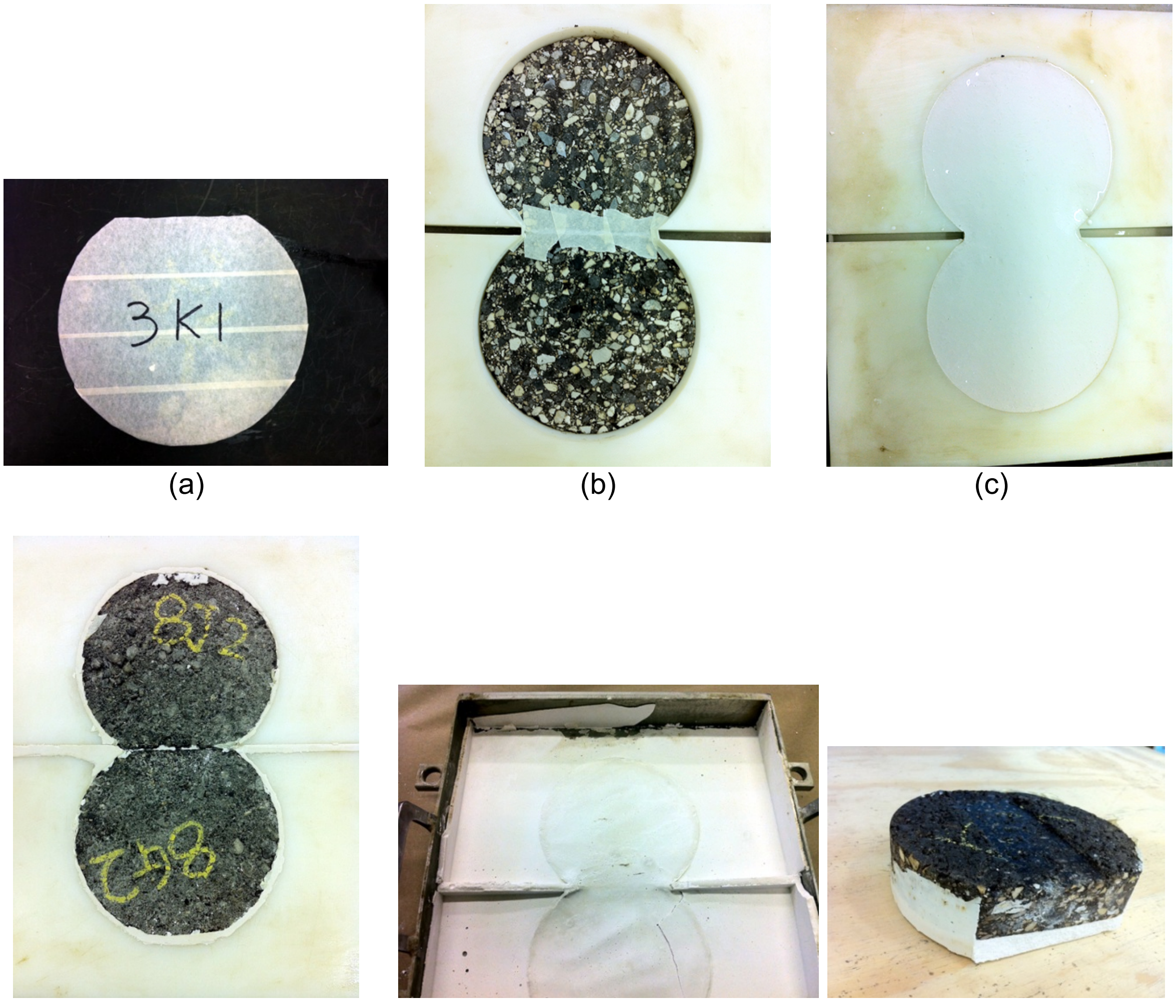


Figure 8. Fracture energies and air void contents for field cores at 0 month and 4 months.

2.5.2 Rutting Test

The 6-in cores with a 1.25-in wearing surface were used for the rutting test. The standard thickness for the wheel track test (WTT) is 60 mm (2.36 in), but the maximum wearing surface thickness, which can be obtained from the field cores, was limited to 1.25 in for new mixes. Therefore, plaster was used underneath the specimen to lift the field specimen to the mold height level. To minimize the effect of the plaster, thinner mounting trays, 40 mm (1.57 in) rather than 60 mm (2.36 in), were used for testing field cores.

Figure 9 shows the procedure for mounting the field cores in the trays. First, the top surface of the field core was taped to prevent the plaster from filling the surface voids when poured into the trays (a). The taped specimens were flipped and loaded into the mold with the taped side down to allow leveling the surface of the two specimens with the plastic mold and to eliminate any hump that may have resulted from vertical impact loading on the specimens (b). The plaster was mixed at approximately a 2:1 ratio of plaster to water. The plaster was poured to a height equal to that of the plastic mold so that the air space between the specimen and the tray was filled; it was cured for at least 3 hr (c). After the plaster was completely cured, each specimen (including its plastic mold) was taken out of the steel mounting tray and flipped back so that the taped side was facing up; the tape was removed and the surface level was checked (d). The plaster was poured into the steel tray to eliminate any air space under the specimen and plastic mold. An additional 3-hr curing time was applied to allow the second plaster to completely set. Figure 9 (e) and (f) show the plaster layer underneath the specimens and the tested specimens, respectively. The WTT was conducted following the same procedure as that for the LMLC and PMLC specimens described in Volume 1.



(a) (b) (c)

(d) (e) (f)

Figure 9. Setup of field cores in the wheel tracking mounting tray.

The density of the field cores was observed to significantly increase 4 months after construction. The rut depths of the 4-month field cores were less than those for the 0-month cores after 20,000 passes (Figure 10). As discussed in Volume 1, air void content plays a significant role in rut development. In addition, in-place aging of the mix would also result in reducing the rut depth as the mix becomes stiffer. Therefore, the 4-month specimens showed less rutting than the 0-month specimens. In addition, there was slightly higher rut depth in the cores from the right wheel path compared to those from the left wheel path for most of the mixes. Usually, the right wheel path may be expected to achieve lower density under compaction due to being unconfined. The control 12.5-mm SMA provided better rutting resistance than the new mixtures did. The trend of rutting of field cores of the control SMA was in agreement with that of the LMLC and PMLC specimens due to their highly modified asphalt binder, PG 76-22 (SBS), as well as the aggregate structure. Among the mixes with modified PG 70-22 (SBS), no significant difference was found, and their rut depth was less than that of the 12.5-mm maximum rutting criteria.

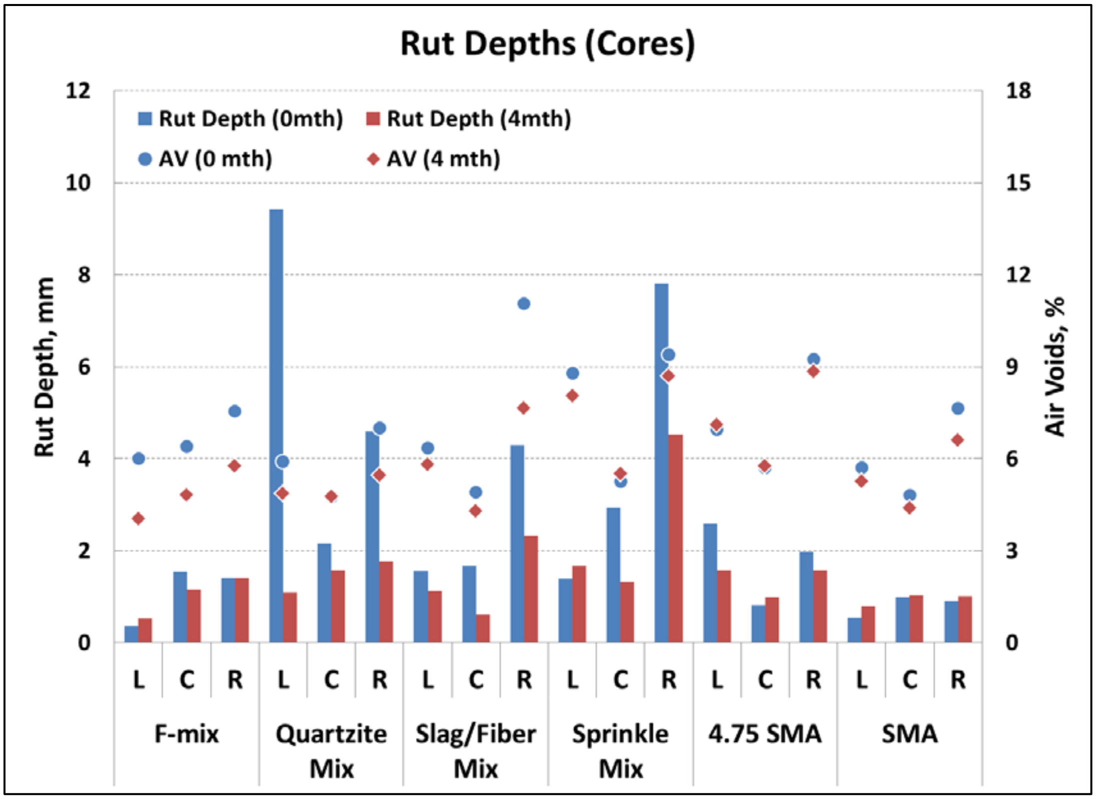


Figure 10. Rut depths from field cores at 0 month and 4 months.

CHAPTER 3 IN-PLACE FIELD TESTING

3.1 FIELD TESTING PROGRAM

In situ field testing was performed immediately after construction and every 4 months for 1 year and then again after another year. These testing intervals provided results for initial field performance and short-term performance for each section. The field testing included onboard sound intensity measurement, laser longitudinal texture profiling, locked-wheel friction, and walking foot inclinometer (dipstick) rut measurement.

3.2 NOISE MEASUREMENTS

The pavement surface noise of each section was evaluated using the onboard sound intensity (OBSI) method, according to AASHTO TP76-10, which utilizes dual vertical sound intensity probes and an ASTM E1136 standard reference test tire (SRTT). OBSI measurements were obtained on the test tires traveling at a constant speed of 45 mph. Data were collected for the right wheel path with the two phase-matched microphone probes simultaneously capturing data from the leading and trailing tire–pavement contact areas. Figure 11 shows the dual-probe instrumentation and the tread pattern of the SRTT.

(a) (b)

Figure 11. (a) OBSI dual-probe system, and (b) SRTT tread pattern.

The average of the front and rear OBSI values was computed over the length of each test section, excluding 50 to 100 ft from the ends of each section to eliminate any unrepresentative surface created by the paving operations. The values were normalized for the ambient air temperature and barometric pressure at the time of testing. The resulting mean sound intensity levels (SILs) were A-weighted to produce the noise-frequency spectra in one-third octave bands from 500 to 5,000 Hz; an example is shown in Figure 12. This chart is the spectrum of the driving lane of Section 1.

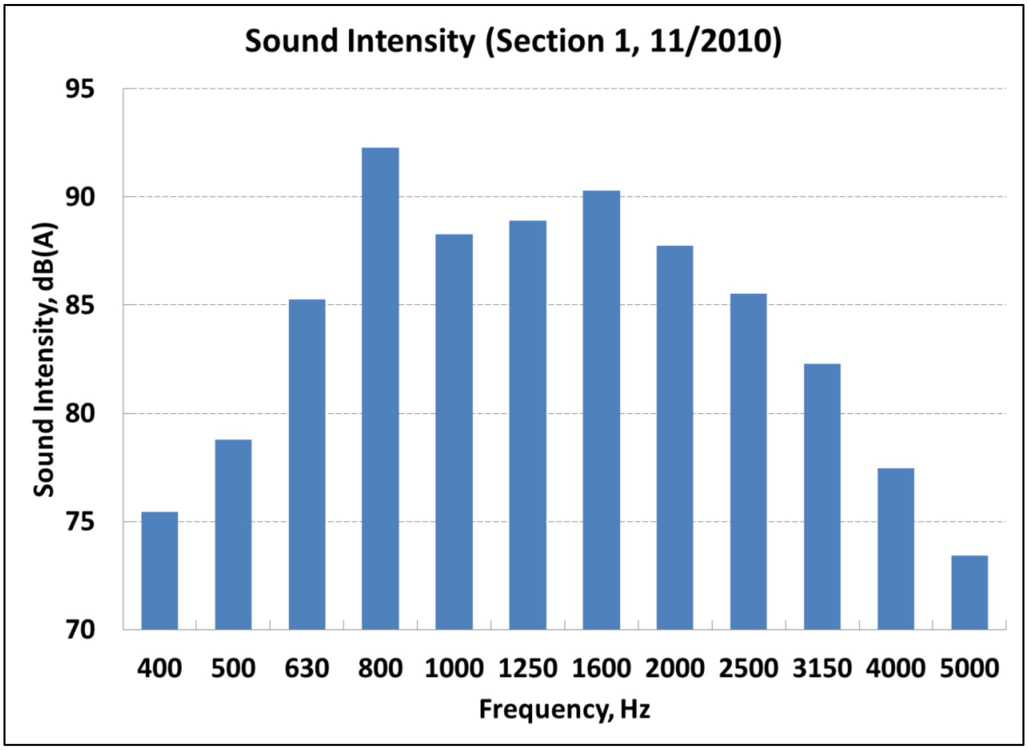


Figure 12. Mean A-weighted sound intensity frequency spectra for Section 1.

The ultimate goal of sound testing is to determine the global SIL by calculating the logarithmic sum of the one-third octave band frequencies. The global SIL for the frequency spectrum in Figure 12 was 97.7 dB(A). The frequency and global values were A-weighted (or filtered to mimic how the human ear interprets the sound) and were reported as A-weighted decibels, or dB(A). It is noteworthy that doubling sound intensity and the power level corresponded to a calculated level of change of 3 dB(A). The values were normalized for environmental effects such as ambient air temperature and barometric pressure at the time of testing, according to AASHTO TP76-10.

In a recent study (Bueno et al. 2011), it was found that the pavement surface temperature significantly affected sound levels. In addition to the tire effect, the medium and high frequency noise is influenced primarily by the pavement temperature, and a decrease in the stiffness of the asphalt surface could result in a reduction in impact and vibration mechanisms; both mechanisms are responsible for sound generation. That study also showed the good linear relationship between pavement temperature and sound level.

Two methods were suggested in the *Tyre/Road Noise Reference Book* (Sandberg and Ejsmont 2002) to adjust sound levels based on the pavement surface temperature at the time of the testing:

$$L_R(\theta_{ref}) = L_R(\theta) + K(\theta_{ref} - \theta)$$

where

L_R: corrected sound level (dB)

θ : measured test surface temperature

θ_{ref} : reference temperature, 20°C

K : temperature coefficient

- For passenger car tires:
  K = –0.03dB(A)/°C when $\theta > \theta_{ref}$
  K = –0.06dB(A)/°C when $\theta < \theta_{ref}$
- For light truck and van tires:
  K = -0.02dB(A)/°C
- For heavy truck and van tires:
  K = 0 (there is no correction)

The temperature correction is intended to be conservative, and its coefficient was obtained for limited types of asphalt mixtures. Another method that can be used for pavement surface temperature correction is SAE J57, Sound Level of Highway Truck Tires. According to this method, sound measurements should be made at various temperatures. Noise levels are normalized to the reference temperature (68°F) by interpolation. The surface temperature coefficient used is the slope of the linear relationship between sound measurements at corresponding temperatures. .

In this project, the second method was used to normalize noise levels to the reference pavement surface temperature (68°F). Because the temperature coefficient largely depends on the asphalt mixture type, the individual temperature coefficient was obtained from the noise measurements from each section at two different temperatures during the same day. The pavement temperature coefficient for each mixture type is shown in Table 8.

Table 8. Temperature Coefficient for Each Section

	Temp (°F) =	**64.9**	**45.0**	**Difference**	**Temperature Coefficient**
Section (WS/LB)*		**SIL, dB(A)**	**SIL, dB(A)**		
1	**F-Mix (2/0)**	98.1	99.3	1.2	–0.107
2	**F-Mix (1.5/0.5)**	98.1	98.7	0.6	–0.057
3	**Quartzite Mix (1.25/0.75)**	97.7	98.7	1.0	–0.087
4	**Quartzite Mix (1/1)**	97.5	98.7	1.2	–0.108
5	**F-mix (2/0)**	98.0	98.3	0.3	–0.029
6	**Slag/Fiber Mix (1/1)**	97.6	98.5	0.8	–0.075
7	**Slag/Fiber Mix (1.25/0.75)**	97.7	98.4	0.7	–0.065
8	**Sprinkle Mix (1.25/0.75)**	98.4	99.2	0.8	–0.071
9	**Sprinkle Mix (1/1)**	98.6	99.3	0.7	–0.061
10	**F-Mix (2/0)**	98.9	99.3	0.4	–0.038
11	**4.75-mm SMA (0.75/1.25)**	96.3	96.6	0.3	–0.027
12	**4.75-mm SMA (1/1)**	95.6	96.1	0.5	–0.044
13	**4.75-mm SMA (1.25/0.75)**	96.9	97.4	0.5	–0.047
14	**12.5-mm SMA (2/0)**	100.0	100.5	0.5	–0.047

* Indicates wearing surface thickness/leveling binder thickness.

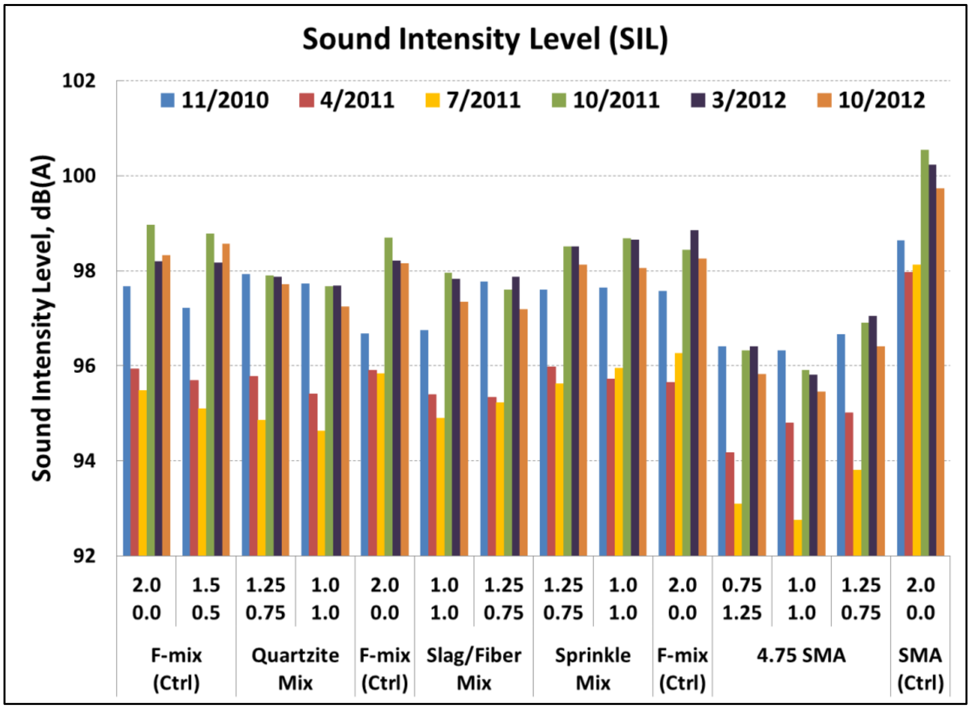
Once the pavement surface temperature coefficients were calculated, the noise levels were normalized with the environmental factors shown in Table 9.

Table 9. Environmental Data for Adjustment of Noise Levels

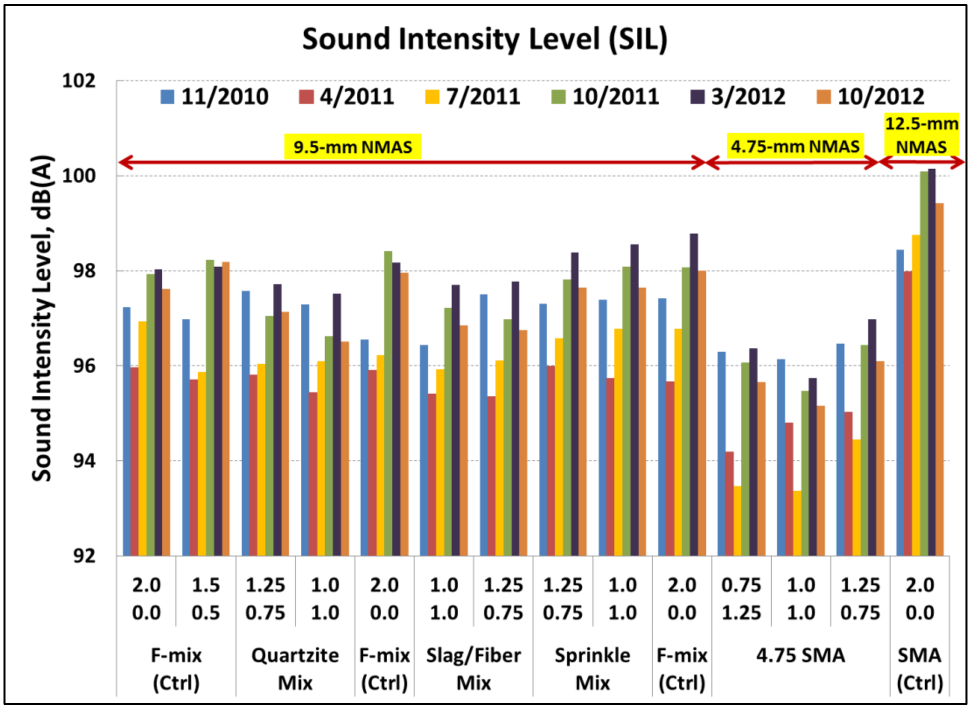
Round	Date	Sky	Pressure, hPa	Air Temperature, °F	Pavement Temperature, °F
1	11/12/2010	Clear	1025.0	55.4	60.6
2	4/10/2011	Thin overcast	1005.3	64.9	68.4
3	7/6/2011	Partly cloudy	1014.1	83.5	92.3
4	10/1/2011	Partly cloudy	1019.4	52.7	50.5
5	3/28/2012	Clear	1021.5	51.8	64.9
6	10/11/2012	—	—	61.3	55.9

The global SILs were calculated as an indication of the noise level for each section. The initial SIL values measured right after construction showed that the control SMA had the highest level of noise, around 98.4 dB(A), and the 4.75-mm SMA had the lowest level of noise, around 96.1 dB(A). A 3 dB(A) difference results in a doubled noise level (Warren 1970). Therefore, the control SMA produced almost double the noise of the 4.75-mm SMA. Most of the dense-graded mixtures, including the control F-mix, had similar noise levels and were higher than the 4.75-mm SMA but lower than the control SMA. In a previous study (Wayson 1998), it was reported that the SMA reduced the noise by about 1 dB(A) compared to dense-graded asphalt mix. However, this study observed that the noise of asphalt pavements is more dominantly affected by the nominal maximum aggregate size than by the asphalt mixture type, as shown in Figure 13. Larger NMAS resulted in more noise among the mixes tested in the study, regardless of aggregate gradations. The SIL values for the sections with various thicknesses did not significantly affect pavement noise because the noise was related more to surface texture than to layer thickness.

After 4 months, the same measurements were taken. The ranking of noise levels for the mixtures did not change over time; however, the SILs decreased during the first several months because the surface of asphalt overlays was densified under traffic loading. The SILs then started to increase as the surface texture became smoother, which might induce noise between the tire and asphalt pavement surface. Hence, the texture depth of the pavement surface decreased over time, as discussed in the next section of this report. The 4.75-mm SMA showed the greatest reduction in noise, around 2.8 dB(A). This might have been caused initially by a relatively thicker asphalt film on the surface, which was worn off; it took longer for noise reduction at the initial stage than for other mixes. The smaller reduction of the SIL, less than 1 dB(A), was measured for the control SMA. In this case, the rougher surface of the 12.5-mm SMA might have had a more dominant effect on noise levels, although this mix also had relatively thicker asphalt film than the other dense-graded mixes. After 2 years, most of the sections with new mixtures, except the sprinkle mix, had lower noise levels than the control mixes. The noise levels for the sprinkle mix were less than those of the control 12.5-mm SMA and were comparable to those of the F-mix. The global SILs for all sections over a period of 2 years are presented in Table 10.



(a)



(b)

Figure 13. Sound intensity levels (a) without pavement surface temperature corrections and (b) after temperature corrections were applied.

Table 10. Global Sound Intensity Levels (SIL)

Section (WS/LB)*		Global Sound Intensity Levels, dB(A)					
		11/2010	4/2011	7/2011	10/2011	3/2012	10/2012
1	**F-Mix (2/0)**	97.2	96.0	96.9	97.9	98.0	97.6
2	**F-Mix (1.5/0.5)**	97.0	95.7	95.9	98.2	98.1	98.2
3	**Quartzite Mix (1.25/0.75)**	97.6	95.8	96.0	97.0	97.7	97.1
4	**Quartzite Mix (1/1)**	97.3	95.4	96.1	96.6	97.5	96.5
5	**F-Mix (2/0)**	96.6	95.9	96.2	98.4	98.2	98.0
6	**Slag/Fiber Mix (1/1)**	96.4	95.4	95.9	97.2	97.7	96.8
7	**Slag/Fiber Mix (1.25/0.75)**	97.5	95.4	96.1	97.0	97.8	96.8
8	**Sprinkle Mix (1.25/0.75)**	97.3	96.0	96.6	97.8	98.4	97.7
9	**Sprinkle Mix (1/1)**	97.4	95.7	96.8	98.1	98.6	97.6
10	**F-Mix (2/0)**	97.4	95.7	96.8	98.1	98.8	98.0
11	**4.75-mm SMA (0.75/1.25)**	96.3	94.2	93.5	96.1	96.4	95.6
12	**4.75-mm SMA (1/1)**	96.1	94.8	93.4	95.5	95.7	95.2
13	**4.75-mm SMA (1.25/0.75)**	96.5	95.0	94.4	96.4	97.0	96.1
14	**12.5-mm SMA (2/0)**	98.4	98.0	98.8	100.1	100.2	99.4

* Indicates wearing surface thickness/leveling binder thickness.

3.3 TEXTURE PROFILING

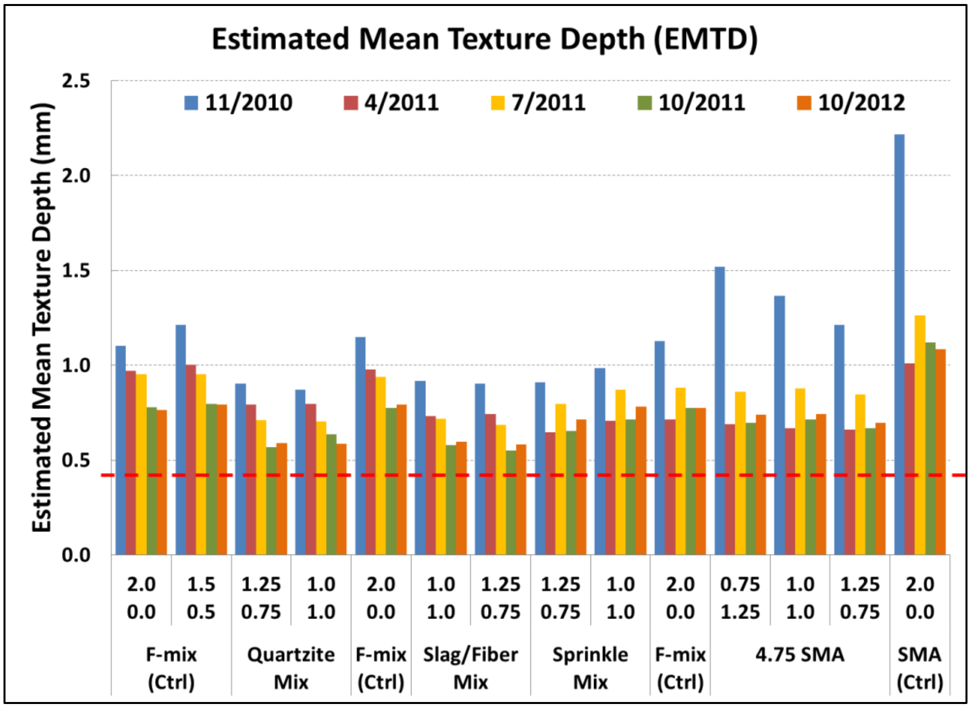
Longitudinal profile measurements were collected in conjunction with OBSI testing using a high-speed inertial profiler integrated into the test vehicle. Figure 14 shows the test vehicle with the profiler positioned in line with the right rear wheel. Profile data were collected from both the right and left wheel paths and from the driving and passing lanes. As with the OBSI data, the profile for each test section were truncated 50 to 100 ft from both ends of each section to exclude any unrepresentative roughness caused by the paving transitions.

Data collected by the profiler were used to compute both the mean roughness index (MRI), according to ASTM E1926, and the estimated mean texture depth (EMTD), according to ASTM E1845. The profiler is regarded as a Class 1 instrument, according to ASTM E950. The MRI is the average of the international roughness index (IRI) values from the left and right wheel paths.

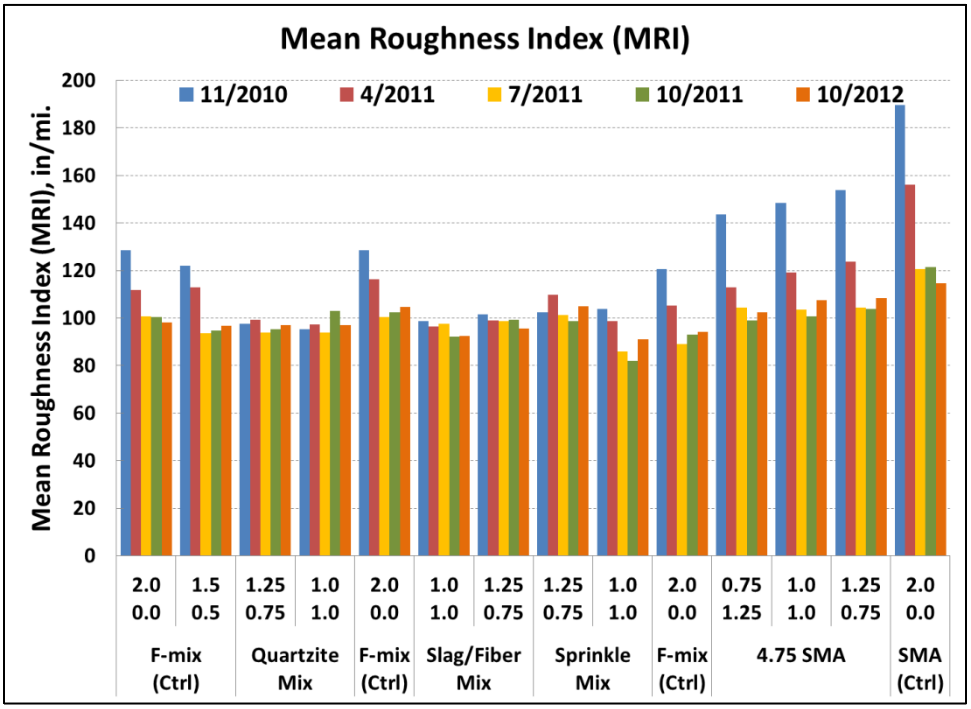
Figure 14. (a) High-speed inertial profiler mounted behind the test vehicle, and (b) test vehicle interior showing the computer screens used by the operator.

The highest measured EMTD values, right after construction, were located in the control 12.5-mm SMA and then the 4.75-mm SMA. The SMAs had a greater texture depth than the dense-graded mixtures regardless of their NMAS. The coarse dense-graded mixture (F-mix) had higher EMTD values than the fine dense-graded mixtures for the same NMAS, as shown in Figure 15 (a). Although texture depths for the new mixtures, especially the fine dense-graded mixtures, were lower than the others, their noise levels and friction features were observed as lower and better, respectively, than the control mixtures. The EMTD of all the sections decreased and was stabilized within 1 year after construction. A more significant decrease was observed in the SMAs than in the dense-graded mixes. When an estimated texture depth is less than 0.016 in (0.4 mm), the risk of wet crashes increases greatly (Hall et al. 2009). The EMTDs in all the sections were above 0.4 mm and should provide sufficient surface friction (Table 11).

The MRI represents ride quality of the vehicles and indicates pavement roughness, which is an indicator of a pavement life cycle in terms of pavement condition. Higher MRI values represent poor ride quality. The highest MRI value was found for the control SMA, around 190 in/mi, and the quartzite mix showed the lowest MRI value at both the 0-month and 4-month measurements, as shown in Table 12. However, the slag/fiber mix had one slightly lower MRI reading at 4 months. In general, the MRI values were significantly less for the fine dense-graded mix than the coarse dense-graded and SMAs. The MRI values of the SMAs decreased more than those of the dense-graded mixtures over the 2-year measurements. The sprinkle mix and quartzite mix sections generally had increased MRI values after 4 months. All sections would provide good ride quality up to 75 mph, per ASTM E1926. Overall, the new fine dense-graded mixtures provided better ride quality than the SMAs and the control F-mix; however, the MRI value of the SMAs showed improvement with time.



(a)



(b)

Figure 15. (a) Estimated mean texture depth (EMTD), and (b) mean roughness index (MRI).

Table 11. Estimated Mean Texture Depth (EMTD)

Section (WS/LB)*		Estimated Mean Texture Depth, mm				
		11/2010	4/2011	7/2011	10/2011	10/2012
1	**F-Mix (2/0)**	1.1	1.0	1.0	0.8	0.8
2	**F-Mix (1.5/0.5)**	1.2	1.0	1.0	0.8	0.8
3	**Quartzite Mix (1.25/0.75)**	0.9	0.8	0.7	0.6	0.6
4	**Quartzite Mix (1/1)**	0.9	0.8	0.7	0.6	0.6
5	**F-Mix (2/0)**	1.1	1.0	0.9	0.8	0.8
6	**Slag/Fiber Mix (1/1)**	0.9	0.7	0.7	0.6	0.6
7	**Slag/Fiber Mix (1.25/0.75)**	0.9	0.7	0.7	0.6	0.6
8	**Sprinkle Mix (1.25/0.75)**	0.9	0.6	0.8	0.7	0.7
9	**Sprinkle Mix (1/1)**	1.0	0.7	0.9	0.7	0.8
10	**F-Mix (2/0)**	1.1	0.7	0.9	0.8	0.8
11	**4.75-mm SMA (0.75/1.25)**	1.5	0.7	0.9	0.7	0.7
12	**4.75-mm SMA (1/1)**	1.4	0.7	0.9	0.7	0.7
13	**4.75-mm SMA (1.25/0.75)**	1.2	0.7	0.8	0.7	0.7
14	**12.5-mm SMA (2/0)**	2.2	1.0	1.3	1.1	1.1

* Indicates wearing surface thickness/leveling binder thickness.

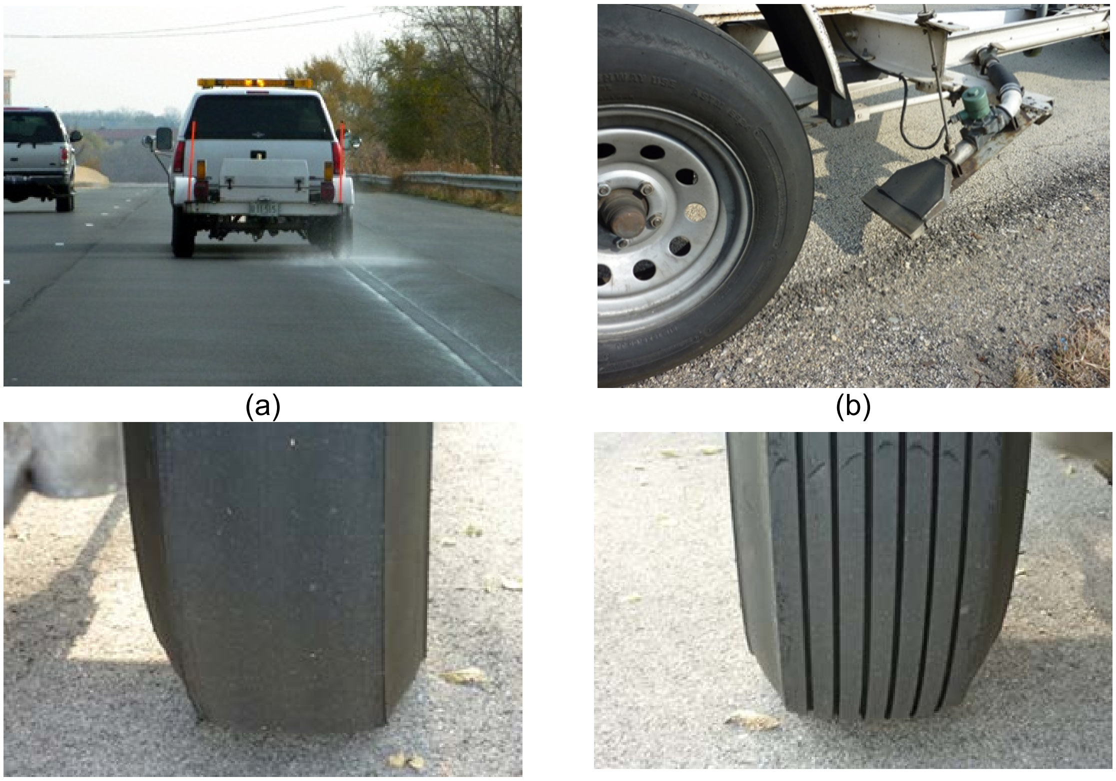
Table 12. Mean Roughness Index (MRI)

Section (WS/LB)*		Mean Roughness Index, in./mi				
		11/2010	4/2011	7/2011	10/2011	10/2012
1	**F-Mix (2/0)**	128.6	111.7	100.6	100.5	98.2
2	**F-Mix (1.5/0.5)**	122.1	113.0	93.6	94.7	96.7
3	**Quartzite Mix (1.25/0.75)**	97.6	99.3	94.0	95.3	96.9
4	**Quartzite Mix (1/1)**	95.2	97.4	94.0	102.9	97.0
5	**F-Mix (2/0)**	128.5	116.3	100.5	102.5	104.7
6	**Slag/Fiber Mix (1/1)**	98.7	96.4	97.6	92.2	92.4
7	**Slag/Fiber Mix (1.25/0.75)**	101.6	98.9	98.8	99.4	95.6
8	**Sprinkle Mix (1.25/0.75)**	102.3	109.9	101.3	98.6	105.1
9	**Sprinkle Mix (1/1)**	103.9	98.8	85.8	82.1	91.1
10	**F-Mix (2/0)**	120.7	105.3	89.1	93.0	94.1
11	**4.75-mm SMA (0.75/1.25)**	143.5	113.0	104.3	98.9	102.4
12	**4.75-mm SMA (1/1)**	148.6	119.3	103.5	100.8	107.6
13	**4.75-mm SMA (1.25/0.75)**	153.7	123.6	104.4	103.8	108.3
14	**12.5-mm SMA (2/0)**	189.7	156.1	120.6	121.4	114.5

* Indicates wearing surface thickness/leveling binder thickness.

3.4 FRICTION EVALUATION

The locked-wheel friction test was conducted in accordance with AASHTO T242 (ASTM E274) to obtain a standard measurement of pavement surface friction under wet conditions, as shown in Figure 16 (a). The two-wheeled trailer was towed at a constant speed of 40 mph, and the tire of the locked wheel skidded along the surface as water was sprayed in front of the wheel, as shown in Figure 16 (b). The torque that developed on the trailer axle, which was caused by the friction generated between the tire and the pavement surface, was measured. The friction number (FN) was calculated from this torque and was used to evaluate the pavement's friction. Smooth tires and ribbed tires were used, as shown in Figures 16 (c) and (d). Seven readings were taken at each section and lane. The friction number from the treaded tire (FN_T) is a measurement of pavement microtexture, which is the frictional characteristic of the aggregate in the mixture. The friction number from the smooth tire (FN_S) is a measurement of pavement macrotexture, which is the frictional characteristic provided by drainage paths in the pavement. Friction numbers range from a high of 100 to a low of 1. The State of Illinois considers FN_S greater than 15 and FN_T greater than 30 acceptable. The friction numbers from these sections for smooth and treaded tires are presented in Tables 13 and 14, respectively.



(a) (b)

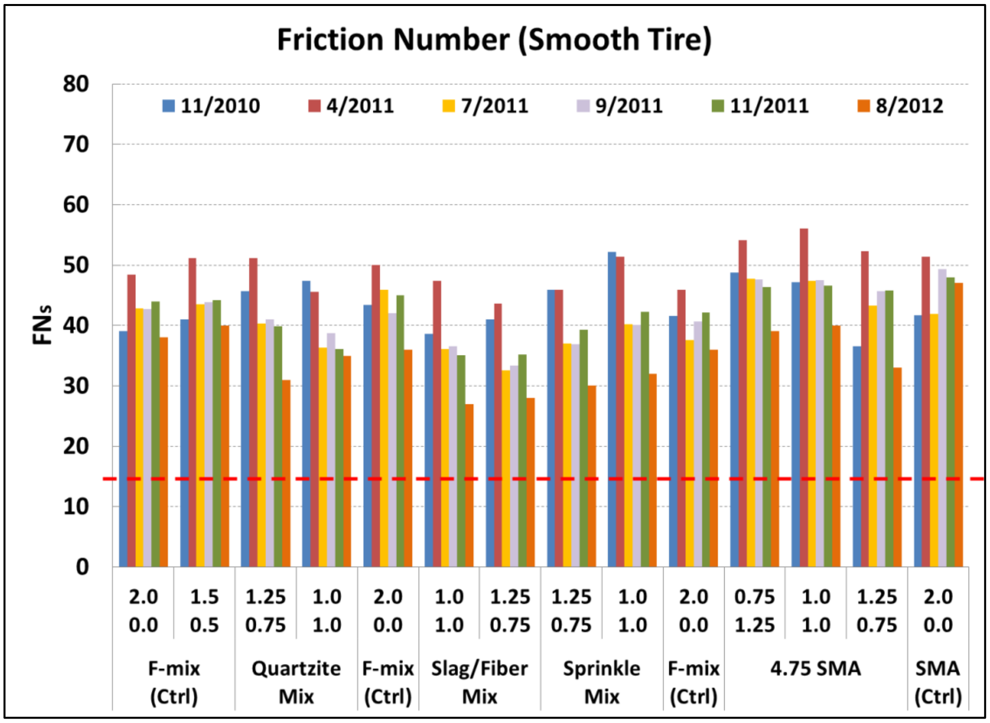
(c) (d)

Figure 16. (a) Locked-wheel friction testing, (b) water applied in front of the test tire, (c) smooth tire, and (d) ribbed tire.

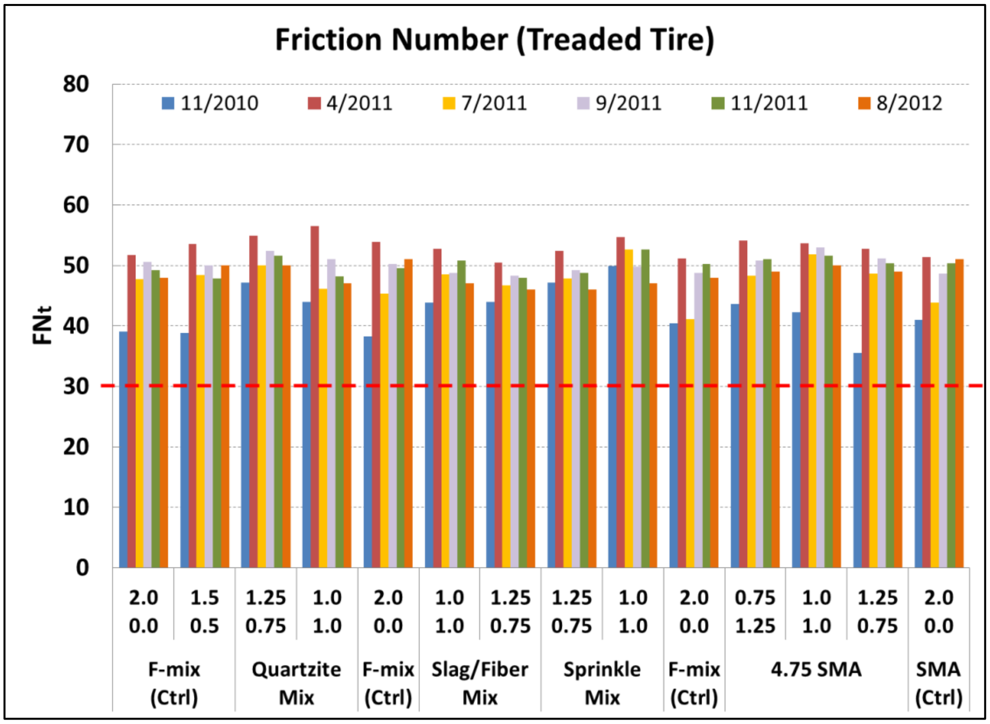
Friction testing results obtained immediately after construction give an initial indication of the friction characteristics of the mix. At that condition, the aggregates were coated with a film of asphalt. Hence, the measured friction would be different than those when the film of asphalt is worn away from the aggregate. Nevertheless, all initial friction measurements met the guideline set by the State of Illinois.

Figure 17 (a) shows the FN_S over 2 years. The initial FN_S collected right after construction showed that the sprinkle mixture with a 1-in wearing surface had the highest FN_S, and the 4.75-mm SMA with a 1.25-in wearing surface had the lowest FN_S. After 4 months, the sprinkle mixture FN_S values were basically unchanged, whereas the other mixtures, especially the SMAs and the F-mix, had significant increases in FN_S. The FN_S of fine dense-graded mixes were relatively lower than those of the control mixes after 2 years due primarily to a smoother pavement surface texture. The friction number of the sprinkle section, which was expected to provide relatively higher frictional performance, decreased more significantly than for the other sections. Traffic could cause further embedment of the sprinkle chips in the surface, resulting in a smoother texture and, hence, reduced friction.

The FN_T values of the asphalt mixtures had some similar trends. As seen in Figure 17 (b), the sprinkle mixture showed the highest initial friction number from a treaded tire, and the SMA had the lowest values initially. After 24 months, the FN_T for all of the mixes increased, with the FN_T for the SMA and the F-mix having the greatest increase. All of the FN_T values met the guidelines set by the State of Illinois. These initial results for all the mixes over 2 years are promising. The sections should continue to be monitored over the next few years.



(a)



(b)

Figure 17. Friction number: (a) smooth tire, and (b) treaded tire.

Table 13. Friction Number (Smooth Tire)

Section (WS/LB)*		Friction Number (Smooth Tire)					
		11/2010	4/2011	7/2011	9/2011	11/2011	8/2012
1	F-Mix (2/0)	39.0	48.4	42.9	42.7	43.8	38.0
2	F-Mix (1.5/0.5)	41.0	51.1	43.5	43.9	43.0	40.0
3	Quartzite Mix (1.25/0.75)	45.7	51.1	40.3	41.0	40.8	31.0
4	Quartzite Mix (1/1)	47.4	45.6	36.3	38.8	37.2	35.0
5	F-Mix (2/0)	43.4	50.0	45.9	42.1	45.0	36.0
6	Slag/Fiber Mix (1/1)	38.6	47.4	36.1	36.5	34.2	27.0
7	Slag/Fiber Mix (1.25/0.75)	41.0	43.6	32.5	33.4	35.4	28.0
8	Sprinkle Mix (1.25/0.75)	45.9	45.9	37.0	36.9	40.4	30.0
9	Sprinkle Mix (1/1)	52.1	51.4	40.3	40.1	42.6	32.0
10	F-Mix (2/0)	41.6	45.9	37.6	40.7	42.0	36.0
11	4.75-mm SMA (0.75/1.25)	48.7	54.1	47.7	47.6	46.2	39.0
12	4.75-mm SMA (1/1)	47.1	56.0	47.4	47.5	47.6	40.0
13	4.75-mm SMA (1.25/0.75)	36.6	52.3	43.3	45.7	46.8	33.0
14	12.5-mm SMA (2/0)	41.6	51.4	41.9	49.3	48.4	47.0

* Indicates wearing surface thickness/leveling binder thickness.

Table 14. Friction Number (Treaded Tire)

Section (WS/LB)*		Friction Number (Treaded Tire)					
		11/2010	4/2011	7/2011	9/2011	11/2011	8/2012
1	F-Mix (2/0)	39.0	51.7	47.7	50.6	49.2	48.0
2	F-Mix (1.5/0.5)	38.9	53.6	48.4	50.0	47.8	50.0
3	Quartzite Mix (1.25/0.75)	47.1	54.9	50.0	52.4	51.6	50.0
4	Quartzite Mix (1/1)	44.0	56.5	46.1	51.1	48.2	47.0
5	F-Mix (2/0)	38.3	53.9	45.3	50.3	49.5	51.0
6	Slag/Fiber Mix (1/1)	43.9	52.7	48.5	48.7	50.8	47.0
7	Slag/Fiber Mix (1.25/0.75)	44.0	50.4	46.7	48.3	47.9	46.0
8	Sprinkle Mix (1.25/0.75)	47.1	52.4	47.9	49.3	48.7	46.0
9	Sprinkle Mix (1/1)	49.9	54.7	52.6	49.8	52.6	47.0
10	F-Mix (2/0)	40.4	51.1	41.1	48.8	50.2	48.0
11	4.75-mm SMA (0.75/1.25)	43.7	54.1	48.3	50.8	51.0	49.0
12	4.75-mm SMA (1/1)	42.3	53.7	51.9	53.0	51.6	50.0
13	4.75-mm SMA (1.25/0.75)	35.6	52.7	48.6	51.2	50.4	49.0
14	12.5-mm SMA (2/0)	41.0	51.4	43.9	48.6	50.3	51.0

* Indicates wearing surface thickness/leveling binder thickness.

3.5 RUT MEASUREMENTS

Transverse profile measurements were taken using a walking foot inclinometer. The changes in vertical distance over time were considered to be the rut depth. The rut data were collected across the wheel paths at 3-in spacings at two locations per section. The starting point for data collection at each location was marked for periodic field testing every 4 months to track rut depths at the same location. Since the minimum spacing of the device is 12 in, a 3-in shift from the previous starting points was made to obtain rut data every 3 in, as shown in Figure 18.


(a) (b)

Figure 18. (a) Dipstick rut measurement, and (b) paint marking the starting point for periodical measurements.

The first measurements were taken as reference transverse profiles. The differences measured after 4 months were the rut depth at each location (Figure 19 and Table 15). The maximum rut depth was generally located along the wheel path due to traffic loading. However, it is still too early to observe significant rut depth on the site.

Table 15. Rut Depths

Section (WS/LB)*		**Rut Depths, mm**			
		4/2011	**7/2011**	**10/2011**	**10/2012**
1	**F-Mix (2/0)**	0.61	1.40	1.59	1.29
2	**F-Mix (1.5/0.5)**	0.65	0.93	1.24	1.04
3	**Quartzite Mix (1.25/0.75)**	1.57	1.54	1.62	1.84
4	**Quartzite Mix (1/1)**	1.05	1.66	1.41	1.48
5	**F-Mix (2/0)**	1.12	1.70	1.74	2.20
6	**Slag/Fiber Mix (1/1)**	1.18	1.60	1.61	0.83
7	**Slag/Fiber Mix (1.25/0.75)**	0.90	1.47	2.01	1.38
8	**Sprinkle Mix (1.25/0.75)**	0.51	0.97	1.26	0.71
9	**Sprinkle Mix (1/1)**	0.36	1.03	1.40	1.08
10	**F-Mix (2/0)**	0.62	2.08	2.25	2.25
11	**4.75-mm SMA (0.75/1.25)**	0.83	1.97	1.63	2.20
12	**4.75-mm SMA (1/1)**	1.68	2.25	2.05	1.60
13	**4.75-mm SMA (1.25/0.75)**	0.60	0.85	1.52	1.11
14	**12.5-mm SMA (2/0)**	0.75	1.01	1.73	0.93

* Indicates wearing surface thickness/leveling binder thickness.

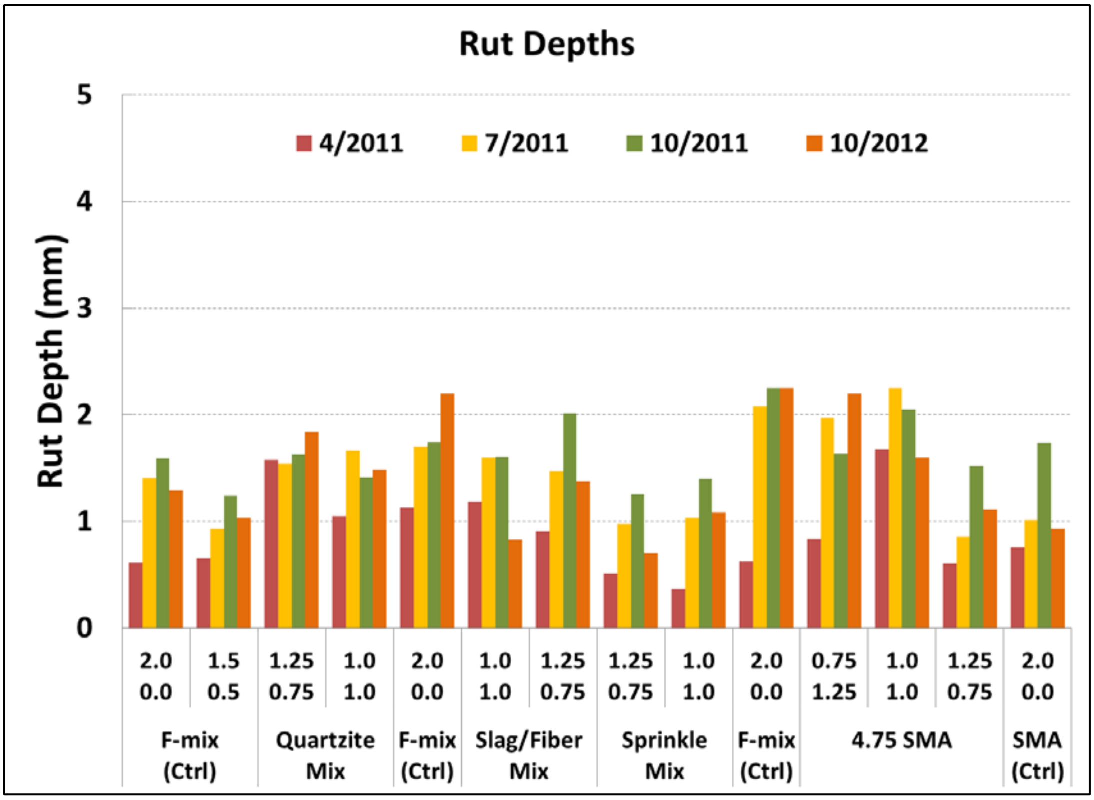


Figure 19. Rut depths at each section.

CHAPTER 4 ENGINEERING BENEFIT ANALYSIS

An engineering benefit analysis was performed to determine the cost effectiveness of the newly developed asphalt mixtures, considering their performances compared to those of the control mixes. The current cost analysis methods focus primarily on life-cycle cost analysis, which generally uses the international roughness index (IRI) as a performance indicator to estimate service life of pavements. User costs are rarely taken into consideration with pavement performances. For example, higher surface friction is believed to increase costs due to fuel consumption but does not take into account any benefits resulting from road safety improvements. Therefore, the engineering benefit analysis in this study included overall performance of each mixture as well as total cost—including both agency costs and user costs.

4.1 OVERALL PERFORMANCE

Five laboratory tests and five on-site performance tests were conducted for each mixture and field section. While laboratory tests examined material characterizations, on-site performance tests captured the effect of pavement thickness and environmental impact under actual traffic loading. Therefore, it is important to establish appropriate performance criteria. For the laboratory tests, the complex modulus test provides material properties over a wide range of loading frequencies and temperatures. High-temperature and low frequency ranges usually indicate rutting potential in hot conditions, whereas thermal cracking behavior can be captured at low temperature and using a high frequency range. To avoid duplicating weight factors on specific performance criteria such as rutting and fracture, complex modulus test results were not included in the overall performance score calculation because rutting and fracture tests were conducted individually in the laboratory. Since rutting potential was investigated in the laboratory and in the field, those values were used for the rutting criteria. For field performance tests, initial, 1-year, and 2-year performances were included in the performance rating.

To compare pavement performances, it is important to select an appropriate method to quantify such performance. Fisher’s least significant difference (LSD) test was used to compare the mean value of each group and to rank them. If the difference between performance groups was not significant, both performance ratings were assigned and an average score of those ratings was used later, in the engineering benefit analysis.

The test results from the laboratory and field were statistically analyzed using the Statistical Analysis System (SAS) program. Fisher’s LSD test was performed with two-way analysis of variance (ANOVA) at a significance level of 0.05 for each mixture’s property and performance. The test results were ranked using the letters from A to E for the laboratory test results and A to J for field test results because more cases with different thickness were considered in the field tests. The letter was changed when the mean was statistically different from others—the letter A represents the best performing mixture followed by the other letters in alphabetic order. With regard to the rankings for noise and mean roughness index (MRI), the letter A represents the least noise and roughness. A double letter such as A/B indicates that the difference in the means was not statistically significant and that the mixture’s ranking could fall in either group.

Fisher’s LSD test was performed on laboratory performance test results for the LMLC and PMLC specimens and field performance test results for 0-, 12-, 24-month measurements. The alphabetic ranks for each mixture with LMLC and PMLC samples are shown in Tables 16 and 17, respectively. Table 16 does not include the ranks for the control mixes because only PMLC specimens were used in the laboratory tests, as described in Volume 1 of this report (Al-Qadi et al. 2013). The field performance test results at 0, 12, and 24 months for each asphalt mixture and thickness and their ranks are shown in Tables 18, 19, and 20, respectively.

After alphabetic ranks were assigned for each mixture and thickness with respect to its properties and performance, those ranks were converted to numbers to calculate overall performance numerically. The results of the laboratory tests on field cores were not included in the overall performance analysis because field core densities vary for different sections. This would significantly affect the test results, especially the rutting potential, which is sensitive to air voids in the specimen. The alphabetic rankings shown in Tables 16 through 20 were converted to numerical scores based on the rankings shown in Table 21.

The overall performance score was calculated using Equation 4.1. This equation allows the decision maker to apply a weight factor (a_i or a_j) for a specific performance value when calculating the overall performance score. For example, rut resistance could be weighted more heavily in high-temperature locations, while fracture resistance could be emphasized more by applying a higher weight factor in cold locations. In addition, if the field test results are considered more important, a greater weight factor ($\alpha < \beta$) could be used. The weight factors were assumed to be the same for all performance and property values for both the laboratory and field tests in this study. In this study, the average value of the test results was used when the test was conducted for more than one condition, such as fracture resistance (10.4°F and –11.2°F), indirect tensile strength (dry and wet), and friction (treaded tire and smooth tire).

$$Overall\ \ Performance\ \ Score = \frac{1}{\alpha+\beta}\left(\alpha \frac{\sum_{i=1}^{n} a_i^L \cdot R_i^L}{\sum_{i=1}^{n} a_i^L} + \beta \frac{\sum_{j=1}^{m} a_j^F \cdot R_j^F}{\sum_{j=1}^{m} a_j^F} \right) \tag{4.1}$$

where

a_i^L, a_j^F : Weight factor of test *i* and *j* for lab performance and field performance, respectively

R_i^L, R_j^F : Performance rating of test *i* and *j* for lab performance and field performance, respectively

α, β : Weight factor for lab performance and field performance

n, m : Number of tests performed in the lab and the field, respectively

Table 22 shows the overall performance score for each section. In general, the new HMAs have higher indirect tensile strength and less noise compared to that of control mixes. The control mixes resulted in lower performance scores than those of the new mixtures. The 1-in thick 4.75-mm SMA has the highest overall performance score.

Table 16. Performance Ranking for Laboratory Test Results (LMLC)

Mix Type	Lab-Mixed and Lab-Compacted								
	Rut Resistance	Durability	Fracture Resistance		Indirect Tensile Strength		Tensile Strength Ratio	Complex Modulus	
			10.4°F	–11.2°F	Dry	Wet		14°F, 25Hz	129°F, 0.1Hz
Quartzite Mix	A	B/C	B	A/B	A	A	B	A	A/B
Sprinkle Mix	B	C	A/B	A/B	A	B	B	A	A
Slag/Fiber Mix	A/B	A/B	A/B	B	A	A/B	B	A	B
4.75-mm SMA	C	A	A	A	B	C	A	A	B

Table 17. Performance Ranking for Laboratory Test Results (PMLC)

Mix Type	Plant-Mixed and Lab-Compacted								
	Rut Resistance	Durability	Fracture Resistance		Indirect Tensile Strength		Tensile Strength Ratio	Complex Modulus	
			10.4°F	–11.2°F	Dry	Wet		14°F, 25Hz	129°F, 0.1Hz
F-Mix (Control)	A	B	B	B	D	E	A	A	B
SMA (Control)	A	C	A	A	C/D	D/E	A	A/B	A
Quartzite Mix	A	B	B	B	B/C	B/C	A	B	B
Sprinkle Mix	A	B	B/C	B	A	A	A	A/B	B
Slag/Fiber Mix	A	A/B	C	B	B	A/B	A	A/B	B
4.75-mm SMA	A	A	B	B	B/C	C/D	A	A/B	B

Table 18. Performance Ranking for Field Test Results (0 Month)

Section (WS/LB)*	**0 Month**					
	Noise	**Friction (Tread)**	**Friction (Smooth)**	**Rut Resistance**	**MRI**	**EMTD**
F-Mix (1.5/0.5)	B/C	F	C	B	C/D	C
F-Mix (2/0)	C/D	E/F	C	B	C/D	C
12.5-mm SMA (2/0)	E	D/E	C	B	F	A
Quartzite Mix (1/1)	C/D	C	B	B	A	D
Quartzite Mix (1.25/0.75)	D	B	B	B/C	A/B	D
Sprinkle Mix (1/1)	C/D	A	A	A	C/D	C/D
Sprinkle Mix (1.25/0.75)	C/D	B	B	A/B	C/D	D
Slag/Fiber Mix (1/1)	A/B	C	C/D	B	A/B	D
Slag/Fiber Mix (1.25/0.75)	C/D	C	C	B	C/D	D
4.75-mm SMA (0.75/1.25)	A	C	A/B	B	D/E	B
4.75-mm SMA (1/1)	A	C/D	B	C	D/E	B/C
4.75-mm SMA (1.25/0.75)	A/B	G	D	A/B	E	C

* Indicates wearing surface thickness/leveling binder thickness.

Table 19. Performance Ranking for Field Test Results (12 Month)

Section (WS/LB)*	**12 Month**					
	Noise	**Friction (Tread)**	**Friction (Smooth)**	**Rut Resistance**	**MRI**	**EMTD**
F-mix (1.5/0.5)	F	E	C	B	A/B	B
F-mix (2/0)	F	D	C/D	B	B	B/C
12.5-mm SMA (2/0)	G	C	A	B	C	A
Quartzite Mix (1/1)	C	E	G	B	B	E
Quartzite Mix (1.25/0.75)	D	A/B	E/F	B/C	A/B	F/G
Sprinkle Mix (1/1)	E/F	A	D/E	A	A	C/D
Sprinkle Mix (1.25/0.75)	E	D/E	F	A/B	B	D/E
Slag/Fiber Mix (1/1)	D	B	G	B	A/B	F
Slag/Fiber Mix (1.25/0.75)	D	E	G	B	B	G
4.75-mm SMA (0.75/1.25)	B	B	A/B	B	B	C/D
4.75-mm SMA (1/1)	A	A/B	A/B	C	B	C
4.75-mm SMA (1.25/0.75)	C	C	B	A/B	B	D

* Indicates wearing surface thickness/leveling binder thickness.

Table 20. Performance Ranking for Field Test Results (24 Month)

Section (WS/LB)*	24 Month					
	Noise	Friction (Tread)	Friction (Smooth)	Rut Resistance	MRI	EMTD
F-Mix (1.5/0.5)	F	A	B/C	A/B	A/B	B
F-Mix (2/0)	E/F	B	C/D	B/C	A/B	B/C
12.5-mm SMA (2/0)	G	A	A	A/B	B	A
Quartzite Mix (1/1)	C/D	C	D/E	B	A/B	D
Quartzite Mix (1.25/0.75)	D/E	A	F/G	B/C	A/B	D
Sprinkle Mix (1/1)	E/F	C	E/F	A/B	A	B
Sprinkle Mix (1.25/0.75)	E/F	C/D	G	A	A/B	B/C
Slag/Fiber Mix (1/1)	C/D	C	H	A	A	D
Slag/Fiber Mix (1.25/0.75)	C/D	D	G/H	B	A/B	D
4.75-mm SMA (0.75/1.25)	A/B	B	B/C	C	A/B	B/C
4.75-mm SMA (1/1)	A	A/B	B	B	A/B	B/C
4.75-mm SMA (1.25/0.75)	B/C	B	E/F	A/B	A/B	C

* Indicates wearing surface thickness/leveling binder thickness.

Table 21. Score for Alphabetic Rank

Laboratory Test									
Rank	A	A/B	B	B/C	C	C/D	D	D/E	E
Score	10	9	8	7	6	5	4	3	2

Field Test																			
Rank	A	A/B	B	B/C	C	C/D	D	D/E	E	E/F	F	F/G	G	G/H	H	H/I	I	I/J	J
Score	10	9.5	9	8.5	8	7.5	7	6.5	6	5.5	5	4.5	4	3.5	3	2.5	2	1.5	1

Table 22. Overall Performance Scores

Section (WS/LB)*	Rut Resistance	Durability	Fracture Resistance	IDT	TSR	Noise	Friction	MRI	EMTD	Over all
F-Mix (1.5/0.5)	9.58	8.00	8.00	3.00	10.00	6.17	7.58	8.83	8.67	7.76
F-Mix (2/0)	9.42	8.00	8.00	3.00	10.00	6.00	7.42	8.67	8.33	7.65
12.5-mm SMA (2/0)	9.58	6.00	10.00	4.00	10.00	4.67	8.75	7.33	10.00	7.81
Quartzite Mix (1/1)	9.50	7.50	8.25	8.50	9.00	7.67	6.92	9.50	6.67	8.17
Quartzite Mix (1.25/0.75)	9.25	7.50	8.25	8.50	9.00	6.83	7.92	9.50	6.17	8.10
Sprinkle Mix (1/1)	9.42	7.00	8.25	9.50	9.00	6.17	8.33	9.17	8.00	8.31
Sprinkle Mix (1.25/0.75)	9.33	7.00	8.25	9.50	9.00	6.33	6.83	8.67	7.33	8.03
Slag/Fiber Mix (1/1)	9.42	9.00	7.75	9.00	9.00	8.00	6.58	9.67	6.33	8.31
Slag/Fiber Mix (1.25/0.75)	9.25	9.00	7.75	9.00	9.00	7.33	6.08	8.67	6.00	8.01
4.75-mm SMA (0.75/1.25)	8.33	10.00	9.00	6.50	10.00	9.50	8.92	8.33	8.33	8.77
4.75-mm SMA (1/1)	8.17	10.00	9.00	6.50	10.00	10.00	9.00	8.33	8.33	8.81
4.75-mm SMA (1.25/0.75)	8.75	10.00	9.00	6.50	10.00	8.67	7.08	8.17	7.67	8.43

* Indicates wearing surface thickness/leveling binder thickness.

4.2 LIFE-CYCLE COST ANALYSIS

Life-cycle cost analysis (LCCA) is a technique for evaluating the overall long-term economic efficiency of a project or product. LCCA incorporates initial costs and discounted future agency, use, and other relevant costs over the life of various investments such as maintenance, rehabilitation, restoring, resurfacing, and reconstruction costs. The main objective of LCCA for this particular project was to evaluate newly developed asphalt mixtures in terms of economic efficiency.

LCCA was performed on six asphalt mixtures and various wearing surface thicknesses. RealCost software, developed by FHWA, was used for deterministic and probabilistic analyses. Agency cost includes material cost and construction cost, which were obtained from the company involved in the field construction on this project. The analysis performed with RealCost provided agency cost and user cost for the sections with different asphalt mixtures at various wearing surface thicknesses.

4.2.1 Agency Costs

The life-cycle agency cost represents all costs related to raw material, production, installation, maintenance, and replacement. For this project, the costs for maintenance and replacement for all study mixtures were assumed to be equal because no life cycles for new mixtures were available at the time. Tables 23 (a) and (b) show agency costs, which include material cost, production cost, and construction cost per ton of asphalt mixture. It is noteworthy that $3 per ton of asphalt mixture was added for using the material transfer vehicle (MTV) for placing the control F-mix and 12.5-mm SMA. In addition, the use of PG 76-22 binder and a relatively high steel slag content increased the cost of the control SMA. The additional screening of CM13 quartzite and FM22 dolomite aggregates on a 4.75-mm (No. 4) sieve to achieve proper aggregate gradation resulted in higher material cost of the 4.75-mm SMA. The control mixes had higher recycled material content: 10% of RAP for the F-mix, and 35.7% and 84% of steel slag for the F-mix and 12.5-mm SMA, respectively. This resulted in relatively lower material cost, even for the control mixes, compared to other typical mixes. An additional $4 per ton of HMA was added to the construction cost of the sprinkle mix to account for the cost of the spreading machine and trucking of sprinkle chips. This cost could be reduced to $2 per ton of HMA when spreading equipment becomes commonly available. Using an MTV to place the new mixes would increase construction cost by $3 per ton of HMA; this will reduce the segregation potential. In addition, savings could be realized in new mixes if they become common. Also, a relatively thicker wearing surface increased the total cost of the asphalt overlay per section.

Table 23 (a). Agency Cost for Asphalt Mixture Type

Mix Type	Cost, $/ton		
	Materials + Production	Construction	Total
F-Mix (Control)	65.63	22.00	87.63
SMA (Control)	91.23	22.00	113.23
Quartzite Mix	61.75	22.00	83.75
Sprinkle Mix	62.00*	26.00	88.00
Slag/Fiber Mix	63.88**	22.00	85.88
4.75-mm SMA	87.89	22.00	109.89
Leveling Binder	61.05	22.00	83.05

* Includes sprinkle chips at a cost of $4/ton of HMA.

** The fiber cost is already included.

Table 23 (b). Agency Cost for Asphalt Mixture Type (with MTV)

Mix Type	Cost, $/ton		
	Materials + Production	Construction	Total
F-Mix (Control)	65.63	25.00	90.63
SMA (Control)	91.23	25.00	116.23
Quartzite Mix	61.75	25.00	86.75
Sprinkle Mix	62.00*	27.00	89.00
Slag/Fiber Mix	63.88**	25.00	88.88
4.75-mm SMA	87.89	25.00	112.89
Leveling Binder	61.05	22.00	83.05

* Includes sprinkle chips at a cost of $2/ton of HMA.
** The fiber cost is already included.

Material quantity per lane-mile at various layer thicknesses was calculated with respect to the layer thickness and density required, as shown in Table 24. Material cost and total agency cost (including material and construction costs) were then calculated by multiplying the material quantity by the cost per ton of asphalt materials, as shown in Tables 25 (a) and (b). The test section with the control 12.5-mm SMA and a 2-in wearing surface was the most expensive section in this project, while the quartzite mix section with a 1-in wearing surface was the least expensive.

Table 24. Material Quantity Calculation

Mix Type	G_{mm}	Material Quantity in Ton/Lane-Mile at Various Layer Thicknesses (in)					
		0.50	0.75	1.00	1.25	1.50	2.00
F-Mix (Control)	2.729	189.7	284.6	379.5	474.3	569.2	758.9
12.5-mm SMA (Control)	2.987	209.9	314.8	419.8	524.7	629.7	839.6
Quartzite Mix	2.504	174.1	261.1	348.2	435.2	522.3	696.3
Sprinkle Mix	2.500*	179.3	266.2	353.1	440.0	526.9	700.7
Slag/Fiber Mix	2.606	181.2	271.8	362.4	452.9	543.5	724.7
4.75-mm SMA	2.454	172.4	258.7	344.9	431.1	517.3	689.8
Leveling Binder	2.500	173.8	260.7	347.6	434.5	521.4	695.2

* This is only for the base mix of the wearing surface used in the sprinkle mix. Its material quantity was calculated by adding the amount of the sprinkle chips to that of the base mix of the wearing surface.

Table 25 (a). Agency Cost for Each Section

Section (WS/LB)*	**Cost, $/Lane-Mile**	
	Materials + Production	**Materials + Production + Construction**
Quartzite Mix (1/1)	42,722	58,029
Quartzite Mix (1.25/0.75)	42,791	58,102
Sprinkle Mix (1/1)*	43,115	59,943
Slag/Fiber Mix (1/1)	44,369	59,989
Sprinkle Mix (1.25/0.75)**	43,197	60,373
Slag/Fiber Mix (1.25/0.75)	44,851	60,551
F-Mix (1.5/0.5)	47,967	64,313
4.75-mm SMA (0.75/1.25)	49,262	64,512
F-Mix (2/0)	49,808	66,504
4.75-mm SMA (1/1)	51,534	66,770
4.75-mm SMA (1.25/0.75)	53,807	69,027
12.5-mm SMA (2/0)	76,597	95,068

* Indicates wearing surface thickness/leveling binder thickness.
**Includes sprinkle chips at a cost of $4/ton of HMA.

Table 25 (b). Agency Cost for Each Section (with MTV)

Section (WS/LB)*	**Cost, $/Lane-Mile**	
	Materials + Production	**Materials + Production + Construction**
Quartzite Mix (1/1)	42,722	59,074
Quartzite Mix (1.25/0.75)	42,791	59,407
Sprinkle Mix (1/1)**	43,115	60,296
Sprinkle Mix (1.25/0.75)**	43,197	60,813
Slag/Fiber Mix (1/1)	44,369	61,076
Slag/Fiber Mix (1.25/0.75)	44,851	61,910
4.75-mm SMA (0.75/1.25)	49,262	65,288
F-Mix (1.5/0.5)	47,967	66,020
4.75-mm SMA (1/1)	51,534	67,804
F-Mix (2/0)	49,808	68,781
4.75-mm SMA (1.25/0.75)	53,807	70,321
12.5-mm SMA (2/0)	76,597	97,587

* Indicates wearing surface thickness/leveling binder thickness.
**Includes sprinkle chips at a cost of $2/ton of HMA.

To simplify the calculation of unit total cost per lane-mile, the analysis period was set at 1 year; the section length was set at 1 mile, with 0.25 mile of work zone transition before and after the section. Both deterministic and probabilistic analyses were performed in this project, and the probabilistic analysis followed a normal distribution.

4.2.2 User Cost

The user cost is based primarily on the time delay experienced by travelers as a result of pavement construction. Its major components are related to the work zone speed limit—specifically, the time delay caused by the work zone speed limit and any related increased vehicle operation cost (VOC). The queue delay is related chiefly to traffic status, which is largely affected by hourly traffic distribution during the day (such as peak hour or non-peak hour).

The construction time for each test section was assumed to be the same, from 7 a.m. to 3 p.m. Likewise, the same work zone speed limit of 25 mph was applied to each section, based on the Illinois Vehicle Code (65 ILC S 5/11-604). The normal speed limit for the test sections was 35 mph; the 10 mph reduction in speed was necessitated by the pavement work. The user cost for a test section was computed using FHWA's RealCost LCCA software.

The traffic data for each section (shown previously in Table 1) were used in the analysis, and the hourly traffic distribution followed the national average provided in the software. The value of user time per vehicle class from 1996 (Walls and Smith 1998) was converted to reflect 2011 costs using the all-items consumer price index (CPI). The CPI was 152.4 in 1996 and 224.939 in 2011, according to the Bureau of Labor Statistics, as shown in Table 26. The escalation factor between 1996 and 2011 was 1.476 (calculated by dividing the 2011 CPI by the 1996 CPI). The value of user time in 2011 was then obtained using that escalation factor, as shown in Table 27. To minimize variations in traffic that might affect the cost analysis, the traffic data used in both the deterministic and probabilistic analyses were the average of traffic data in all the sections, as shown in Table 28.

Table 26. Consumer Price Index for 1996 and 2011

Consumer Price Index (CPI)	
All-Items Component, 2011	224.939
All-Items Component, 1996	152.4
Escalation Factor	**1.476**

Table 27. User Time Values for 2011

Value of User Time $/Hr	Year 2011		
Vehicle Class	**Minimum**	**Most Likely**	**Maximum**
Passenger Vehicles	14.76	17.09	19.19
Single-Unit Trucks	25.09	27.36	29.52
Combination-Unit Trucks	31.00	32.93	35.42

Table 28. Traffic Data for Deterministic and Probabilistic Analyses

Traffic Data	Deterministic	Probabilistic		
		Minimum	Most Likely	Maximum
Annual Average Daily Traffic (AADT)	26,114	22,900	26,114	31,000
Single-Unit Trucks as a Percentage of AADT (%)	1.7	1.7	1.7	1.3
Combination-Unit Trucks as a Percentage of AADT (%)	2.0	1.4	2.0	1.9

4.2.3 Deterministic Results

A deterministic cost analysis was performed for each mixture and thickness. Tables 29 (a) and (b) show the total cost, including agency cost and user cost. The analysis was performed using a fixed cost without allowing any change or variation of input parameters. The user cost for 2-in F-mix and 12.5-mm SMA sections was almost half that of other sections because the 2-in F-mix and 12.5-mm SMA sections were placed with a single lift, while the others had two lifts—one is the leveling binder, and the other is the wearing surface. Therefore, the sections with two lifts required traffic control twice, which almost doubled user cost.

Even after the user costs were applied, the control 12.5-mm SMA with a 2-in wearing surface was the most expensive section, at $101,210 per lane-mile of total cost, and the quartzite section with a 1-in wearing surface was the least expensive section, almost 35% less costly than the control 12.5-mm SMA. In general, the new mixtures were less expensive than the control mixes except for the 4.75-mm SMA sections with a 1-in- and a 1.25-in wearing surface. The relatively high total cost of the 4.75-mm SMA was caused primarily by additional screening of the typical stockpile aggregate to obtain proper gradation and its relatively high asphalt binder content. Although 84% of the aggregate by weight used in the control 12.5-mm SMA was steel slag, its highly modified asphalt binder contributed to its relatively high total cost.

Table 29 (a). Deterministic Total Cost

Section (WS/LB)*	Agency Cost, $1000	User Cost, $1000	Total Cost, $1000
Quartzite Mix (1/1)	58.03	7.25	65.28
Quartzite Mix (1.25/0.75)	58.10	7.25	65.35
Sprinkle Mix (1/1)**	59.94	7.25	67.19
Slag/Fiber Mix (1/1)	59.99	7.25	67.24
Sprinkle Mix (1.25/0.75)**	60.37	7.25	67.62
Slag/Fiber Mix (1.25/0.75)	60.55	7.25	67.80
F-Mix (2/0)	66.50	3.62	70.12
F-Mix (1.5/0.5)*	64.31	7.25	71.56
4.75-mm SMA (0.75/1.25)	64.51	7.25	71.76
4.75-mm SMA (1/1)	66.77	7.25	74.02
4.75 SMA (1.25/0.75)	69.03	7.25	76.28
12.5 SMA (2/0)	95.07	3.62	98.69

* Indicates wearing surface thickness/leveling binder thickness.
**Includes sprinkle chips at a cost of $4/ton of HMA.

Table 29 (b). Deterministic Total Cost (with MTV)

Section (WS/LB)*	Agency Cost, $1000	User Cost, $1000	Total Cost, $1000
Quartzite Mix (1/1)	59.07	7.25	66.32
Quartzite Mix (1.25/0.75)	59.41	7.25	66.66
Sprinkle Mix (1/1)**	60.30	7.25	67.55
Sprinkle Mix (1.25/0.75)**	60.81	7.25	68.06
Slag/Fiber Mix (1/1)	61.08	7.25	68.33
Slag/Fiber Mix (1.25/0.75)	61.91	7.25	69.16
F-Mix (2/0)	68.78	3.62	72.40
4.75-mm SMA (0.75/1.25)	65.29	7.25	72.54
F-Mix (1.5/0.5)	66.02	7.25	73.27
4.75-mm SMA (1/1)	67.80	7.25	75.05
4.75-mm SMA (1.25/0.75)	70.32	7.25	77.57
12.5-mm SMA (2/0)	97.59	3.62	101.21

* Indicates wearing surface thickness/leveling binder thickness.
**Includes sprinkle chips at a cost of $2/ton of HMA.

4.2.4 Probabilistic Results

Probabilistic cost analysis considers the risk and uncertainty of the input parameters such as traffic status change and material cost change. It helps decision makers minimize the risk of uncertainty of different variables. Tables 30 (a) and (b) present the probabilistic cost for each section with different mixture types and wearing surface thicknesses, calculated using RealCost software. The quartzite mix section had the lowest total cost among the sections evaluated. As expected, the user cost has more of an impact on uncertainty (with its higher standard deviation) than the agency cost. The minimum and maximum total costs represent the best- and worst-case scenarios that can occur for the tasks analyzed.

4.3 ENGINEERING BENEFIT ANALYSIS

The engineering cost analysis for an asphalt overlay is a performance-based cost analysis that considers both total cost (including agency and user costs) and overall performance score. It provides a key input for cost-effectiveness evaluation. The engineering cost per unit performance in this study was calculated by dividing total cost by the overall performance scores, as shown in Tables 31 (a) and (b).

Total cost per unit performance is the initial cost of providing unit overall performance for each mixture and section. The quartzite mix placed with a 1-in wearing surface and a 1-in leveling binder was the most cost-effective section. All of the sections with new mixtures had a lower cost per unit performance than the control mixtures, even though the control mixes contained significant amount of recycled materials. The control 12.5-mm SMA did not provide any significant benefits compared to its costs. No recycled materials were used in the new mixes for this project. However, if recycled materials are considered for use in the newly developed mixes, the total cost is expected to be reduced unless the addition of recycled materials results in a performance decrease. The thicker wearing surface did not improve performance significantly, and the thinner layer was more cost effective than the thicker wearing surface in terms of cost per overall unit performance.

If life cycle assessment (LCA) is applied where the impact of environment is considered, the sprinkle mix will show great sustainability benefits because of the reduced use of imported aggregates. This results in fewer emissions for aggregate transportation and production.

Table 30 (a). Probabilistic Total Cost

Section (WS/LB)*	Agency Cost, $1000		User Cost, $1000		Total Cost, $1000			
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Minimum	Maximum
Quartzite Mix (1.25/0.75)	59.53	2.19	7.24	0.32	66.77	2.51	59.68	74.68
Quartzite Mix (1/1)	59.68	2.30	7.24	0.32	66.92	2.62	59.41	74.20
Sprinkle Mix (1/1)**	61.49	2.17	7.24	0.32	68.73	2.49	61.62	75.63
Slag/Fiber Mix (1/1)	61.61	2.20	7.24	0.32	68.85	2.52	61.24	76.26
Sprinkle Mix (1.25/0.75)**	61.76	2.12	7.24	0.32	69.00	2.44	62.11	76.67
Slag/Fiber Mix (1.25/0.75)	61.95	2.19	7.24	0.32	69.19	2.51	62.46	77.10
F-Mix (1.5/0.5)	65.49	1.85	7.24	0.32	72.73	2.17	66.92	79.53
F-Mix (2/0)	69.13	3.57	3.62	0.16	72.75	3.73	61.31	83.92
4.75-mm SMA (0.75/1.25)	65.62	1.63	7.23	0.32	72.85	1.95	66.10	80.70
4.75-mm SMA (1/1)	67.84	1.39	7.23	0.32	75.07	1.71	69.92	79.84
4.75-mm SMA (1.25/0.75)	69.81	1.08	7.23	0.32	77.04	1.40	72.41	81.37
12.5-mm SMA (2/0)	97.76	3.77	3.62	0.16	101.38	3.93	89.68	114.73

* Indicates wearing surface thickness/leveling binder thickness.
**Includes sprinkle chips at a cost of $4/ton of HMA.

Table 30 (b). Probabilistic Total Cost (with MTV)

Section (WS/LB)*	Agency Cost, $1000		User Cost, $1000		Total Cost, $1000			
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Minimum	Maximum
Quartzite Mix (1/1)	60.73	2.30	7.24	0.32	67.97	2.62	60.46	75.25
Quartzite Mix (1.25/0.75)	60.83	2.19	7.24	0.32	68.07	2.51	60.98	75.98
Sprinkle Mix (1/1)**	62.12	2.54	7.24	0.32	69.36	2.86	61.14	77.32
Sprinkle Mix (1.25/0.75)**	62.43	2.49	7.24	0.32	69.67	2.81	61.72	78.55
Slag/Fiber Mix (1/1)	62.70	2.20	7.24	0.32	69.94	2.52	62.33	77.35
Slag/Fiber Mix (1.25/0.75)	63.31	2.19	7.24	0.32	70.55	2.51	63.82	78.46
4.75-mm SMA (0.75/1.25)	66.40	1.63	7.23	0.32	73.63	1.95	66.88	81.48
F-Mix (1.5/0.5)	66.42	0.61	7.24	0.32	73.66	0.93	71.21	76.41
F-Mix (2/0)	70.22	1.95	3.62	0.16	73.84	2.11	67.40	80.12
4.75-mm SMA (1/1)	68.87	1.39	7.23	0.32	76.10	1.71	70.95	80.87
4.75-mm SMA (1.25/0.75)	71.10	1.08	7.23	0.32	78.33	1.40	73.70	82.66
12.5-mm SMA (2/0)	99.00	1.97	3.62	0.16	102.62	2.13	96.32	109.77

* Indicates wearing surface thickness/leveling binder thickness.
**Includes sprinkle chips at a cost of $2/ton of HMA.

Table 31 (a). Cost Per Unit Performance

Section (WS/LB)*	Agency Cost, $/Lane-Mile	Overall Performance Scores	Cost Per Unit Performance, $/Lane-Mile/Performance
Quartzite Mix (1/1)	58,029	8.17	7,103
Quartzite Mix (1.25/0.75)	58,102	8.10	7,173
Sprinkle Mix (1/1)**	59,943	8.31	7,213
Slag/Fiber Mix (1/1)	59,989	8.31	7,219
4.75-mm SMA (0.75/1.25)	64,512	8.77	7,356
Sprinkle Mix (1.25/0.75)**	60,373	8.03	7,518
Slag/Fiber Mix (1.25/0.75)	60,551	8.01	7,559
4.75-mm SMA (1/1)	66,770	8.81	7,579
4.75-mm SMA (1.25/0.75)	69,027	8.43	8,188
F-Mix (1.5/0.5)*	64,313	7.76	8,288
F-Mix (2/0)	66,504	7.65	8,693
12.5-mm SMA (2/0)	95,068	7.81	12,173

* Indicates wearing surface thickness/leveling binder thickness.

**Includes sprinkle chips at a cost of $4/ton of HMA.

Table 31 (b). Cost Per Unit Performance (with MTV)

Section (WS/LB)*	Agency Cost, $/Lane-Mile	Overall Performance Scores	Cost Per Unit Performance, $/Lane-Mile/Performance
Quartzite Mix (1/1)	59,074	8.17	7,231
Sprinkle Mix (1/1)**	60,296	8.31	7,256
Quartzite Mix (1.25/0.75)	59,407	8.10	7,334
Slag/Fiber Mix (1/1)	61,076	8.31	7,350
4.75-mm SMA (0.75/1.25)	65,288	8.77	7,444
Sprinkle Mix (1.25/0.75)**	60,813	8.03	7,573
4.75-mm SMA (1/1)	67,804	8.81	7,696
Slag/Fiber Mix (1.25/0.75)	61,910	8.01	7,729
4.75-mm SMA (1.25/0.75)	70,321	8.43	8,342
F-Mix (1.5/0.5)	66,020	7.76	8,508
F-Mix (2/0)	68,781	7.65	8,991
12.5-mm SMA (2/0)	97,587	7.81	12,495

* Indicates wearing surface thickness/leveling binder thickness.

**Includes sprinkle chips at a cost of $2/ton of HMA.

CHAPTER 5 SUMMARY AND CONCLUSIONS

The field study evaluated pavement performances of newly developed mixes in terms of friction, noise, rutting, and ride quality and identified whether the new mixes offer improved pavement performance with lower costs. An engineering benefit analysis was performed to evaluate the cost effectiveness of new asphalt overlay applications at various thicknesses with different asphalt mixtures.

The results of the field performance tests showed that the new mixtures performed better and were more cost effective than the control mixes. The following points summarize the conclusions of this study.

- Newly developed mixes including fine dense-graded and 4.75-mm SMA were successfully placed and compacted at thinner layers, with thicknesses ranging from 0.75 in to 1.25 in. The Bailey method used for the mix design provided a proper aggregate structure for new mixtures to allow compactability in the field.
- The use of sprinkle mix is expected to increase when special spreading equipment for the precoated chips becomes available. The sprinkle chips, precoated with 0.75% of asphalt binder by weight, were embedded in the wearing surface by applying vibration during compaction. No significant pop-out of sprinkle chips was observed during the 2-year performance evaluation after construction. The initial surface friction of the sprinkle mix was excellent; however, friction significantly decreased over time and became similar to that of other fine dense-graded mixtures. Rough aggregate chips would improve the friction and possibly the adhesion to asphalt binder. This should be considered in future experimental work.
- Although the cost of adding sprinkle chips was approximately $4 per ton of HMA (expected to be $2 if commonly used), the use of a less expensive aggregate for the wearing surface mixture reduced the total mixture cost.
- Special care should be taken when fibers are added. The plastic vinyl bags, containing fibers, created fiber lumps in the asphalt mixtures that stuck in the augers, resulting in an uneven pavement surface. If fibers become used more routinely, this problem could be appropriately addressed.
- The noise level for each mixture was influenced primarily by the NMAS of the asphalt mixture. The larger nominal maximum aggregate size (NMAS) produced relatively higher noise levels between the tire and the pavement surface. The 4.75-mm SMA was the quietest mixture, and the control SMA with 12.5-mm NMAS produced the highest noise levels. The fine dense-graded mixtures showed more noise reduction after 4 months of construction than the SMA and coarse dense-graded mixtures.
- The estimated mean texture depth (EMTD) of fine dense-graded mixtures was less than that of other mixtures. The control SMA with 12.5-mm NMAS was observed to have higher EMTD values due to the rough surface texture. The ride quality for each section, which can be evaluated by the mean roughness index (MRI), was the highest (best) for the quartzite section and the lowest (worst) for the control SMA. The fine dense-graded mixtures, which were newly developed, provided better ride quality than the SMAs did; however, the ride quality of the SMAs improved over time. It is noteworthy that the 4.75-mm SMA provided better ride quality than the 12.5-mm SMA.
- The measured friction of HMA is affected by asphalt content, aggregate gradation, NMAS, and aggregate type. SMA friction increased over time as the asphalt film became worn off under traffic. The use of steel slag increased surface friction.

- No significant rut depth was measured in the field after 2 years but long-term monitoring, over the next 10 years, is suggested to track any significant rutting development.
- The overall performance ratings showed that the newly developed mixes provided significantly better overall performance than the control mixtures, especially for noise level and indirect tensile strength. Although the control mixtures contained significant amounts of recycled materials, total costs of the new mixes were less than the control mixes except for the sections of the 4.75-mm SMA with a 1-in and a 1.25-in wearing surface, due to the additional cost for scalping the aggregates on a 4.75-mm (No. 4) sieve, which may be eliminated if use of this mix becomes common.
- The cost per unit performance of the quartzite mix with a 1-in-thick wearing surface was the lowest, while the control 12.5-mm SMA had the highest cost per unit performance. All of the newly developed mixes are more cost effective than the control mixes. The sprinkle treatment, however, is expected to have more sustainable impact because most aggregates used are local.
- The use of recycled materials such as RAS and RAP in the newly developed mixes is expected to reduce the total cost while maintaining the overall performance.

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APPENDIX A: DENSITY OF LEVELING BINDER

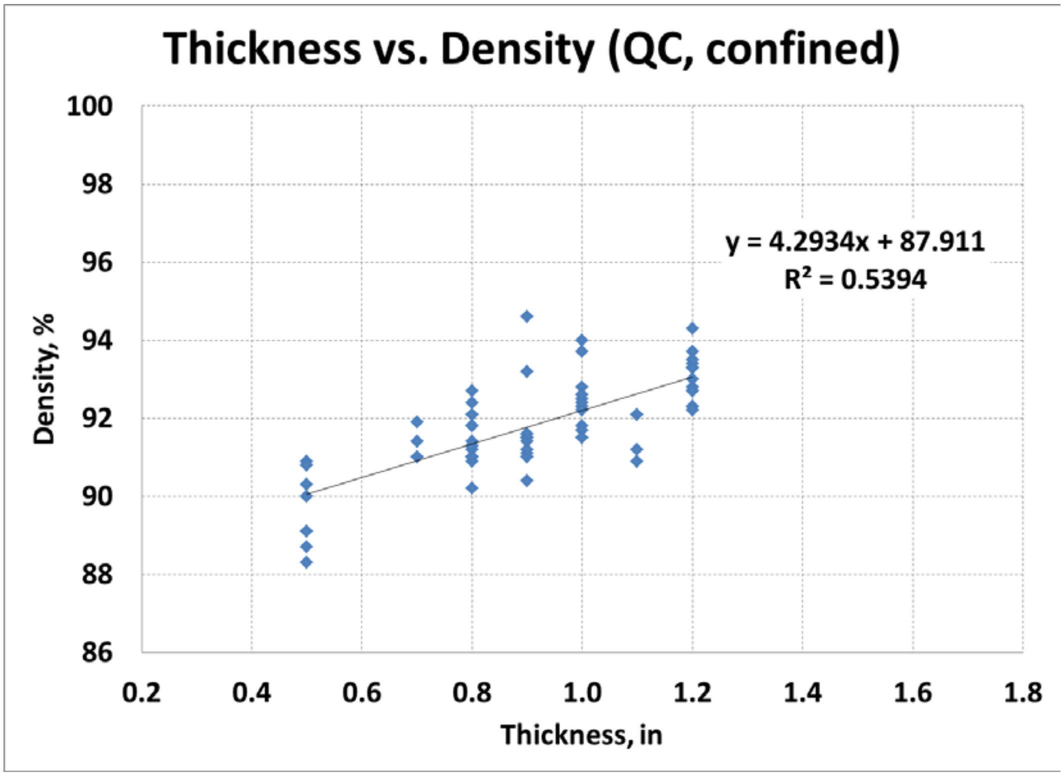
The application of fine dense-graded mix as a leveling binder is appropriate if target density and layer thickness are achieved. The quality control (QC) data from the contractor and quality assurance (QA) data from IDOT, which were obtained from field cores, are summarized in this appendix.

Table A.1. Density and Thickness from Cores (QC)

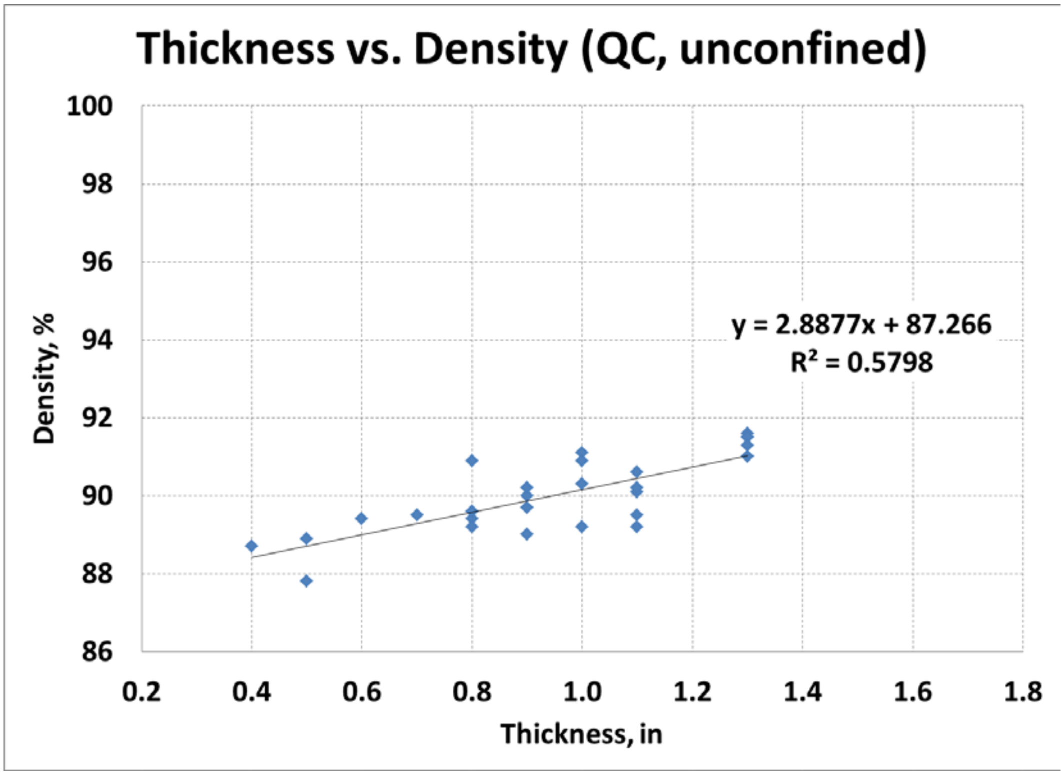
Quality Control Data (Contractor)		**Design Leveling Binder Thickness, in**			
		0.50	**0.75**	**1.00**	**1.25**
Average Density, % (std)	Confined	**89.73** (1.03)	**91.39** (0.56)	**92.47** (1.01)	**93.07** (0.51)
	Unconfined	**88.47** (0.59)	**89.69** (0.55)	**90.11** (0.75)	**91.12** (0.56)
Average Thickness, in (std)	Confined	**0.50** (0.00)	**0.81** (0.07)	**1.03** (0.10)	**1.20** (0.00)
	Unconfined	**0.47** (0.06)	**0.81** (0.10)	**1.05** (0.05)	**1.26** (0.09)
Number of Roller Passes		**N/A**	**9**	**11**	**13**

Table A.2. Density and Thickness from Cores (QA)

Quality Assurance Data (IDOT)		**Design Leveling Binder Thickness, in**	
		1.00	**1.25**
Average Density, % (std)	Confined	**92.06** (1.92)	**92.62** (1.28)
	Unconfined	**90.47** (1.50)	**91.13** (0.64)
Average Thickness, in (std)	Confined	**1.20** (0.14)	**1.35** (0.07)
	Unconfined	**1.23** (0.06)	**1.38** (0.15)
Number of Roller Passes		**11**	**13**

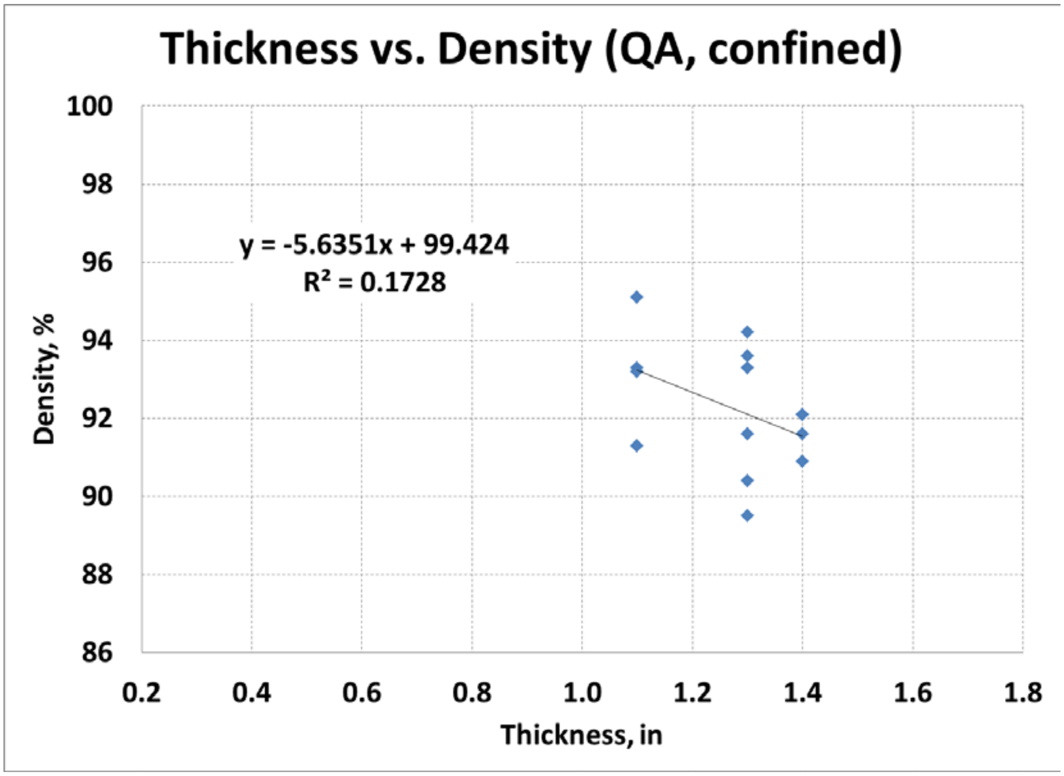


(a)

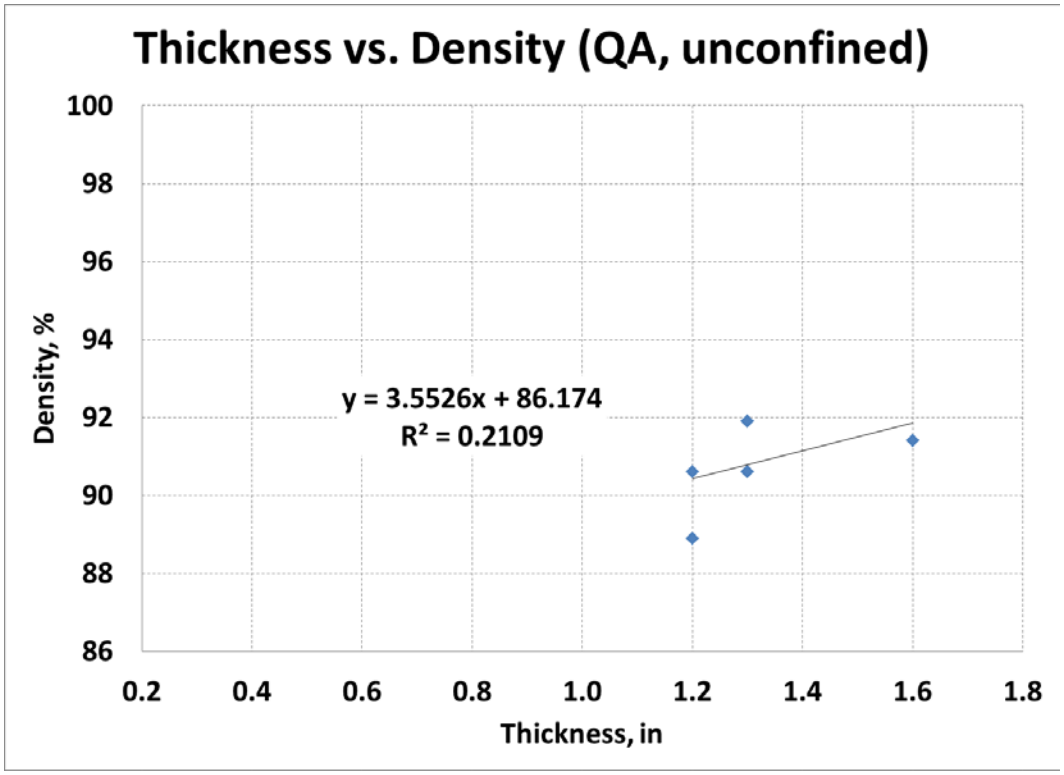


(b)

Figure A.1. Thickness and density from QC (a) confined, and (b) unconfined.



(a)



(b)

Figure A.2. Thickness and density from QA (a) confined, and (b) unconfined.

Although the data show positive trend between HMA layer thickness and its density, the correlation is statistically insignificant. This could be well explained because of the thin overlay construction used in this study.

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