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Develop Surface Aggregate Classification of Reclaimed Asphalt Pavement: Technical Report

Technical Report 0-7025-R1

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

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Pavement skid resistance is critical for public safety in wet-weather conditions. To improve pavement skid resistance, the use of Surface Aggregate Classification A (SAC-A) aggregate has increased significantly each year to meet the friction demand of pavements. Texas Department of Transportation specifications allow for the use of reclaimed asphalt pavement (RAP) to conserve natural resources and save costs. The unknown is the contribution of RAP to skid resistance and friction of the pavement surface, especially when pavements constructed with SAC-A are reclaimed and used for production. Intuitively, the RAP must have some contribution to friction, but this contribution has not been evaluated and quantified.

The researchers conducted field evaluations, RAP and raw aggregate characterization, RAP mixture design, and RAP mixture slab testing. These investigations focused on the skid resistance and texture of aggregates, mixtures, and pavement surfaces. Based on the research results and findings, the researchers determined the potential of using RAP to conserve SAC-A resources and evaluated the impact of RAP on mixtures' skid resistance. The preliminary criteria and guidelines were developed for using RAP in surface mixes to meet skid requirements. The rationale, description, and application of the criteria and guidelines are presented in this document. Further investigation is needed to refine the criteria and guidelines when more material (aggregate, RAP, and mixture) types are available.</td></tr>
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The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear here solely because they are considered essential to the object of this report.

The researcher in charge was Dr. Sheng Hu, P.E. (Texas, #103577).

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LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
AIMS	Aggregate Imaging System
AIR	Acid-Insoluble Residue
AMD	After Micro-Deval
ARTS	Aggregate Ring Texturing System
ASTM	American Society for Testing and Materials
BMD	Before Micro-Deval
BRSQC	Bituminous Rated Source Quality Catalog
CTM	Circular Track Meter
DFT	Dynamic Friction Tester
DGA	Dense-Graded Asphalt
FHWA	Federal Highway Administration
HDPE	High-Density Polyethylene
HMA	Hot-Mix Asphalt
IFI	International Friction Index
JTRP	Joint Transportation Research Program
LA	Los Angeles
LAPS	Laser Analyzer for Pavement Surface
MDOT	Maryland Department of Transportation
MPD	Mean Profile Depth
MTD	Mean Texture Depth
MTD/SA	Materials and Tests Division and Soils and Aggregates Section
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
PFC	Porous Friction Course
PIARC	Permanent International Association of Road Congress
PSV	Polished Stone Value
RAP	Reclaimed Asphalt Pavement
SAC	Surface Aggregate Classification
SMA	Stone-Matrix Asphalt

SP D	Superpave D
TxDOT	Texas Department of Transportation
TTI	Texas A&M Transportation Institute
WMA	Warm-Mix Asphalt

CHAPTER 1 INTRODUCTION

BACKGROUND AND OBJECTIVES

Pavement skid resistance is critical for public safety in wet-weather conditions. Crashes on wet pavements are related to inadequate pavement skid resistance. To improve pavement skid resistance, the use of Surface Aggregate Classification A (SAC-A) aggregate has increased significantly each year to meet the friction demand of pavements. This demand will be even greater as the population of Texas grows and the likelihood of wet-surface crashes and fatalities increases. It is important for the Texas Department of Transportation (TxDOT) to develop specifications, methods, and means to conserve the existing SAC-A resources. TxDOT specifications allow for the use of reclaimed asphalt pavement (RAP) to conserve natural resources and save costs. The use of RAP will only increase since both TxDOT and the industry are proponents of using recycled materials. The unknown is the contribution of RAP to the skid resistance and friction of the pavement surface, especially when pavements constructed with SAC-A are reclaimed and used for production. These RAP materials may potentially help reduce the need for SAC-A aggregates. Intuitively, RAP must have some contribution to friction, but this contribution has not been evaluated and quantified.

The main objectives of this project were to:

- Determine the potential of conserving SAC-A resources by using RAP.
- Develop the Surface Aggregate Classification (SAC) rating for RAP.
- Develop guidelines for using RAP in surface mixes to enhance skid resistance.

During this project, the researchers conducted field evaluations, RAP and raw aggregate characterization, RAP mixture design, and RAP mixture slab testing. These investigations focused on the skid resistance and texture of aggregates, mixtures, and pavement surfaces. Based on the research results and findings, the researchers determined the potential of using RAP to conserve SAC-A resources and evaluated the impact of RAP on mixtures' skid resistance. Preliminary criteria and guidelines were developed for using RAP in surface mixes to meet skid requirements. The rationale, description, and application of the criteria and guidelines are presented in this document.

REPORT ORGANIZATION

This report is organized into the following seven chapters:

- Chapter 1: Introduction, with a brief description of the project background, objectives, and report organization.
- Chapter 2: Review of the current state of the knowledge and practice of using RAP in surface mixes.
- Chapter 3: Field evaluation of skid problems reported by districts to evaluate the pavement field surface friction numbers and textures, find the relationship among these surface characteristics, and identify the potential cause of the low skid numbers.

- Chapter 4: Assembly and characterization of RAP materials to identify the cause of the low skid numbers when good quality materials were used and determine if RAP was a contributing factor.
- Chapter 5: Laboratory evaluation of the impact of RAP on the skid resistance of asphalt mixtures. The overall purpose was to study the impact of RAP on the skid resistance of asphalt mixes and to use this information to develop the SAC rating for RAP materials.
- Chapter 6: Preliminary criteria and guidelines for using RAP in surface mixes to enhance skid resistance.
- Chapter 7: Conclusions and recommendations.

CHAPTER 2 REVIEW OF CURRENT STATE OF THE KNOWLEDGE AND PRACTICE

Traffic-related accidents are detrimental to the U.S. economy. The National Highway Traffic Safety Administration (NHTSA) indicated that the total cost due to traffic crashes in 2014 was estimated at $242 billion (NHTSA 2014). In 2015, the estimated number of traffic fatalities increased to 35,200, about 7.7 percent higher than the fatalities reported in 2014 (NHTSA 2016). Research has shown that 15 to 18 percent of total crashes occur on wet pavements (Smith 1977; Federal Highway Administration [FHWA] 1990). Crashes on wet pavements are related to inadequate pavement skid resistance during braking and maneuvering when frictional demand exceeds the friction force developed at the tire-road interface. To improve pavement skid resistance, the use of SAC-A aggregate has significantly increased each year to meet the friction demand of pavements. The 2019 forecast for the demand of SAC-A aggregates will be over 1.9 million tons and will more than likely increase in the upcoming years. This demand will be even greater as the population of Texas grows and the likelihood of wet-surface crashes and fatalities increases.

TxDOT specifications allow for the use of RAP. The use of RAP in pavements is desirable since it offers both economic and environmental benefits. When properly designed and constructed, pavements including RAP can perform as well as or better than pavements constructed from virgin materials. However, there are two concerns when using RAP in pavement surface courses. One is friction resistance, which is the primary concern in many states. The other concern is the possibility that using too much RAP (or the RAP being too stiff) could over-stiffen the surface course, making it more susceptible to cracking or raveling. Both concerns are highly related because RAP is typically removed from old roadways and may contain different types of aggregates, binders, patches, chip seals, etc., all intermingled in one stockpile. When properly processed and stored, however, the variability of RAP can be controlled and may not be as high as perceived. Especially when pavements constructed with SAC-A are reclaimed and used for production, intuitively there must be some contribution to friction, but this contribution has not been evaluated and quantified. Suppose this effect or contribution to pavement friction can be evaluated and quantified. In that case, the use of fractionated RAP will help reduce the risk of negative effects on pavement friction and help reduce the need for new SAC-A aggregates.

This chapter reviews the current state of the knowledge and practice of surface aggregate selection, friction/skid resistance measurements, the use of RAP in surface mixtures, and the impact of RAP on skid resistance.

TEXAS SURFACE AGGREGATE SOURCES AND SPECIFICATIONS

Texas Aggregate Source

As seen in Figure 2-1, there are relatively few sources of SAC-A aggregates inside Texas. TxDOT needs to develop specifications, methods, and means to conserve the existing SAC-A resources.

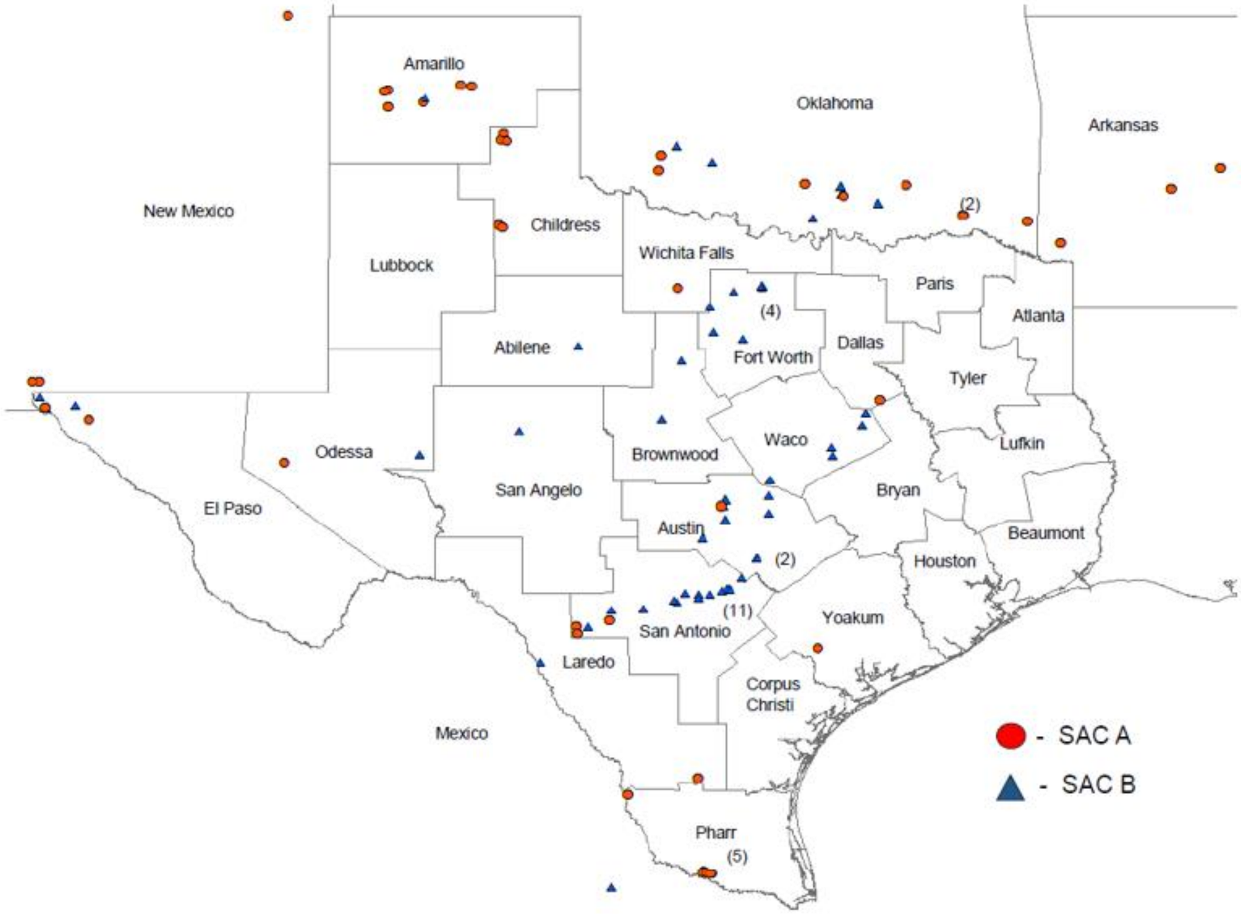


Figure 2-1. SAC-A Source Distribution.

TxDOT Surface Aggregate Selection

TxDOT maintains a program during surface aggregate selection to ensure that pavements with good skid-resistant characteristics are used. This program is referred to as the Wet Surface Crash Reduction Program. It consists of three separate phases, Phase I: Wet Surface Crash Data Analysis, Phase II: Aggregate Selection, and Phase III: Skid Testing. As a first step in the aggregate selection, the pavement engineer must determine the overall friction demand (low, moderate, or high) on the roadway surface according to the annual crash reports published by the Traffic Operations Division. The next step in the aggregate selection process involves matching the overall frictional demand with an appropriate surface aggregate classification. Frictional and durability indicator tests (such as polish value, soundness, acid insolubility, and Micro-Deval) are used to classify the aggregates. For example, Table 2-1 lists the SAC classification criteria. The Soils and Aggregates Section of the Construction Division is responsible for using the aggregate classification criteria and listing the results in the Bituminous Rated Source Quality Catalog (BRSQC) every six months. The third step consists of skid analysis and will include a mandatory collection of skid data that will become part of the new Pavement Management Information System.

Table 2-1. SAC Classification Criteria.

Property	Test Method	SAC-A	SAC-B	SAC-C
Acid-insoluble residue, % min	Tex-612-J	55	—	—
5-cycle Mg, % max	Tex-411-A	25	30	35
Crushed faces, 2 or more, % min	Tex-460-A	85	85	85

Note: — means not applicable.

Figure 2-2 shows the TxDOT surface aggregate selection guidelines in TxDOT Form 2088, including the factors and criteria used to determine total frictional demand and total friction available. To meet the requirement, the total friction available should always exceed the total friction demand.

Selection Guidelines for Bituminous Surface Aggregate Classification (SAC) — **DESIGNER'S RATING**

Demand for Friction	Low (1)	Moderate (2)	High (3)	1	2	3
Rain Fall (inches/year)	≤20	>20 ≤40	>40			
Traffic (ADT)	≤5000	>5000 ≤15,000	>15,000			
Speed (mph)	≤35	>35 ≤60	>60			
Trucks (%)	≤8	>8 ≤15	>15			
Vertical Grade (%)	≤2	>2 ≤5	>5			
Horizontal Curve (º)	≤3	>3 ≤7	>7			
Driveways (per mile)	≤5	>5 ≤10	>10			
Intersecting Roadways (ADT)	≤500	>500 ≤750	>750			
Wet Surface Crashes (%)	≤5	>5 <15	≥15			
Summary of Total Frictional Demand				0		
***Available Friction**	**Low (2)**	**Moderate (5)**	**High (8)**	**2**	**5**	**8**
Cross Slope (%)	<2	2 - 3	3 - 4			
Surface Design Life (years)	>10	>5 ≤10	≤5			
Macro Texture of proposed surface	Fine (Such as: HMAC Type 'D' and 'F')	Medium (Such as: HMAC Type 'C', CMHB, SuperPave, Microsurface)	Coarse (Such as: PFC, SMA, Seal Coat, NovaChip)			
Aggregate MicroTexture	SAC C	SAC B	SAC A			
Summary of Total Friction Available				0		
Does total available friction equal or exceed total frictional demand?				Yes	No	

Figure 2-2. TxDOT Surface Aggregate Selection Guidelines.

RAP CHARACTERISTICS AND IMPACT ON SURFACE MIXTURES

Raw RAP is typically generated by two methods, milling from surface layers or removing from full-depth hot-mix asphalt (HMA) layers. These materials are processed by crushing, sieving, and stockpiling. By crushing or screening the raw RAP, the material is mixed and oversized materials are removed. Storing processed RAP under a covered roof is recommended to avoid excessive moisture and reduce fuel consumption. Many investigations (Solaimanian and Kennedy 1996, Stroup-Gardiner and Wagner 1999) have shown that high variability in RAP material greatly affects the variability of the asphalt content, the gradation of the product mixture, and the percentages of dust. The screening processes can reduce the amount of aged binder on the fine aggregate or dust (Mayes et al. 1998). Therefore, the processed RAP can be a consistent product (Nady 1997).

Figure 2-3 shows the average percentage of RAP used in HMA/warm-mix asphalt (WMA) mixtures in each state by construction season according to the National Asphalt Pavement Association survey (Williams et al. 2019).

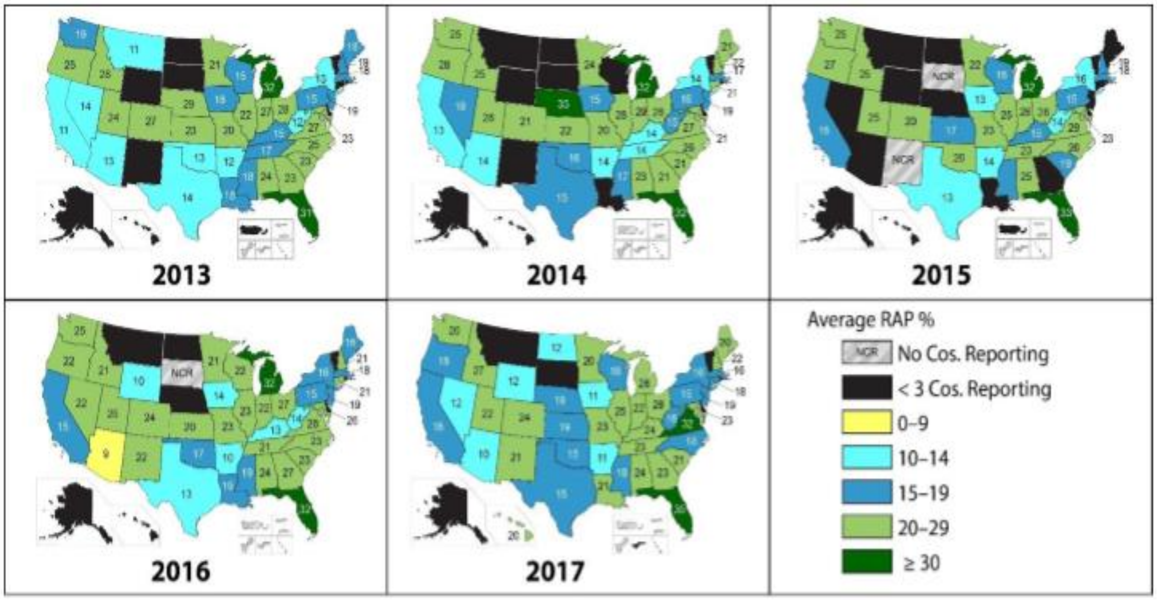


Figure 2-3. Average Percentage of RAP Used in HMA/WMA Mixtures in Each State (Williams et al. 2019).

The Mississippi Department of Transportation funded the laboratory investigation of high RAP content pavement surface layers carried out by Jesse D. Doyle and Isaac L. Howard in 2010. This research aimed to examine the possibility of decently high (≈ 25 to 50 percent) RAP content WMA as surface blends and overlays. One of the tasks performed was to test frictional resistance and surface texture of mixtures with varying RAP content fabricated with the linear asphalt compactor. To assess the potential impacts on skid resistance by incorporating high quantities of RAP in surface blends, three blends were tried that included 0, 50, and 100 percent RAP. One factor analysis of variance tests were performed to assess the importance of RAP levels to estimate pavement friction. RAP was not found to have a statistically significant effect on pavement friction parameters at a 95 percent confidence level for both response variables (Doyle and Howard 2010).

In 2012, the Joint Transportation Research Program (JTRP) project supported by Indiana DOT and Purdue University evaluated the impact of RAP on pavement surface frictional properties (McDaniel et al. 2012). In this study, the laboratory-fabricated RAP and the field-sampled RAP were mixed with surface mixtures at different RAP percentage levels. The laboratory testing showed that the addition of poor-quality RAP materials did impact the friction properties and cracking resistance of the mixtures, but that lower amounts of RAP had little effect. The frictional performance of the laboratory-fabricated and field-sampled RAP materials were acceptable at a content of 25 percent but were questionable at 40 percent.

One research study was carried out by Greg White (2019) to quantify the impact of RAP on airport asphalt surfaces in Australia. This research created two diverse asphalt blends with and without RAP. All asphalt blends were intended to be thick reviewed and Marshall-planned 14 mm ostensible nominal maximum aggregate sized. The RAP of the first mixture was recovered from texturing of the underlying layer and removal of temporary ramps and was used to surface a runway catering up to the B737-800-sized aircraft. The RAP of the second mixture was recovered from the removal of temporary ramps and was used to surface a runway accommodating turboprop and regional jet aircraft. Friction testing was performed along the full length of the runway surface developed with the first mixture at two speeds: 65 km/hr and 95 km/hr. The friction testing results indicated that the addition of RAP was associated with a significant reduction in the measured surface friction at both 65 km/hr and 95 km/hr test speeds. For example, the 95 km/hr average friction result decreased from 0.55 to 0.47 where RAP was included. The reduction in friction was observed despite the measured surface texture being unaffected.

In Spain, another research study was conducted by José Manuel Lizárraga et al. (2018) to evaluate the mechanical performance, in laboratory and in-situ, of two mixtures containing high RAP contents (70 percent and 100 percent). Both mixtures presented similar skid resistance values to those obtained in the conventional HMA mixture. In general, the 70 percent RAP mixture exhibited the highest percentage of skid resistance (64 percent) four months after compaction of the mixtures. This result can be attributed to the mixture produced with the coarse RAP fraction obtained from the in-service road pavement sections. The polished stone values could have been higher than those exhibited by the RAP obtained from the urban test section.

AGGREGATE PROPERTIES AFFECTING PAVEMENT SKID RESISTANCE AND CORRESPONDING LAB TESTS

The following describes the aggregate (raw aggregate or RAP aggregate) properties that affect pavement skid resistance.

Polish Resistance

Polish resistance refers to the ability of the aggregate to maintain its microtexture after it is subjected to repeated traffic loadings. The most common methods used to evaluate the polish resistance include the polished stone value (PSV) test and the acid-insoluble residue (AIR) test. In the PSV test, the aggregate is polished by an accelerated polishing machine, and then the aggregate surface friction is measured using a British pendulum. The AIR test is performed to measure the noncarbonate ingredients of the aggregates, which contribute to aggregate resistance. The procedures to determine the polishing procedures are stipulated in the American Society for Testing and Materials (ASTM) E303-93 (ASTM 2018) and Tex-438-A (TxDOT 1999a). The protocols, ASTM standard D3042-17 (ASTM 2017a) and Tex-612-J (TxDOT 2000), provide the guidelines for determining the AIR of a given aggregate sample. Values of 30 to 35 for the PSV test and 50 to 70 percent for the AIR test are recommended to ensure sufficient frictional resistance.

Abrasion Resistance

Abrasion resistance refers to the ability of aggregates to resist mechanical degradation. The Micro-Deval and Los Angeles (LA) abrasion tests are used to evaluate the abrasion resistance of the aggregates. The Micro-Deval test consists of a container with small steel balls, and the aggregate, with the presence of water, is polished in the rotating container. Also, the LA abrasion test is used to measure the coarse aggregate resistance to degradation by inserting the aggregate and large steel balls into a rotating drum (American Association of State Highway and Transportation Officials [AASHTO] T96 [AASHTO 2019], ASTM C131 [ASTM 2017b] or Tex-410-A [TxDOT 1999b]). Values of losses less than 17 to 20 percent for the Micro-Deval test and 35 to 45 percent for the LA abrasion test are recommended to provide sufficient frictional resistance.

Soundness

The soundness of aggregates can be defined as the ability to resist degradation due to climatic and environmental factors such as thawing, freezing, wetting, and drying. Test guidelines are stipulated in AASHTO T104 (AASHTO 2020a), ASTM C88 (ASTM 2017c), or Tex-411-A (TxDOT 1999c). The soundness is quantified using the magnesium sulfate soundness test by quantifying the loss percentage of aggregates after cycles of hydration-dehydration. Loss percentages ranging from 10 to 20 percent are typical and provide adequate frictional performance.

Angularity, Texture, and Form

Aggregate shape characteristics, including angularity, texture, and form, are essential parameters in pavement skid resistance. The coarse and angular aggregates provide higher pavement friction than flat and elongated aggregates. Also, an aggregate with a rough surface provides higher friction than an aggregate with a smooth surface. The Aggregate Imaging System (AIMS) is used to quantify aggregate shape characteristics (Masad et al. 2010). Also, other methods, including laser-based aggregate analysis systems, are used to perform the same function. For example, the recently developed Aggregate Ring Texturing System (ARTS) uses the line laser to measure both the microtexture of the same ring-shaped specimens prepared for Dynamic Friction Tester (DFT) evaluation (Arámbula et al. 2018).

EFFECTS OF PAVEMENT SURFACE TEXTURE ON SKID RESISTANCE

Today, it is generally agreed that the pavement friction property depends on both macro- and microtexture. An international standard for road surface texture terminology has been established by the Technical Committee on Surface Characteristics of the World Road Association's Permanent International Association of Road Congress (PIARC), as follows:

- Megatexture: Wavelength 50 mm to 500 mm (2 to 20 inches).
- Macrotexture: Wavelength 0.5 mm to 50 mm (0.02 to 2 inches).
- Microtexture: Wavelength 0.1 mm to 0.5 mm (0.0004 to 0.02 inches).

If both macro- and microtexture are maintained at high levels, they can provide enough resistance to prevent wet accidents. In wet conditions, water acts as a lubricant between the tires and pavement surface, leading to reduced friction (Dahir 1978). The macrotexture of pavement is dependent on aggregate gradation, compaction level, and mixture design, while the microtexture is dependent on aggregate shape characteristics (Crouch et al. 1995).

Skid resistance has two mechanisms—adhesion and hysteresis—as shown in Figure 2-4. These two mechanisms are highly affected by pavement macrotexture and microtexture. Adhesion develops due to the direct contact between the tires and pavement surface, especially in areas with high local pressure (Cairney 1997). Pavement microtexture is significant to the adhesion component that originates from molecular bonds between stone and rubber. In addition, pavement macrotexture contributes to the hysteresis component of friction (Ivey et al. 1992). Hysteresis develops due to energy dissipation caused by the deformation of the tire's rubber around bulges and depressions in the pavement surface (Cairney 1997).

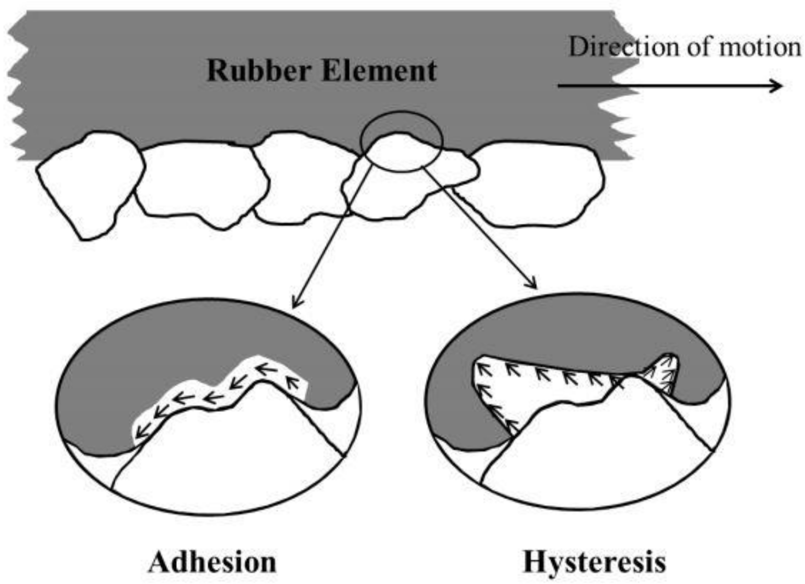


Figure 2-4. Key Mechanisms of Tire-Pavement Friction (Hall et al. 2009).

Adhesion and microtexture affect skid resistance at all speeds, and they have a prevalent influence at speeds below 30 mph. Hysteresis and macrotexture have little significance at low speeds; however, macrotexture is an essential factor for safety in wet conditions as speed increases (Galambos et al. 1997).

Hogervorst (1974) showed that the reduction in skid resistance is associated with vehicle speed and depends on pavement microtexture and macrotexture (Figure 2-5). The study results showed that skid resistance decreased with increased vehicle speed, and pavements with coarse and rough surfaces provide better skid resistance than fine and polished surfaces.

Road Surface		Surface Texture	
		macro	micro
A		coarse	rough
B		coarse	polished
C		fine	rough
D		fine	polished

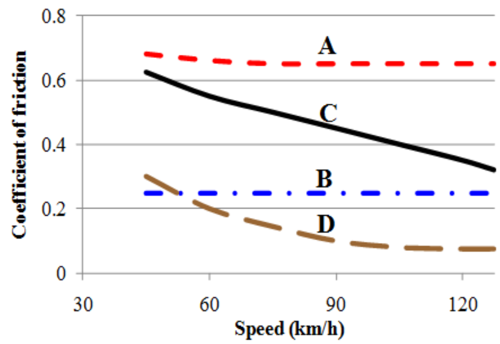


Figure 2-5. Change in Pavement Friction with Speed (Hogervorst 1974).

PAVEMENT TEXTURE MEASUREMENTS

There are several methods used for quantifying the macrotexture of asphalt pavements. These methods include the circular track meter (CTM), sand patch, stereophotogrammetric, and laser-based (or electro-optic) techniques.

CTM Device

The CTM device is used to measure the mean profile depth (MPD) in the field and laboratory (Figure 2-6). The device has a charge-coupled laser displacement sensor attached to an arm. The arm rotates in a circle with a diameter of 28.4 cm. The laser sensor can collect 1,024 data points per round. The average MPD is calculated and reported according to the ASTM E2157 (ASTM 2015a).

Figure 2-6. CTM Device.

Sand Patch Method

The sand patch method is used to quantify the macrotexture of the pavement surface by measuring the mean texture depth (MTD) following ASTM E1845 (ASTM 2016). The sand patch method includes a brush for cleaning the surface, a cup and spreading tool to distribute the sand, and a scale tape (Figure 2-7). An amount of 100 g of sand is used in each test. The sand sample should pass through a No. 30 sieve and be retained in a No. 50 sieve. The sand is spread in a circle on the pavement surface, and the circle's diameter is measured. The MTD is determined using Equation 2-1 as a function of sand volume and the diameter of the sand patch.

$$MTD = \frac{4V}{3.14\,D^2} \tag{2-1}$$

where
MTD = mean texture depth (mm).
D = average diameter of sand patch circle (cm).
V = sand volume (cm^3; weight of sand/density of sand).

Figure 2-7. Sand Patch Method (Sarsam et al. 2015).

Stereophotogrammetric Technique

This technique is based on a three-dimensional (3D) measurement of pavement surface texture. The 3D images indicate physical changes to the pavement surface that cannot be accurately quantified using two-dimensional (2D) profiles. The changes in the aggregate surface due to the polishing process can be observed and quantified using 3D measurements (Dunford 2013). Stereophotogrammetry relies on taking various images from different angles to estimate the 3D coordinates of a point. Close-range photogrammetry is a version of stereophotogrammetry that uses an ordinary camera to take various images from different angles to construct the 3D profile. Previous research demonstrated that this technique could be used to quantify the macrotexture, microtexture, and megatexture (McQuaid et al. 2014). Figure 2-8 shows the pavement 3D image obtained from stereophotogrammetric techniques.

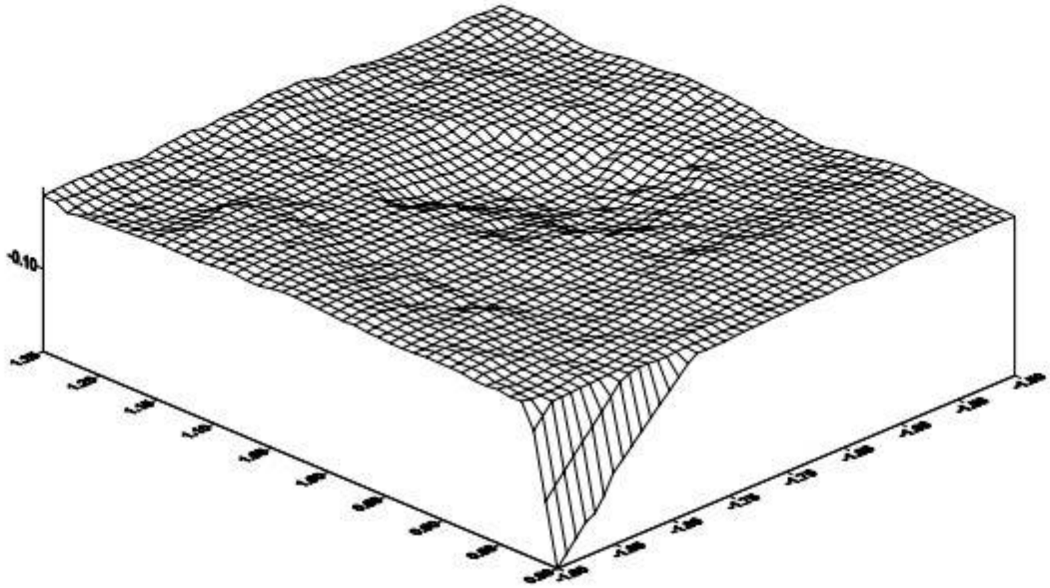
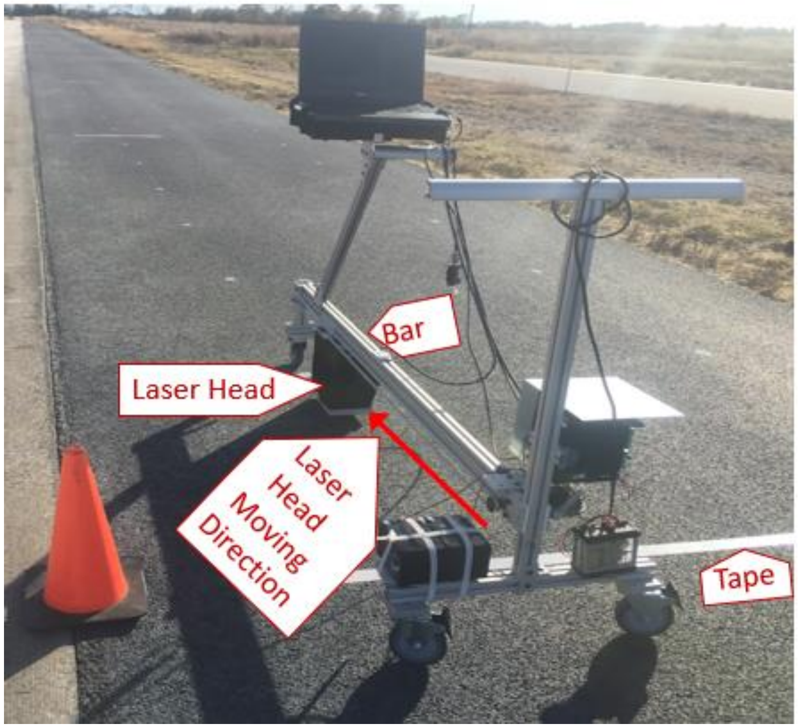


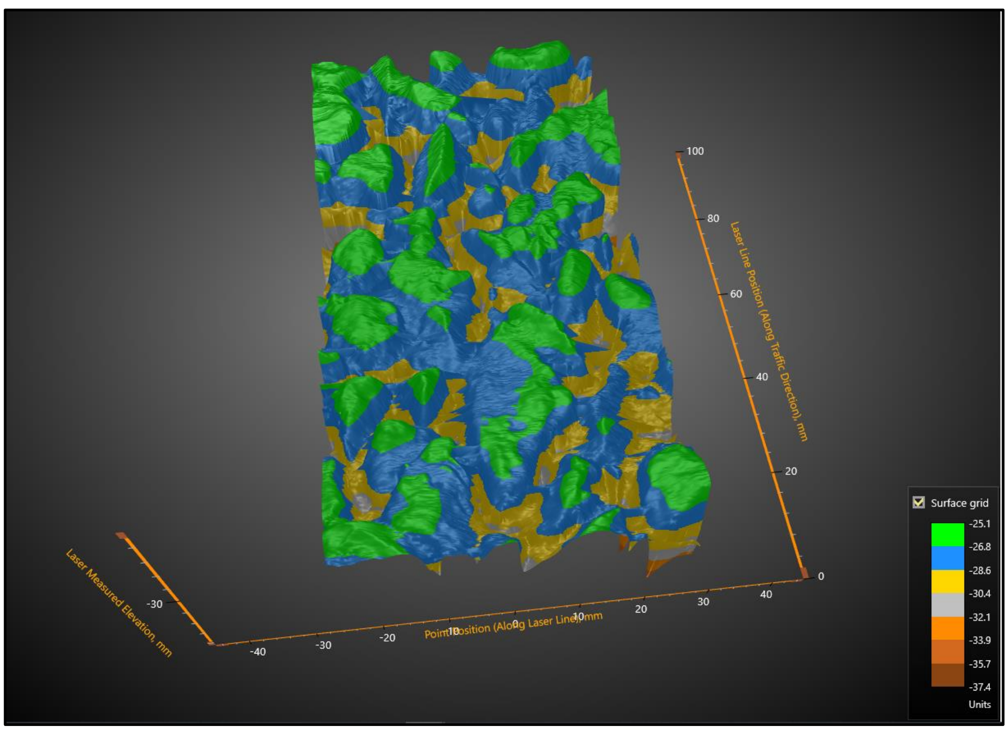
Figure 2-8. 3D Pavement Surface from Stereophotogrammetric Technique (Mustaffar et al. 2004).

TTI Laser Analyzer for Pavement Surface Device

Most recently, the Texas A&M Transportation Institute (TTI) developed a device called the Laser Analyzer for Pavement Surface (LAPS) during National Cooperative Highway Research Program (NCHRP) Project 10-98 to measure both the macrotexture and microtexture of the surface. Figure 2-9a shows the device on an open-graded friction course pavement surface in front of a marking tape on the ground. The bar length is around 1500 mm, and the effective width of the laser line is around 50 mm. The laser head travels along the bar, thus by one pass of the laser head, the laser-measured area is 1500 mm × 50 mm. Figure 2-9b shows the corresponding measured profile in 3D plots. In NCHRP Project 10-98, the LAPS-measured data were used as a reference to validate the other high-speed laser measurements. The LAPS can determine both macro-MPD and micro-MPD values.



(a)



(b)

Figure 2-9. LAPS Test (a) Equipment (b) 3D Profiles.

PAVEMENT FRICTION/SKID RESISTANCE MEASUREMENTS

Several devices are used to measure skid resistance in the field, and some of them can be used in both the field and laboratory.

Locked-Wheel Skid Trailer

Wet pavement friction measurements can be obtained by using the towed friction trailer according to ASTM E274 (ASTM 2020a). The ASTM towed friction trailer allows two types of tires for friction evaluations, including the Standard Rib Tire for Pavement Skid-Resistance Test ASTM E501 (ASTM 2020b) and Standard Smooth Tire for Pavement Skid-Resistance ASTM E524 (ASTM 2020c).

The skid number (SN) is calculated using the following equation:

$$SN = \left(\frac{F}{N}\right) * 100 \tag{2-2}$$

where
SN = skid number.
F = friction force.
N = normal (vertical) load on the test tire.

The skid trailer (Figure 2-10) is an appropriate method in terms of accuracy and safety. However, the data cannot be collected continuously, and the skid trailer cannot measure the low friction accurately. When using the skid trailer, water is sprayed in front of the left wheel, and the left wheel is locked while the truck is traveling at a certain speed (e.g., 50 mph for Texas). The friction force that resists the tire's rotation is measured (Masad et al. 2010).

Figure 2-10. Locked-Wheel Skid Trailer.

DFT

The DFT is used to measure the coefficient of friction ASTM E1911 (ASTM 2019). This device consists of a circular disk with three rubber pads (Figure 2-11). The circular disk rotates up to 100 km/h. Once the disk reaches the specified speed, the disk is lowered to the pavement surface, and the coefficient of friction is measured as the speed of the rotating disk gradually decreases. The pavement microtexture is quantified by the value of the coefficient of friction at 20 km/h (DFT_{20}). Note that the DFT can also be used on lab-fabricated slabs and aggregate rings to measure the coefficient of friction.

Figure 2-11. DFT Equipment.

FRICTION AND SKID RESISTANCE MODELS

Measurements, MPD and DFT_{20}, from the CTM and DFT, are used to calculate the International Friction Index (IFI) according to ASTM E1960 (ASTM 2015b). The IFI was developed in the PIARC International Experiment to Compare and Harmonize Texture and Skid Resistance Measurements. The index allows for harmonizing friction measurements with different equipment to a common calibrated index. The IFI consists of two parameters that report the calibrated wet friction at 60 km/h (F60) and the speed constant of wet pavement friction (S_p), as shown below. A significance of the IFI model is that the measurement of friction with a device does not have to be at one of the speeds run in the experiment. Thus, the model still works well if a device cannot maintain its normal operating speed and must run at a higher or lower speed because of traffic.

$$F60 = 0.081 + 0.732 DFT_{20} e^{\frac{-40}{S_p}} \quad (2\text{-}3)$$

$$S_p = 14.2 + 89.7 MPD \quad (2\text{-}4)$$

where

$F60$ = calibrated wet friction number at 60 km/h.
S_p = speed constant (gradient) of wet pavement friction.
MPD = mean profile depth.

DFT_{20} = wet friction number measured at the speed of 20 km/h.

Other prediction models for friction and skid resistance of asphalt pavements are described below.

Masad et al. (2007) developed a method to evaluate the change in the asphalt pavement skid resistance depending on aggregate texture, properties of mixtures, and environmental conditions. This method relies on using the Micro-Deval test and AIMS to evaluate the resistance of aggregates to polishing and abrasion. In 2010, Masad et al. conducted a study that included measurements in the field and laboratory. Several slabs with different asphalt mixtures and aggregate types were prepared and tested in the laboratory. Three mixture designs (Type C, Type D, and porous friction course [PFC]) were evaluated. The mixtures were prepared and compacted in a special metal mold using a vibrator roller compactor, as shown in Figure 2-12a. The researchers evaluated the friction at three different locations on a single test slab (Figure 2-12b). The three-wheel polishing machine (Figure 2-12c) was used to polish the test slabs, and the measurements of the friction and MPD were collected using the DFT and CTM (Figure 2-12d) after different polishing cycles (5,000, 10,000, 20,000, 35,000, 50,000, 75,000, and 100,000). The British pendulum test and the sand patch method were also used in this study. Masad et al. (2010) found that the change in the calculated IFI (F60) with the polishing cycles based on the MPD and DFT_{20} measurements could be described by the following equation:

$$IFI\ (N) = a_{mix} + b_{mix} * e^{(-c_{mix} * N)} \qquad (2\text{-}5)$$

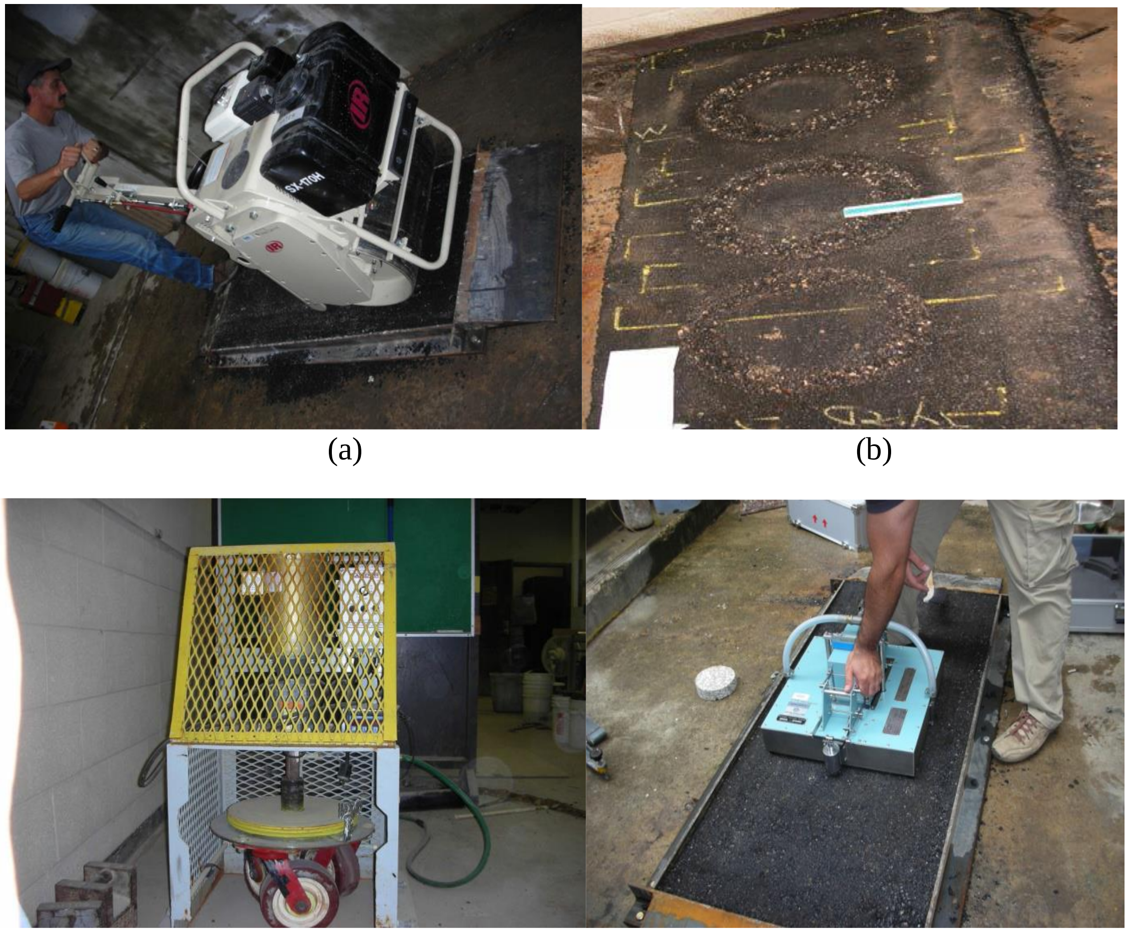
where

a_{mix} = terminal IFI value for the mix.

$a_{mix} + b_{mix}$ = initial IFI value for the mix.

c_{mix} = rate of change in IFI for the mix.

N = number of polishing cycles in the laboratory.



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

Figure 2-12. Laboratory Experiments: (a) Walk-Behind Roller Compactor, (b) Test Slabs, (c) Three-Wheel Polishing Machine, and (d) DFT and CTM Measurements (Masad et al. 2010)

Kassem et al. (2013) conducted a study to validate the IFI models developed by Masad et al. (2010). Square-shaped slabs were prepared in the laboratory using three different aggregates (Limestone 1, Limestone 2, and sandstone), and four asphalt mixture designs (Type F, Type C, stone-matrix asphalt [SMA], and PFC) were evaluated. The sandstone had a rough texture with better abrasion resistance than Limestone 1. The findings also indicated that coarse mixtures had better friction than fine ones. After considering the developed model's aggregate texture and angularity indices, the results demonstrated a high correlation between the measured and predicted IFI.

Wu et al. (2012) developed a new model to estimate skid resistance based on 12 mixtures with various mix types and aggregate sources. The aggregates included sandstone and siliceous limestone, and four mix types were evaluated (19-mm Superpave Level 2 mix, 12.5-mm Superpave Level 2 mix, SMA, and PFC). The selection of the aggregates was based on the mixture construction in Louisiana. The Micro-Deval was used to polish the prepared slabs according to AASHTO T327 (AASHTO 2012). Also, the British pendulum number was measured according to AASHTO T278 (AASHTO 1990) and T279 (AASHTO 1996).

Additionally, the macrotexture and microtexture of the prepared slabs were measured using the CTM and DFT after different polishing cycles. The model presented in the following equation was developed, and the significance of the model is that if the initial surface macrotexture (MPD^i) and microtexture ($DFN_{20}{}^i$) can be determined in a laboratory mix design, the friction number ($F60$) for the designed mixture at any polishing cycle may be estimated. The coefficient of determination (R^2) for the equation is 88 percent. The researchers also demonstrated that aggregates with low skid resistance could be blended with good quality aggregates to achieve adequate skid resistance.

$$F60 = \left(2.18 + 13.5 * MPD^i + 0.38 * DFN_{20}{}^i\right) * e^{(-1.73*10^{-6}*N)} \qquad (2\text{-}6)$$

where
$F60$ = calibrated wet friction number at 60 km/h.
MPD^i = initial macrotexture in terms of MPD as measured by CTM.
$DFN_{20}{}^i$ = initial microtexture as measured by DFT at a speed of 20 km/h.
N = polishing cycle number.

Kowalski et al. (2010) developed a polishing model to estimate the terminal friction level (referred to as F60 @ X_1) and the polishing rate (a4), as seen in Figure 2-13. X_1 represents the number of wheel passes at which the terminal friction level is reached. McDaniel et al. (2012) used this model to quantify changes in the F60 values of the RAP mixture in the JTRP study *Evaluation of Reclaimed Asphalt Pavement for Surface Mixtures*. Their results showed that the addition of RAP indeed influences friction, as seen in Figure 2-14. The more RAP material is added, the lower the friction value becomes. This general trend can be observed for both dense-graded asphalt (DGA) and SMA mixtures. For SMA mixtures, the changes in the F60 @ X1 values generally decrease linearly, while for the DGA mixtures, the F60 drops more between samples with RAP contents of 15 percent and 25 percent than between 0 and 15 percent or 25 to 40 percent. The RAP in this study was laboratory fabricated using poor-quality aggregate (for friction) to represent a "worst case."

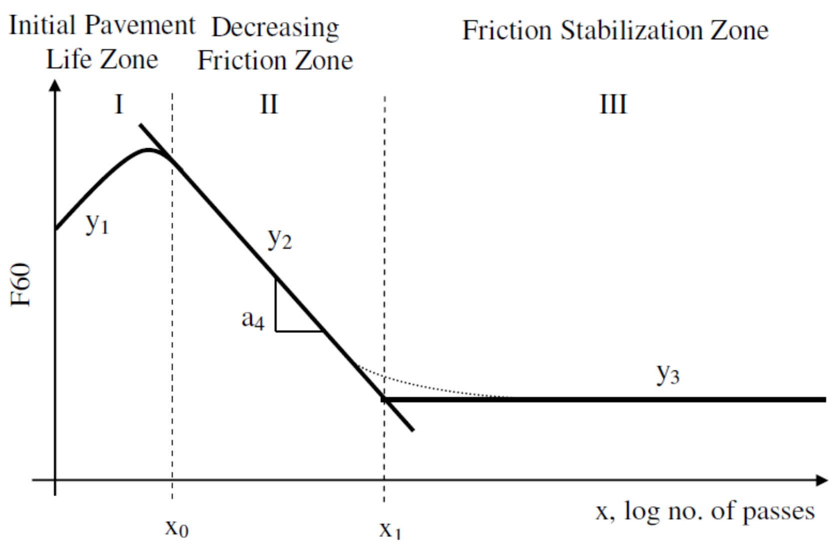


Figure 2-13. Polishing Model (Kowalski et al. 2010).

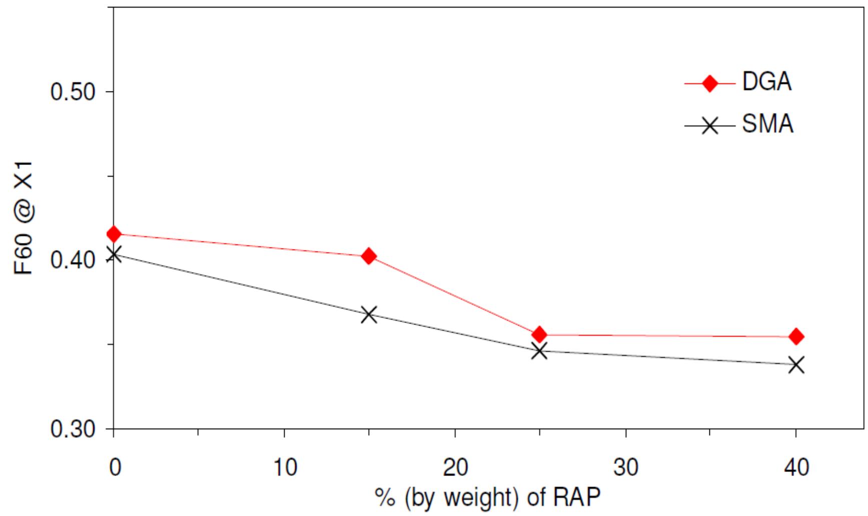


Figure 2-14. Distribution of Friction Terminal Value (F60 @ x1).

In TxDOT Project 0-6746 (Chowdhury et al. 2017), researchers investigated 35 sections of asphalt pavements to examine surface friction for revising the HMA surface friction model. Furthermore, the researchers measured SNs using a skid trailer to enhance the skid data collected from the TxDOT Pavement Management Information System database. Based on their research findings, a modified model was developed to predict the skid number, SN (50), of the asphalt pavement surface:

$$SN\ (50) = 4.81 + 140.32(IFI - 0.045)e^{\frac{-20}{S_p}} \qquad (2\text{-}7)$$

where

SN (50) = the skid number measured at 50 mph (80 km/h), and

S_p = the speed constant parameter.

SUMMARY

This chapter reviewed current knowledge and methods of characterizing RAP and evaluating pavement surface texture and skid resistance and the potential impact of RAP on surface mixture friction performance. Various states have guidelines for RAP usage and the percentage allowed in the surface mixes and aggregate gradation policy. Numerous studies have concluded that the friction and durability performance of asphalt surface courses with 10 to 25 percent RAP performed well under low traffic. However, no research was currently found to investigate the skid resistance (or texture) of RAP aggregate itself or categorize RAP aggregates like other raw aggregates (e.g., SAC-A or SAC-B). The potential positive impact of high skid-resistant RAP on surface mixture was unknown or not quantitatively studied.

CHAPTER 3 FIELD EVALUATION OF SKID PROBLEMS REPORTED BY DISTRICTS

In recent years, several TxDOT districts have reported low skid resistance values on surface mixes containing SAC-A materials. The researchers performed the following: (a) identified three districts reporting low field skids in their corresponding SAC-A sections: Lufkin District (FM 356), Atlanta District (IH 20), and El Paso District (IH 10); (b) obtained basic information about these sections including the section location, mix design spreadsheet (aggregates, RAP, asphalt binder, etc.), skid measurements, pavement performance, etc.; (c) performed field evaluations of the selected test sections, which included coefficients of friction measured from the DFT, pavement macrotexture measurements (or MPD) with a CTM device, and pavement microtexture and macrotexture measurements with TTI's newly developed laser device, ARTS; and (d) analyzed the field test data and summarized the findings into a technical memorandum and report for TxDOT's Research and Technology Implementation Division and the districts. This chapter includes the following:

- Description of the identified sections, such as the location, skid numbers, and mixture design information.
- Presentation of the field evaluation results, such as the DFT and laser texturing results.
- Comparison and analysis of the DFT and macrotexture and microtexture results.
- Summary of the findings and conclusions.

TEST SECTIONS

The researchers inquired many districts to identify the test sections with potential skid problems while using SAC-A aggregates. With the help and information provided by TxDOT engineers, three test sections were identified: (1) FM 356 in the Lufkin District, (2) IH 20 in the Atlanta District, and (3) IH 10 in the El Paso District. The test sections were reported to have low field skids, although the surfaces belong to SAC-A materials. In addition, the mixture designs and the corresponding raw aggregates of these sections were available, which made them good candidates for test sections. The section location, skid numbers, and the corresponding mixture design information are described below.

FM 356 Section

The section in the Lufkin District is located around 1.12 miles from the intersection with US 190, as seen in Figure 3-1. The pavement surface was constructed in 2017, and the skid numbers were collected in 2018 on the southbound side (Lane A) and are around 19.

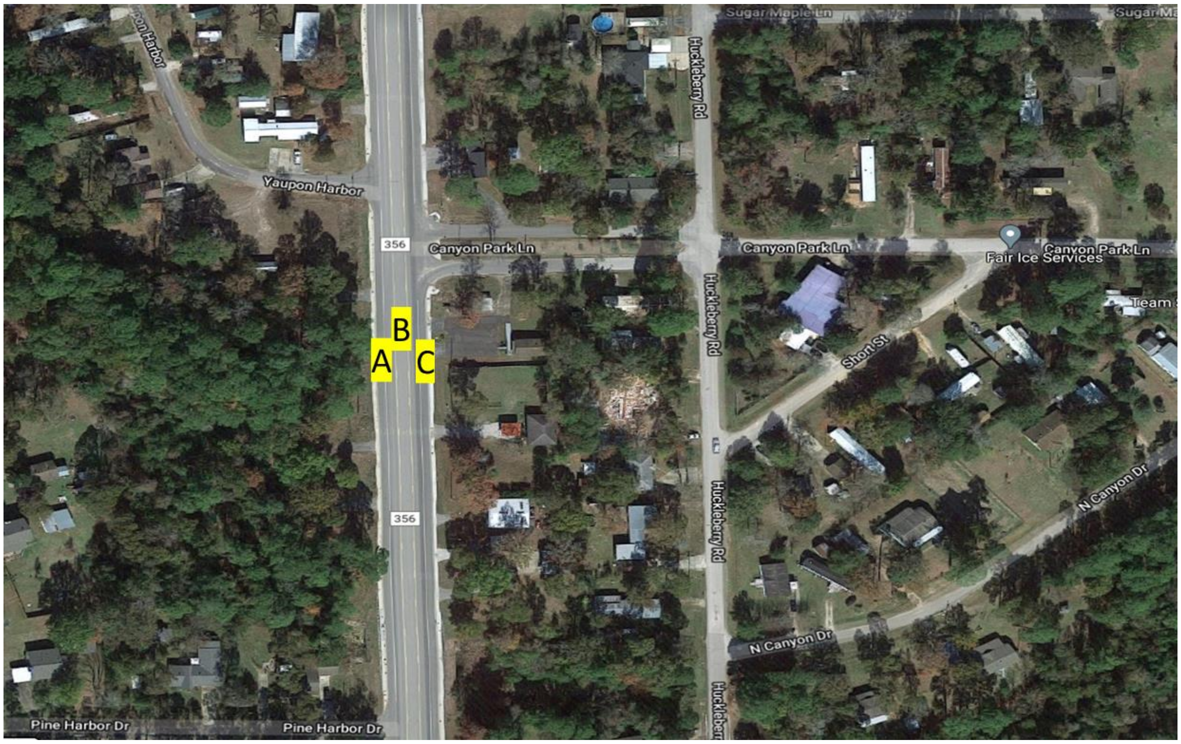


Figure 3-1. FM 356 Section Location.

Figure 3-2 shows the FM 356 mixture design. This design is a Superpave C mixture. The aggregate stockpile percentages are 29 percent sandstone (SAC-A), 10 percent limestone (SAC-B), 24.9 percent limestone screenings, 15 percent washed sand, 1 percent lime, and 20 percent RAP.

TEXAS DEPARTMENT OF TRANSPORTATION
AUSTIN ASPHALT
2014 HMACP MIXTURE DESIGN : COMBINED GRADATION

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SAMPLE ID:	17EDELVA_0168	SAMPLE DATE:	11/9/2017
LOT NUMBER:	239R S-A	LETTING DATE:	03/07/2017
SAMPLE STATUS:	COMPLETE	CONTROLLING CSJ:	0319-01-064
COUNTY:	TRINITY	SPEC YEAR:	2014
SAMPLED BY:		SPEC ITEM:	03446047
SAMPLE LOCATION:		SPECIAL PROVISION:	
MATERIAL CODE:	0344CM0000	MIX TYPE:	344-SP-C
MATERIAL NAME:	ITEM 344 COMPLETE MIX QCQA ALL MIX TYPES		
PRODUCER:	VULCAN MATERIALS		
AREA ENGINEER:	JESSE SISCO	PROJECT MANAGER:	STEPHEN THORNTON
COURSE\LIFT:	Surface	STATION:	
DIST. FROM CL:			

WMA Additive in Design?	No
Target Discharge Temp., °F:	
WMA TECHNOLOGY:	
WMA RATE:	UNITS:
CONTRACTOR DESIGN #:	239R

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAP	10.0
RAS:	5.0
RB Ratio:	20.0

Recycled Binder, %	
Bin No.8 :	0.9
Bin No.9 :	0.0
Bin No.10 :	0.0
Total	*0.9*

Use this value in the QC/QA template>>

Ratio of Recycled to Total Binder, %
(based on binder percent (%) entered below in this worksheet)
18.8

Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10	
	AGGREGATE BIN FRACTIONS							"RECYCLED MATERIALS"			
Source:	Sandstone	Limestone_Dolomit	Limestone_Dolomit					Fractionated RAP			Material Type
Pit:	Brownlee	Marble Falls Quarry	Marble Falls Quarry					Pavers Supply			Material Source
Number:	1402704	1402702	1402702								RAS Type
Producer:	Capitol Aggregates	Oldcastle Materials Texas	Oldcastle Materials Texas	Pavers Supply	Austin White Lime						RAP/RAS Producer
Sample ID:				Washed Sand	Lime						Sample ID
								Recycled Asphalt Binder (%)			
								4.5			
Hydrated Lime?:								20.0 (% of Tot. Mix)	(% of Tot. Mix)	(% of Tot. Mix)	Total Bin
Individual Bin (%):	29.0 Percent	10.0 Percent	24.9 Percent	15.0 Percent	1.0 Percent	Percent	Percent	20.1 (% of Aggreg)	(% of Aggreg)	(% of Aggreg)	100.0%

Sieve Size:	Bin 1 Cum.% Passing	Bin 1 Wtd Cum. %	Bin 2 Cum.% Passing	Bin 2 Wtd Cum. %	Bin 3 Cum.% Passing	Bin 3 Wtd Cum. %	Bin 4 Cum.% Passing	Bin 4 Wtd Cum. %	Bin 5 Cum.% Passing	Bin 5 Wtd Cum. %
1"	100.0	29.0	100.0	10.0	100.0	24.9	100.0	15.0	100.0	1.0
3/4"	100.0	29.0	100.0	10.0	100.0	24.9	100.0	15.0	100.0	1.0
1/2"	99.0	28.7	58.2	5.8	100.0	24.9	100.0	15.0	100.0	1.0
3/8"	74.3	21.5	17.1	1.7	100.0	24.9	100.0	15.0	100.0	1.0
No. 4	5.9	1.7	1.8	0.2	99.8	24.9	100.0	15.0	100.0	1.0
No. 8	2.0	0.6	1.4	0.1	78.7	19.6	100.0	15.0	100.0	1.0
No. 16	2.0	0.6	1.4	0.1	56.0	13.9	100.0	15.0	100.0	1.0
No. 30	2.0	0.6	1.4	0.1	38.0	9.5	91.0	13.7	100.0	1.0
No. 50	2.0	0.6	1.4	0.1	24.9	6.2	61.0	9.2	100.0	1.0
No. 200	2.0	0.6	1.1	0.1	4.2	1.0	3.2	0.5	100.0	1.0

Sieve Size:	Bin 6 Cum.% Passing	Bin 6 Wtd Cum. %	Bin 7 Cum.% Passing	Bin 7 Wtd Cum. %	Bin 8 Cum.% Passing	Bin 8 Wtd Cum. %	Bin 9 Cum.% Passing	Bin 9 Wtd Cum. %	Bin 10 Cum.% Passing	Bin 10 Wtd Cum. %	Combined Gradation Cum. % Passing	Lower	Upper	Within Spec's
												Lower & Upper Specification Limits		
1"					100.0	20.1					100.0	100.0	100.0	Yes
3/4"					100.0	20.1					100.0	98.0	100.0	Yes
1/2"					100.0	20.1					95.5	90.0	100.0	Yes
3/8"					96.0	19.3					83.5	58.0	90.0	Yes
No. 4					72.0	14.5					57.2	28.0	90.0	Yes
No. 8					50.0	10.1					46.4	28.0	58.0	Yes
No. 16					41.0	8.2					38.9	2.0	58.0	Yes
No. 30					32.0	6.4					31.3	2.0	58.0	Yes
No. 50					23.0	4.6					21.7	2.0	58.0	Yes
No. 200					6.0	1.2					4.42	2.0	10.0	Yes

(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specificaitons- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:	2.00	Binder Substitution?	Yes	Binder Originally Specified:	PG 70-22	Substitute Binder:	PG 64-22
Asphalt Source:	Valero	Binder Percent, (%):	4.8	Asphalt Spec. Grav.:	1.028		
Antistripping Agent:	Evotherm	Percent, (%):	0.5				

Figure 3-2. FM 356 Mixture Design.

Although the percentage of sandstone (SAC-A) stockpile is only 29 percent, the percentage of the coarse components (retaining on the No. 4 sieve) from SAC-A over the total coarse component is 63.8 percent, as seen in Figure 3-3. *Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges* (TxDOT 2014) specifies that "Class B aggregate may be blended with a Class A aggregate to meet requirements for Class A materials. Ensure that at least 50 percent by weight, or volume if required, of the material retained on the No. 4 sieve comes from the Class A." Thus, the mixture of FM 356 belongs to SAC-A material.

Aggregate Classification

		Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8
Individual Bin (%):		Bin No.1 = 29 %	Bin No.2 = 10 %	Bin No.3 = 24.9 %	Bin No.4 = 15 %	Bin No.5 = 1 %			Bin No.8 = 20.1 %
Aggregate Source:		Sandstone	Limestone_Dolomite	Limestone_Dolomite					Fractionated RAP
Aggregate Number:		1402704	1402702	1402702					
Class (A) Rock (Y/N):		Yes	No	No					
Sieve Size:		Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %
Passing	Retained								
-	1"	0.0	0.0	0.0	0.0	0.0			0.0
1"	3/4"	0.0	0.0	0.0	0.0	0.0			0.0
3/4"	1/2"	0.3	4.2	0.0	0.0	0.0			0.0
1/2"	3/8"	7.2	4.1	0.0	0.0	0.0			0.8
3/8"	No. 4	19.8	1.5	0.0	0.0	0.0			4.8
No. 4	No. 8	1.1	0.0	5.3	0.0	0.0			4.4
No. 8	No. 16	0.0	0.0	5.7	0.0	0.0			1.8
No. 16	No. 30	0.0	0.0	4.5	1.4	0.0			1.8
No. 30	No. 50	0.0	0.0	3.3	4.5	0.0			1.8
No. 50	No. 200	0.0	0.0	5.2	8.7	0.0			3.4
No. 200	Pan	0.6	0.1	1.0	0.5	1.0			1.2
Total:		29.0	10.0	24.9	15.0	1.0			20.1
Percent of plus No. 4		27.3	9.8	0.0	0.0	0.0			5.6
Percent of plus No. 8		28.4	9.9	5.3	0.0	0.0			10.1

Percent of plus No. 4 from class (A) Rock:	27.3
Total Percent of plus No. 4	42.8
Percent of plus No. 4 from class (A) Rock:	63.8

Percent of plus No. 8 from class (A) Rock:	28.4
Total Percent of plus No. 8	53.6
Percent of plus No. 8 from class (A) Rock:	53.0

Figure 3-3. FM 356 Aggregate Classification.

IH 20 Section

The section in the Atlanta District is located on IH 20 from SH 43 to US 59 on the eastbound side of the roadway. The pavement surface was constructed in 2015, and the skid numbers were collected in 2016 and 2018. Figure 3-4 shows the section and skid number collection locations (the green teardrops represent the location of 2016 measurements; the yellow ones represent 2018).

Figure 3-4. IH 20 Section Location.

Table 3-1 lists the skid numbers measured in 2016 and 2018. In general, the numbers measured in 2018 were smaller than those in 2016.

Table 3-1. IH 20 Skid Numbers.

Fiscal Year	Skid Number	Skid Test Date	Responsible District	Measured Latitude	Measured Longitude
2016	32.0	7/18/2016	19—Atlanta	32.488767	−94.412636
2016	30.0	7/18/2016	19—Atlanta	32.488848	−94.404218
2016	28.0	7/18/2016	19—Atlanta	32.488860	−94.395541
2016	27.0	7/18/2016	19—Atlanta	32.489110	−94.386916
2016	30.0	7/18/2016	19—Atlanta	32.489367	−94.378334
2016	35.0	7/18/2016	19—Atlanta	32.490077	−94.369676
2016	33.0	7/18/2016	19—Atlanta	32.490925	−94.361079
2016	36.0	7/18/2016	19—Atlanta	32.491283	−94.352411
2016	38.0	7/18/2016	19—Atlanta	32.491640	−94.343820
2018	20.6	6/20/2018	19—Atlanta	32.488737	−94.413486
2018	19.4	6/20/2018	19—Atlanta	32.488892	−94.404829
2018	19.6	6/20/2018	19—Atlanta	32.488843	−94.396346
2018	19.6	6/20/2018	19—Atlanta	32.489094	−94.387738
2018	24.4	6/20/2018	19—Atlanta	32.489352	−94.378922
2018	21.6	6/20/2018	19—Atlanta	32.489939	−94.370518
2018	34.7	6/21/2018	19—Atlanta	32.490831	−94.363394
2018	38.0	6/21/2018	19—Atlanta	32.491185	−94.354861
2018	36.1	6/21/2018	19—Atlanta	32.491536	−94.346335

Figure 3-5 shows the mixture design of the IH 20 section. This design is a dense-graded Type D mixture, and the aggregate stockpile percentages of this mixture are 50 percent igneous 1/2 inch, 10 percent igneous 3/8 inch, 30 percent igneous screenings, and 10 percent field sand. Since igneous is SAC-A aggregate, the percentage of coarse component (retaining on the No. 4 sieve) from the SAC-A aggregate is 100 percent, as seen in Figure 3-6.

TEXAS DEPARTMENT OF TRANSPORTATION

HMACP MIXTURE DESIGN : COMBINED GRADATION

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SAMPLE ID:	A1405	SAMPLE DATE:	RECVD. ON 3-5-14
LOT NUMBER:	IH 20	LETTING DATE:	IM 0207 (072)
SAMPLE STATUS:	DESIGN	CONTROLLING CSJ:	0495-09-049
COUNTY:	HARRISON	SPEC YEAR:	2004
SAMPLED BY:	MARK DEAN	SPEC ITEM:	3268
SAMPLE LOCATION:	STOCKPILE AT PLANT	SPECIAL PROVISION:	
MATERIAL CODE:		MIX TYPE:	SS3268_D_Fine_Surface
MATERIAL NAME:	TYPE D HOTMIX		
PRODUCER:	LONGVIEW ASPHALT, INC. -- MARSHALL PLANT		
AREA ENGINEER:	ANDERSON	PROJECT MANAGER:	
COURSE\LIFT:	Surface	STATION:	
DIST. FROM CL:			

WMA Additive in Design?	No
Target Discharge Temp., °F:	325
WMA TECHNOLOGY:	
WMA RATE:	UNITS:
CONTRACTOR DESIGN # :	H1405

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAP	10.0
RAS:	5.0
RB Ratio:	20.0

Use this value in the QC/QA template>>

Recycled Binder, %	
Bin No.8 :	0.0
Bin No.9 :	0.0
Bin No.10 :	0.0
Total	***0.0***

Ratio of Recycled to Total Binder, % *(based on binder percent (%) entered below in this worksheet)*
0.0

	AGGREGATE BIN FRACTIONS							"RECYCLED MATERIALS"			
	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10	
Aggregate Source:	Igneous	Igneous	Igneous								Material Type
Aggregate Pit:	Jones Mill	Jones Mill	Jones Mill	GLOVER PIT							Material Source
Aggregate Number:	0050122	0050122	0050122	LOCAL SOURCE							RAS Type
Sample ID:	1/2" C.A.	3/8" C.A.	SCREENINGS	FIELD SAND							Sample ID

Recycled Asphalt Binder (%)

	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		Combined Gradation			
Hydrated Lime?:																% of Tot.		% of Tot.		% of Tot.	Total Bin	Lower & Upper Specification Limits		
Individual Bin (%):	50.0	Percent	10.0	Percent	30.0	Percent	10.0	Percent		Percent		Percent		Percent		% of Aggreg		% of Aggreg		% of Aggreg	100.0%			
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing	Lower	Upper	Within Spec's
3/4"	100.0	50.0	100.0	10.0	100.0	30.0	100.0	10.0													100.0	100.0	100.0	Yes
1/2"	100.0	50.0	100.0	10.0	100.0	30.0	100.0	10.0													100.0	98.0	100.0	Yes
3/8"	90.4	45.2	100.0	10.0	100.0	30.0	100.0	10.0													95.2	85.0	100.0	Yes
No. 4	34.3	17.2	35.0	3.5	95.4	28.6	100.0	10.0													59.3	50.0	70.0	Yes
No. 8	9.6	4.8	7.8	0.8	71.2	21.4	100.0	10.0													36.9	35.0	46.0	Yes
No. 30	3.1	1.6	3.0	0.3	28.8	8.6	100.0	10.0													20.5	15.0	29.0	Yes
No. 50	2.5	1.3	2.6	0.3	19.6	5.9	99.5	10.0													17.3	7.0	20.0	Yes
No. 200	1.8	0.9	1.8	0.2	10.4	3.1	16.6	1.7													5.9	2.0	7.0	Yes

(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specificaitons- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:		Binder Substitution?	No	Binder Originally Specified:	PG 76-22
Asphalt Source:	LION PG 76-22 MUSKOGEE, OK	Binder Percent, (%):	5.0	Asphalt Spec. Grav.:	1.025
Antistripping Agent:	NONE	Percent, (%):			

Substitute Binder:

Figure 3-5. IH 20 Mixture Design.

Aggregate Classification

		Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6
Individual Bin (%):		Bin No.1 = 50 %	Bin No.2 = 10 %	Bin No.3 = 30 %	Bin No.4 = 10 %		
Aggregate Source:		Igneous	Igneous	Igneous			
Aggregate Number:		0050122	0050122	0050122	LOCAL SOURCE		
Class (A) Rock (Y/N):		Yes	Yes	Yes	No		
Sieve Size:		Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %
Passing	Retained						
-	3/4"	0.0	0.0	0.0	0.0		
3/4"	1/2"	0.0	0.0	0.0	0.0		
1/2"	3/8"	4.8	0.0	0.0	0.0		
3/8"	No. 4	28.1	6.5	1.4	0.0		
No. 4	No. 8	12.4	2.7	7.3	0.0		
No. 8	No. 30	3.3	0.5	12.7	0.0		
No. 30	No. 50	0.3	0.0	2.8	0.0		
No. 50	No. 200	0.4	0.1	2.8	8.3		
No. 200	Pan	0.9	0.2	3.1	1.7		
Total:		50.0	10.0	30.0	10.0		
Percent of plus No. 4		32.9	6.5	1.4	0.0		
Percent of plus No. 8		45.2	9.2	8.6	0.0		

Percent of plus No. 4 from class (A) Rock:	40.7
Total Percent of plus No. 4	40.7
Percent of plus No. 4 from class (A) Rock:	**100.0**

Percent of plus No. 8 from class (A) Rock:	63.1
Total Percent of plus No. 8	63.1
Percent of plus No. 8 from class (A) Rock:	100.0

Figure 3-6. IH 20 Aggregate Classification.

IH 10 Section

The section in the El Paso District is a mill and inlay project along both IH 10 frontage roads between FM 1281 and FM 1110. All construction work was done in September 2018, and the skid test ran in May 2019. Figure 3-7 shows the section and the skid number collection locations.

Figure 3-7. IH 10 Section Location.

Table 3-2 lists the skid numbers measured on the IH 10 frontage roads (both sides). Most of these numbers are close to or smaller than 30, indicating low skid resistance.

Table 3-2. IH 10 Skid Numbers.

Fiscal Year	Skid Number	Skid Test Date	Measured Latitude	Measured Longitude
2019	28.6	5/6/2019	31.657313	−106.238646
2019	23.0	5/6/2019	31.651311	−106.233974
2019	28.1	5/6/2019	31.645246	−106.229264
2019	30.3	5/6/2019	31.639254	−106.224605
2019	31.0	5/6/2019	31.633084	−106.219821
2019	36.4	5/6/2019	31.627005	−106.215097
2019	24.8	5/6/2019	31.621006	−106.210447
2019	25.1	5/6/2019	31.614963	−106.205766
2019	29.0	5/6/2019	31.608841	−106.201013
2019	22.3	5/6/2019	31.602689	−106.196241
2019	27.5	5/6/2019	31.656079	−106.236332
2019	27.1	5/6/2019	31.650080	−106.231710
2019	24.4	5/6/2019	31.644058	−106.227032
2019	30.5	5/6/2019	31.637976	−106.222314
2019	26.2	5/6/2019	31.631865	−106.217566
2019	30.4	5/6/2019	31.625874	−106.212924
2019	31.1	5/6/2019	31.619815	−106.208227
2019	28.0	5/6/2019	31.613735	−106.203511
2019	25.4	5/6/2019	31.607609	−106.198761
2019	19.1	5/6/2019	31.601542	−106.194063

Figure 3-8 shows the mixture design of the IH 10 section. This design is a Superpave C mixture. The aggregate stockpile percentages of this mixture are 28 percent igneous 3/4 inch (SAC-A), 25.1 percent limestone 3/8 inch (SAC-B), 27 percent limestone screenings, and 20 percent RAP. The percentage of coarse components (retaining on the No. 4 sieve) from the SAC-A aggregate is 53.4 percent, as seen in Figure 3-9.

TEXAS DEPARTMENT OF TRANSPORTATION
JOBE MATERIALS, L.P.
2014 HMACP MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook — TX2MIXDE14 - File Version: 12/20/19 09:05:44

SAMPLE ID:	2451018MIRIGOYE059	SAMPLE DATE:	9/18/2018
LOT NUMBER:	1	LETTING DATE:	07/11/2018
SAMPLE STATUS:	COMPLETE	CONTROLLING CSJ:	2121-04-086
COUNTY:	EL PASO	SPEC YEAR:	2014
SAMPLED BY:	MARIO IRIGOYEN LUJANO	SPEC ITEM:	03446047
SAMPLE LOCATION:	JOBE SEC 14 PLANT	SPECIAL PROVISION:	
MATERIAL CODE:	0344CM0000	MIX TYPE:	344-SP-C
MATERIAL NAME:	ITEM 344 COMPLETE MIX QCQA ALL MIX TYPES		
PRODUCER:			
AREA ENGINEER:	ROBERT FLORES	PROJECT MANAGER:	MONICA DUBRULE
COURSE\LIFT:	Surface	STATION:	DIST. FROM CL:

WMA Additive in Design?	Yes
Target Discharge Temp., °F:	275
WMA TECHNOLOGY:	Double Barrel Green (A
WMA RATE: 2.0	UNITS: % by weight of asphalt
CONTRACTOR DESIGN #:	JM344SPC20SP7022

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAP	10.0
RAS:	5.0
RB Ratio:	30.0

Use this value in the QC/QA template>>

Recycled Binder, %	
Bin No.8 :	1.0
Bin No.9 :	0.0
Bin No.10 :	0.0
Total	***1.0***

Ratio of Recycled to Total Binder, %
(based on binder percent (%) entered below in this worksheet)
21.7

	AGGREGATE BIN FRACTIONS							"RECYCLED MATERIALS"			
Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10	
Source:	imestone_Dolomit	Igneous	imestone_Dolomit	imestone_Dolomit				Fractionated RAP			Material Type
Pit:	Ned Finney Quarry	Padre Canyon	Ned Finney Quarry	Ned Finney Quarry				txdot			Material Source
Number:	2407220	2411613	2407220	2407220							RAS Type
Producer:											RAP/RAS Producer
Sample ID:	3/4 SAC B	3/4 SAC A	3/8	Fines							Sample ID

Recycled Asphalt Binder (%): 5.0 — Combined Gradation

Sieve Size:	Bin No.1 Cum.% Passing	Bin No.1 Ind.% Cum.%	Bin No.2 Cum.% Passing	Bin No.2 Ind.% Cum.%	Bin No.3 Cum.% Passing	Bin No.3 Ind.% Cum.%	Bin No.4 Cum.% Passing	Bin No.4 Ind.% Cum.%	Bin No.5 Cum.% Passing	Bin No.5 Ind.% Cum.%	Bin No.6 Cum.% Passing	Bin No.6 Ind.% Cum.%	Bin No.7 Cum.% Passing	Bin No.7 Ind.% Cum.%	Bin No.8 Cum.% Passing	Bin No.8 Ind.% Cum.%	Bin No.9 Cum.% Passing	Bin No.9 Ind.% Cum.%	Bin No.10 Cum.% Passing	Bin No.10 Ind.% Cum.%	Total Bin Cum. % Passing	Lower	Upper	Within Spec's
Hydrated Lime?:															20.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix	Total Bin	Lower & Upper Specification Limits		
Individual Bin (%):		Percent	28.0	Percent	25.1	Percent	27.0	Percent		Percent		Percent		Percent	19.9	% of Aggreg		% of Aggreg		% of Aggreg	100.0%			
1"			100.0	28.0	100.0	25.1	100.0	27.0							100.0	19.9					100.0	100.0	100.0	Yes
3/4"			100.0	28.0	100.0	25.1	100.0	27.0							100.0	19.9					100.0	98.0	100.0	Yes
1/2"			73.0	20.4	100.0	25.1	100.0	27.0							100.0	19.9					92.4	90.0	100.0	Yes
3/8"			45.0	12.6	89.0	22.3	100.0	27.0							97.0	19.3					81.2	58.0	90.0	Yes
No. 4			5.0	1.4	30.0	7.5	99.0	26.7							73.0	14.5					50.2	28.0	90.0	Yes
No. 8			4.0	1.1	4.0	1.0	83.0	22.4							47.0	9.4					33.9	28.0	58.0	Yes
No. 16			3.5	1.0	3.0	0.8	54.0	14.6							35.0	7.0					23.3	2.0	58.0	Yes
No. 30			3.0	0.8	2.0	0.5	37.3	10.1							27.0	5.4					16.8	2.0	58.0	Yes
No. 50			2.0	0.6	1.5	0.4	26.5	7.2							20.0	4.0					12.1	2.0	58.0	Yes
No. 200			1.8	0.5	1.0	0.3	13.6	3.7							8.0	1.6					6.0	2.0	10.0	Yes

(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specificaitons- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:	2.00	Binder Substitution?	Yes	Binder Originally Specified:	PG 70-22	Substitute Binder:	PG 64-22
Asphalt Source:	Andover	Binder Percent, (%):	4.6	Asphalt Spec. Grav.:	1.002		
Antistripping Agent:		Percent, (%):					

Figure 3-8. IH 10 Mixture Design.

Aggregate Classification

	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8
Individual Bin (%):		Bin No.2 = 28 %	Bin No.3 = 25.1 %	Bin No.4 = 27 %				Bin No.8 = 19.9 %
Aggregate Source:	Limestone_Dolomite	Igneous	Limestone_Dolomite	Limestone_Dolomite				Fractionated RAP
Aggregate Number:	2407220	2411613	2407220	2407220				
Class (A) Rock (Y/N):	No	Yes	No	No	No			

Sieve Size: Passing	Sieve Size: Retained	Bin No.1 Individual Ret., %	Bin No.2 Individual Ret., %	Bin No.3 Individual Ret., %	Bin No.4 Individual Ret., %	Bin No.5 Individual Ret., %	Bin No.6 Individual Ret., %	Bin No.7 Individual Ret., %	Bin No.8 Individual Ret., %
-	1"		0.0	0.0	0.0				0.0
1"	3/4"		0.0	0.0	0.0				0.0
3/4"	1/2"		7.6	0.0	0.0				0.0
1/2"	3/8"		7.8	2.8	0.0				0.6
3/8"	No. 4		11.2	14.8	0.3				4.8
No. 4	No. 8		0.3	6.5	4.3				5.2
No. 8	No. 16		0.1	0.3	7.8				2.4
No. 16	No. 30		0.1	0.3	4.5				1.6
No. 30	No. 50		0.3	0.1	2.9				1.4
No. 50	No. 200		0.1	0.1	3.5				2.4
No. 200	Pan		0.5	0.3	3.7				1.6
Total:			28.0	25.1	27.0				19.9
Percent of plus No. 4			26.6	17.6	0.3				5.4
Percent of plus No. 8			26.9	24.1	4.6				10.5

Percent of plus No. 4 from class (A) Rock:	26.6
Total Percent of plus No. 4	49.8
Percent of plus No. 4 from class (A) Rock:	**53.4**

Percent of plus No. 8 from class (A) Rock:	26.9
Total Percent of plus No. 8	66.1
Percent of plus No. 8 from class (A) Rock:	40.7

Figure 3-9. IH 10 Aggregate Classification.

FIELD EVALUATION

During the field evaluation, three types of tests were performed: (1) the CTM laser test for macro-MPD determination, (2) the ARTS laser test for micro- and macro-MPD determination, and (3) the DFT test for friction coefficient determination. This chapter provides a brief description of each test and presents the field test results for each section.

CTM Test

The CTM test was conducted according to ASTM E2157: Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter (ASTM 2015a). The laser in the CTM is a point laser, and the profile determined is a 2D profile (distance in the X coordinate and elevation in the Z coordinate). The device has a laser displacement sensor attached to an arm that rotates in a circle with a diameter of 284 mm. The laser sensor can collect 1,024 data points per round (Figure 3-10). Thus, the CTM can scan the 892-mm-long circumference of the pavement at a sampling rate of one point every 0.87 mm. The scanned circumference is further divided into eight 100-mm-long segments for analysis. The CTM is used to characterize the macrotexture of the pavement. The MPD value for each of the eight segments of the scanned circumference was calculated according to ASTM E1845 (ASTM 2016) and averaged to obtain the MPD of the test surface (Figure 3-11). The final macrotexture MPD for each test surface used in the analysis consisted of the average value of three repeated runs.

(a) (b)

Figure 3-10. CTM Test Device (a) Front and (b) Bottom.

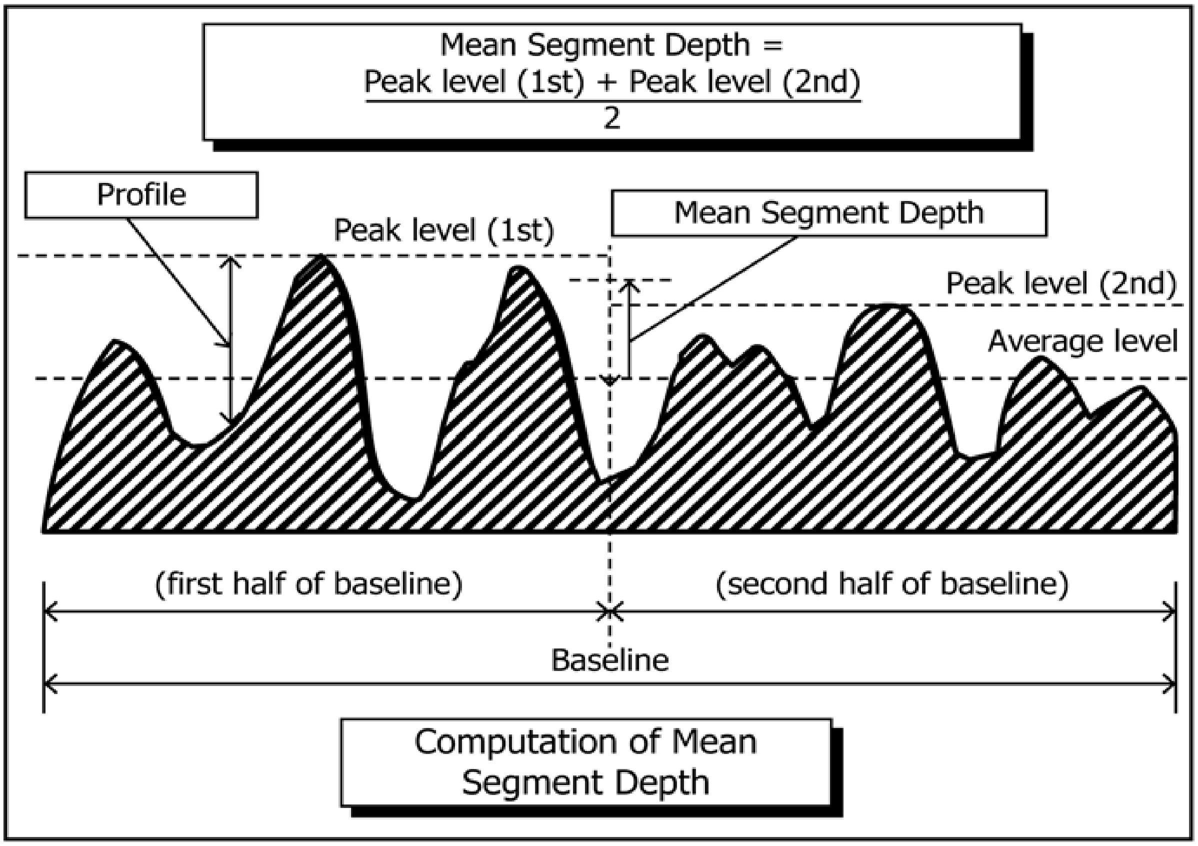
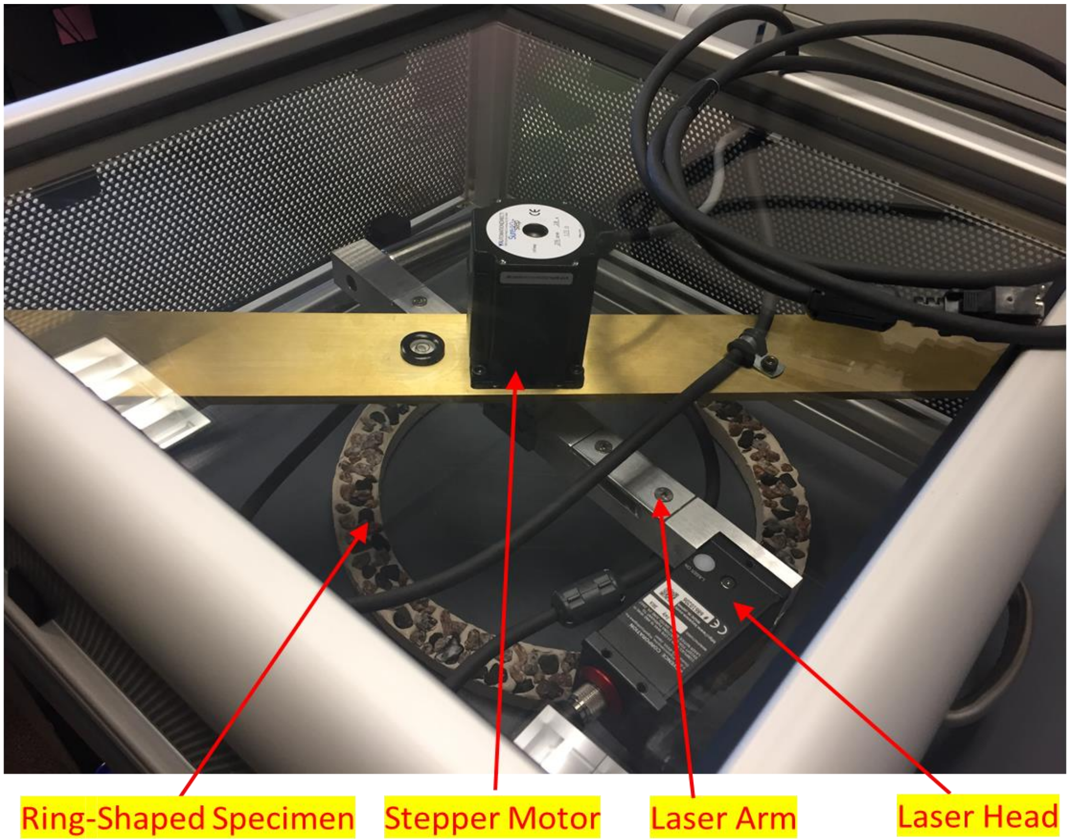


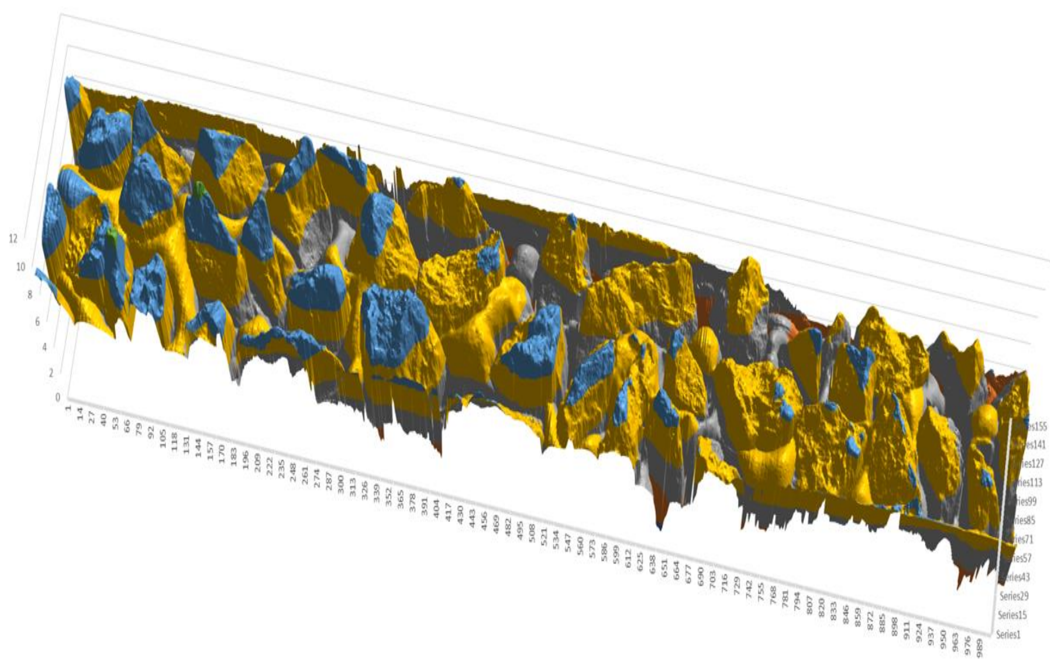
Figure 3-11. ASTM E1845 Macro-MPD Calculation.

ARTS Test

The ARTS was originally developed during TxDOT Project 5-6921-01 to determine the microtexture for the ring-shaped aggregate specimens (Arámbula et al. 2018). As Figure 3-12a shows, the laser head is mounted onto an arm that rotates in a circle with the same diameter as CTM (284 mm). Unlike the CTM laser (point laser), the ARTS laser is a line laser with a maximum line width of 40 mm, which is enough to cover the ring width (25 mm). The data point interval along the laser line is 0.05 mm. The laser line is parallel to the arm and perpendicular to the arm-rotating direction. Thus, the ARTS measurement covers the whole ring-shaped area and generates a 3D profile (distance [X coordinate], data point position along the laser line [Y coordinate], and elevation [Z coordinate]), as shown in Figure 3-12b. Since ARTS can produce a high-resolution 3D profile, it is ideal for the microtexture determination of aggregate surface in the rings.



(a)



(b)

Figure 3-12. (a) ARTS Device and Aggregate Ring-Shaped Specimen and (b) 3D Profile.

The researchers modified and enhanced the ARTS data processing algorithm and software to handle the pavement and mixture slab surfaces during this project. The main difference between the pavement (or mixture slab) surface and the aggregate ring surface is that the pavement surface has coarse and fine aggregates. In contrast, the aggregate ring only has coarse aggregate (passing 3/8 inch and retaining on 1/4 inch sieve). In addition, the macrotexture determination is needed for pavement surfaces (Figure 3-13), while it is not necessary for aggregate rings.

Currently, there are no standardized methods for microtexture characterization. Zuniga-Garcia and Prozzi (2019) studied different texture parameters and suggested that MPD was the most significant parameter to explain the distinct friction measures. Serigos et al. (2014) compared the surface microtexture parameters using different segment lengths and recommended a 1-mm baseline to mitigate the effect of outliers. In the ARTS software, the analysis segment lengths for pavement surface microtexture and macrotexture are set to 1 mm and 100 mm, respectively; the MPD values are consistent with the studies and findings mentioned above.

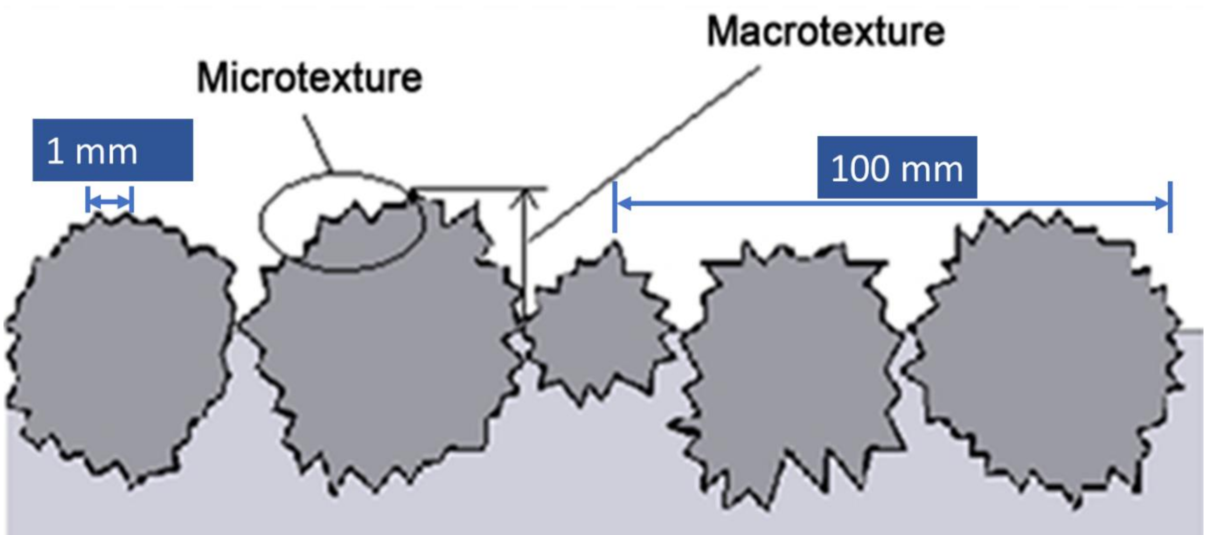
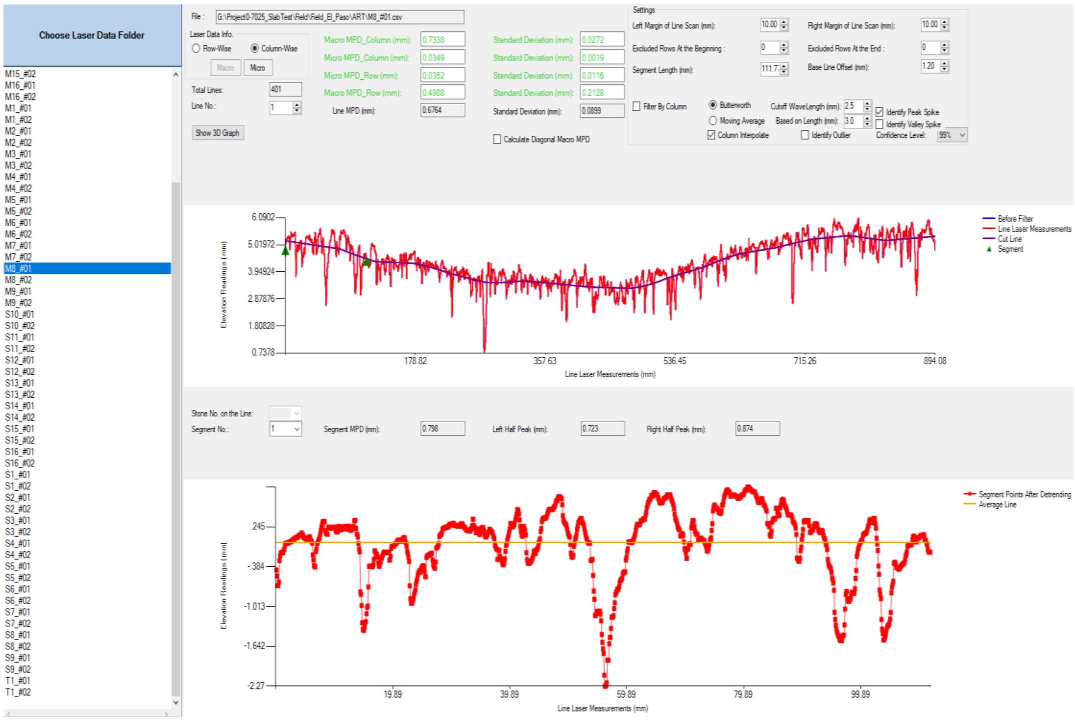
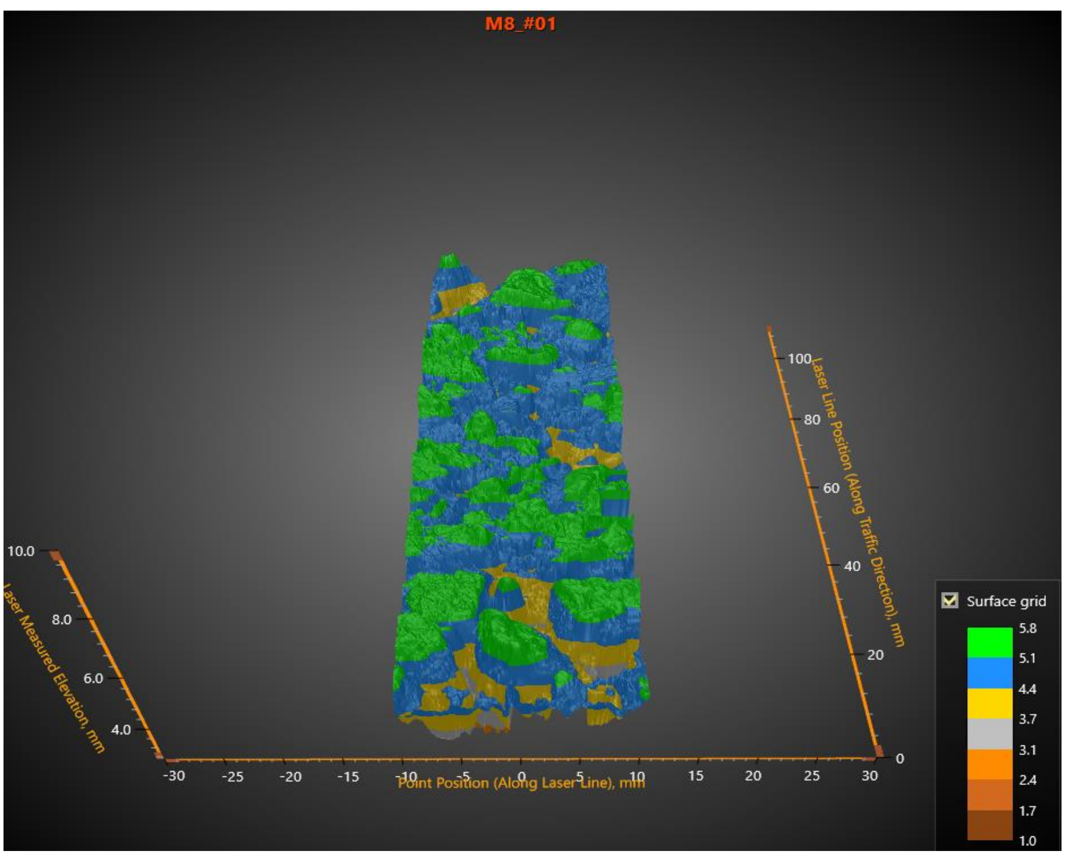


Figure 3-13. Pavement Surface Microtexture and Macrotexture.

As seen in Figure 3-14a, the modified ARTS can determine both the micro- and macro-MPD for pavement (or mixture slab) surface. The measured area covers the same area as the aggregate ring and DFT test areas. Compared to CTM, the ARTS measurement includes more than 500 circumferences' (500 data points for a 25-mm laser line) profile data rather than 1 circumference's profile data in the CTM measurement. In Figure 3-14a, users can select any circumference and segment to view the corresponding MPD values (micro or macro). The ARTS reports the average MPD values for all the circumferences segments. Figure 3-14b shows an ARTS-measured pavement surface 3D profile.



(a)

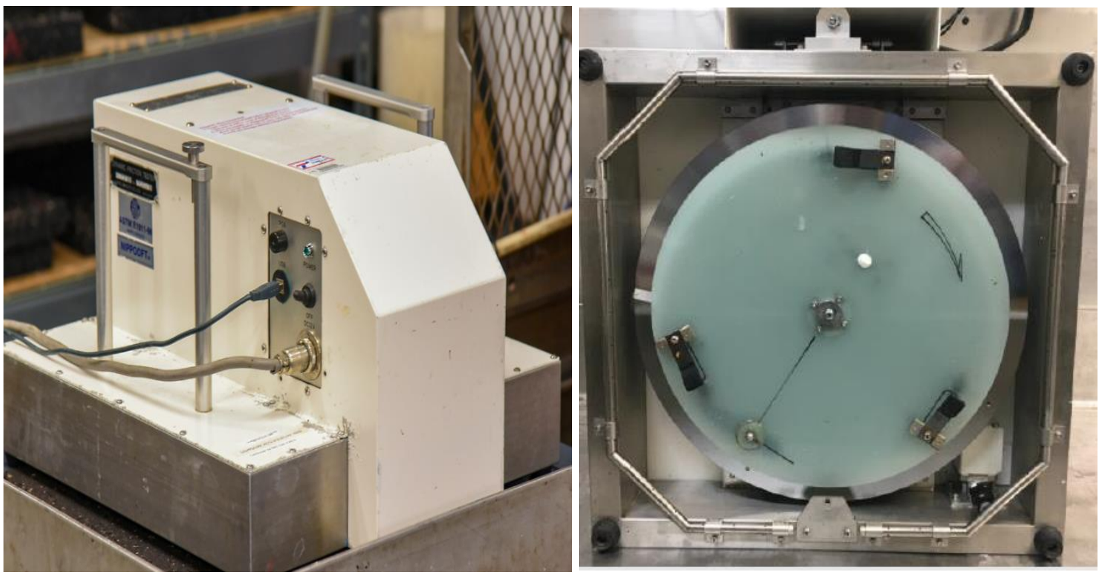


(b)

Figure 3-14. Modified ARTS (a) User Interface and (b) 3D Profile of Pavement Surface.

DFT Test

A DFT device (Figure 3-15) consists of a horizontal spinning disk fitted with three spring-loaded rubber sliders (each slider’s length is 0.75 inches, width is 0.625 inches, and height is 0.25 inches). The water is sprayed in front of the sliders, and a constant load is applied to the slider as the disk rotates on the test surface. The torque is monitored continuously as the disk’s rotational velocity drops because of the friction between the sliders and the test surface. The torque is then used to calculate the surface friction coefficients. The DFT test has been widely used for friction measurement in various conditions to explore the speed dependency of pavement friction by measuring friction at various speeds. ASTM E1911 (ASTM 2019) is a specification on measuring paved surface frictional properties with the DFT.



(a) (b)

Figure 3-15. DFT Test Device (a) Front and (b) Bottom.

Three repeated runs were conducted for each DFT test. The results obtained from the DFT, shown in Figure 3-16, were used to estimate the surface friction at different speeds. This research selected two speeds, 20 km/h and 60 km/h, to describe the DFT numbers at high and low speeds. These parameters were estimated as the average of the three repeated runs at the corresponding speed. Using the average instead of a single value provided a more robust analysis and increased the confidence in the results.

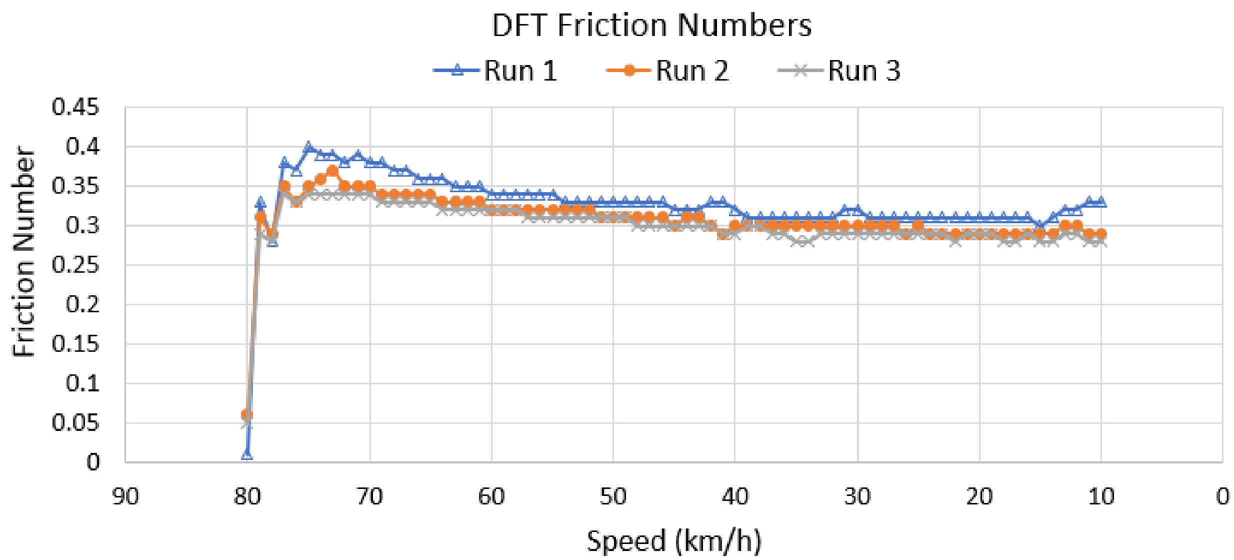


Figure 3-16. DFT Friction Numbers at Different Speeds.

FM 356 Field Evaluation

In March 2020, the researchers traveled to the Lufkin District FM 356 section and selected the field evaluation location. The section was from the intersection of Tree Line Drive to the intersection of Pine Harbor Drive, as seen in Figure 3-17. The section length was around 1,500 ft. The interval of the tests was 100 ft.

Figure 3-18 shows the pavement surface condition at that time. The wheel path and shoulder had the same surface mixture at that time.

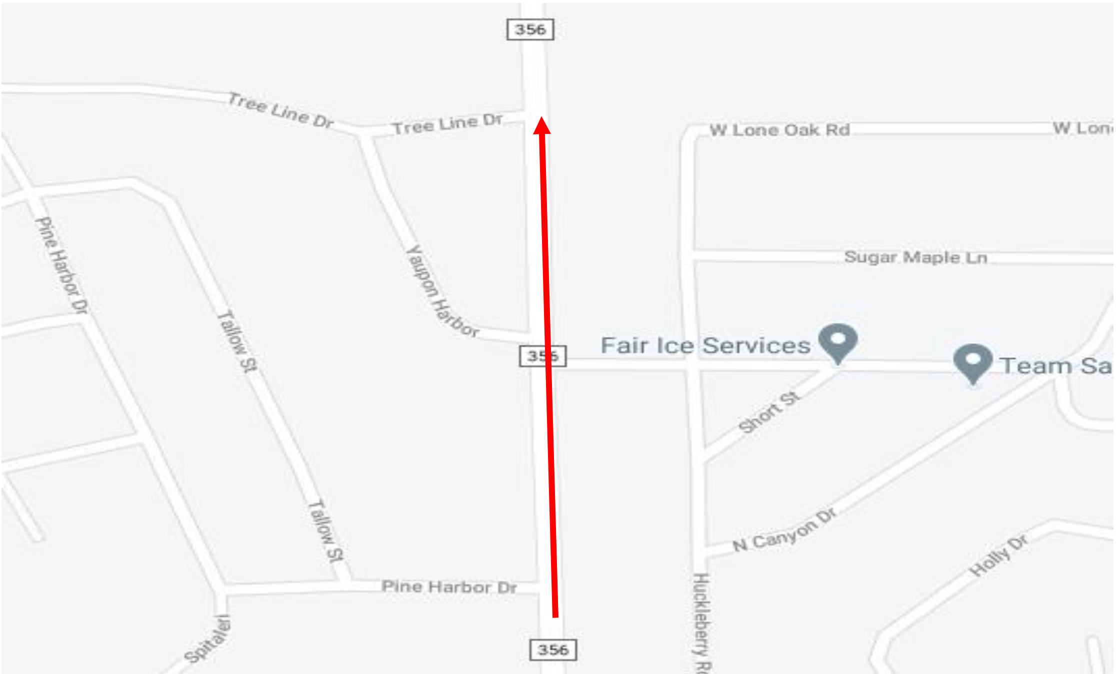


Figure 3-17. FM 356 Field Evaluation Location.

Figure 3-18. Photo Taken at the FM 356 Section in March 2020.

Due to the COVID-19 shelter-in-place order and the travel restrictions starting in March 2020, the field evaluation of FM 356 was postponed. However, this section was seal coated during the second half of 2020. Thus, when the researchers conducted the field evaluation in January 2021, the evaluations were mainly on the shoulder, representing the pavement surface under little traffic polishing (Figure 3-19).

Figure 3-19. Field Evaluation at the FM 356 Section in January 2021.

For each test station, the researchers performed the laser tests (CTM and ARTS) first and then the DFT test. This was because the DFT test needs water on the pavement, which will cause reflection and affect the laser test result. Each test equipment was carefully aligned to ensure each tested the same area. For example, the DFT and the ARTS covered the same ring area, and the CTM point laser circumference was in the middle of the ring area. Figure 3-20, Figure 3-21, and Figure 3-22 show the CTM, ARTS, and DFT results, respectively. For each station, three repeated runs were performed for the CTM and DFT tests, and two repeated runs were performed for the ARTS test. The figures show the average value for each station.

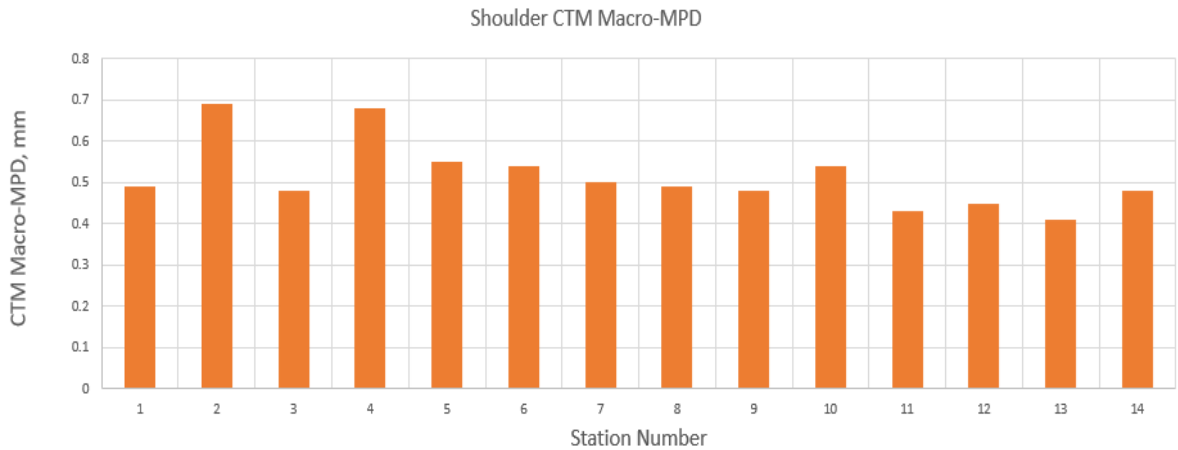
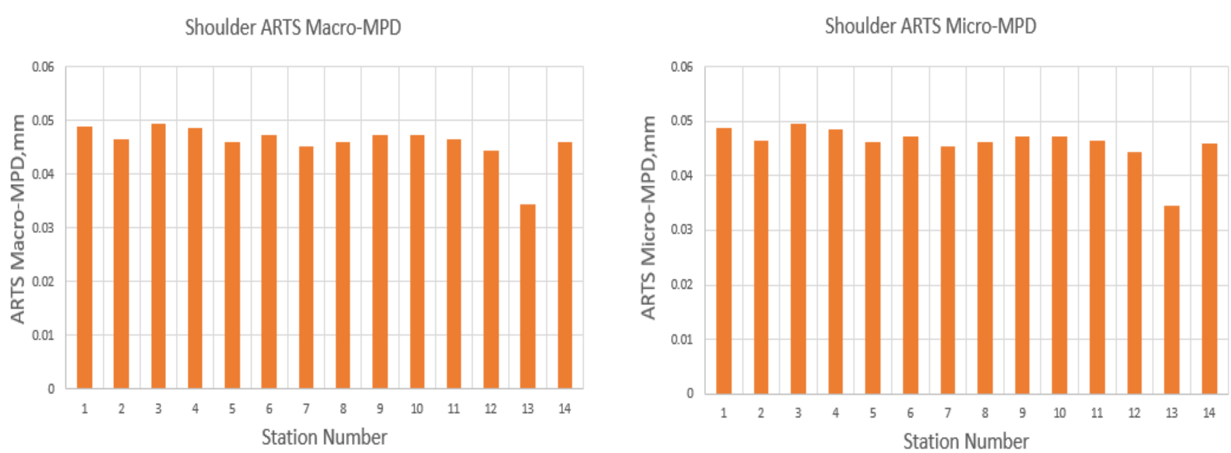
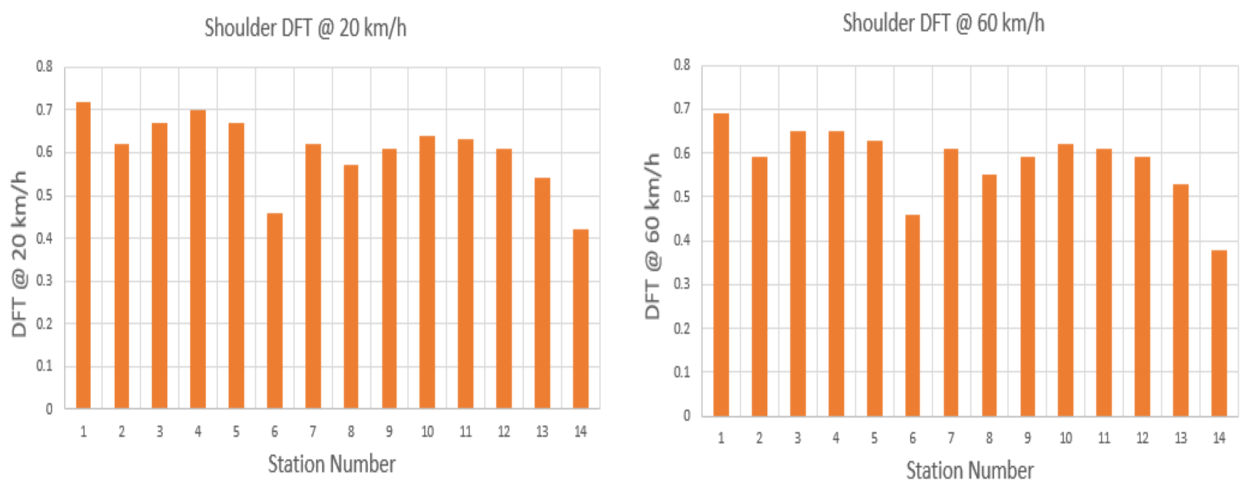


Figure 3-20. FM 356 Shoulder CTM Macro-MPD Results.



(a) (b)

Figure 3-21. FM 356 Shoulder ARTS (a) Macro-MPD and (b) Micro-MPD Results.



(a) (b)

Figure 3-22. FM 356 Shoulder DFT at (a) 20 km/h and (b) 60 km/h Results.

Figure 3-23 compares the ARTS macro-MPD and the CTM macro-MPD station by station. The CTM values are very close to the ARTS values; the two sets of values have a very good relationship.

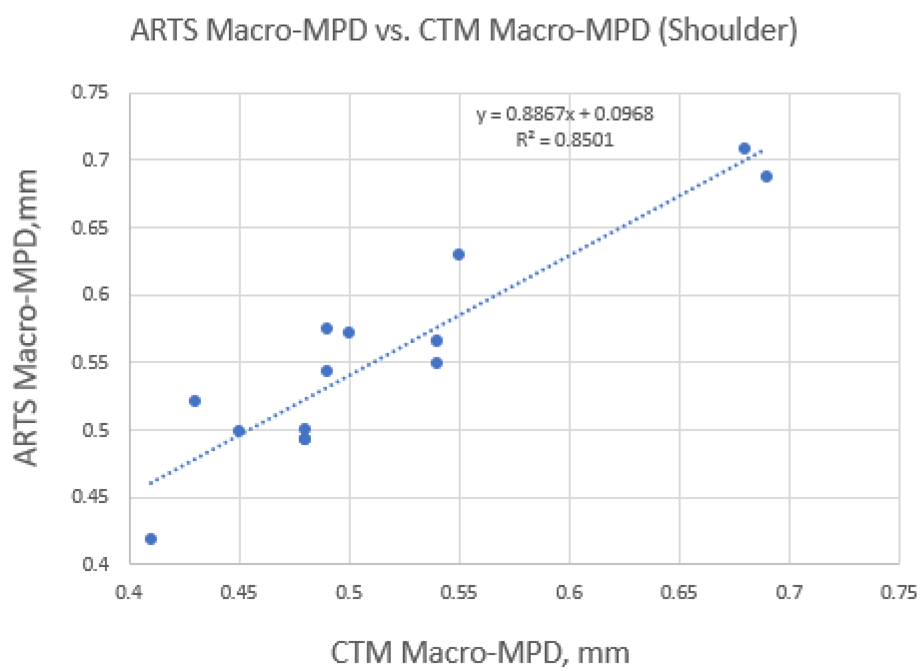


Figure 3-23. Comparison between FM 356 ARTS Macro-MPD and CTM Macro-MPD Station by Station.

Table 3-3 lists the test results by averaging all stations. These numbers will be used to compare with other test sections later.

Table 3-3. FM 356 Shoulder Test Results by Averaging All Stations.

CTM Macro-MPD, mm	DFT @ 20 km/h	DFT @ 60 km/h	ARTS Micro-MPD, mm	ARTS Macro-MPD, mm
0.515	0.606	0.582	0.046	0.553

IH 20 Field Evaluation

In March 2021, the researchers traveled to the Atlanta District IH 20 section and selected the field evaluation location close to the intersection with SH 43, as seen in Figure 3-24. The selected section was around 1,500 ft, and the test interval was 100 ft. Figure 3-25 shows the pavement surface condition at that time. The wheel path and the shoulder had the same surface mixture at this location.

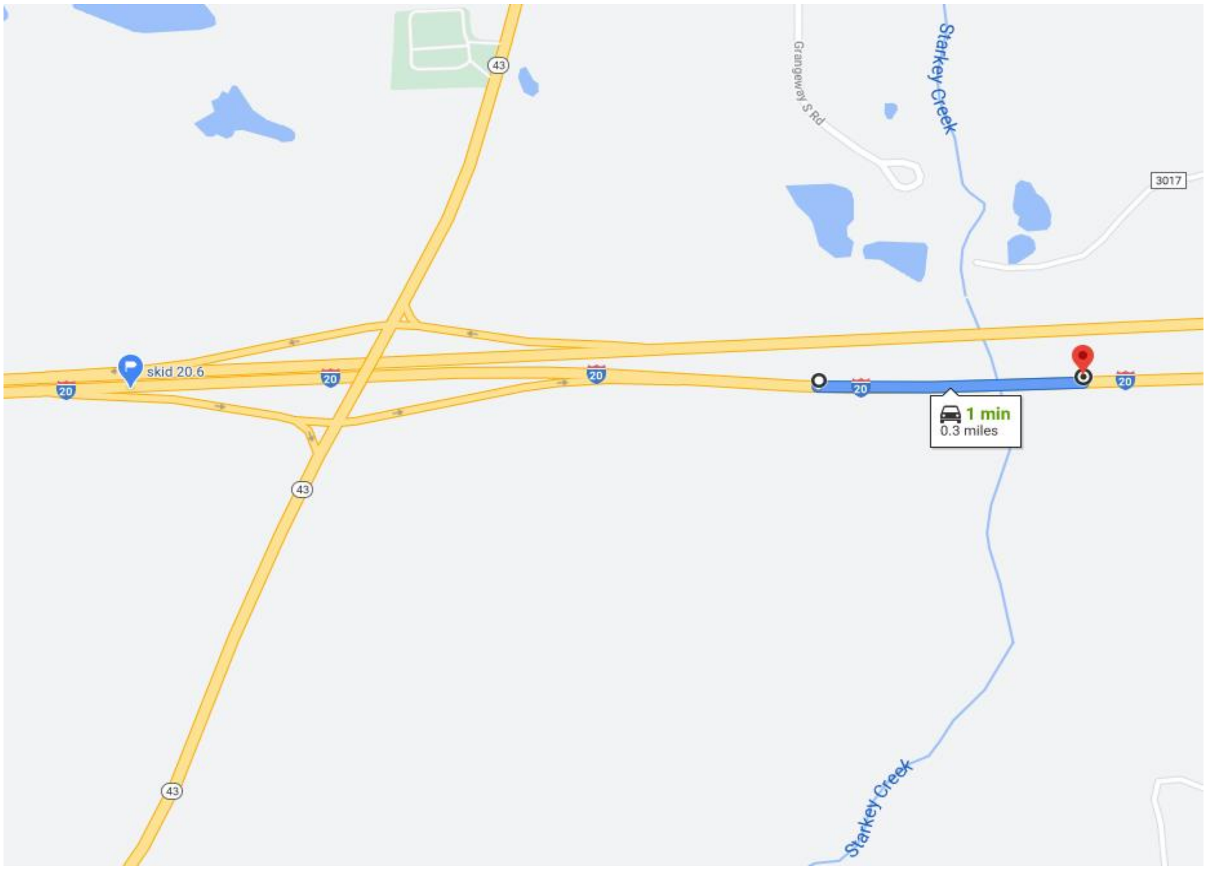


Figure 3-24. IH 20 Field Evaluation Location.

Figure 3-25. IH 20 Pavement Surface Condition in March 2021.

With the coordination of the project manager and help from the TxDOT traffic control team, the field evaluation of the IH 20 section was conducted on March 18, 2021. The CTM, ARTS, and DFT tests were conducted on the wheel path and the shoulder (Figure 3-26). Figure 3-27, Figure 3-28, and Figure 3-29 show the IH 20 CTM, ARTS, and DFT test results, respectively. For each test location, three repeated runs were performed for the CTM and DFT tests, and two repeated runs were performed for the ARTS test. Each figure shows both the main-lane wheel path and shoulder test results for comparison.

Figure 3-26. Field Evaluation at the IH 20 Section in March 2021.

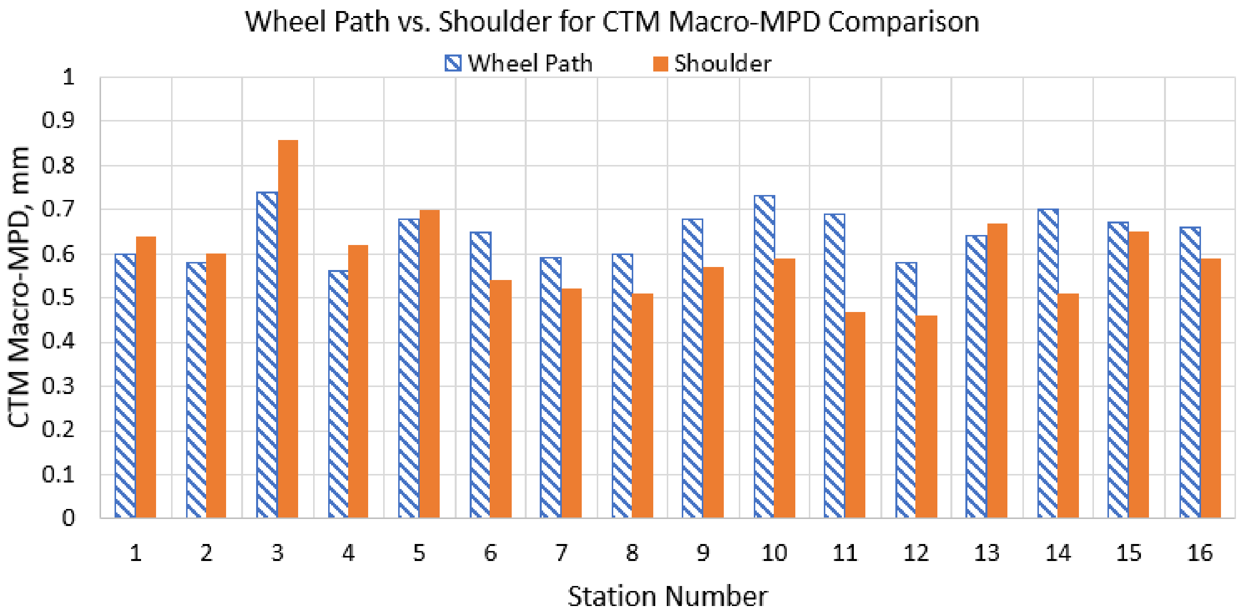
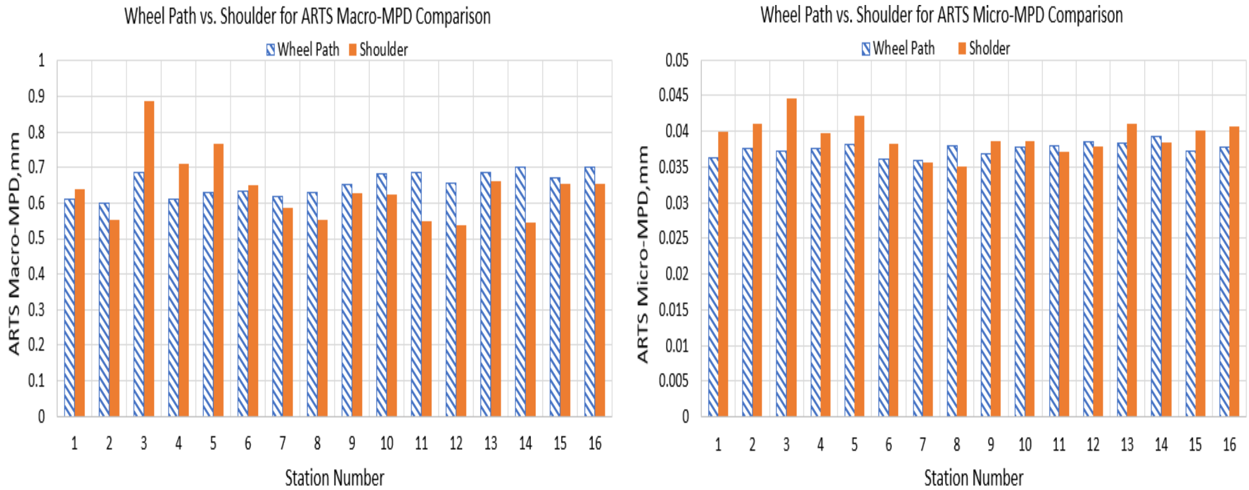
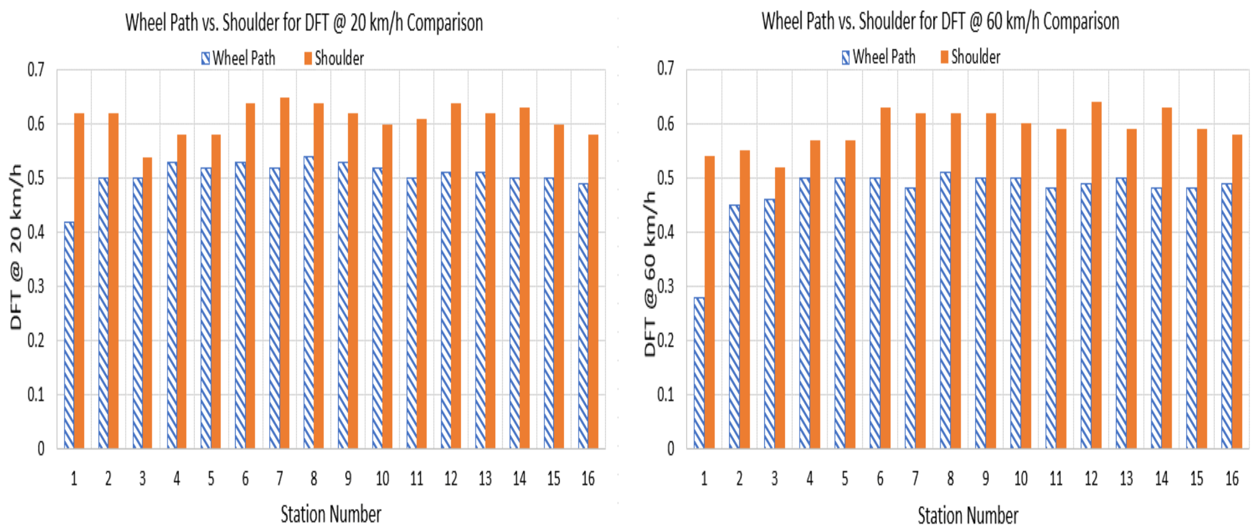


Figure 3-27. IH 20 CTM Macro-MPD Results.



(a) (b)

Figure 3-28. IH 20 ARTS (a) Macro-MPD and (b) Micro-MPD Results.



(a) (b)

Figure 3-29. IH 20 DFT at (a) 20 km/h and (b) 60 km/h Results.

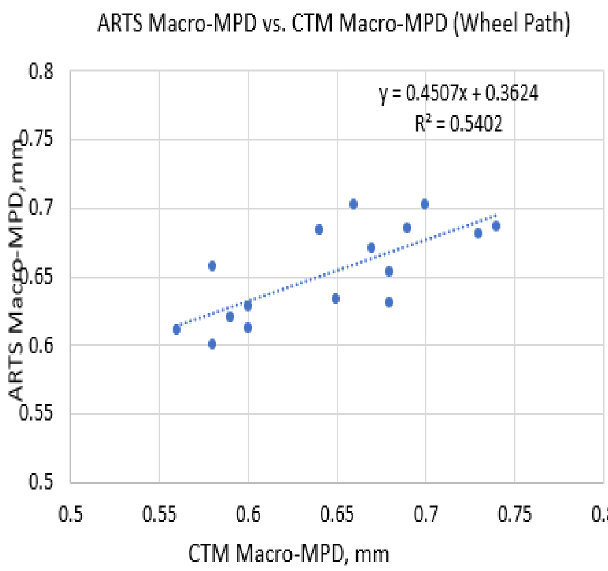
Comparing the CTM values in Figure 3-27 indicates that, for some stations, the shoulder CTM macro-MPD values are larger and, for other stations, smaller than the main-lane values. The same trend for the ARTS macro-MPD values is in Figure 3-28a. However, Figure 3-29 shows that the shoulder DFT values are consistently larger than the main-lane DFT values. Similarly, most shoulder ARTS micro-MPD values are larger than the main-lane values (Figure 3-28b). An unpaired t-test (also known as an independent t-test) was performed between the shoulder and the main-lane values; the results are listed in Table 3-4. The unpaired t-test is a statistical procedure that compares the averages/means of two independent or unrelated groups to determine if there is a significant difference between the two groups. The t-test value < 0.05 indicates that the difference is significant.

It can be concluded from Table 3-4 that the DFT values (both at 20 km/h and 60 km/h) have significant differences between the main-lane wheel path and the shoulder; the ARTS micro-MPD also has significant differences as well. However, the macro-MPD values (both CTM macro-MPD and ARTS macro-MPD) do not have significant differences (the t-test value is 0.0739 and 0.519, respectively). This result implies that the traffic polish might mainly change the DFT values and microtexture (micro-MPD values), while the macrotexture (macro-MPD) might not be affected much.

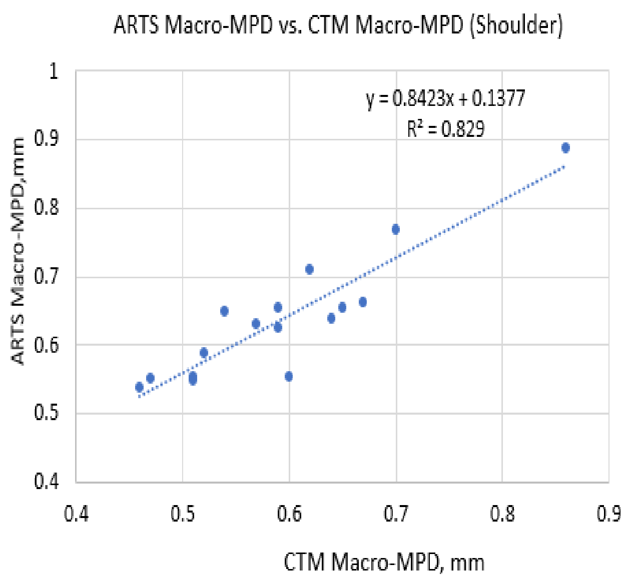
Table 3-4. IH 20 Unpaired t-Test Results between Wheel Path and Shoulder.

CTM Macro-MPD, mm	DFT @ 20 km/h	DFT @ 60 km/h	ARTS Micro-MPD, mm	ARTS Macro-MPD, mm
0.0739	2.44E-11	5.34E-08	0.0086	0.519

Figure 3-30 shows the comparison between the IH 20 ARTS macro-MPD and the CTM macro-MPD station by station. In general, a larger CTM macro-MPD value corresponds to a larger ARTS macro-MPD value, and the differences between the values are not significant.



(a)



(b)

Figure 3-30. Comparison between IH 20 ARTS Macro-MPD and CTM Macro-MPD Station by Station on the (a) Wheel Path and (b) Shoulder.

Although the R^2 for the wheel path is not high (0.54) in this case, the difference between the CTM macro-MPD and the ARTS macro-MPD is small (less than 10 percent), as seen in Table 3-5.

Table 3-5. IH 20 Main-Lane Wheel-Path Macro-MPD Comparison between CTM and ARTS.

Station Number	CTM Macro-MPD, mm	ARTS Macro-MPD, mm	Difference (%)
1	0.6	0.61	−2.0
2	0.58	0.60	−3.5
3	0.74	0.69	7.7
4	0.56	0.61	−8.5
5	0.68	0.63	7.7
6	0.65	0.63	2.5
7	0.59	0.62	−4.8
8	0.6	0.63	−4.5
9	0.68	0.65	4.0
10	0.73	0.68	7.2
11	0.69	0.68	0.8
12	0.58	0.64	−9.5
13	0.64	0.68	−6.5
14	0.7	0.70	−0.3
15	0.67	0.67	−0.1
16	0.66	0.70	−6.1

Table 3-6 lists the test results by averaging all stations. These numbers will be used for comparison with other test sections later.

Table 3-6. IH 20 Test Results by Averaging All Stations.

Location	CTM Macro-MPD, mm	DFT @ 20 km/h	DFT @ 60 km/h	ARTS Micro-MPD, mm	ARTS Macro-MPD, mm
Shoulder	0.594	0.611	0.591	0.0393	0.638
Wheel Path	0.647	0.508	0.475	0.0375	0.654

IH 10 Field Evaluation

In April 2021, the researchers traveled to the El Paso District IH 10 section and selected the field evaluation location (frontage road), which was close to the intersection with FM 1110 (Darrington Road), as seen in Figure 3-31. The selected section was around 1,500 ft, and the test interval was 100 ft. Figure 3-32 shows the pavement surface condition at that time. The wheel path and the shoulder had the same surface mixture at this location.

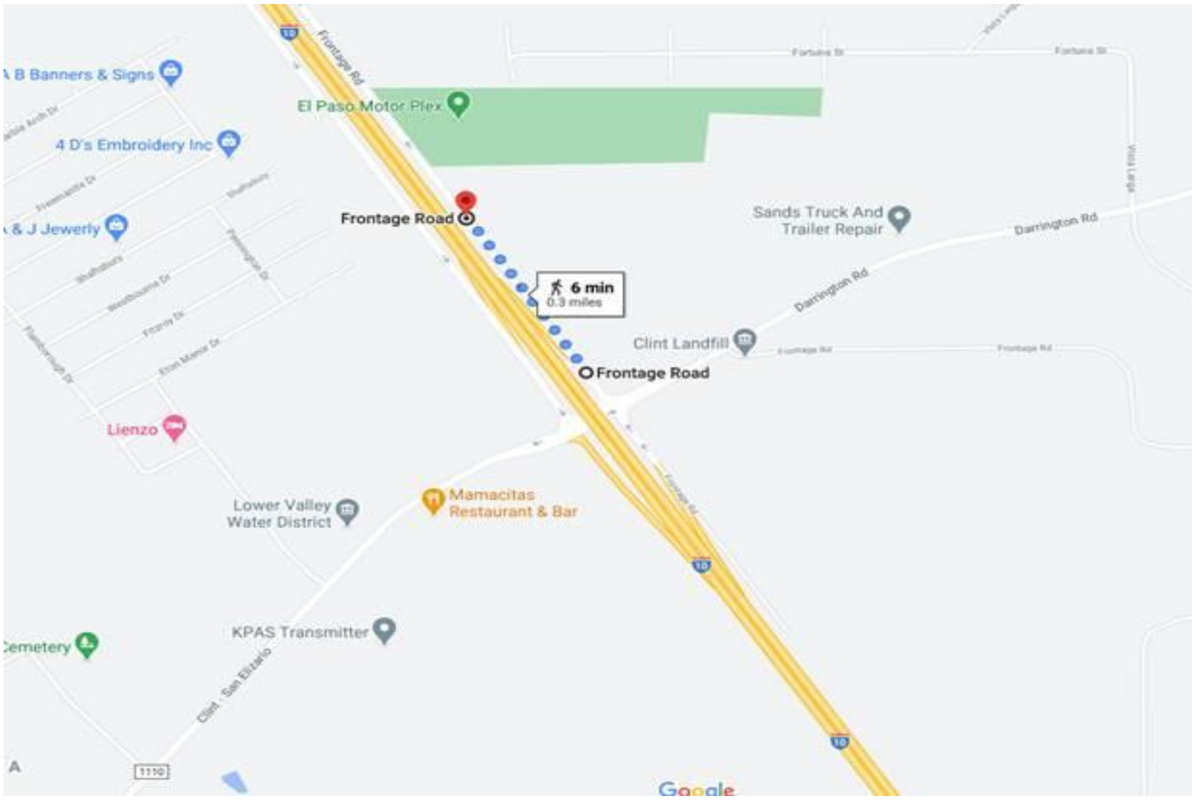


Figure 3-31. IH 10 Field Evaluation Location.

Figure 3-32. IH 10 Pavement Surface Condition in April 2021.

With the coordination of the project manager and help from the TxDOT traffic control team, the field evaluation of the IH 10 section was conducted on April 19, 2021. The CTM, ARTS, and DFT tests were conducted on the wheel path and the shoulder (Figure 3-33).

Figure 3-33. Field Evaluation at the IH 10 Section in April 2021.

Figure 3-34, Figure 3-35, and Figure 3-36 show the IH 10 CTM, ARTS, and DFT test results (both shoulder and wheel path), respectively. For each station, three repeated runs were performed for the CTM and DFT tests, and two repeated runs were performed for the ARTS test. The figures show the average value for each test location.

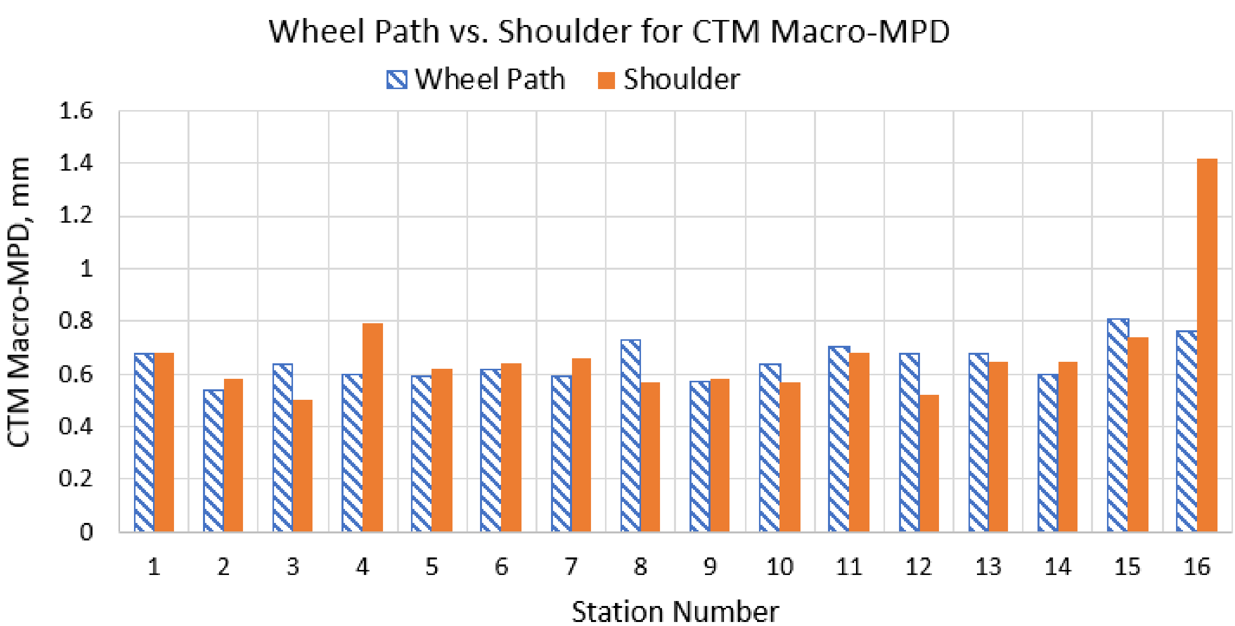
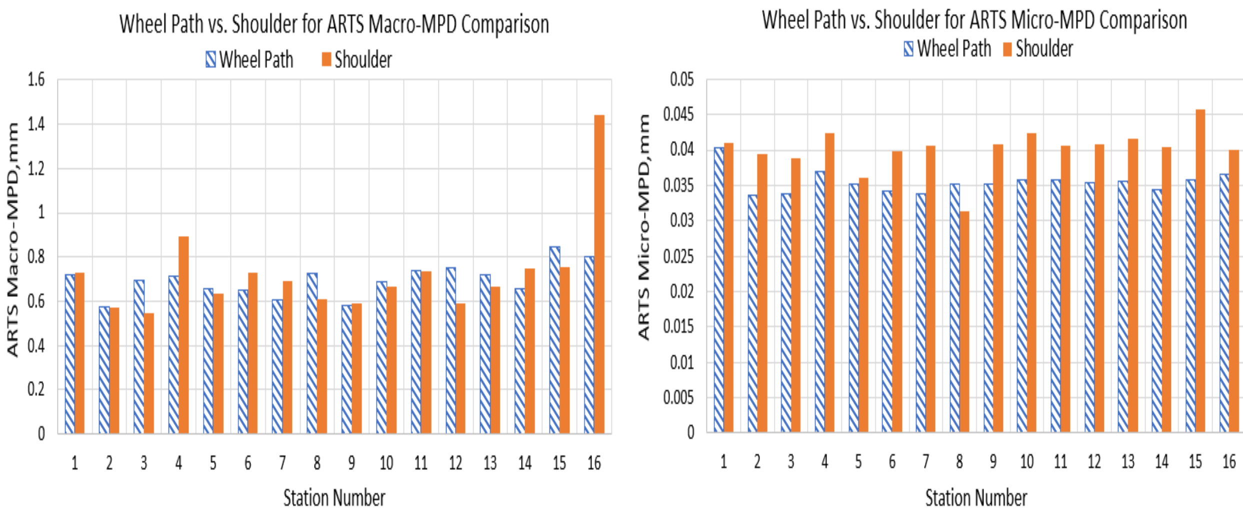
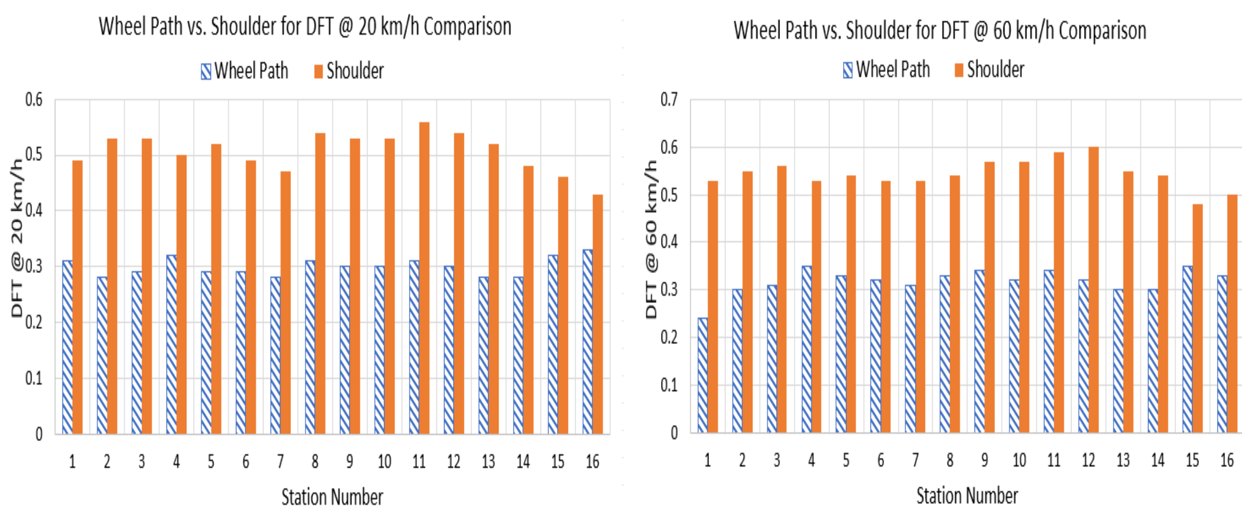


Figure 3-34. IH 10 CTM Macro-MPD Results.



(a) (b)

Figure 3-35. IH 10 ARTS (a) Macro-MPD and (b) Micro-MPD Results.



(a) (b)

Figure 3-36. IH 10 DFT at (a) 20 km/h and (b) 60 km/h Results.

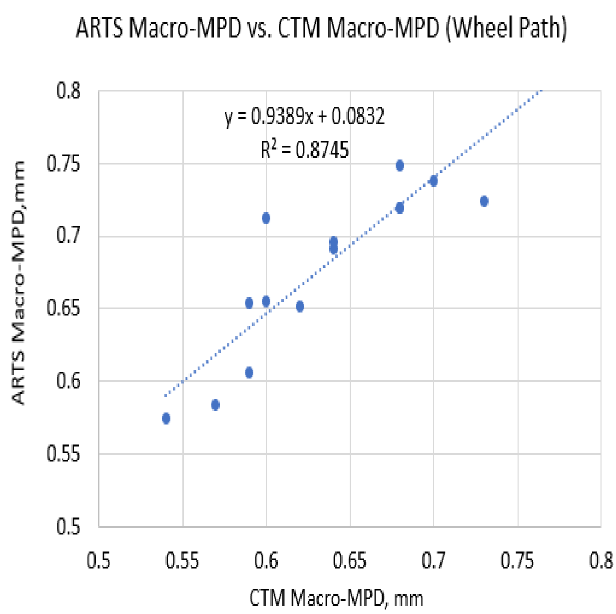
Figure 3-36 shows that the IH 10 shoulder DFT values are consistently larger than the main-lane (wheel-path) DFT values. A similar trend can be observed for the ARTS micro-MPD values in Figure 3-35b. No such trend can be found for macro-MPD either in Figure 3-34 (CTM macro-MPD) or Figure 3-35a (ARTS macro-MPD). These findings are consistent with the findings from the IH 20 test results.

An unpaired t-test was performed between the IH 10 shoulder and the main-lane values; the results are listed in Table 3-7. Since the t-test value < 0.05 indicates that the difference is significant, it can be concluded that (a) the shoulder DFT values are larger than the main-lane (wheel-path) DFT values and the difference is statistically significant, (b) the shoulder micro-MPD values are larger than the main-lane wheel-path micro-MPD values and the difference is statistically significant, and (c) the shoulder macro-MPD values are not statistically different from the main-lane wheel-path macro-MPD values. These conclusions from the IH 10 field data are consistent with the IH 20 field data conclusions.

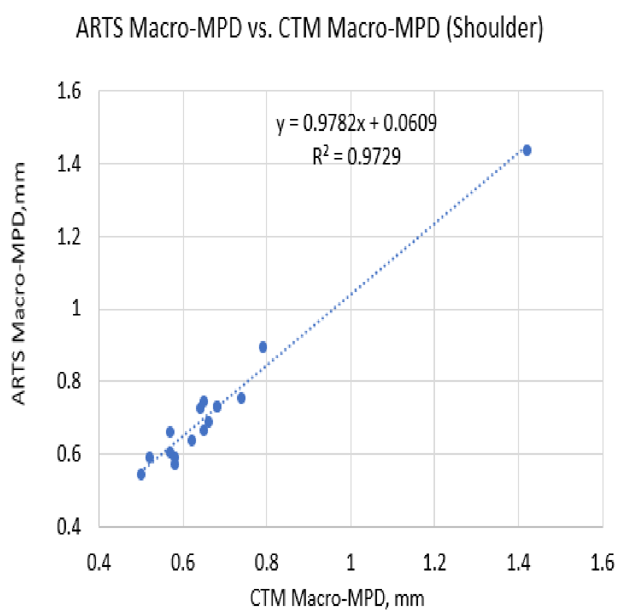
Table 3-7. IH 10 Unpaired t-Test Results between the Wheel Path and Shoulder.

CTM Macro-MPD, mm	DFT @ 20 km/h	DFT @ 60 km/h	ARTS Micro-MPD, mm	ARTS Macro-MPD, mm
0.6429	7.3342E-20	2.6965E-20	8.06863E-06	0.6058

Figure 3-37 shows the comparison between the IH 10 ARTS macro-MPD and the CTM macro-MPD station by station. In general, a larger CTM macro-MPD value corresponds to a larger ARTS macro-MPD value, and the differences between the values are not significant. The R^2 values are high for both the wheel path and shoulder (0.87 and 0.97).



(a)



(b)

Figure 3-37. Comparison between IH 10 ARTS Macro-MPD and CTM Macro-MPD Station by Station on the (a) Wheel Path and (b) Shoulder.

Table 3-8 lists the test results by averaging all stations. These numbers will be used for comparison with other test sections later.

Table 3-8. IH 10 Test Results by Averaging All Stations.

Location	CTM Macro-MPD, mm	DFT @ 20 km/h	DFT @ 60 km/h	ARTS Micro-MPD, mm	ARTS Macro-MPD, mm
Shoulder	0.678	0.508	0.544	0.0401	0.724
Wheel Path	0.652	0.299	0.318	0.0355	0.695

Comparison among Field Sections

Table 3-9 lists the test results of three field sections together for comparison. The number in the table is the result of averaging all stations in the corresponding field section.

Table 3-9. Test Results Comparison among Sections.

Sections	CTM Macro-MPD, mm	DFT @ 20 km/h	DFT @ 60 km/h	ARTS Micro-MPD, mm	ARTS Macro-MPD, mm	Skid Number
FM 356 Shoulder	0.515	0.606	0.582	0.0460	0.553	—
IH 20 Shoulder	0.594	0.611	0.591	0.0393	0.638	—
IH 10 Shoulder	0.678	0.508	0.544	0.0401	0.724	—
FM 356 Wheel Path	—	—	—	—	—	19 (2018)
IH 20 Wheel Path	0.647	0.508	0.475	0.0375	0.654	32 (2016)–26 (2018)
IH 10 Wheel Path	0.652	0.299	0.318	0.0355	0.695	19–25 (2019)

Note: — means not applicable.

The DFT (both at 20 km/h and at 60 km/h) rankings (from high to low values) among the three sections are IH 20 > FM 356 > IH 10, as seen in Figure 3-38. However, neither the micro-MPD ranking nor the macro-MPD ranking is consistent with the DFT ranking.

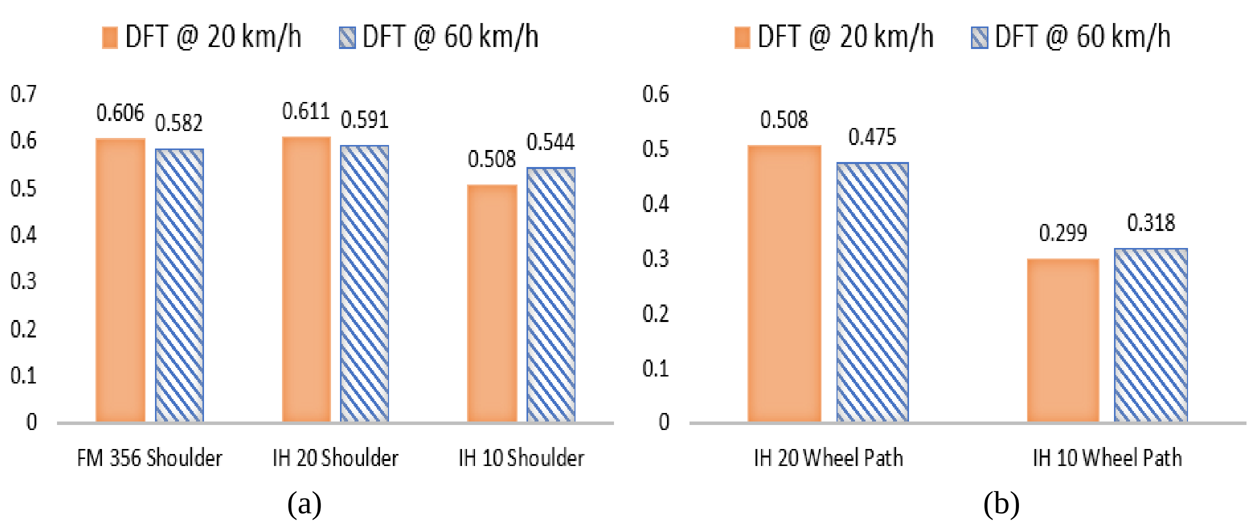


Figure 3-38. DFT Results Comparison among Three Field Sections on the (a) Shoulder and (b) Wheel Path.

The field DFT ranking is consistent with the ranking of lab DFT tests on mixture slabs, as seen in Figure 3-39. Chapter 4 will describe the aggregate and mixture slab tests in more detail.

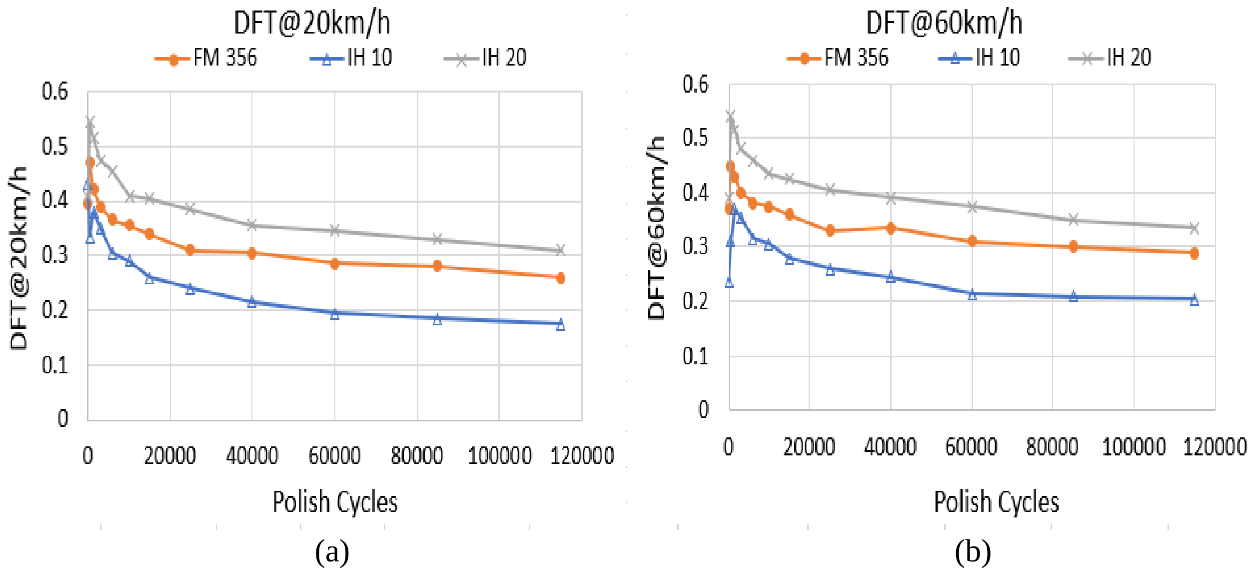


Figure 3-39. DFT Results Comparison among Mixture Slabs of Three Test Sections at (a) 20 km/h and (b) 60 km/h.

SUMMARY AND CONCLUSIONS

This chapter describes the field evaluation work. Three test sections were identified: (1) FM 356 in the Lufkin District, (2) IH 20 in the Atlanta District, and (3) IH 10 in the El Paso District. The test sections were reported to have low field skids, although the surfaces belong to SAC-A materials. The overall goal was to evaluate the pavement field surface friction numbers and textures (in terms of macro-MPD and micro-MPD), find the relationship among these surface characteristics, and identify the potential cause of the low skid numbers. Three types of tests were performed on the test sections: (1) the CTM laser test for macro-MPD determination, (2) the ARTS laser test for micro- and macro-MPD determination, and (3) the DFT test for friction number determination. The conclusions and findings are summarized as follows:

- The FM 356 section surface is a Superpave C mixture with 29 percent sandstone (coarse aggregate); the percentage of coarse component (retaining on the No. 4 sieve) from the SAC-A aggregate (sandstone) over the total coarse component is 63.8 percent. The IH 20 section surface is a dense-graded Type D mixture with all igneous aggregates (coarse and fine); the percentage of coarse component (retaining on the No. 4 sieve) from the SAC-A aggregate (igneous) is 100 percent. The IH 10 section surface is a Superpave C mixture with 28 percent igneous (coarse aggregate); the percentage of coarse component (retaining on the No. 4 sieve) from the SAC-A aggregate (igneous) is 53.4 percent.
- The pavement shoulder DFT values (at 60 km/h and 20 km/h) are larger than the wheel path DFT values. The difference is statistically significant. These findings confirm that the traffic polish makes the pavement surface smoother and less skid-resistant. The results are consistent with the IH 20 skid number results, which significantly decreased from 2016 to 2018.

- The pavement shoulder micro-MPD values are larger than the wheel path DFT values. The difference is also statistically significant. These findings confirm that the traffic's aggregate surface microtexture gets polished and contributes to the lower skid resistance of the main-lane wheel path.
- The pavement shoulder macro-MPD values are not statistically different from the main-lane wheel-path macro-MPD values. This result implies traffic polish does not change the macrotexture in these sections by much. This lack of change is reasonable since the macrotexture mainly depends on the arrangement of the aggregates (both coarse and fine), and this arrangement will not change much if no significant distress (such as bleeding, cracking, stripping, etc.) appears on the pavement surface.
- The CTM macro-MPD values have a good relationship with the ARTS macro-MPD values. Their value difference for each station is usually less than 10 percent. Since the ARTS is equipped with a line laser and provides a 3D profile rather than a CTM 2D profile, the ARTS macro-MPD might be more representative to describe the surface macrotexture. In addition, the ARTS can determine the micro-MPDs based on the same 3D profile. Due to these features, the ARTS is considered a very convenient tool for pavement texture analysis.
- The DFT ranking (from high to low values) among the three sections is IH 20 > FM 356 > IH 10. The field DFT ranking is consistent with the ranking of lab DFT tests on mixture slabs.
- Neither the micro-MPD ranking nor the macro-MPD ranking is consistent with the DFT ranking of the field pavements or lab-molded mixture slabs. It is widely agreed that pavement macrotexture and microtexture are the primary contributors to pavement friction performance at high and low traffic speeds (Henry 2000). However, there is no unique relationship between texture and friction; though strong and statistically significant, the relationship is different for each pavement surface type (Izeppi et al. 2010, Zuniga-Garcia and Prozzi 2019). Thus far, no consistent relationships have been developed for pavement texture and friction. More details are described and discussed in the next chapter.

CHAPTER 4 ASSEMBLE AND CHARACTERIZE RAP MATERIALS

The overall goal of the work completed in this chapter was to identify the cause of the low skid numbers when good quality materials were used, to determine if RAP was a contributing factor, and to determine what, if any, other factors (such as raw aggregates, mix type, microtexture/macrotexture, and the impact of mix fines) were involved. To achieve the goal, the researchers performed the following:

- Characterized RAP using ignition, sieve analysis, Micro-Deval, DFT, and ARTS tests. The RAP materials were from four sources: RAP stockpile from Knife River Company, RAP stockpile from Vulcan Materials Company (used in FM 356 surface mixture), RAP stockpiles from El Paso County (used in IH 10 surface mixture), and SH 37 surface-milled RAP.
- Characterized raw aggregates used in FM 356, IH 20, and IH 10 mixtures using sieve analysis, Micro-Deval, and aggregate ring tests (DFT and ARTS tests).
- Fabricated FM 356, IH 20, and IH 10 mixture slabs in the lab using the corresponding raw aggregates and performed a three-wheel polishing test, DFT test, and laser texturing tests (ARTS and CTM) at certain polished cycles.
- Redesigned these mixtures by adding/removing RAP or changing the type/percentage of RAP, fabricated mixture slabs accordingly, and performed the tests mentioned above.
- Assembled the RAP and raw aggregate information and implemented the blended DFT calculation method for all these original and redesigned mixtures.
- Analyzed the aggregate and mixture slab test data, evaluated the influence of RAP on the mixture skid resistance, and determined if RAP or other factors such as mix type, macrotexture, or microtexture were contributing factors.

The following sections organize this chapter:

- Description of the lab tests performed to characterize RAP, aggregates, and mixture slabs, such as the ignition test, sieve analysis test, Micro-Deval test, aggregate ring fabricating, DFT and ARTS tests on aggregate rings, three-wheel polishing test on mixture slabs, DFT/CTM/ARTS test on mixture slabs, etc.
- Presentation of the lab test results on different types of raw aggregate, RAP, and mixture slabs (including the field test section mixture and redesigned mixture slabs).
- Assembly and analysis of the RAP aggregate, raw aggregates, mixture design information, and calculation of blended DFT for all the original and redesigned mixtures.
- Presentation of findings and conclusions.

LAB TESTS

This chapter describes the lab tests performed to characterize RAP, aggregates, and mixture slabs. These lab tests include the RAP ignition test, aggregate sieve analysis test, Micro-Deval test, aggregate ring fabricating, DFT and ARTS tests on aggregate rings, mixture slab fabricating, three-wheel polishing test on mixture slabs, DFT/CTM/ARTS test on mixture slabs, and the corresponding preparation work. Some tests, such as aggregate ring tests, are newly developed and have no specifications yet. Combining the aggregate, mixture, and field pavement test results may elucidate answers to (or provide more understanding about) why some pavements had low skid numbers when good quality materials were used and if RAP was a contributing factor.

Below are the descriptions of each lab test and the corresponding preparation work.

Ignition Test

To characterize RAP aggregate, the binder in the RAP material needs to be removed first. The ignition test is done to burn out the binder and determine the binder content. To make sure each ignition test sample was consistent and representative, the researchers first mixed several buckets of RAP material, dried them in a 60°C conditioning room, and then used a mechanical splitter to reduce the portion until obtaining the appropriate quantity for the ignition test (Figure 4-1). The test followed the TxDOT standard test method Tex-236-F: Determining Asphalt Content from Asphalt Paving Mixtures by the Ignition Method (TxDOT 2019). In this method, the sample is heated to 538°C for 30 to 40 minutes until all the asphalt is burned off. The mass difference before and after ignition is determined as the asphalt content.

(a)

(b)

(c)

Figure 4-1. Ignition Test—(a) RAP Material Splitting, (b) Sample, and (c) Furnace.

Sieve Analysis

The researchers used this test method to determine the particle size distribution of aggregate samples, including raw and RAP aggregates. First, according to AASHTO R76 (AASHTO 2016), the researchers used the mechanical splitter to reduce the portion until obtaining the appropriate mass for two replicates of sieve analysis for each aggregate stockpile. Then the samples were placed in the oven and dried to constant weight at a temperature of 107°C. The test followed the TxDOT standard test method Tex-200-F: Sieve Analysis of Fine and Coarse Aggregates, Part II (TxDOT 2016a) to determine a weight-based washed sieve analysis. This procedure assesses the aggregate size distribution by allowing the material to pass through a series of sieves of progressively smaller mesh size and weighing the amount of material that retains on each sieve as a fraction of the whole mass. The passing percentage of each sieve is incorporated into the mixture design. Figure 4-2 shows the sampling and test equipment.

(a) (b)

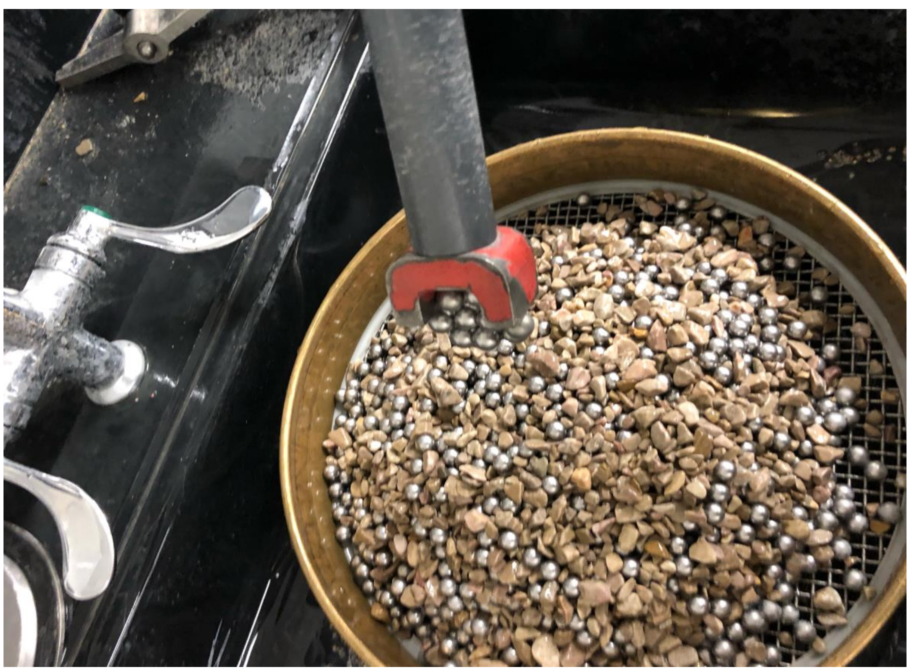
Figure 4-2. Sieve Analysis Test—(a) Sampling and (b) Equipment.

Micro-Deval Abrasion

TxDOT's aggregate laboratory subjected aggregate samples from each source to Micro-Deval abrasion following standard test method Tex-461-A (TxDOT 2016b). The procedure requires a 1,500 ± 5 g sample of aggregates that have been sieved, washed, and oven-dried to constant weight at a temperature of 110°C. The container used for testing is prepared by adding 5,000 ± 5 g of stainless steel balls. These balls are placed before putting the aggregate test sample in the container to minimize abrasion. After introducing the aggregate sample, 2,000 ± 500 ml of water is poured into the container to saturate the sample for a minimum of 1 hour. After saturation, the container is placed on its side in the Micro-Deval apparatus and tested at 100 ± 5 rpm for 105 ± 1 minute in the case of bituminous aggregates.

After the established test time, sieve No. 4 (4.75 mm) and sieve No. 16 (1.18 mm) are stacked and used to decant the aggregate sample. The sample is then washed until the water running from the stack of sieves is clear, and all material passing sieve No. 16 has been removed. A magnet is then used to remove the stainless steel balls from the aggregate test sample. Subsequently, the remaining aggregate is oven-dried overnight at 230°F (110°C) and weighed after verifying the drying. The initial aggregate sample weight and oven-dry weight after the Micro-Deval test procedure are used to calculate the percent loss due to abrasion. Figure 4-3 shows the test device, sample, and post-processing, such as washing and removing the stainless steel balls using a magnet.

(a) (b)



(c)

Figure 4-3. Micro-Deval Test—(a) Device, (b) Sample, and (c) Post-Processing.

Ring-Shaped Specimen Preparation

There is no specification for preparing an aggregate ring-shaped specimen yet. The researchers followed the procedure developed by TxDOT Materials and Tests Division and Soils and

Aggregates Section (MTD/SA). In November 2019, Richard Izzo, Jeffrey Perabo, and other engineers provided a demonstration and training to the researchers on preparing the ring-shaped specimens. The process consists of several steps. First, a high-density polyethylene (HDPE) template (Figure 4-4) is needed. This template has a 1/2-inch (12.7 mm) deep and 1-inch (25.4 mm) wide circular channel. The outer diameter of the circular channel is 12 inches (305 mm).

Before filling the channel with polyester, a debonding grease was applied to the surface of the channel so the ring could be easily removed from the HDPE template after testing. Then a ratio of 0.8 lb (351 g) of polyester (filler) to 0.06 oz (1.7 g) methyl ethyl ketone peroxide (hardener) was mixed and poured into the channel. This ratio is good for allowing enough time to place and roll the aggregates before the polyester sets. After that, a 1/8-inch (3.18 mm) notched-out plastic spatula was used to remove the excessive polyester to a level approximately 1/8 inch (3.18 mm) below the surface of the HDPE template. Next, the HDPE template was placed on a turntable and slowly rotated while the aggregates were deposited with a scoop of the same width as the channel. Aggregate particles were then manually placed in areas of the ring that did not receive a tight arrangement of aggregates. Further, a hard rubber roller, wider than the ring, was rolled over the full circumference of the ring until the aggregate was flush with the surface of the HDPE template. Finally, the ring-shaped specimen was left to cure for about 1 hour before testing. Figure 4-5 shows the main steps.

The aggregate size selected for preparing the ring specimen passes a 3/8-inch sieve and retains on a 1/4-inch sieve. The aggregates before Micro-Deval abrasion and after Micro-Deval abrasion were used to fabricate aggregate rings and were subjected to a series of tests.

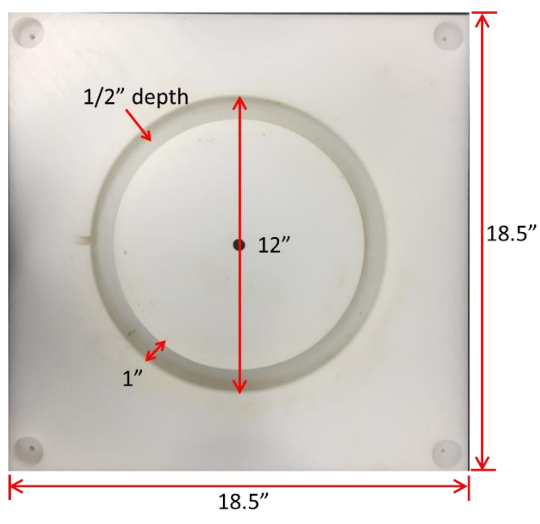


Figure 4-4. HDPE Template of Aggregate Ring Specimen.

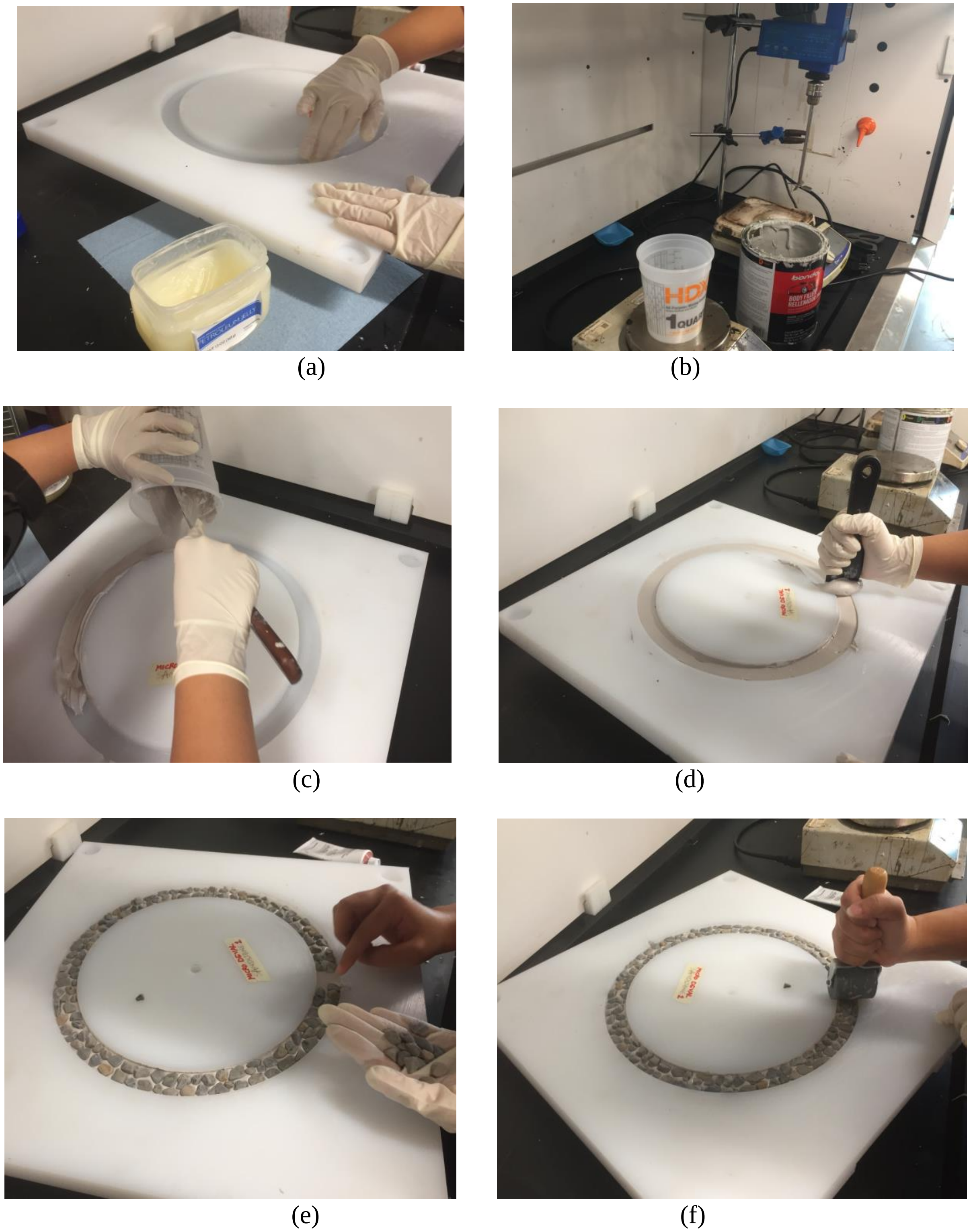
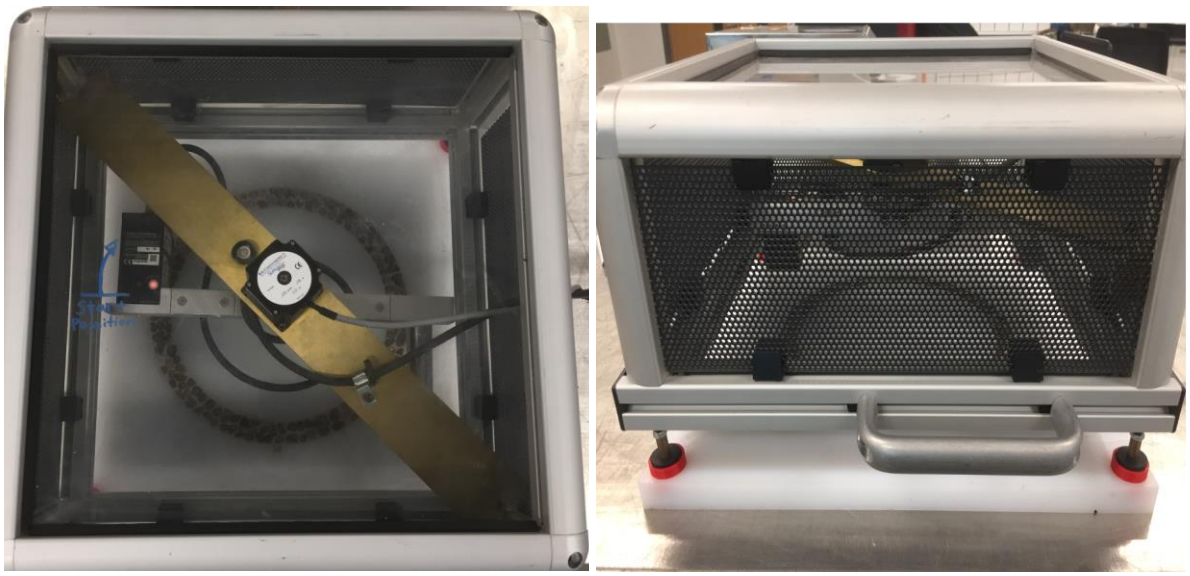


Figure 4-5. Ring Specimen Preparation Steps—(a) Apply Grease, (b) Weigh and Mix Filler and Hardener, (c) Pour the Polyester, (d) Use Notched Spatula to Remove Excessive Polyester, (e) Place Aggregate Particles, and (f) Roll over the Surface.

ARTS Test on Aggregate Rings

The laser-based system ARTS was employed to obtain the micro-MPD. This test was originally developed during TxDOT Project 5-6921-01 (Arámbula et al. 2018). As Figure 4-6 shows, the laser head is mounted onto an arm, which rotates in a circle with a diameter of 284 mm. The height of the laser head above the surface of the aggregate can be adjusted slightly with the feet or the mounting blocks at each end of the brass motor support bar. However, no adjustment should be needed after the initial setup. There is also a circular level mounted in the brass bar for reference. Four foot-cups (red color) were fabricated and put in the four corners of the HDPE template to fit the laser equipment; thus, the laser head is best positioned to cover the ring area and have the appropriate measuring height.



(a) (b)

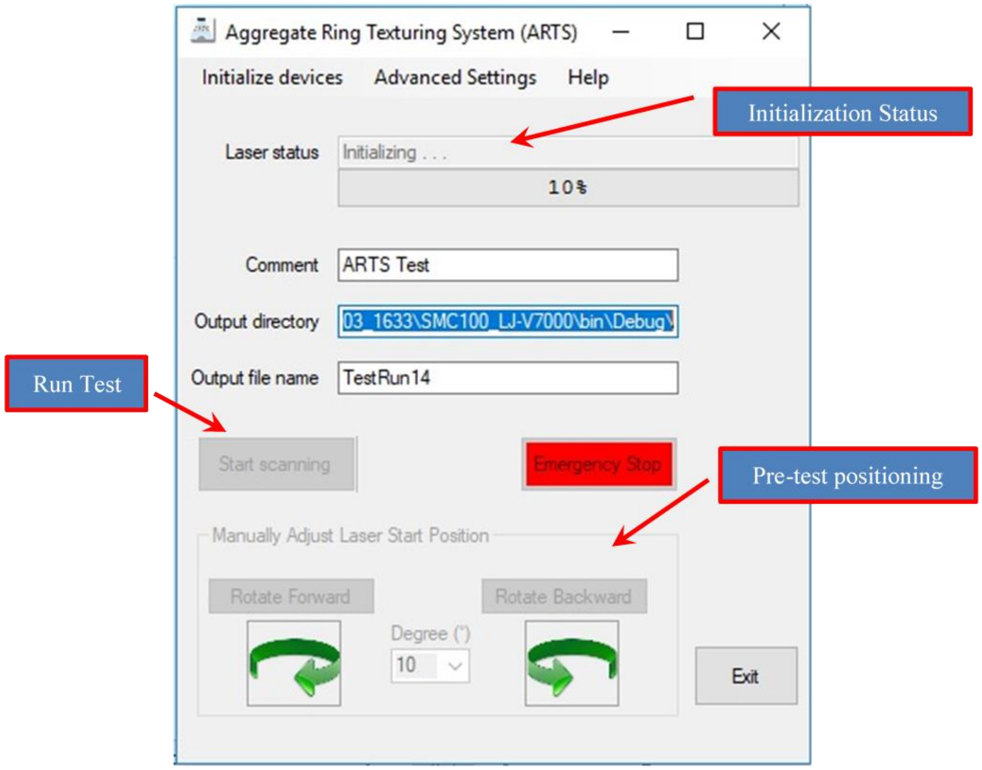
Figure 4-6. ARTS Device—(a) Top View and (b) Side View.

The ARTS laser is a line laser with a maximum measurable line width of 40 mm, enough to cover the ring width of 25 mm. The data point interval along the laser line is 0.05 mm, so there are 800 data points along the line. The laser line is parallel to the arm and perpendicular to the arm-rotating direction. Thus, the ARTS measurement covers the whole ring-shaped area and generates a 3D profile (distance [X coordinate], data point position along the laser line [Y coordinate], and elevation [Z coordinate]). Figure 4-7 shows the ring specimen photo and the ARTS-generated 3D profile. The stones in the 3D profile are one-to-one mapping to the stones in the photo. Since ARTS can produce a high-resolution 3D profile, it is ideal for the microtexture determination of aggregate surface in the rings.

(a) (b)

Figure 4-7. Aggregate Ring—(a) Specimen Photo and (b) ARTS 3D Profile (One-to-One Mapping of Stones).

Figure 4-8 shows the ARTS software user interfaces. Users click the "Start Scanning" button (Figure 4-8a) to collect data. The laser head will rotate 360 degrees in one direction (forward) and then 360 degrees reverse (backward). Two separate profile data files will be automatically collected and be differentiated by adding the suffix of "_f" (forward) or "_b" (backward) to the corresponding file name. Double-clicking each file name in the user interface of the data processing software (Figure 4-8b) initiates the identification of the stone surface and the calculation of the micro-MPD of each stone in the ring. ARTS reports the average MPD values for all the stones' surface profile segments. Users can also select any stone and segment on that stone surface profile to view the corresponding micro-MPD values.



(a)

(b)

Figure 4-8. ARTS Software User Interface of (a) Data Collecting and (b) Data Processing.

As shown in Figure 4-9, the computed micro-MPD from the corresponding forward and backward scans show excellent agreement, aligning right on top of the 45-degree equality line. There is no systematic bias between the data from the corresponding forward and backward laser scans, which means that ARTS results have very high repeatability.

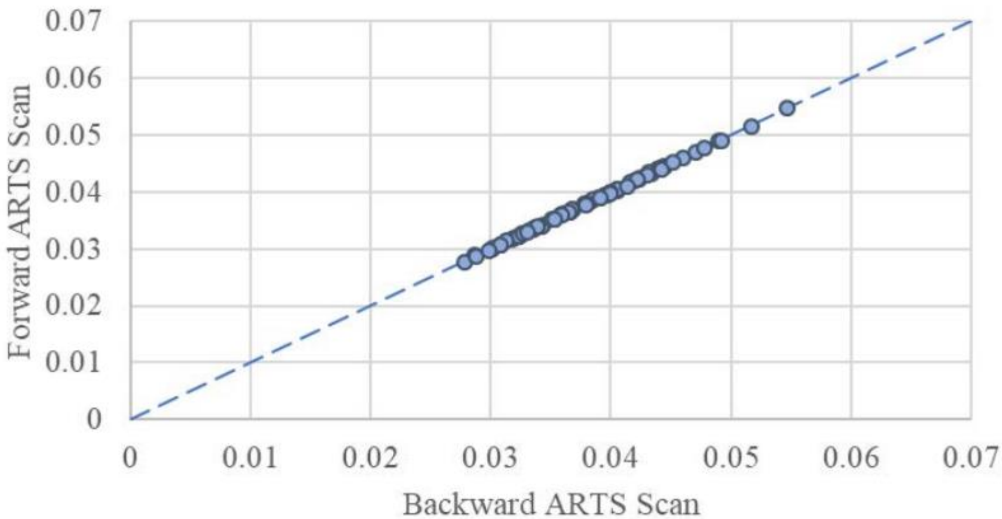


Figure 4-9. Micro-MPD Value Comparison between Forward and Backward Scans.

DFT Test on Aggregate Rings

Figure 4-10 shows the DFT device on aggregate rings. Since the aggregate ring HDPE template was designed to fit both ARTS and DFT, the three rubber sliders will align with the aggregate ring surface once the DFT device feet fit in the foot-cups on the HDPE template. The test followed ASTM E1911 (ASTM 2019), the same specification for measuring pavement surfaces. More details have been described in Chapter 3 and will not be repeated here.

(a) (b)

Figure 4-10. DFT on Aggregate Ring—(a) Top View and (b) Side View.

Mixture Slab Preparation

To measure the texture and friction of the asphalt mixture, the mixture slabs need to be fabricated to provide a pavement-like surface. The researchers used an asphalt roller compactor to make these slabs. The advantages of this compactor are: (a) aggregate orientation represents field compaction, (b) the compactor simulates the action of large paving rollers, and (c) the compaction level can be programmed to target a specific load or thickness. The procedure followed was ASTM D8079-16 (ASTM 2017d)—Standard Practice for Preparation of Compacted Slab Asphalt Mix Samples Using a Segmented Rolling Compactor. The dimension of the rigid specimen mold permits the compaction of a 500 × 400 mm asphalt mixture slab specimen, as seen in Figure 4-11. The mass of the total asphalt mixture needed to achieve the desired height (50 mm) is calculated according to the target air voids 7 ± 1 percent. The slab's weight plus the mold is very heavy (around 100 lb), so tools are needed to help with lifting and moving.

(a) (b)

Figure 4-11. (a) Asphalt Mixture Roller Compactor and (b) Rigid Specimen Mold.

Three-Wheel Polishing on Mixture Slab

The three-wheel polishing test simulates the polishing of asphalt pavement surfaces caused by vehicular traffic. Figure 4-12 shows the three-wheel polishing device. The device has three patterned pneumatic tires and can exert 146 ± 5 lb force through the tires to the test surfaces. The driving mechanism for the vertical shaft is an electric motor geared to rotate the shaft and wheel assembly at a speed of 60 ± 5 revolutions per minute. The automatic counter can shut off the machine at a predetermined number of revolutions. The tire tread should have a ribbed pattern and be free of visible contamination. When replacement is necessary, all tires should be replaced simultaneously with tires having the same tread pattern. The continuous water flush system is a recirculating system that includes a water reservoir tank, filter screen, pump, and spray bar. The water is applied uniformly across the surface of the specimen during the polishing such that any dislodged material is flushed away. The researchers fabricated two spacers (Figure 4-12) to help properly position the specimen so that each time the wheels polish the same ring area on the slab.

The test procedure followed was AASHTO PP 104-20 (AASHTO 2020b). One polishing cycle equals one 360-degree revolution of the three-wheel carriage. The National Center for Asphalt Technology (NCAT) report (Heitzman et al. 2019) indicates that the slabs with 100,000 cycles and 150,000 cycles of polishing had similar friction coefficients (the statistical p-value was 0.827 between the two groups, which is larger than 0.05 and means the difference between the groups is not significant). Therefore, it was suggested that polishing slabs for 100,000 cycles was adequate to achieve the terminal friction coefficient. In this research, the maximum number of polishing cycles for each slab was 115,000.

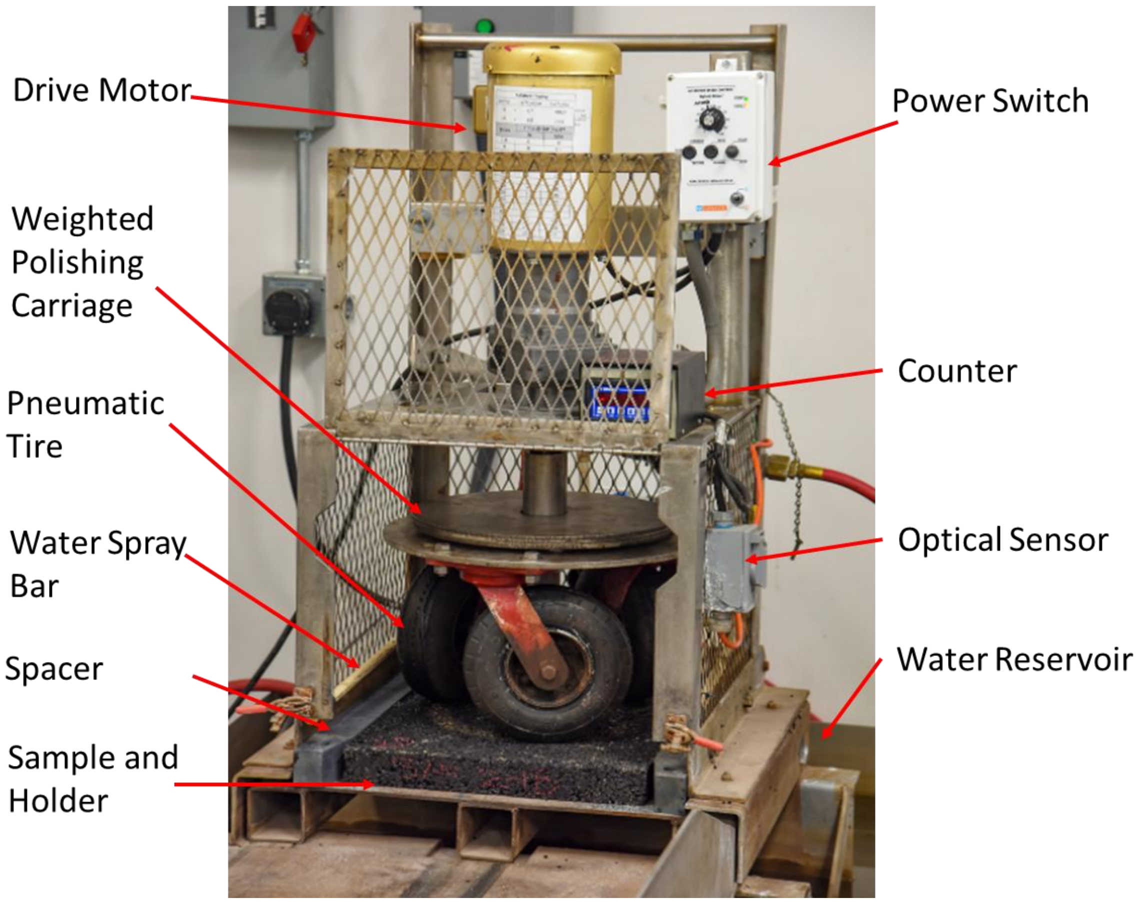
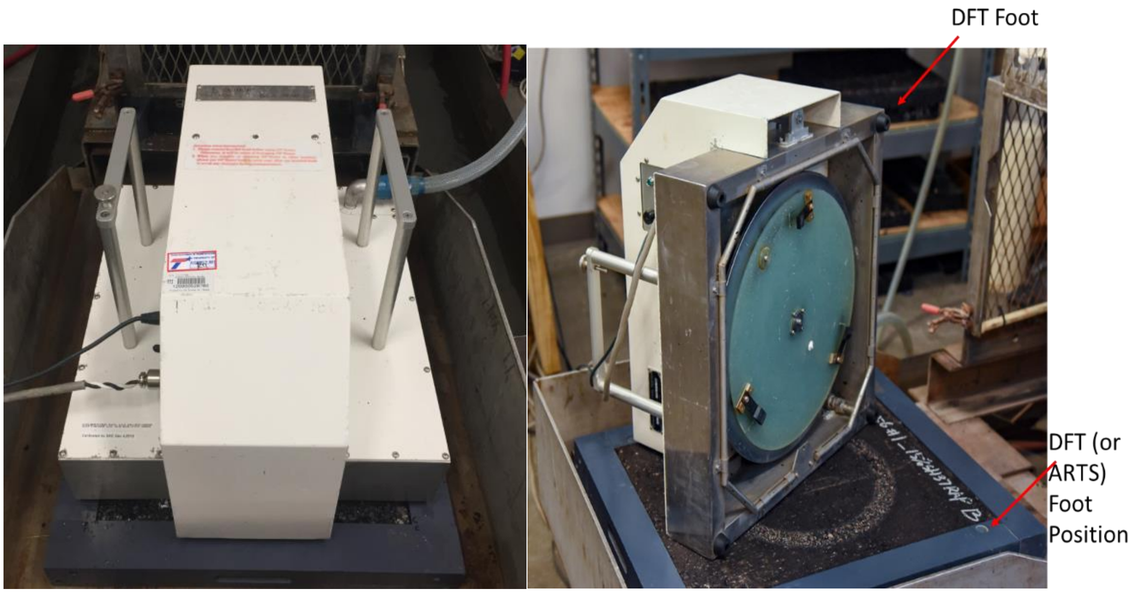


Figure 4-12. Three-Wheel Polishing Device.

DFT Test on Mixture Slab

The DFT test on the mixture slab followed ASTM E1911 (ASTM 2019), the same specification for measuring pavement surface. More details have been described in Chapter 3 and will not be repeated here. A hard plastic frame was fabricated to help support and properly position the DFT device. Four circular-shaped dents were marked to fit the four feet of the DFT device, as seen in Figure 4-13.



(a) (b)

Figure 4-13. DFT on Mixture Slab—(a) Top View and (b) Side View.

CTM Test on Mixture Slab

The CTM test was conducted according to ASTM E2157: Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter (ASTM 2015a). More details have been described in Chapter 3. The same frame used for the DFT test was also used for the CTM test. As Figure 4-14 shows, the CTM device is aligned according to the line marked on the frame, ensuring that the CTM laser measured the same polished ring area as the other tests.

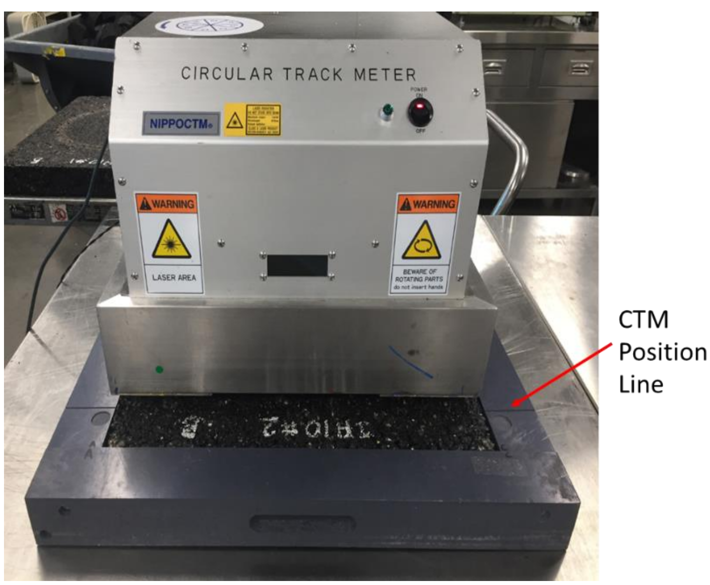


Figure 4-14. CTM on Mixture Slab.

ARTS Test on Mixture Slab

As mentioned before, the researchers modified and enhanced the ARTS data processing algorithm and software to handle the pavement and mixture slab surfaces during this project. The macrotexture determination is needed for mixture slab surfaces but is not necessary for aggregate rings. More details have been described in Chapter 3. The same frame used for the DFT test was used to align the ARTS equipment, as seen in Figure 4-15.

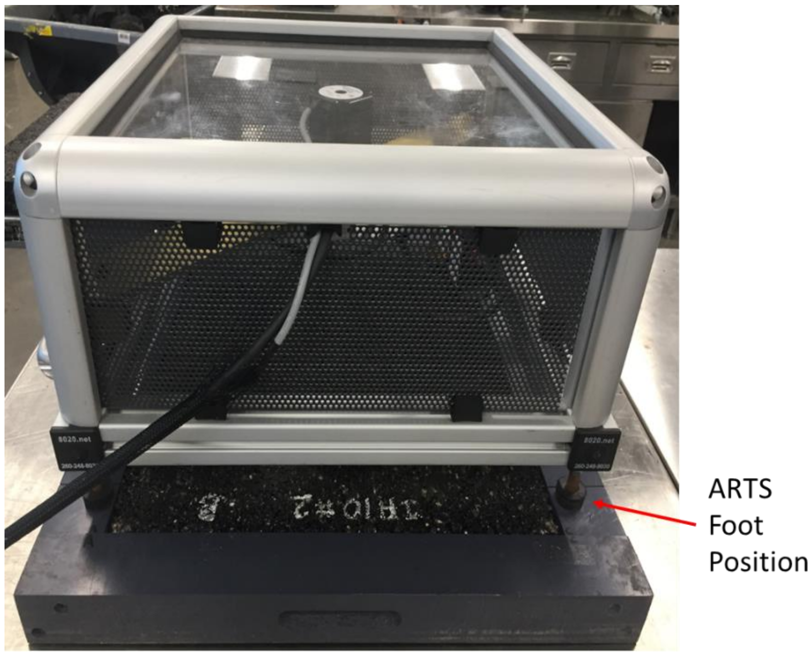


Figure 4-15. ARTS Test on Mixture Slab.

TEST RESULTS

RAP from different sources was characterized. In addition, the mixtures of the three field sections and their corresponding raw aggregates were characterized. Below presents the test results for the RAP ignition test, aggregate sieving analysis, Micro-Deval test, DFT and ARTS tests on aggregate rings, and three-wheel polishing/DFT/CTM/ARTS tests on mixture slabs.

To determine if RAP was a contributing factor to low skid numbers, some mixtures were redesigned by adding/removing RAP or changing the type/percentage of RAP. The corresponding mixture slabs were molded and evaluated. The results are presented below.

RAP Binder Contents and Aggregate Gradations

The RAP materials characterized were from four sources: (a) RAP stockpile from Knife River Company, (b) RAP stockpile from Vulcan Materials Company (used in FM 356 surface mixture), (c) RAP stockpiles from El Paso County (used in IH 10 surface mixture), and (d) SH 37 surface-milled RAP. Among these RAP materials, the SH 37 RAP was milled from the SAC-A surface mixture, and the other RAP materials may be a blend from different surface mixtures. The researchers could not track the original design of these RAP materials. For the SH 37 RAP, the researchers contacted the Paris District and RK Hall Construction and identified several possible SH 37 mixture designs. All designs clearly show the mixture was SAC-A with very high sandstone percentages.

Figure 4-16 shows the RAP binder contents obtained by the ignition test.

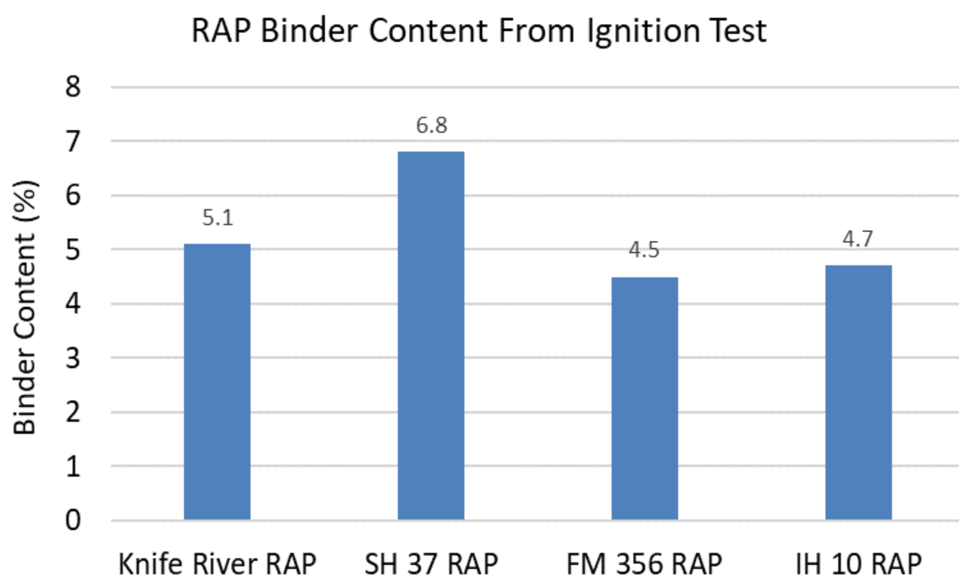


Figure 4-16. RAP Binder Contents (from the Ignition Test).

The RAP gradation numbers and plots are shown in Table 4-1 and Figure 4-17, respectively.

Table 4-1. RAP Aggregate Sieve Analysis Results.

Sieve Size	Knife River RAP	SH 37 RAP	FM 356 RAP	IH 10 RAP
3/4	100	100	100	100
1/2	93.2	100	98.2	95.8
3/8	83.2	95	92.4	84.6
No. 4	58.6	76	70.5	60.4
No. 8	41.9	56	53.7	44.2
No. 16	32.6	43	43.5	34.4
No. 30	27.0	36	36.2	27.8
No. 50	20.4	30	23.2	20.3
No. 200	10.6	11.4	4.6	7.8

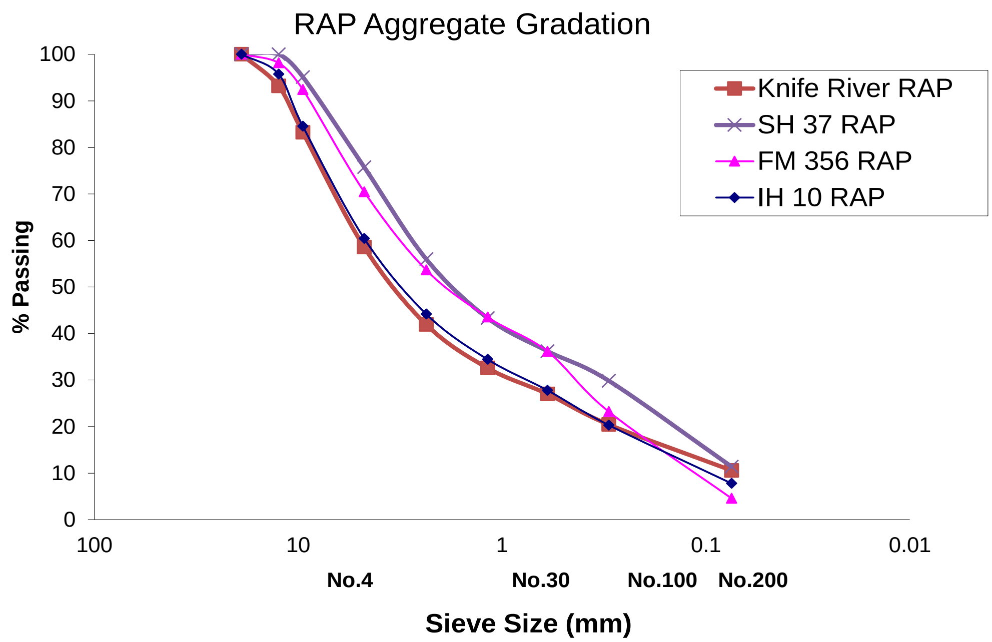


Figure 4-17. RAP Aggregate Gradation Curves.

Field Test Section Raw Aggregate Gradations

The gradations of raw aggregates from the FM 356, IH 20, and IH 10 test section mixtures were also determined by sieving analysis tests. With the gradation results of raw aggregates, the researchers were able to check the gradations, confirm that materials were collected from the correct stockpiles, obtain the needed information for Micro-Deval tests, and redesign the mixtures by adjusting stockpile percentages. Table 4-2, Table 4-3, and Table 4-4 list the sieve analysis results of raw aggregates from the FM 356, IH 20, and IH 10 test sections, respectively.

Table 4-2. FM 356 Aggregate Sieve Analysis Results.

Sieve Size	Sandstone	Limestone	Screenings	Sand	FM 356 RAP
3/4	100.0	99.0	100.0	100.0	100.0
1/2	99.3	63.0	100.0	100.0	98.2
3/8	72.7	30.0	100.0	100.0	92.4
No. 4	11.4	4.0	100.0	100.0	70.5
No. 8	2.7	3.0	88.7	99.9	53.7
No. 16	2.3	3.0	58.6	99.7	43.5
No. 30	2.2	2.0	39.7	97.2	36.2
No. 50	2.2	2.0	25.1	59.4	23.2
No. 200	2.0	1.7	5.0	0.5	4.6

Table 4-3. IH 20 Aggregate Sieve Analysis Results.

Sieve Size	Igneous 1/2	Igneous 3/8	Igneous Screenings	Sand
3/4	100.0	100.0	100.0	100.0
1/2	99.5	100.0	100.0	100.0
3/8	91.0	99.0	100.0	99.5
No. 4	31.3	38.0	96.9	97.2
No. 8	7.2	9.0	74.0	96.0
No. 16	3.7	5.0	49.9	95.0
No. 30	3.1	3.0	33.8	92.2
No. 50	2.9	2.0	22.5	71.5
No. 200	2.2	1.5	10.7	6.4

Table 4-4. IH 10 Aggregate Sieve Analysis Results.

Sieve Size	Igneous	Limestone	Screenings	IH 10 RAP
3/4	100.0	100.0	100.0	100.0
1/2	73.9	100.0	100.0	95.8
3/8	52.4	84.0	100.0	84.6
No. 4	15.3	25.0	99.6	60.4
No. 8	4.1	5.0	79.6	44.2
No. 16	2.6	3.0	52.0	34.4
No. 30	2.2	3.0	35.1	27.8
No. 50	1.9	3.0	24.3	20.3
No. 200	1.3	2.3	14.3	7.8

Figure 4-18, Figure 4-19, and Figure 4-20 show the gradation comparison of raw aggregates from the FM 356, IH 20, and IH 10 test section mixtures, respectively. In the legends, "In Design" indicates the gradation curves are based on the original design numbers; "TTI Sampled" indicates the curves are based on the test data from the collected raw aggregate materials. Overall, the "TTI Sampled" aggregate gradation matches the gradation of the original design.

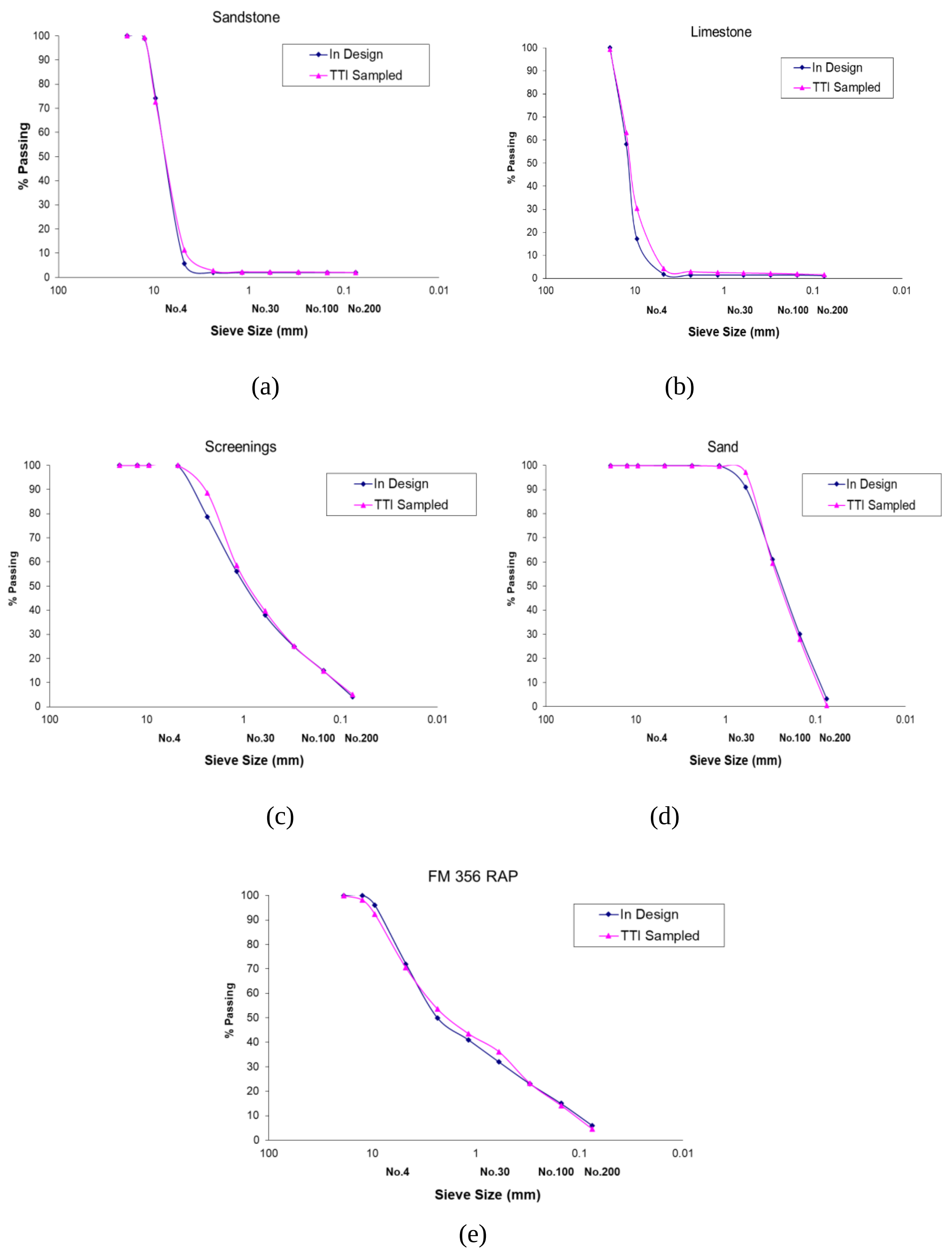
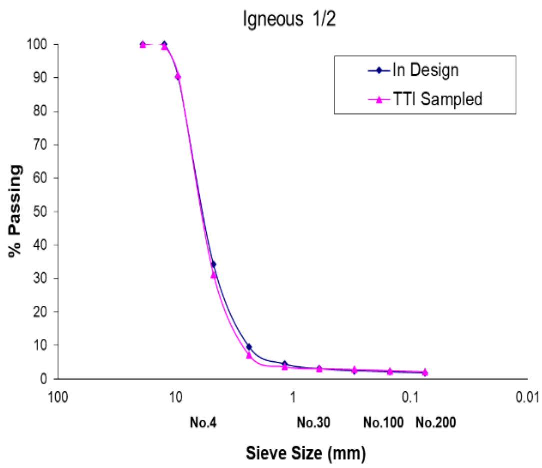
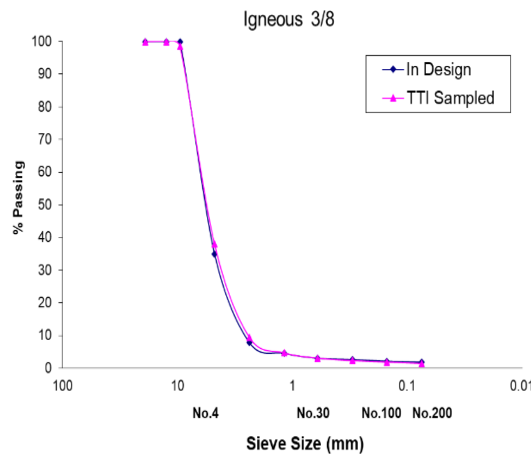


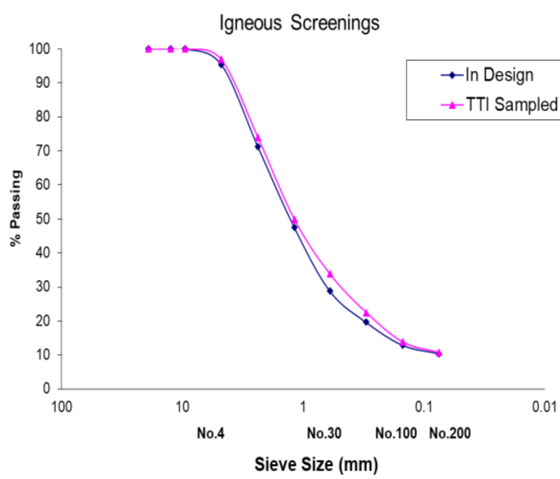
Figure 4-18. FM 356 Aggregate Gradation Comparison—(a) Sandstone, (b) Limestone, (c) Screenings, (d) Sand, and (e) RAP.



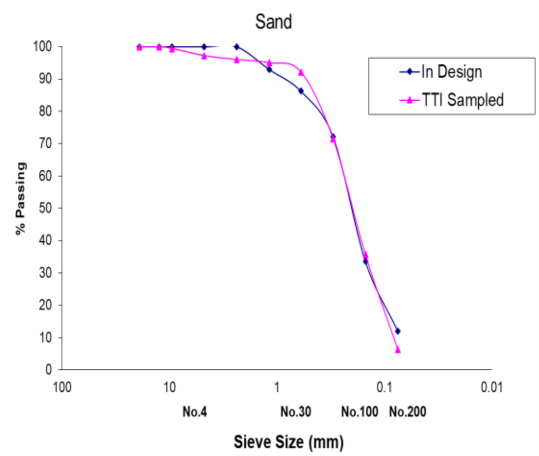
(a)



(b)



(c)



(d)

Figure 4-19. IH 20 Aggregate Gradation Comparison—(a) Igneous 1/2, (b) Igneous 3/8, (c) Igneous Screenings, and (d) Sand.

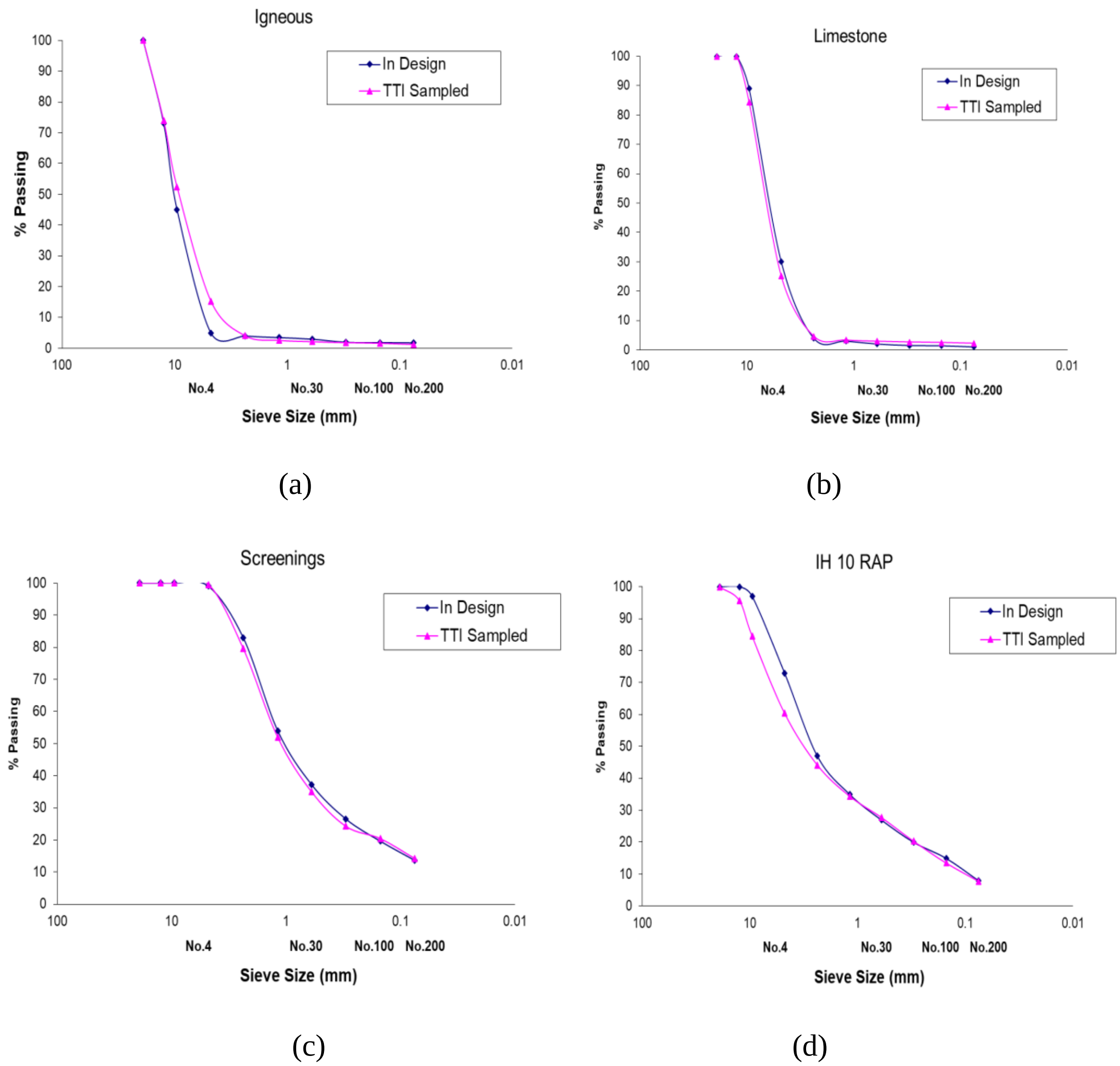


Figure 4-20. IH 10 Aggregate Gradation Comparison—(a) Igneous, (b) Limestone, (c) Screenings, and (d) RAP.

Micro-Deval Results

The Micro-Deval test sample needs to be prepared based on the stockpile gradations. Table 4-5 lists the weight and total revolutions in the specification Tex-461-A (TxDOT 2016b). The specification indicates the "use [of] Gradations A and B for coarse aggregate stockpiles and Gradation C for coarse and intermediate aggregate stockpiles that best match the material sampled." According to the previous gradation results, all RAP materials belong to the intermediate aggregate stockpile, and Gradation C should be used. For the other coarse raw aggregates, Gradation B or C should be used, depending on their specific gradations. Note that Gradation B and C material have different testing times (105 minutes versus 95 minutes).

Table 4-5. Aggregate Weights for Preparing Test Samples (Tex-461-A).

Sieve Size	Individual Retained Sieve Weights, g			
	Gradation A	Gradation B	Gradation C	Fine Aggregate
3/4–1/2 inch	660 ± 5	—	—	—
1/2–3/8 inch	330 ± 5	750 ± 5	—	—
3/8–1/4 inch	330 ± 5	375 ± 5	750 ± 5	—
1/4 inch–#4	180 ± 5	375 ± 5	750 ± 5	—
#4–#8	—	—	—	50 ± 1
#8–#16	—	—	—	125 ± 1
#16–#30	—	—	—	125 ± 1
#30–#50	—	—	—	100 ± 1
#50–#100	—	—	—	75 ± 1
#100–#200	—	—	—	25 ± 1
Total Weight, g	1,500 ± 5	1,500 ± 5	1,500 ± 5	500 ± 5
Timer, minutes	120 ± 1	105 ± 1	95 ± 1	15 ± 5

Note: — means not applicable.

Figure 4-21 shows the Micro-Deval test results for the aggregates. For each aggregate, two Micro-Deval specimens were prepared and tested. The test result differences between two replicates are usually less than 10 percent.

Since the percentage of retaining on the No. 4 sieve of RAP is usually small (less than 50 percent), the ignition test has to be conducted many (sometimes more than 10) times to obtain enough RAP aggregates for the Micro-Deval tests. The RAP aggregate Micro-Deval test is more time-consuming compared to other raw aggregates. In addition, Figure 4-21 shows that RAP aggregates have a larger Micro-Deval percent loss than the other raw aggregates (except SH 37 RAP). One possible reason is that the ignition method may change the properties of some aggregates due to the generation of micro-cracks in the aggregate by heat (Han et al. 2011).

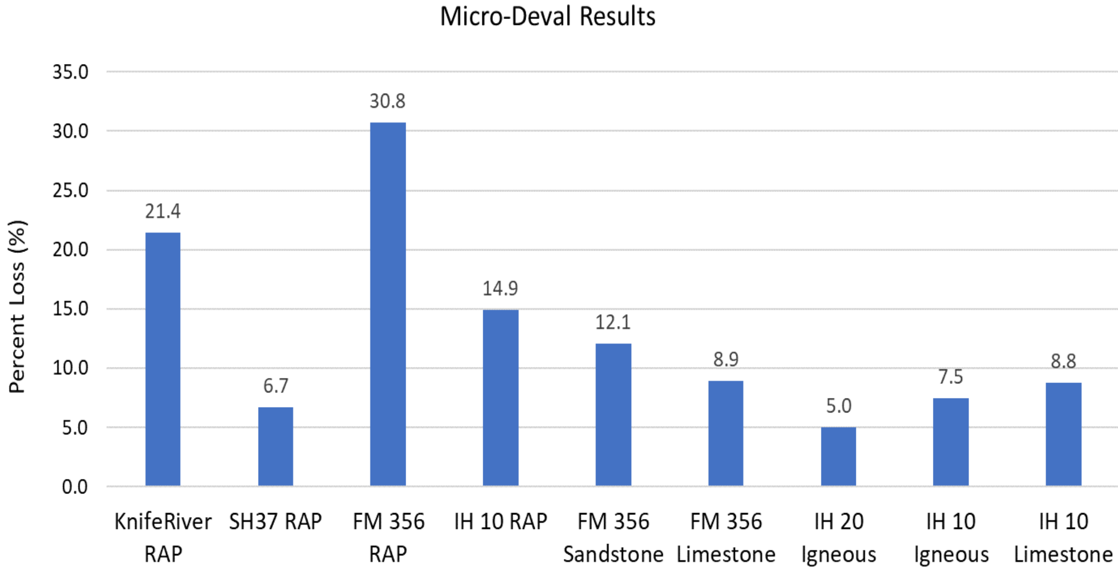


Figure 4-21. Micro-Deval Test Results.

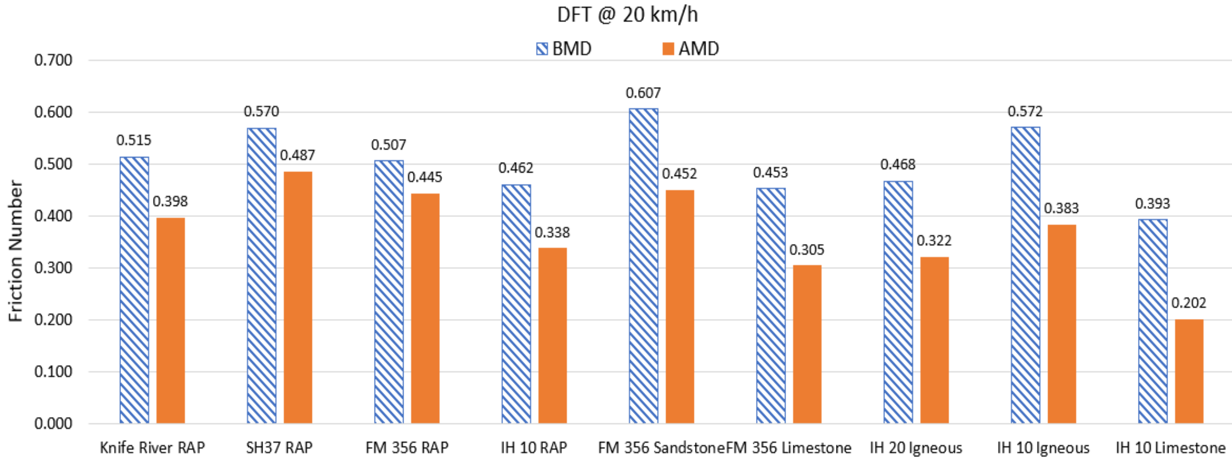
Aggregate DFT Results

For each type of aggregate, four aggregate rings were made to determine the friction number and texture—two rings using the aggregate before the Micro-Deval (BMD) test and two rings using the aggregate after the Micro-Deval (AMD) test. Figure 4-22 shows an example (IH 10 RAP aggregate rings).

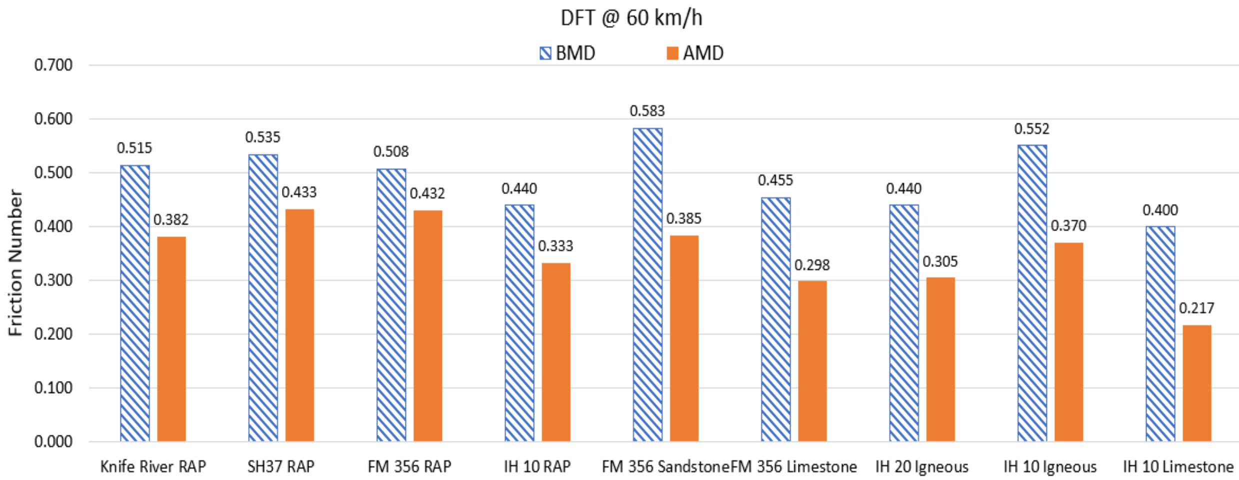
Figure 4-22. IH 10 RAP Aggregate Rings.

Three repeated runs were conducted on each aggregate ring for each DFT test. Two speeds were selected to describe the DFT number at 20 km/h and 60 km/h to represent the low and high speeds. These parameters were estimated as the average of the three repeated runs at the corresponding speed.

Figure 4-23 shows the DFT test results. Each number in the figure is the average value of two replicates (aggregate ring specimens). The AMD DFT numbers are significantly smaller than the BMD DFT numbers.



(a)



(b)

Figure 4-23. DFT Test Results at (a) 20 km/h and (b) 60 km/h.

Aggregate ARTS Results

Figure 4-24 shows the ARTS micro-MPD results. Each number in the figure is the average value of two replicates (aggregate ring specimens). The comparison between the two ring specimens is shown in Figure 4-25, which indicates the ARTS test is quite repeatable.

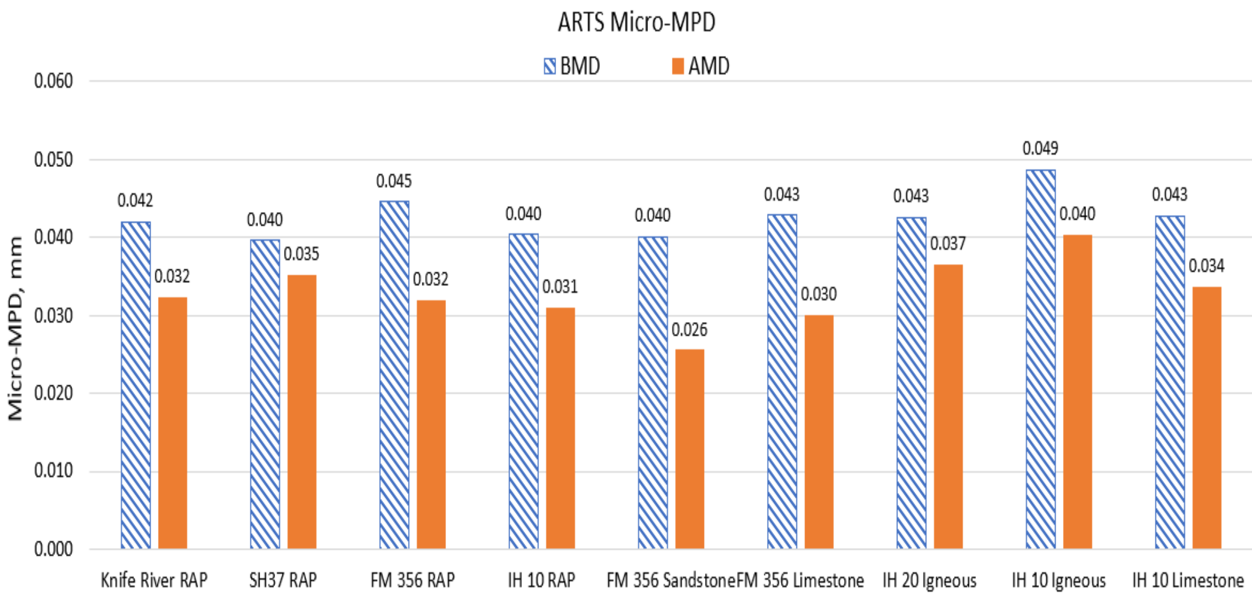


Figure 4-24. ARTS Micro-MPD Results.

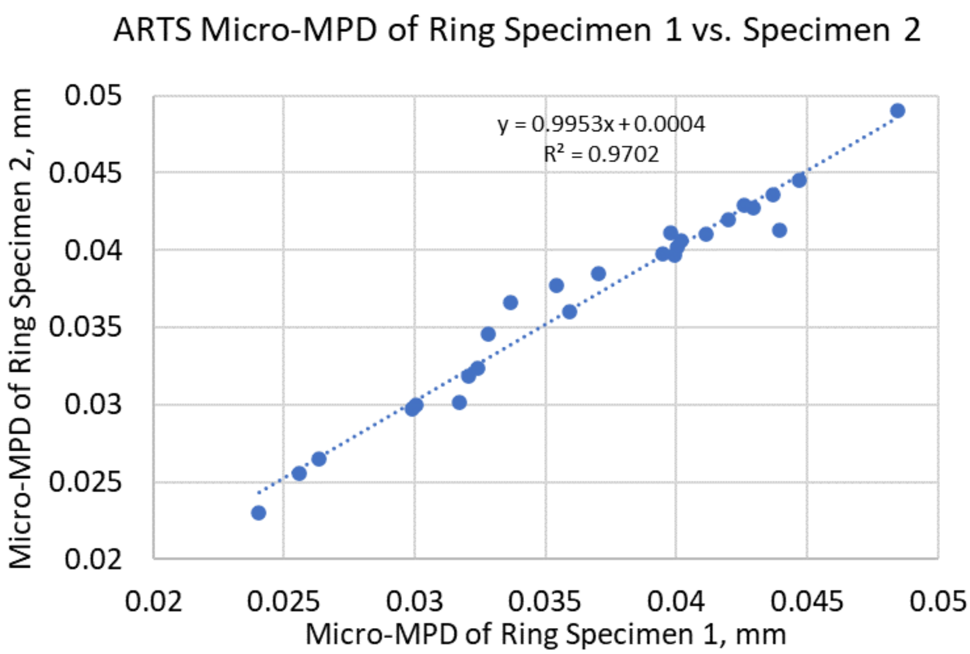
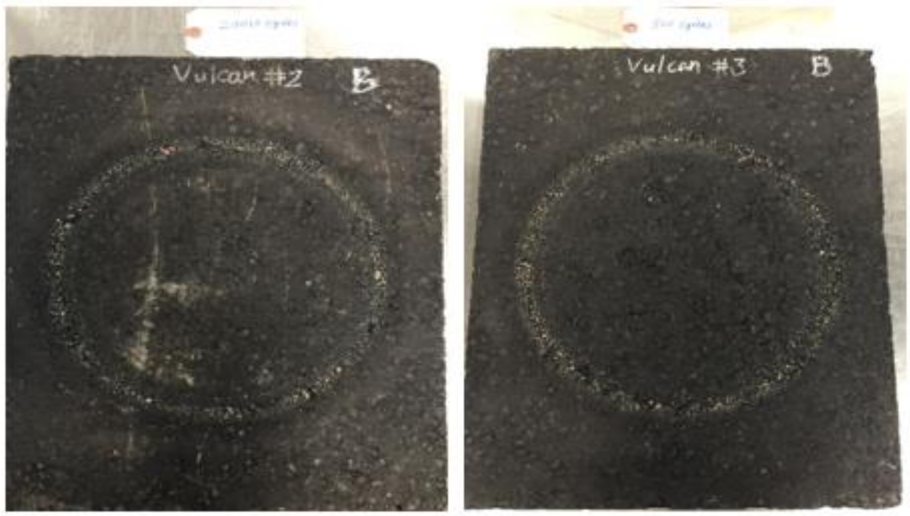


Figure 4-25. Comparison of ARTS Micro-MPD Values between Two Specimens.

Mixture Slab DFT Results

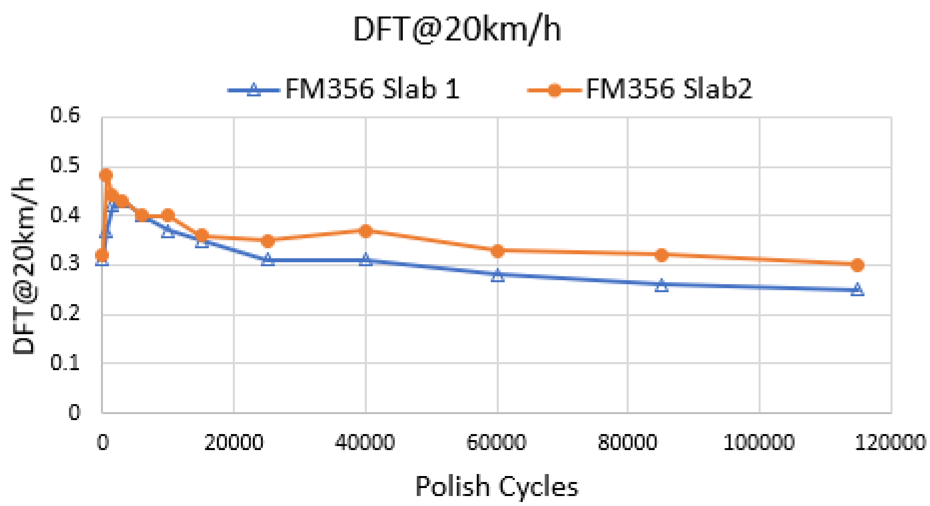
For each field section mixture, at least two slabs were fabricated. Each slab would be polished by a three-wheel polish machine and eventually go through 115,000 cycles. The researchers stopped the polishing at 500, 1,500, 3,000, 6,000, 10,000, 15,000, 25,000, 40,000, 60,000, 85,000 and 115,000 cycles to conduct the DFT test, CTM test, and ARTS test. The changing of the texture (micro- and macro-MPD) and the friction number during polishing were then investigated.

The FM 356 mixture slabs and DFT test results are shown in Figure 4-26 and Figure 4-27, respectively. As seen in Figure 4-27, the DFT values first increased, and the maximum DFT values occurred at approximately 500–2,000 polish cycles. After reaching a peak point, the DFT values decreased as the polish cycle increased. This pattern is due to the development of early surface roughness or the textures of the coated aggregate particles by removing the excess binder from the surface and exposing the aggregate (Wu et al. 2016). The DFT values reached a relatively stable number at around 100,000 cycles.

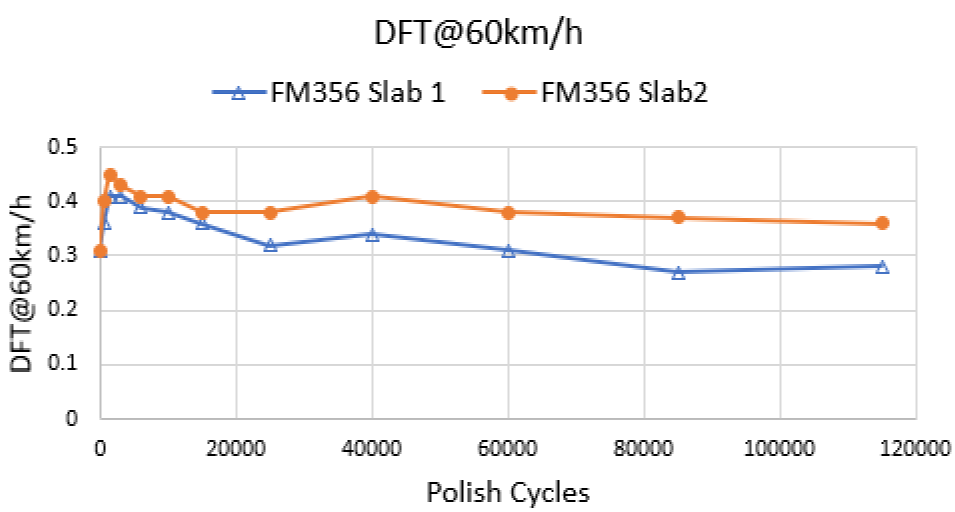


(a) (b)

Figure 4-26. FM 356 Mixture—(a) Slab 1 and (b) Slab 2.



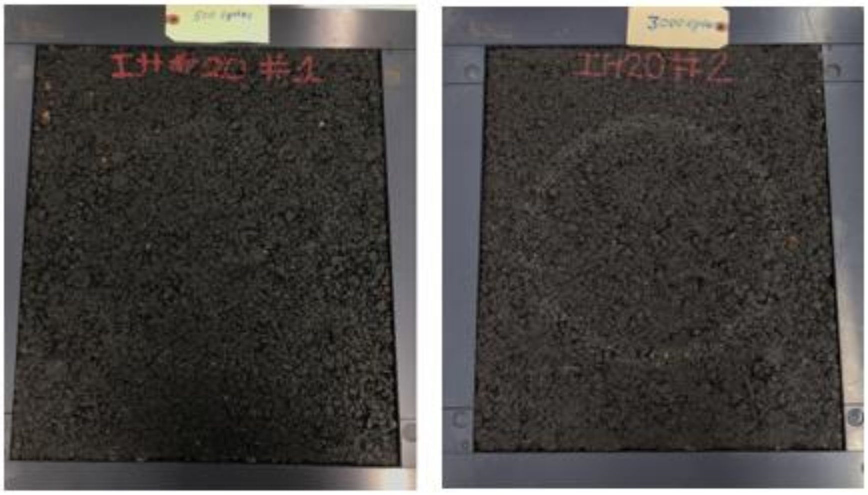
(a)



(b)

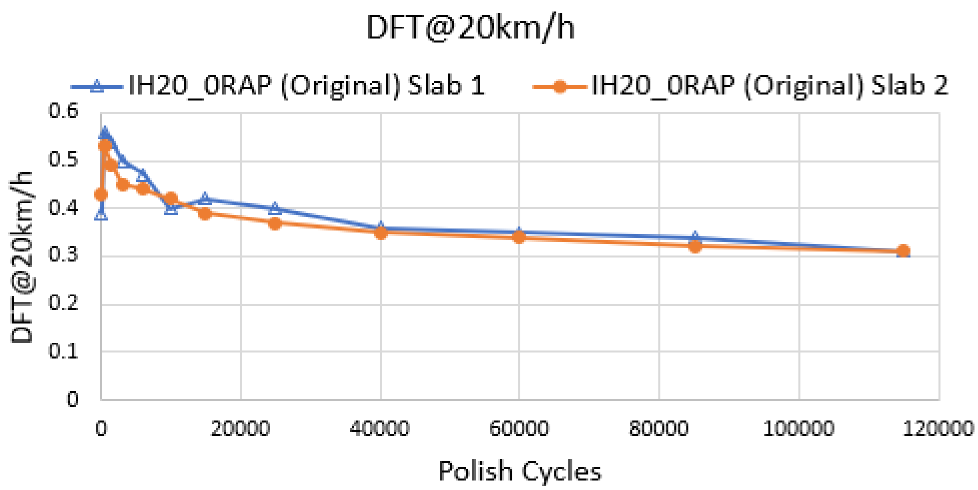
Figure 4-27. DFT Test Results on FM 356 Mixture Slabs at (a) 20 km/h and (b) 60 km/h.

The IH 20 mixture slabs and DFT test results are shown in Figure 4-28 and Figure 4-29, respectively.

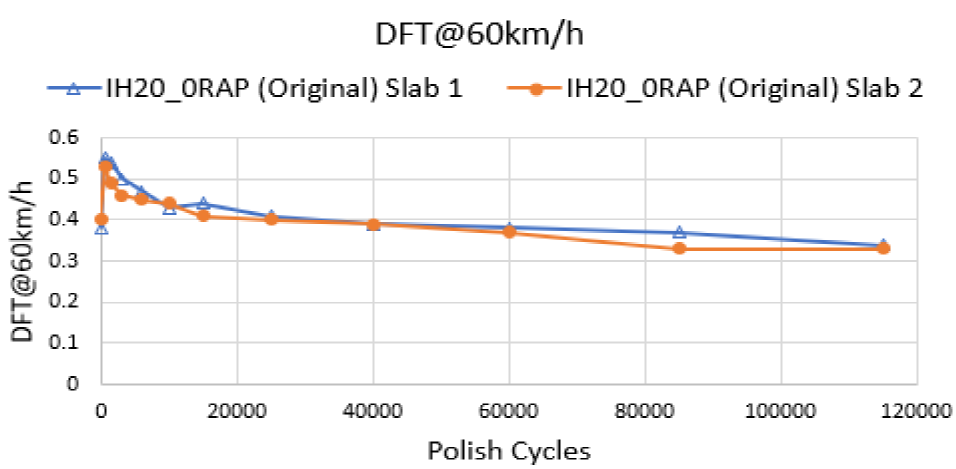


(a) (b)

Figure 4-28. IH 20 Mixture—(a) Slab 1 and (b) Slab 2.



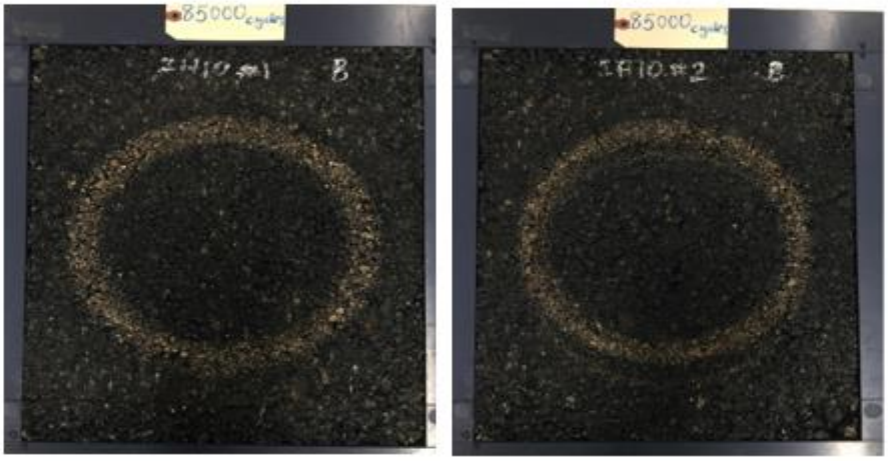
(a)



(b)

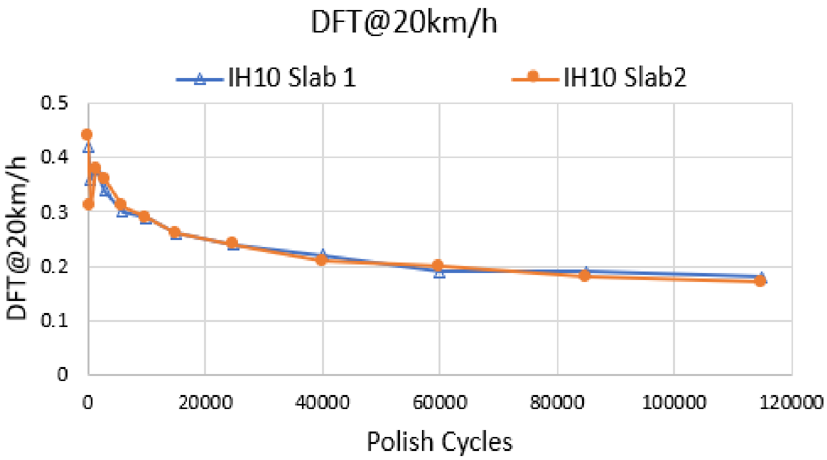
Figure 4-29. DFT Test Results on IH 20 Mixture Slabs at (a) 20 km/h and (b) 60 km/h.

The IH 10 mixture slabs and DFT results are shown in Figure 4-30 and Figure 4-31, respectively.

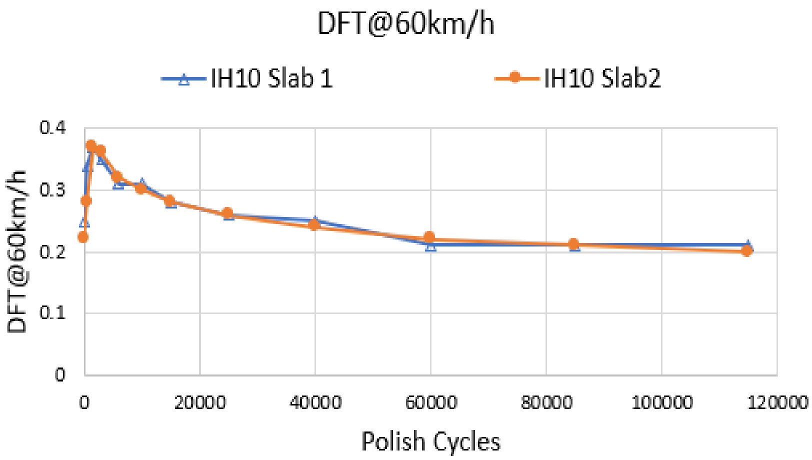


(a) (b)

Figure 4-30. IH 10 Mixture—(a) Slab 1 and (b) Slab 2.



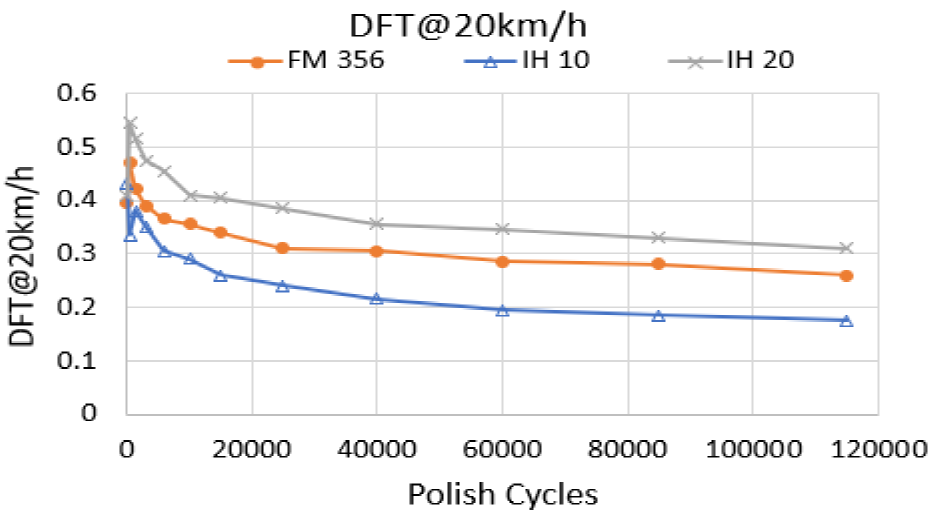
(a)



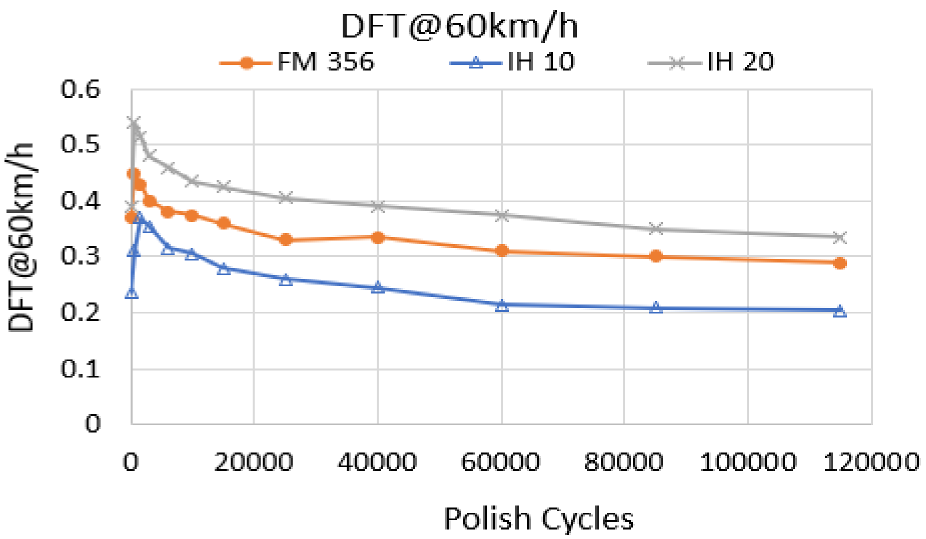
(b)

Figure 4-31. DFT Test Results on IH 10 Mixture Slabs at (a) 20 km/h and (b) 60 km/h.

Figure 4-32 shows the comparison among the three mixtures in which each DFT value is the average between Slab 1 and Slab 2. The ranking of the DFT number on the mixture slabs is IH 20 > FM 356 > IH 10, which is consistent with the DFT results on the field pavements presented in Chapter 3.



(a)



(b)

Figure 4-32. DFT Results Comparison among Field Section Mixtures.

Mixture Slab CTM Results

Figure 4-33, Figure 4-34, and Figure 4-35 show the CTM macro-MPD results for the FM 356, IH 20, and IH 10 mixture slabs, respectively. The macro-MPD of FM 356 and IH 10 increased as the polish cycles increased; the macro-MPD of IH 20 did not change much during polishing. By checking the slabs and the photos (Figure 4-26, Figure 4-28, and Figure 4-30), the researchers found both the FM 356 slabs and IH 10 slabs had noticeable missing fine particles (or binders), which may be the reason for the significant increase of the macro-MPD.

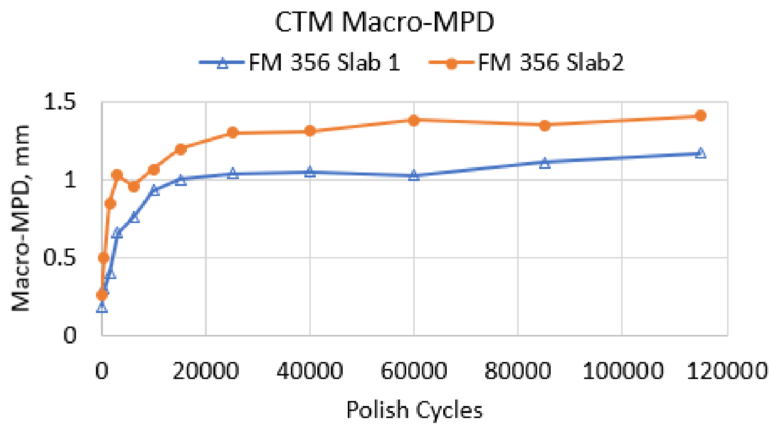


Figure 4-33. CTM Macro-MPD on FM 356 Mixture Slabs.

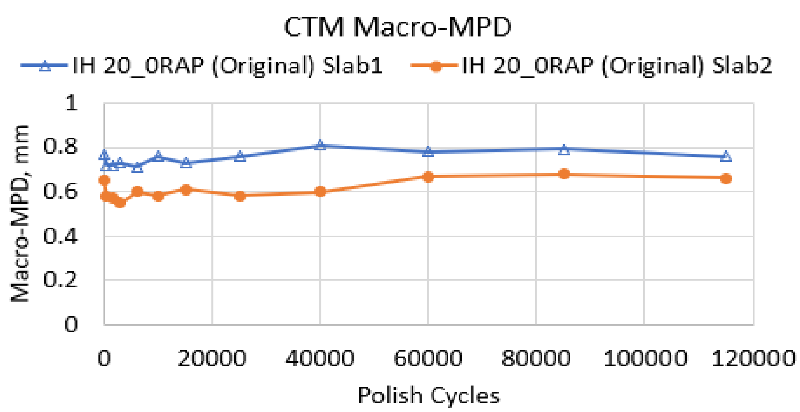


Figure 4-34. CTM Macro-MPD on IH 20 Mixture Slabs.

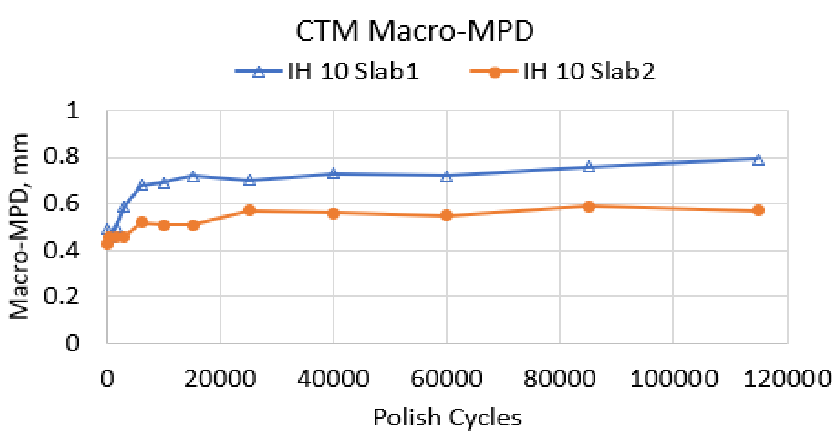


Figure 4-35. CTM Macro-MPD on IH 10 Mixture Slabs.

Figure 4-36 shows the CTM macro-MPD comparison among the three mixtures in which each CTM macro-MPD value is the average between Slab 1 and Slab 2. The ranking of the CTM macro-MPD on the mixture slabs is FM 356 > IH 20 > IH 10, which is not consistent with the DFT results on the slabs or field pavements. This ranking is not consistent with the field CTM macro-MPD either since no significant distress (such as bleeding, cracking, stripping, raveling, etc.) appeared on the pavement surface during the field evaluation.

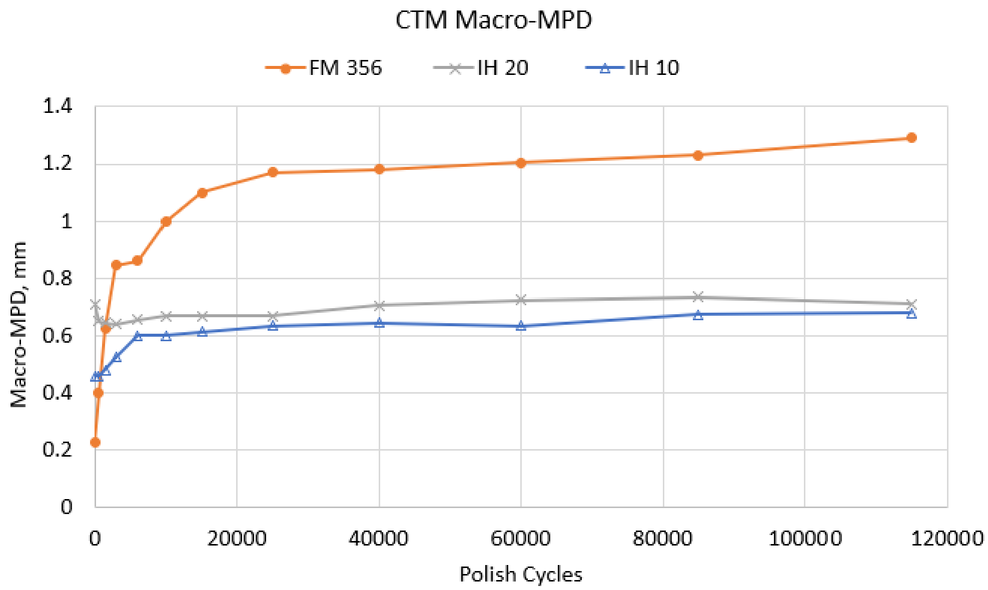
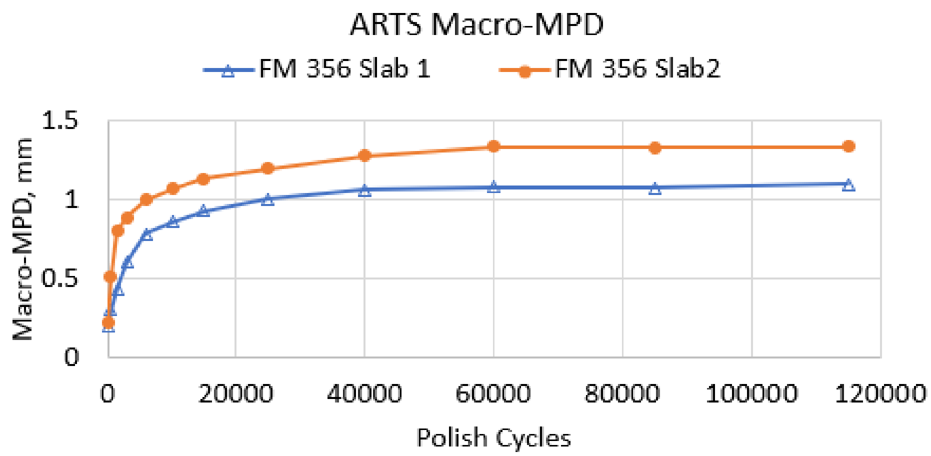


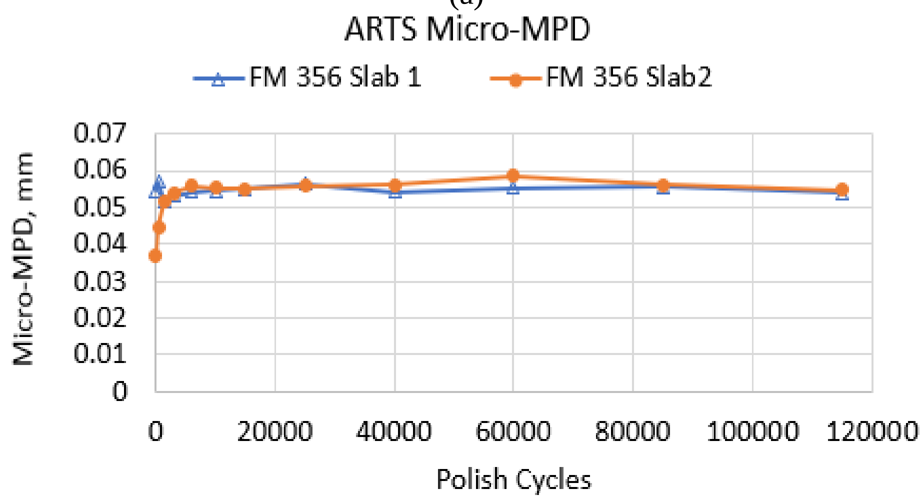
Figure 4-36. CTM Macro-MPD Comparison among Field Section Mixtures.

Mixture Slab ARTS Results

Figure 4-37, Figure 4-38, and Figure 4-39 show the ARTS macro-MPD and micro-MPD results for the FM 356, IH 20, and IH 10 mixture slabs. Overall, the ARTS macro-MPD results are close to the CTM macro-MPD results. The micro-MPD results show the values first increased, and the maximum micro-MPD values occurred after 20,000 polish cycles. After reaching this peak point, the micro-MPD values started to decrease as the polish cycle increased, but the value at the end was still higher than the value before polishing. One possible reason is that the binder coated the aggregate and showed less microtexture in the beginning. The polishing removed the binder from the surface and exposed the aggregate texture. Unlike the DFT test, the micro-MPD values peaked much later than the peak of the DFT values.

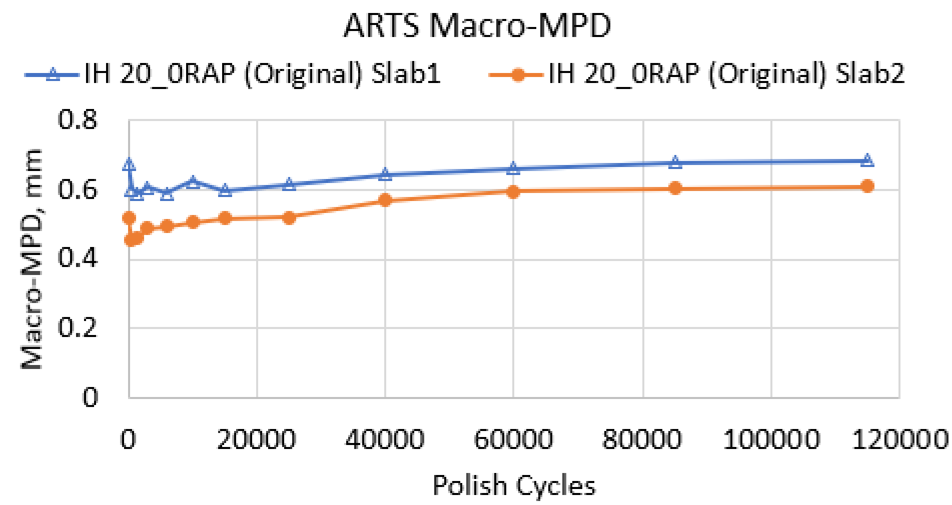


(a)

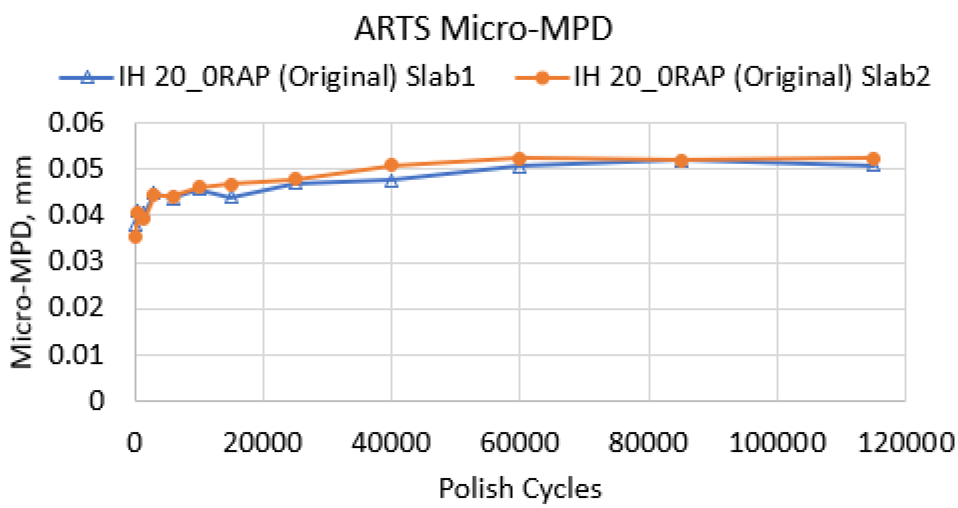


(b)

Figure 4-37. ARTS Test Results on FM 356 Mixture Slabs—(a) Macro-MPD and (b) Micro-MPD.

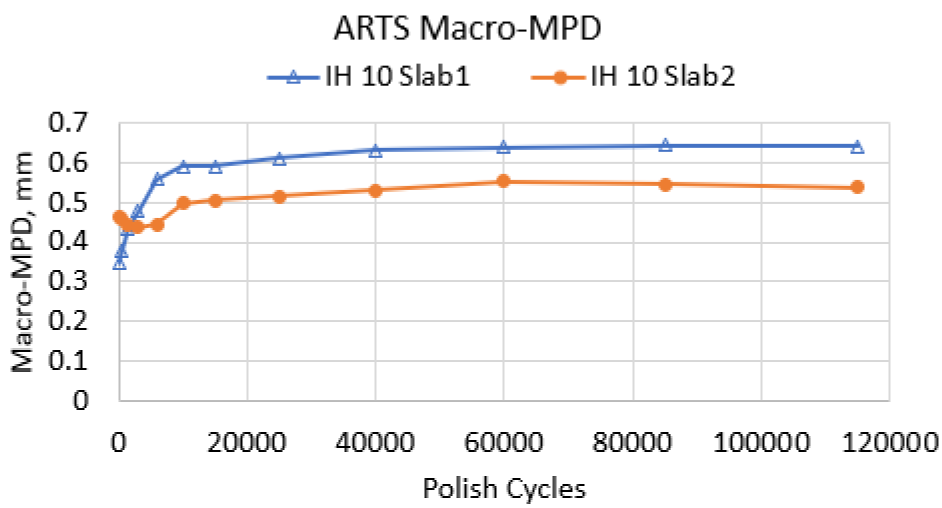


(a)

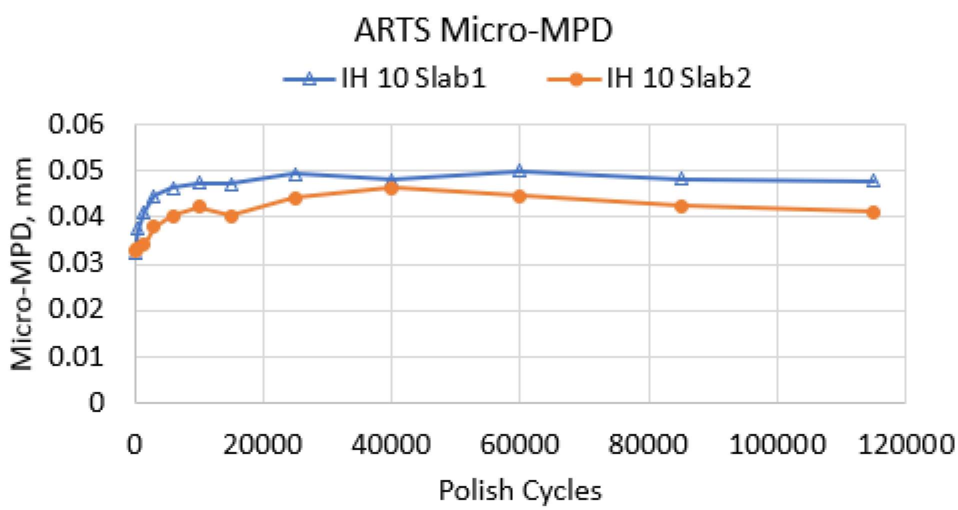


(b)

Figure 4-38. ARTS Test Results on IH 20 Mixture Slabs—(a) Macro-MPD and (b) Micro-MPD.



(a)



(b)

Figure 4-39. ARTS Test Results on IH 10 Mixture Slabs—(a) Macro-MPD and (b) Micro-MPD.

Figure 4-40 shows the ARTS test results comparison among the three mixtures. Again, the ARTS macro-MPD results are close to the CTM macro-MPD results. For the micro-MPD, the ranking is FM 356 > IH 20 > IH 10, which is not consistent with the DFT results on the slabs or field pavements.

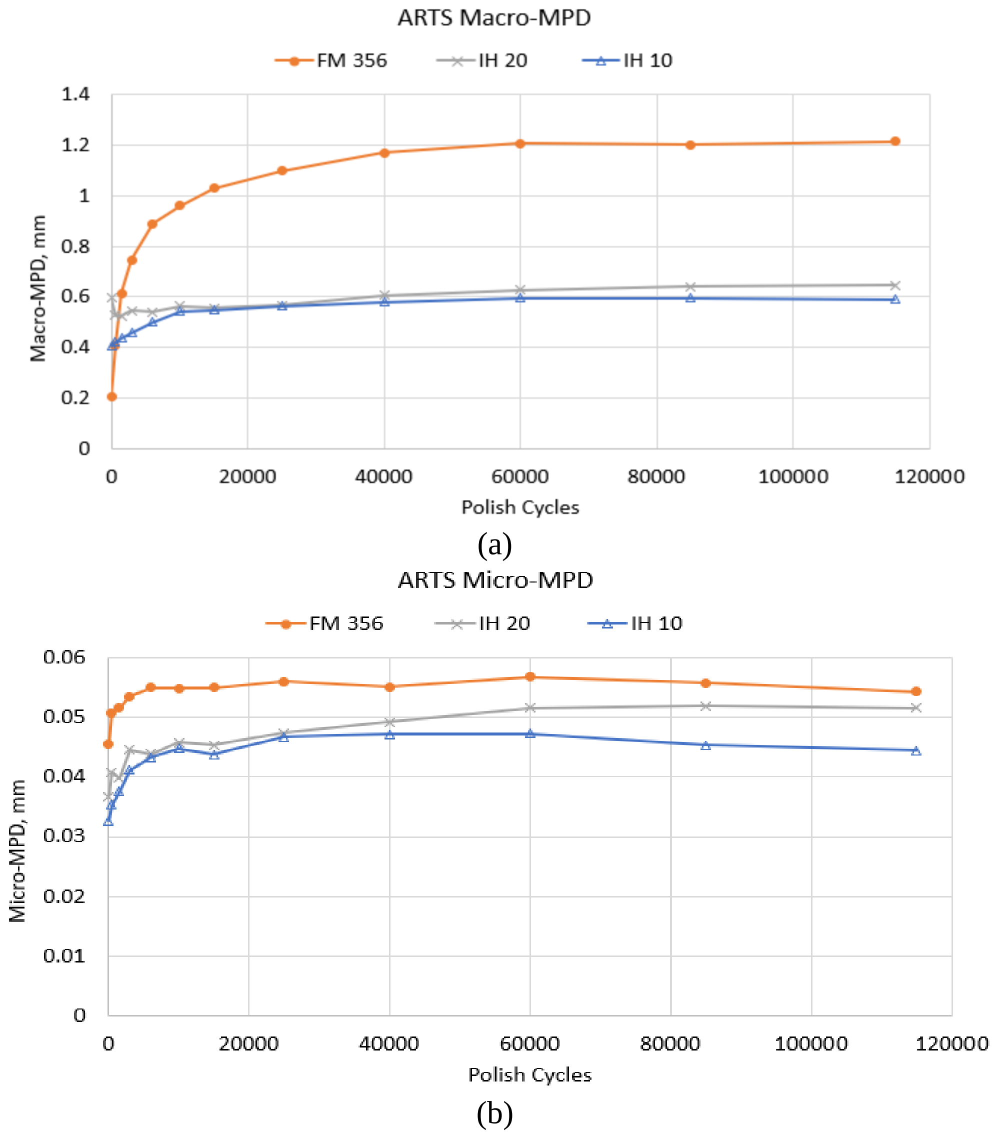


Figure 4-40. ARTS Test Results Comparison among Field Section Mixtures—(a) Macro-MPD and (b) Micro-MPD.

Mixture Redesign and DFT Results

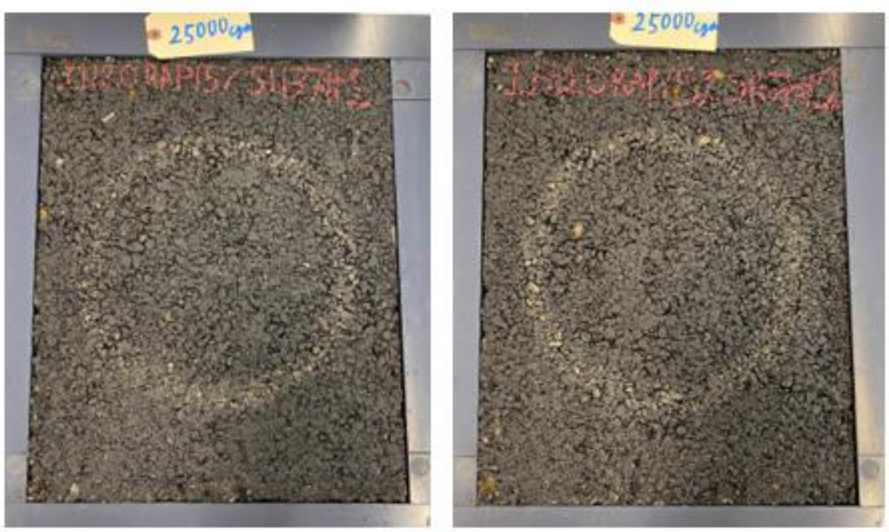
IH 20 had no RAP in the original mixture designs, while FM 356 and IH 10 had 20 percent RAP. The researchers redesigned the mixtures by removing/adding RAP and checking how their DFT values would be affected. The redesigned mixtures presented in this technical memorandum include: (a) IH 20 mixture with 15 percent RAP (SH 37), (b) IH 20 mixture with 30 percent RAP (SH 37), (c) IH 10 mixture with 0 RAP, and (d) IH 10 mixture with 15 percent RAP (SH 37). The stockpile percentages in the redesigned mixtures were adjusted to make the final blended aggregate gradation the same as (or very close to) the original designs. The corresponding mixture design, slab photos, and DFT results are presented below.

Figure 4-41, Figure 4-42, and Figure 4-43 show the mixture design, slab photos, and DFT results of the IH 20 mixture with 15 percent RAP (SH 37). The stockpile percentages are 38.3 percent igneous 1/2 inch, 16 percent igneous 3/8 inch, 25 percent igneous screenings, 6 percent field sand, and 15 percent SH 37 RAP.

	AGGREGATE BIN FRACTIONS														"RECYCLED MATERIALS"						
	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		
Aggregate Source:	Igneous		Igneous		Igneous										Fractionated RAP						Material Type
Aggregate Pit:	Jones Mill		Jones Mill		Jones Mill		SMITH PIT														Material Source
Aggregate Number:	0050122		0050122		0050122		LOCAL SOURCE														RAS Type
Sample ID:	1/2" C.A.		3-8" C.A.		SCREENINGS		FIELD SAND								SH37 RAP						Sample ID
															Recycled Asphalt Binder (%)						
															6.8						
Hydrated Lime?:															15.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix	Total Bin
Individual Bin (%):	38.3	Percent	16.0	Percent	25.0	Percent	6.0	Percent		Percent		Percent		Percent	14.7	% of Aggreg		% of Aggreg		% of Aggreg	100.0%
Sieve Size:	Cum.% Passing	Ind. Cum. %	Cum.% Passing	Ind. Cum. %	Cum.% Passing	Ind. Cum. %	Cum.% Passing	Ind. Cum. %	Cum.% Passing	Ind. Cum. %	Cum.% Passing	Ind. Cum. %	Cum.% Passing	Ind. Cum. %	Cum.% Passing	Ind. Cum. %	Cum.% Passing	Ind. Cum. %	Cum.% Passing	Ind. Cum. %	Cum.% Passing
3/4"	100.0	38.3	100.0	16.0	100.0	25.0	100.0	6.0							100.0	14.7					100.0
1/2"	100.0	38.3	100.0	16.0	100.0	25.0	100.0	6.0							100.0	14.7					100.0
3/8"	90.4	34.6	100.0	16.0	100.0	25.0	100.0	6.0							95.1	14.0					95.6
No. 4	34.3	13.1	35.0	5.6	95.4	23.9	100.0	6.0							75.8	11.1					59.7
No. 8	9.6	3.7	7.8	1.2	71.2	17.8	100.0	6.0							56.0	8.2					37.0
No. 30	3.1	1.2	3.0	0.5	28.8	7.2	96.3	5.8							36.2	5.3					20.0
No. 50	2.5	1.0	2.6	0.4	19.6	4.9	72.1	4.3							29.9	4.4					15.0
No. 200	1.8	0.7	1.8	0.3	10.4	2.6	12.0	0.7							11.4	1.7					6.0

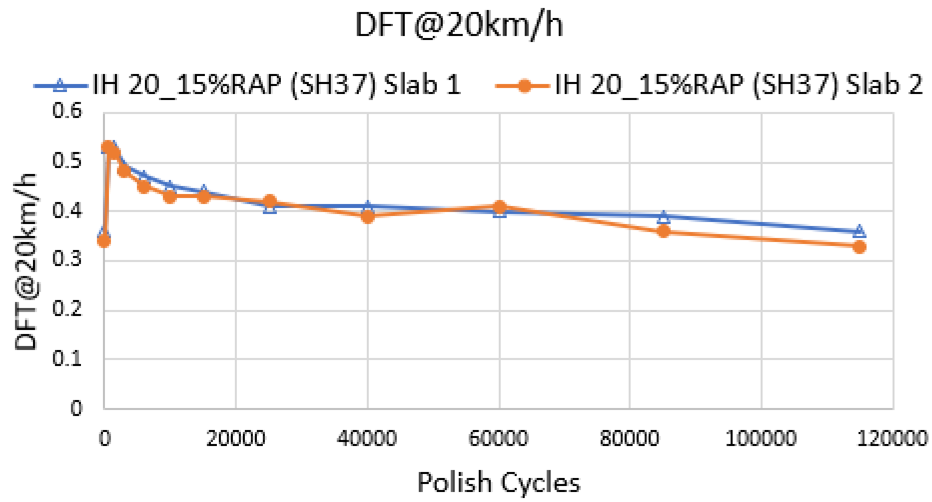
Percent of plus No. 4 from class (A) Rock:	36.7
Total Percent of plus No. 4	40.3
Percent of plus No. 4 from class (A) Rock:	**91.1**

Figure 4-41. Mixture Design of IH 20 with 15 Percent RAP (SH 37).

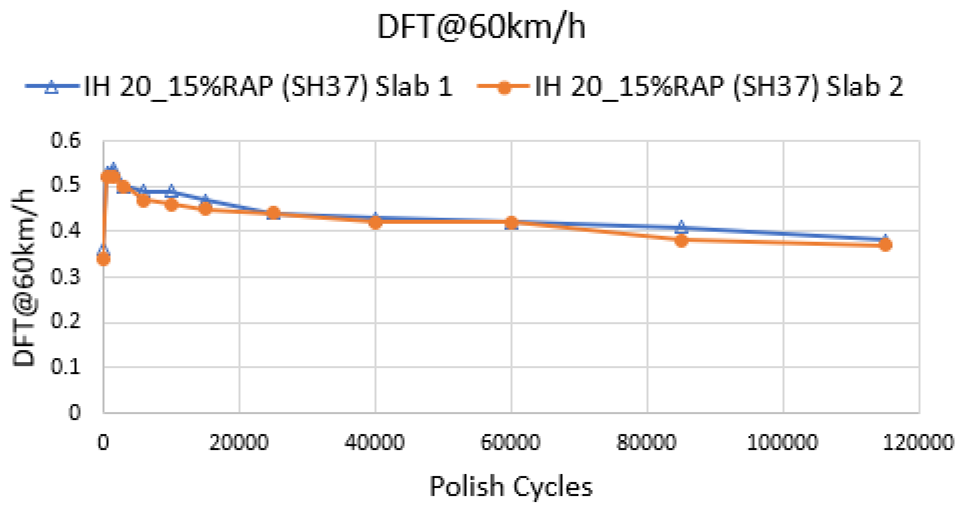


(a) (b)

Figure 4-42. IH 20 with 15 Percent RAP (SH 37) Mixture—(a) Slab 1 and (b) Slab 2.



(a)



(b)

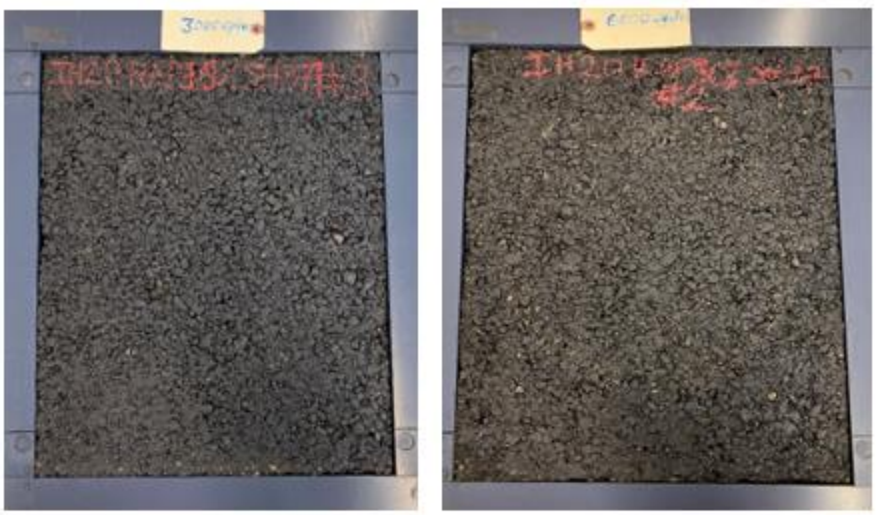
Figure 4-43. DFT Test Results on IH 20 with 15 Percent RAP (SH 37) Mixture Slabs at (a) 20 km/h and (b) 60 km/h.

Figure 4-44, Figure 4-45, and Figure 4-46 show the mixture design, slab photos, and DFT results of the IH 20 mixture with 30 percent RAP (SH 37). The stockpile percentages are 45 percent igneous 1/2 inch, 4 percent igneous 3/8 inch, 19.5 percent igneous screenings, 2.1 percent field sand, and 30 percent SH 37 RAP.

	AGGREGATE BIN FRACTIONS														"RECYCLED MATERIALS"						
	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		
Aggregate Source:	Igneous		Igneous		Igneous										Fractionated RAP						Material Type
Aggregate Pit:	Jones Mill		Jones Mill		Jones Mill		SMITH PIT														Material Source
Aggregate Number:	0050122		0050122		0050122		LOCAL SOURCE														RAS Type
Sample ID:	1/2" C.A.		3-8" C.A.		SCREENINGS		FIELD SAND								SH37 RAP						Sample ID
															Recycled Asphalt Binder (%)						
															6.8						
Hydrated Lime?:															30.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix	Total Bin
Individual Bin (%):	45.0	Percent	4.0	Percent	19.5	Percent	2.1	Percent		Percent		Percent		Percent	29.4	% of Aggreg		% of Aggreg		% of Aggreg	100.0%
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing
3/4"	100.0	45.0	100.0	4.0	100.0	19.5	100.0	2.1							100.0	29.4					100.0
1/2"	100.0	45.0	100.0	4.0	100.0	19.5	100.0	2.1							100.0	29.4					100.0
3/8"	90.4	40.7	100.0	4.0	100.0	19.5	100.0	2.1							95.1	28.0					94.2
No. 4	34.3	15.4	35.0	1.4	95.4	18.6	100.0	2.1							75.8	22.3					59.8
No. 8	9.6	4.3	7.8	0.3	71.2	13.9	100.0	2.1							56.0	16.5					37.1
No. 30	3.1	1.4	3.0	0.1	28.8	5.6	96.3	2.0							36.2	10.6					19.8
No. 50	2.5	1.1	2.6	0.1	19.6	3.8	72.1	1.5							29.9	8.8					15.3
No. 200	1.8	0.8	1.8	0.1	10.4	2.0	12.0	0.3							11.4	3.3					6.5

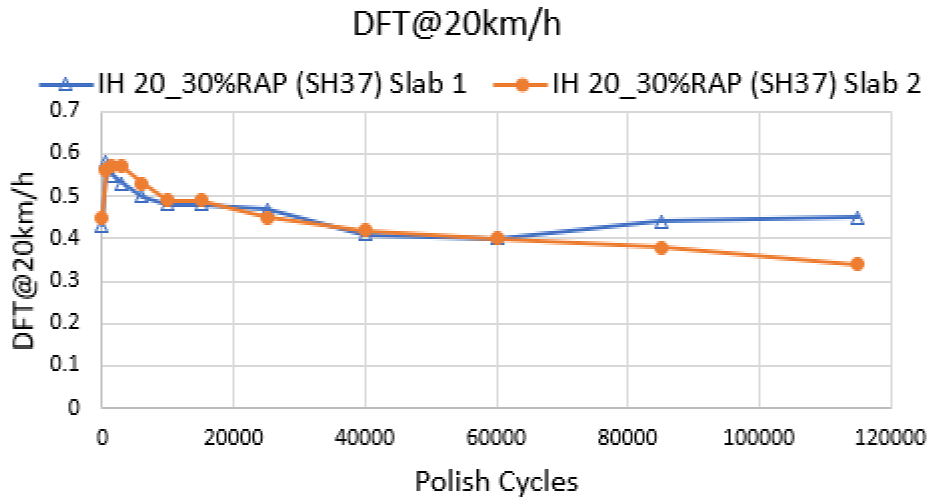
Percent of plus No. 4 from class (A) Rock:	33.1
Total Percent of plus No. 4	40.2
Percent of plus No. 4 from class (A) Rock:	**82.3**

Figure 4-44. IH 20 with 30 Percent RAP (SH 37) Mixture Design.

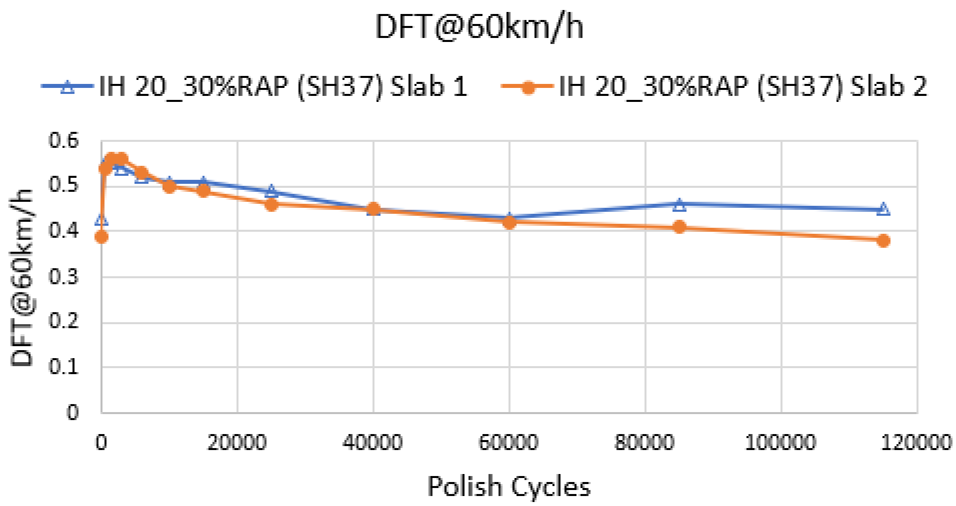


(a) (b)

Figure 4-45. IH 20 with 30 Percent RAP (SH 37) Mixture—(a) Slab 1 and (b) Slab 2.



(a)



(b)

Figure 4-46. DFT Test Results on IH 20 with 30 Percent RAP (SH 37) Mixture Slabs at (a) 20 km/h and (b) 60 km/h.

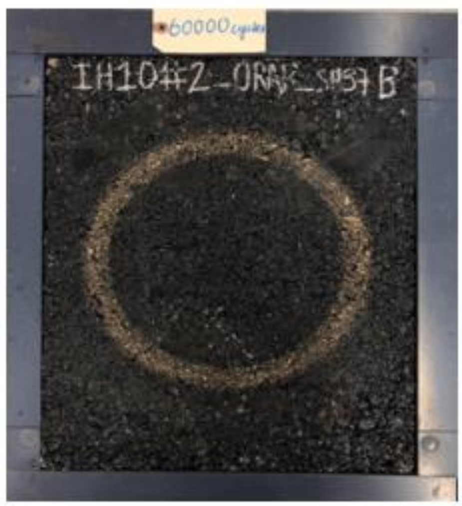
Figure 4-47, Figure 4-48, and Figure 4-49 show the mixture design, slab photos, and DFT results of the IH 10 mixture with no RAP. The stockpile percentages are 27.6 percent igneous 3/4 inch, 34.5 percent limestone 3/8 inch, and 38 percent limestone screenings.

	AGGREGATE BIN FRACTIONS														"RECYCLED MATERIALS"						
Aggregate	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		
Source:	Limestone_Dolomit		Igneous		Limestone_Dolomit		Limestone_Dolomit								Fractionated RAP						Material Type
Pit:	Ned Finney Quarry		Padre Canyon		Ned Finney Quarry		Ned Finney Quarry								txdot						Material Source
Number:	2407220		2411613		2407220		2407220														RAS Type
Producer:																					RAP/RAS Producer
Sample ID:	3/4 SAC B		3/4 SAC A		3/8		Fines														Sample ID
															Recycled Asphalt Binder (%)						
															6.8						
Hydrated Lime?:															0.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix	Total Bin
Individual Bin (%):		Percent	27.5	Percent	34.5	Percent	38.0	Percent		Percent		Percent		Percent		% of Aggreg		% of Aggreg		% of Aggreg	100.0%
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing
1"			100.0	27.5	100.0	34.5	100.0	38.0							100.0	0.0					100.0
3/4"			100.0	27.5	100.0	34.5	100.0	38.0							100.0	0.0					100.0
1/2"			73.0	20.1	100.0	34.5	100.0	38.0							100.0	0.0					92.6
3/8"			45.0	12.4	89.0	30.7	100.0	38.0							97.0	0.0					81.1
No. 4			5.0	1.4	30.0	10.4	99.0	37.6							73.0	0.0					49.3
No. 8			4.0	1.1	4.0	1.4	83.0	31.5							47.0	0.0					34.0
No. 16			3.5	1.0	3.0	1.0	54.0	20.5							35.0	0.0					22.5
No. 30			3.0	0.8	2.0	0.7	37.3	14.2							27.0	0.0					15.7
No. 50			2.0	0.6	1.5	0.5	26.5	10.1							20.0	0.0					11.1
No. 200			1.8	0.5	1.0	0.3	13.6	5.2							8.0	0.0					6.0

Percent of plus No. 4 from class (A) Rock:	26.1
Total Percent of plus No. 4	50.7
Percent of plus No. 4 from class (A) Rock:	**51.6**

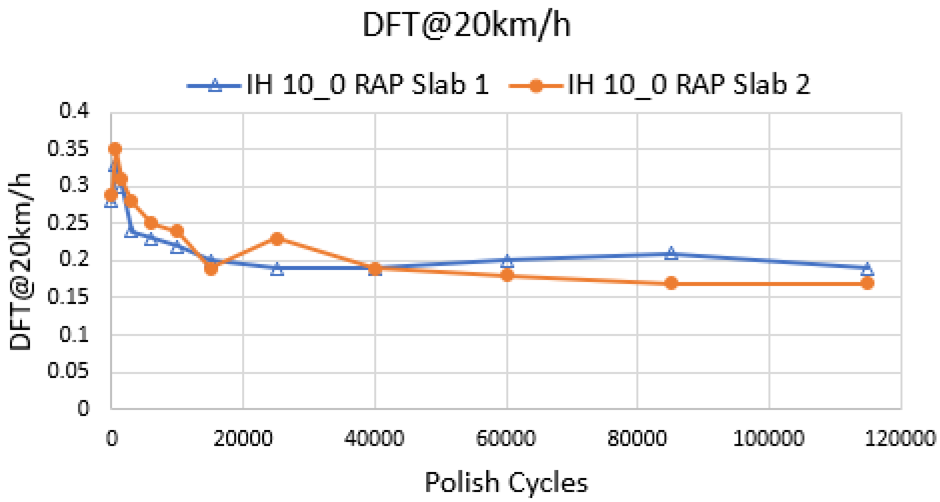
Figure 4-47. IH 10 with 0 Percent RAP Mixture Design.

(a)

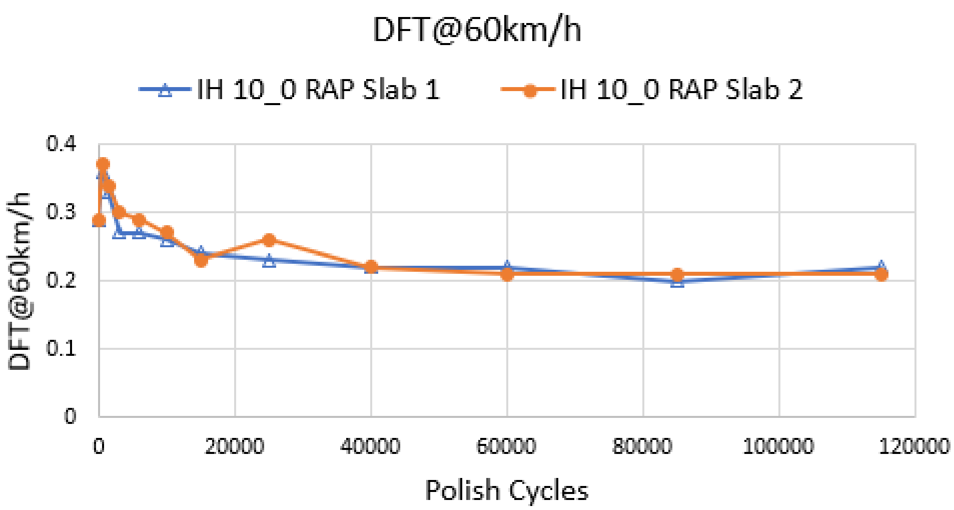


(b)

Figure 4-48. IH 10 with 0 Percent RAP Mixture—(a) Slab 1 and (b) Slab 2.



(a)



(b)

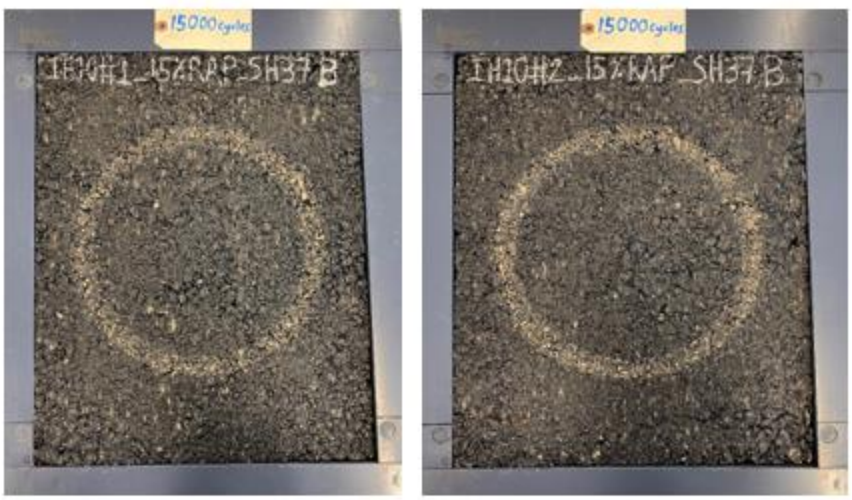
Figure 4-49. DFT Test Results on IH 10 with 0 Percent RAP Mixture Slabs at (a) 20 km/h and (b) 60 km/h.

Figure 4-50, Figure 4-51, and Figure 4-52 show the mixture design, slab photos, and DFT results of the IH 10 mixture with 15 percent RAP (SH 37). The stockpile percentages are 27 percent igneous 3/4 inch, 30.3 percent limestone 3/8 inch, 28 percent limestone screenings, and 15 percent SH 37 RAP.

	AGGREGATE BIN FRACTIONS														"RECYCLED MATERIALS"						
Aggregate	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		
Source:	mestone_Dolom		Igneous		nestone_Dolom		mestone_Dolomi								Fractionated RAP						Material Type
Pit:	Ned Finney Quarry		Padre Canyon		Ned Finney Quarry		Ned Finney Quarry								txdot						Material Source
Number:	2407220		2411613		2407220		2407220														RAS Type
Producer:																					RAP/RAS Producer
Sample ID:	3/4 SAC B		3/4 SAC A		3/8		Fines														Sample ID
															Recycled Asphalt Binder (%)						
															6.8						
Hydrated Lime?:															15.0	% of Tot. Mix		% of Tot.		% of Tot.	Total Bin
Individual Bin (%):		Percent	27.0	Percent	30.3	Percent	28.0	Percent		Percent		Percent		Percent	14.7	% of Aggreg		% of Aggreg		% of Aggreg	100.0%
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing
1"			100.0	27.0	100.0	30.3	100.0	28.0							100.0	14.7					100.0
3/4"			100.0	27.0	100.0	30.3	100.0	28.0							100.0	14.7					100.0
1/2"			73.0	19.7	100.0	30.3	100.0	28.0							100.0	14.7					92.7
3/8"			45.0	12.2	89.0	27.0	100.0	28.0							95.1	14.0					81.1
No. 4			5.0	1.4	30.0	9.1	99.0	27.7							75.8	11.1					49.3
No. 8			4.0	1.1	4.0	1.2	83.0	23.2							56.0	8.2					33.8
No. 16			3.5	0.9	3.0	0.9	54.0	15.1							43.3	6.4					23.3
No. 30			3.0	0.8	2.0	0.6	37.3	10.4							36.2	5.3					17.2
No. 50			2.0	0.5	1.5	0.5	26.5	7.4							29.9	4.4					12.8
No. 200			1.8	0.5	1.0	0.3	13.6	3.8							11.4	1.7					6.3

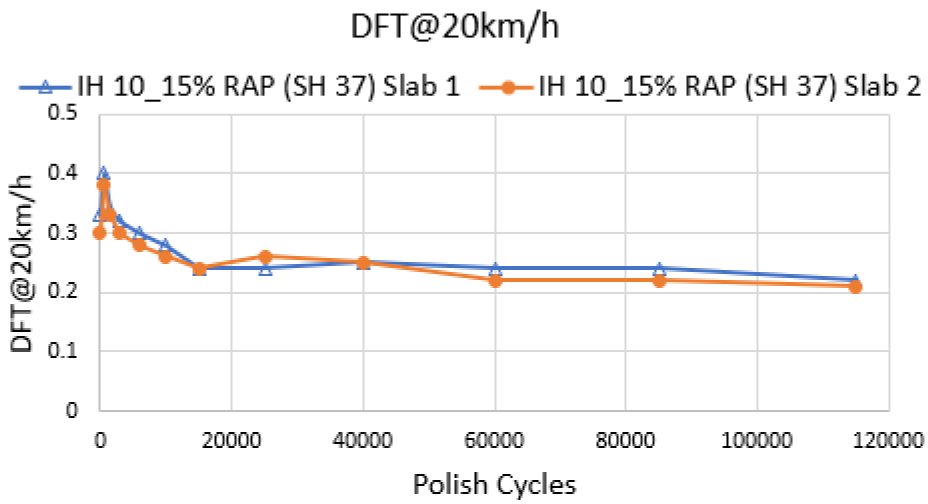
Percent of plus No. 4 from class (A) Rock:	25.7
Total Percent of plus No. 4	50.7
Percent of plus No. 4 from class (A) Rock:	**50.6**

Figure 4-50. IH 10 with 15 Percent RAP (SH 37) Mixture Design.

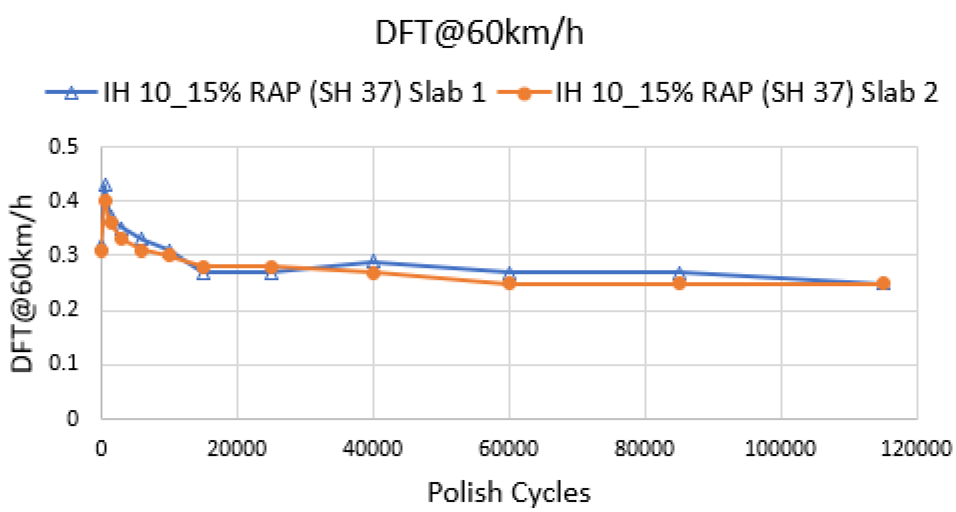


(a) (b)

Figure 4-51. IH 10 with 15 Percent RAP (SH 37) Mixture—(a) Slab 1 and (b) Slab 2.



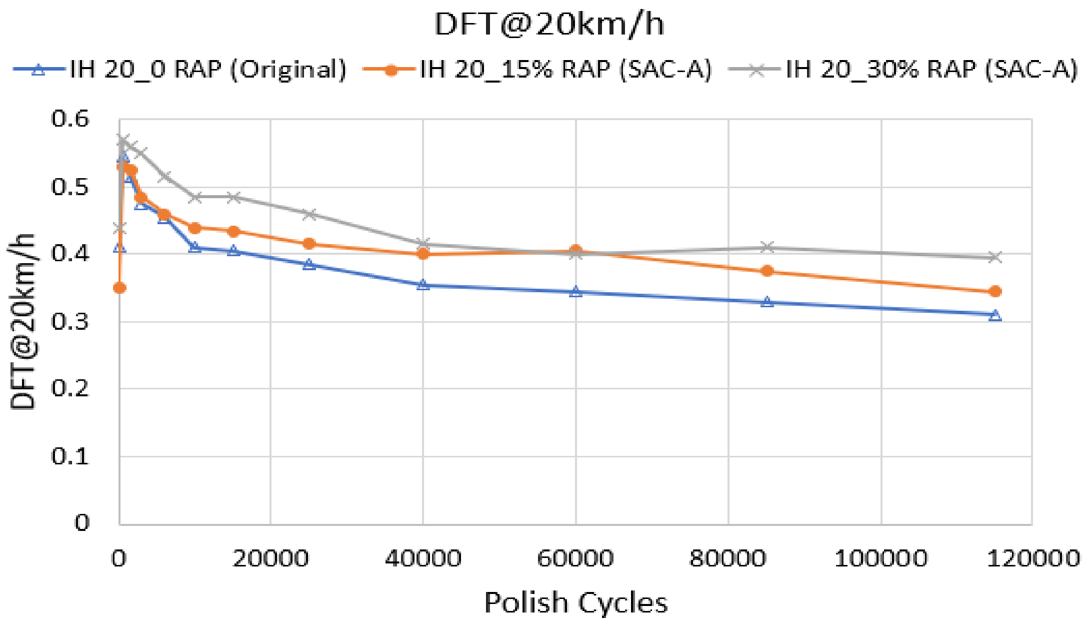
(a)



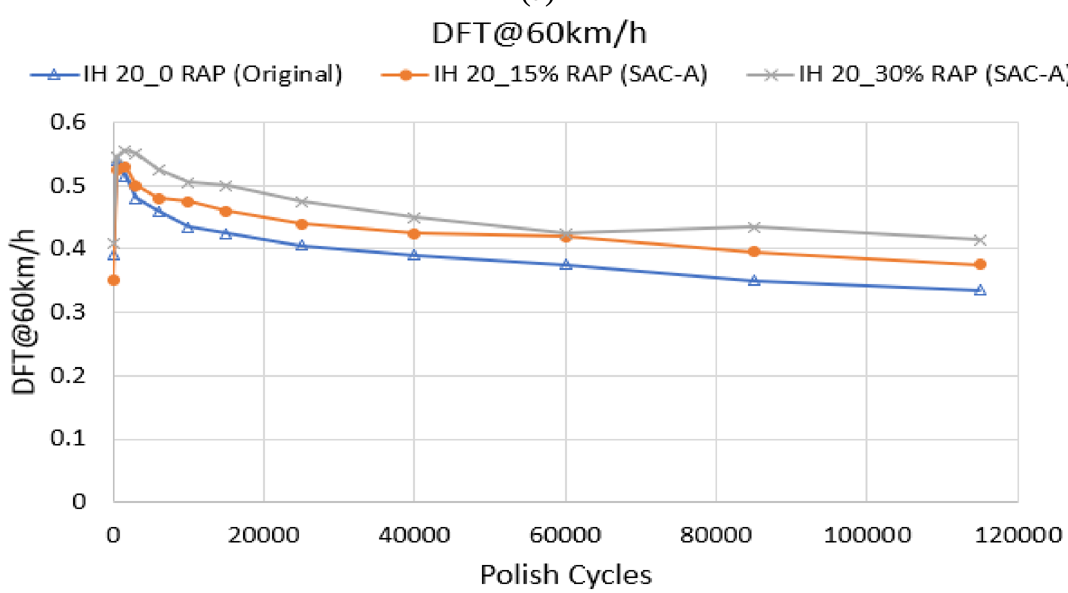
(b)

Figure 4-52. DFT Test Results on IH 10 with 15 Percent RAP (SH 37) Mixture Slabs at (a) 20 km/h and (b) 60 km/h.

Figure 4-53 shows the DFT test results comparison of the IH 20 mixtures. The figure clearly shows that adding SH 37 RAP (SAC-A RAP) increases the DFT values of the IH 20 mixture. The ranking is IH 20_30 percent RAP (SH 37) > IH 20_15 percent RAP (SH 37) > IH 20_0 RAP.



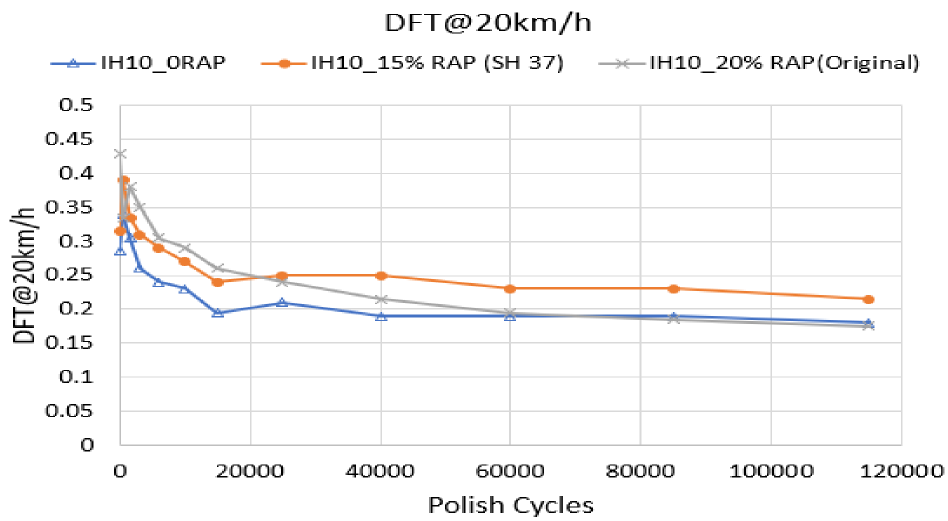
(a)



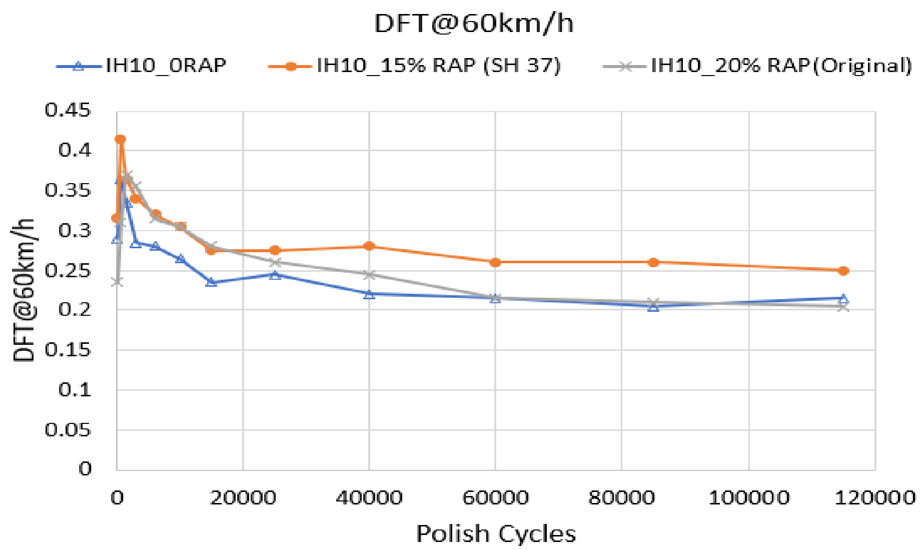
(b)

Figure 4-53. DFT Test Results Comparison among IH 20 Redesigned Mixtures at (a) 20 km/h and (b) 60 km/h.

Figure 4-54 shows the DFT test results comparing the IH 10 mixtures. The figure shows that removing the RAP from the IH 10 original design did not improve the DFT values. Replacing the original RAP with the SH 37 RAP (SAC-A) significantly improved the DFT values. The ranking is IH_15 percent RAP (SH 37) > IH 10_20 percent RAP (Original) ≥ IH 10_0 RAP.



(a)



(b)

Figure 4-54. DFT Test Results Comparison among IH 10 Redesigned Mixtures at (a) 20 km/h and (b) 60 km/h.

The test results of these redesigned mixtures indicate that SAC-A RAP can significantly improve the DFT value of asphalt mixtures. The aggregate ring DFT values of IH 10 RAP is higher than limestone, which explains why removing the RAP from the IH 10 mixture did not improve the DFT numbers of the mixture.

ASSEMBLE TEST INFORMATION AND DETERMINE BLENDED DFT

In this section, the researchers combined the aggregate DFT values into blended DFT values for each asphalt mixture. The relationship between the blended DFT value and the mixture slab DFT value was also investigated. The blended DFT calculation method is similar to that used by Maryland DOT (MDOT) (MDOT 2012a, 2012b, and 2016) and TxDOT Soils and Aggregates Section (Izzo 2020). Both TxDOT and MDOT methods assume a constant number, 0.3, for all RAP aggregate DFT since the RAP aggregate DFT is not measured in either method.

In the MDOT method, the aggregate retaining on a 3/8-inch sieve is thought of as coarse aggregate. In contrast, in the TxDOT method, the aggregate retaining on No. 4 (3/16 inch) or No. 8 (3/32 inch) sieve is thought of as coarse aggregate. As seen in Figure 4-55a, the MDOT aggregate ring size is larger than the TxDOT aggregate ring size. The aggregate size selected for the MDOT ring is between 1/2 inch and 3/8 inch, and the material required is around 7 lb for a single layer. After pouring the epoxy into the steel mold and reaching a satisfactory bonding, the sample will go through 100,000 cycles of three-wheel polishing (Figure 4-55b) before the DFT test.

(a) (b)

Figure 4-55. MDOT (a) Aggregate Ring and (b) Polishing Before DFT Measurement.

In this research, the TxDOT method was adopted since the aggregate size for the ring is between 3/8 inches and 1/4 inches. The blended DFT values were determined based on the aggregates retaining on No. 4 or No. 8 sieve were compared. The measured RAP aggregate ring DFT values were employed and compared with the result of using constant number 0.3. The calculation tried and compared the aggregate DFT values of both BMD and AMD.

Summary of Aggregate DFT Values

The aggregate DFT values used for the blended DFT calculation are summarized in Table 4-6. Since there is no significant difference between DFT at 60 km/h and DFT at 20 km/h, only DFT at 20 km/h values (both BMD and AMD) are used hereafter.

Table 4-6. Summary of Aggregate DFT Values.

Mixture Name	Stockpile	Quarry	DFT of BMD at 20 km/h	DFT of BMD at 60 km/h	DFT of AMD at 20 km/h	DFT of AMD at 60 km/h
FM 356	Sandstone	Brownlee	0.61	0.58	0.45	0.39
FM 356	Limestone	Marble Falls	0.45	0.46	0.31	0.30
FM 356	RAP	—	0.51	0.51	0.45	0.43
IH 20	Igneous	Jones Mill	0.47	0.44	0.32	0.31
IH 10	Limestone	Ned Finney	0.39	0.40	0.20	0.22
IH 10	Igneous	Padre Canyon	0.57	0.55	0.38	0.37
IH 10	RAP	—	0.46	0.44	0.34	0.33
—	RAP (SH 37)	—	0.57	0.54	0.49	0.43

Note: — means not applicable.

Blended DFT Calculation for FM 356/IH 10/IH 20 Mixtures

The blended DFT calculation was based on the stockpile gradation and the percentage of retaining on the No. 4 or No. 8 sieve. The DFT of fine aggregates was assigned the same value as the coarse aggregate if the aggregates were from the same quarry and had the same product code. The DFT values of the sand stockpile were assumed to be 40 (BMD) and 30 (AMD); however, these numbers did not affect the blended results since the percentage of retaining on the No. 8 was 0.

Figure 4-56, Figure 4-57, and Figure 4-58 show the blended DFT calculation for the FM 356, IH 20, and IH 10 mixtures, respectively.

Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.8
Source:	Sandstone	Limestone_ Dolomite	Limestone_ Dolomite	Washed Sand	Lime	Fractionated RAP
Bin %	29	10	24.9	15	1	20.1
No. 4, Cum % Passing	5.9	1.8	99.8	100	100	72
Retained on No. 4, %	94.1	98.2	0.2	0	0	28
% Used	27.289	9.82	0.0498	0	0	5.628
Normalized	63.78	22.95	0.12	0.00	0.00	13.15
Aggregate DFT (BMD) *100	61.00	45.00	45.00	40.00	0.00	51.00
Aggregate DFT (AMD) *100	45.00	31.00	31.00	30.00	0.00	45.00
Stockpile DFT (AMD) *100	38.91	10.33	0.05	0.00	0.00	6.71
Stockpile DFT (AMD)*100	28.70	7.11	0.04	0.00	0.00	5.92
Blended DFT (BMD) *100	**55.99**					
Blended DFT (AMD)*100	**41.77**					

(a)

Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.8
Source:	Sandstone	Limestone_ Dolomite	Limestone_ Dolomite	Washed Sand	Lime	Fractionated RAP
Bin %	29	10	24.9	15	1	20.1
No. 8, Cum % Passing	2	1.4	78.7	100	100	50
Retained on No. 8, %	98	98.6	21.3	0	0	50
% Used	28.42	9.86	5.3037	0	0	10.05
Normalized	52.99	18.38	9.89	0.00	0.00	18.74
Aggregate DFT (BMD) *100	61.00	45.00	45.00	40.00	0.00	51.00
Aggregate DFT (AMD) *100	45.00	31.00	31.00	30.00	0.00	45.00
Stockpile DFT (AMD) *100	32.32	8.27	4.45	0.00	0.00	9.56
Stockpile DFT (AMD)*100	23.85	5.70	3.07	0.00	0.00	8.43
Blended DFT (BMD) *100	**54.60**					
Blended DFT (AMD)*100	**41.04**					

(b)

Figure 4-56. FM 356 Mixture Blended DFT Results Based on the Retaining of (a) the No. 4 Sieve and (b) the No. 8 Sieve.

Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4
Source:	Igneous	Igneous	Igneous	FIELD SAND
Bin %	50	10	30	10
No. 4, Cum % Passing	34.3	35	95.4	100
Retained on No. 4, %	65.7	65	4.6	0
% Used	32.85	6.5	1.38	0
Normalized	80.65	15.96	3.39	0.00
Aggregate DFT (BMD) *100	47.00	47.00	47.00	40.00
Aggregate DFT (AMD) *100	32.00	32.00	32.00	30.00
Stockpile DFT (AMD) *100	37.91	7.50	1.59	0.00
Stockpile DFT (AMD)*100	25.81	5.11	1.08	0.00
Blended DFT (BMD) *100	**47.00**			
Blended DFT (AMD)*100	**32.00**			

(a)

Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4
Source:	Igneous	Igneous	Igneous	FIELD SAND
Bin %	50	10	30	10
No. 8, Cum % Passing	9.6	7.8	71.2	100
Retained on No. 8, %	90.4	92.2	28.8	0
% Used	45.2	9.22	8.64	0
Normalized	71.68	14.62	13.70	0.00
Aggregate DFT (BMD) *100	47.00	47.00	47.00	40.00
Aggregate DFT (AMD) *100	32.00	32.00	32.00	30.00
Stockpile DFT (AMD) *100	33.69	6.87	6.44	0.00
Stockpile DFT (AMD)*100	22.94	4.68	4.38	0.00
Blended DFT (BMD) *100	**47.00**			
Blended DFT (AMD)*100	**32.00**			

(b)

Figure 4-57. IH 20 Mixture Blended DFT Results Based on the Retaining of (a) the No. 4 Sieve and (b) the No. 8 Sieve.

Aggregate	Bin No.2	Bin No.3	Bin No.4	Bin No.8
Source:	Igneous	Limestone_ Dolomite	Limestone_ Dolomite	Fractionated RAP
Bin %	28	25.1	27	19.9
No. 4, Cum % Passing	5	30	99	73
Retained on No. 4, %	95	70	1	27
% Used	26.6	17.57	0.27	5.373
Normalized	53.40	35.27	0.54	10.79
Aggregate DFT (BMD) *100	57.00	39.00	39.00	46.00
Aggregate DFT (AMD) *100	38.00	20.00	20.00	34.00
Stockpile DFT (AMD) *100	30.44	13.76	0.21	4.96
Stockpile DFT (AMD)*100	20.29	7.05	0.11	3.67
Blended DFT (BMD) *100	**49.37**			
Blended DFT (AMD)*100	**31.12**			

(a)

Aggregate	Bin No.2	Bin No.3	Bin No.4	Bin No.8
Source:	Igneous	Limestone_ Dolomite	Limestone_ Dolomite	Fractionated RAP
Bin %	28	25.1	27	19.9
No. 8, Cum % Passing	4	4	83	47
Retained on No. 8, %	96	96	17	53
% Used	26.88	24.096	4.59	10.547
Normalized	40.66	36.45	6.94	15.95
Aggregate DFT (BMD) *100	57.00	39.00	39.00	46.00
Aggregate DFT (AMD) *100	38.00	20.00	20.00	34.00
Stockpile DFT (AMD) *100	23.17	14.21	2.71	7.34
Stockpile DFT (AMD)*100	15.45	7.29	1.39	5.42
Blended DFT (BMD) *100	**47.44**			
Blended DFT (AMD)*100	**29.55**			

(b)

Figure 4-58. IH 10 Mixture Blended DFT Results Based on the Retaining of (a) the No. 4 Sieve and (b) the No. 8 Sieve.

The blended DFT results for the three mixtures are summarized in Table 4-7. These numbers are calculated based on the measured RAP aggregate DFT values.

Table 4-7. Summary of Blended DFT Values Using Measured RAP DFT.

Mixture Name	Blended DFT * 100 (BMD, +#4)	Blended DFT * 100 (BMD, +#8)	Blended DFT * 100 (AMD, +#4)	Blended DFT * 100 (AMD, +#8)
FM 356	56.0	54.6	41.8	41.0
IH 20	47.0	47.0	32.0	32.0
IH 10	49.4	47.4	31.1	29.6

According to Table 4-7, the FM 356 mixture had significantly higher blended DFT numbers than the other two mixtures; the IH 20 and IH 10 mixtures had close numbers. The blended DFT numbers ranking high to low are FM 356 > IH 10 > IH 20 based on the BMD, and FM 356 > IH 20 > IH 10 based on the AMD. However, neither rankings are consistent with the lab-molded mixture slab test or the field test result. The DFT ranking of the mixture slab and field pavement surface is IH 20 > FM 356 > IH 10.

Table 4-8 summarizes the blended DFT results using the constant number 0.3 for all RAP aggregate DFT values (BMD and AMD). Since 0.3 is smaller than the measured RAP aggregate DFT values (Table 4-6), the blended DFT values for FM 356 and IH 10 are getting smaller, but the ranking is unchanged.

Table 4-8. Summary of Blended DFT Values Using Constant RAP DFT (0.3).

Mixture Name	Blended DFT * 100 (BMD, +#4)	Blended DFT * 100 (BMD, +#8)	Blended DFT * 100 (AMD, +#4)	Blended DFT * 100 (AMD, +#8)
FM 356	53.2	50.7	39.8	38.2
IH 20	47.0	47.0	32.0	32.0
IH 10	47.6	44.9	30.7	28.9

Blended DFT Calculation for Redesigned IH 20 Mixtures

Figure 4-59 and Figure 4-60 show the blended DFT calculation for the redesigned IH 20 mixtures.

Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.8
Source:	Igneous	Igneous	Igneous	FIELD SAND	Fractionated RAP
Bin %	38.3	16	25	6	14.7
No. 4, Cum % Passing	34.3	35	95.4	100	75.8
Retained on No. 4, %	65.7	65	4.6	0	24.2
% Used	25.1631	10.4	1.15	0	3.5574
Normalized	62.49	25.83	2.86	0.00	8.83
Aggregate DFT (BMD) *100	47.00	47.00	47.00	40.00	57.00
Aggregate DFT (AMD) *100	32.00	32.00	32.00	30.00	49.00
Stockpile DFT (AMD) *100	29.37	12.14	1.34	0.00	5.04
Stockpile DFT (AMD)*100	20.00	8.26	0.91	0.00	4.33
Blended DFT (BMD) *100	47.88				
Blended DFT (AMD)*100	33.50				

(a)

Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.8
Source:	Igneous	Igneous	Igneous	FIELD SAND	Fractionated RAP
Bin %	38.3	16	25	6	14.7
No. 8, Cum % Passing	9.6	7.8	71.2	100	56
Retained on No. 8, %	90.4	92.2	28.8	0	44
% Used	34.6232	14.752	7.2	0	6.468
Normalized	54.92	23.40	11.42	0.00	10.26
Aggregate DFT (BMD) *100	47.00	47.00	47.00	40.00	57.00
Aggregate DFT (AMD) *100	32.00	32.00	32.00	30.00	49.00
Stockpile DFT (AMD) *100	25.81	11.00	5.37	0.00	5.85
Stockpile DFT (AMD)*100	17.57	7.49	3.65	0.00	5.03
Blended DFT (BMD) *100	48.03				
Blended DFT (AMD)*100	33.74				

(b)

Figure 4-59. IH 20 with 15 Percent RAP (SH 37) Mixture Blended DFT Results Based on the Retaining of (a) the No. 4 Sieve and (b) the No. 8 Sieve.

Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.8
Source:	Igneous	Igneous	Igneous		Fractionated RAP
Bin %	45	4	19	2	30
No. 4, Cum % Passing	34.3	35	95.4	100	75.8
Retained on No. 4, %	65.7	65	4.6	0	24.2
% Used	29.565	2.6	0.874	0	7.26
Normalized	73.36	6.45	2.17	0.00	18.02
Aggregate DFT (BMD) *100	47.00	47.00	47.00	40.00	57.00
Aggregate DFT (AMD) *100	32.00	32.00	32.00	30.00	49.00
Stockpile DFT (AMD) *100	34.48	3.03	1.02	0.00	10.27
Stockpile DFT (AMD)*100	23.48	2.06	0.69	0.00	8.83
Blended DFT (BMD) *100	**48.80**				
Blended DFT (AMD)*100	**35.06**				

(a)

Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.8
Source:	Igneous	Igneous	Igneous		Fractionated RAP
Bin %	45	4	19	2	30
No. 8, Cum % Passing	9.6	7.8	71.2	100	56
Retained on No. 8, %	90.4	92.2	28.8	0	44
% Used	40.68	3.688	5.472	0	13.2
Normalized	64.53	5.85	8.68	0.00	20.94
Aggregate DFT (BMD) *100	47.00	47.00	47.00	40.00	57.00
Aggregate DFT (AMD) *100	32.00	32.00	32.00	30.00	49.00
Stockpile DFT (AMD) *100	30.33	2.75	4.08	0.00	11.94
Stockpile DFT (AMD)*100	20.65	1.87	2.78	0.00	10.26
Blended DFT (BMD) *100	**49.09**				
Blended DFT (AMD)*100	**35.56**				

(b)

Figure 4-60. IH 20 with 30 Percent RAP (SH 37) Mixture Blended DFT Results Based on the Retaining of (a) the No. 4 Sieve and (b) the No. 8 Sieve.

The blended DFT results for the IH 20 mixtures are summarized in Table 4-9 (using measured RAP DFT) and Table 4-10 (using the constant RAP DFT, 0.3).

Table 4-9. IH 20 Redesigned Mixture Blended Values Using Measured RAP DFT.

Mixture Name	Blended DFT * 100 (BMD, +#4)	Blended DFT * 100 (BMD, +#8)	Blended DFT * 100 (AMD, +#4)	Blended DFT * 100 (AMD, +#8)
IH 20_0RAP (Original)	47.0	47.0	32.0	32.0
IH 20_15% RAP (SH 37)	47.9	48.0	33.5	33.7
IH 20_30% RAP (SH 37)	48.8	49.1	35.1	35.6

Table 4-10. IH 20 Redesigned Mixture Blended DFT Using Constant RAP DFT (0.3).

Mixture Name	Blended DFT * 100 (BMD, +#4)	Blended DFT * 100 (BMD, +#8)	Blended DFT * 100 (AMD, +#4)	Blended DFT * 100 (AMD, +#8)
IH 20_0RAP (Original)	47.0	47.0	32.0	32.0
IH 20_15% RAP (SH 37)	45.5	45.3	31.8	31.8
IH 20_30% RAP (SH 37)	43.9	43.4	31.6	31.6

According to the IH 20 slab mixture DFT results, the DFT ranking is IH 20_30% RAP (SH 37) > IH 20_15% RAP (SH 37) > IH 20_0 RAP, which is consistent with the ranking in Table 4-9. The ranking in Table 4-10 contrasts with this ranking. Table 4-10 indicates that assuming a constant number for RAP may lead to an unreasonable blended DFT and a wrong prediction of mixture skid resistance.

Blended DFT Calculation for Redesigned IH 10 Mixtures

Figure 4-61 and Figure 4-62 show the blended DFT calculation for the redesigned IH 10 mixtures.

Aggregate	Bin No.2	Bin No.3	Bin No.4
Source:	Igneous	Limestone_ Dolomite	Limestone_ Dolomite
Bin %	27.5	34.5	38
No. 4, Cum % Passing	5	30	99
Retained on No. 4, %	95	70	1
% Used	26.125	24.15	0.38
Normalized	51.57	47.68	0.75
Aggregate DFT (BMD) *100	57.00	39.00	39.00
Aggregate DFT (AMD) *100	38.00	20.00	20.00
Stockpile DFT (AMD) *100	29.40	18.59	0.29
Stockpile DFT (AMD)*100	19.60	9.54	0.15
Blended DFT (BMD) *100	**48.28**		
Blended DFT (AMD)*100	**29.28**		

(a)

Aggregate	Bin No.2	Bin No.3	Bin No.4
Source:	Igneous	Limestone_ Dolomite	Limestone_ Dolomite
Bin %	27.5	34.5	38
No. 8, Cum % Passing	4	4	83
Retained on No. 8, %	96	96	17
% Used	26.4	33.12	6.46
Normalized	40.01	50.20	9.79
Aggregate DFT (BMD) *100	57.00	39.00	39.00
Aggregate DFT (AMD) *100	38.00	20.00	20.00
Stockpile DFT (AMD) *100	22.81	19.58	3.82
Stockpile DFT (AMD)*100	15.20	10.04	1.96
Blended DFT (BMD) *100	**46.20**		
Blended DFT (AMD)*100	**27.20**		

(b)

Figure 4-61. IH 10 with 0 RAP Mixture Blended DFT Results Based on the Retaining of (a) the No. 4 Sieve and (b) the No. 8 Sieve.

Aggregate	**Bin No.2**	**Bin No.3**	**Bin No.4**	**Bin No.8**
Source:	Igneous	Limestone_ Dolomit	Limestone_ Dolomit	Fractionated RAP
Bin %	27	30.3	28	14.7
No. 4, Cum % Passing	5	30	99	75.8
Retained on No. 4, %	95	70	1	24.2
% Used	25.65	21.21	0.28	3.5574
Normalized	50.59	41.84	0.55	7.02
Aggregate DFT (BMD) *100	57.00	39.00	39.00	57.00
Aggregate DFT (AMD) *100	38.00	20.00	20.00	49.00
Stockpile DFT (AMD) *100	28.84	16.32	0.22	4.00
Stockpile DFT (AMD)*100	19.23	8.37	0.11	3.44
Blended DFT (BMD) *100	**49.37**			
Blended DFT (AMD)*100	**31.14**			

(a)

Aggregate	**Bin No.2**	**Bin No.3**	**Bin No.4**	**Bin No.8**
Source:	Igneous	Limestone_ Dolomit	Limestone_ Dolomit	Fractionated RAP
Bin %	27	30.3	28	14.7
No. 8, Cum % Passing	4	4	83	56
Retained on No. 8, %	96	96	17	44
% Used	25.92	29.088	4.76	6.468
Normalized	39.13	43.92	7.19	9.77
Aggregate DFT (BMD) *100	57.00	39.00	39.00	57.00
Aggregate DFT (AMD) *100	38.00	20.00	20.00	49.00
Stockpile DFT (AMD) *100	22.31	17.13	2.80	5.57
Stockpile DFT (AMD)*100	14.87	8.78	1.44	4.78
Blended DFT (BMD) *100	**47.80**			
Blended DFT (AMD)*100	**29.88**			

(b)

Figure 4-62. IH 10 with 15 Percent RAP (SH 37) Mixture Blended DFT Results Based on the Retaining of (a) the No. 4 Sieve and (b) the No. 8 Sieve.

The blended DFT results for the IH 10 mixtures are summarized in Table 4-11 (using measured RAP DFT) and Table 4-12 (using the constant RAP DFT, 0.3).

Table 4-11. IH 10 Redesigned Mixture Blended Values Using Measured RAP Aggregate DFT.

Mixture Name	Blended DFT * 100 (BMD, +#4)	Blended DFT * 100 (BMD, +#8)	Blended DFT * 100 (AMD, +#4)	Blended DFT * 100 (AMD, +#8)
IH 10_20% RAP (Original)	49.4	47.4	31.1	29.6
IH 10_0 RAP	48.3	46.2	29.3	27.2
IH 10_15% RAP (SH 37)	49.4	47.8	31.1	29.9

Table 4-12. IH 10 Redesigned Mixture Blended DFT Values Using Constant RAP DFT (0.3).

Mixture Name	Blended DFT * 100 (BMD, +#4)	Blended DFT * 100 (BMD, +#8)	Blended DFT * 100 (AMD, +#4)	Blended DFT * 100 (AMD, +#8)
IH 10_20% RAP (Original)	47.6	44.9	30.7	28.9
IH 10_0 RAP	48.3	46.2	29.3	27.2
IH 10_15% RAP (SH 37)	47.5	45.2	29.8	28.0

According to the IH 10 slab mixture DFT results, the DFT ranking is IH_15% RAP (SH 37) > IH 10_20% RAP (Original) ≥ IH 10_0 RAP, which is consistent with the ranking in Table 4-11. The ranking in Table 4-12 is not consistent with the mixture slab DFT ranking. This difference in the rankings confirms the necessity of using measured RAP aggregate DFT values when applying the blended DFT method.

For redesigned mixtures, although the blended DFT ranking (using the measured aggregate DFT) shows consistency with the mixture slab DFT ranking, the increase of blended DFT values seems much smaller than the increase of mixture slab DFT values when incorporating SAC-A RAP. One reason might be that the benefit of SAC-A RAP was underestimated if only accounting for coarse aggregate (retaining on the No. 4 or No. 8 sieve). For example, more than 50 percent of the SH 37 RAP aggregate component is the fine aggregate (76 percent passing No. 4 sieve and 56 percent passing No. 8 sieve), which might also increase the mixture slab DFT values but was ignored in the blended DFT calculation.

SUMMARY AND CONCLUSIONS

In this chapter, the researchers performed aggregate testing and mixture tests. The test types include an ignition test, a sieve analysis test, a Micro-Deval test, DFT and ARTS tests on aggregate rings, a three-wheel polishing test on mixture slabs, a DFT test, and a laser texturing test (ARTS and CTM) at certain polished cycles on mixture slabs, etc. The materials included FM 356, IH 20, and IH 10 mixture slabs fabricated using the corresponding raw aggregates. In addition, these mixtures were redesigned by adding/removing RAP or changing the type/percentage of RAP. The corresponding mixture slabs were fabricated and evaluated.

By assembling all the lab test and field test information, the conclusions and findings are summarized as follows:

- The aggregate sieve analysis results confirm that the raw aggregates for each mixture were correctly collected, and the gradations agree with the original design.
- The Micro-Deval results show that the RAP aggregates may have a larger Micro-Deval percent loss than the other raw aggregates (except SH 37 RAP). One possible reason is that the ignition method may change the properties of some aggregates due to the generation of micro-cracks in the aggregates by heat.
- The aggregate ring DFT results show that some RAP has higher DFT values than limestone (SAC-B) aggregate. The RAP milled from SH 37 is SAC-A RAP, which has a similar DFT value to other SAC-A aggregates such as igneous or sandstone.
- Both DFT and ARTS micro-MPD on aggregate ring test results clearly show that the BMD values are significantly larger than the AMD values.
- At first, the DFT values on the mixture slabs increased, and the maximum DFT values occurred at approximately 500–2,000 polish cycles. This increase is due to removing the excess binder from the surface and exposing the aggregate. After reaching the peak point, the DFT values decreased as the polish cycle increased. The DFT values reached a relatively stable number at around 100,000 cycles.
- The ranking of the DFT number on the mixture slabs is IH 20 > FM 356 > IH 10, which is consistent with the DFT results on the field pavements presented in Chapter 3.
- Neither the macro-MPD nor micro-MPD rankings were consistent with the DFT ranking. This difference in rankings confirms the field observation in Chapter 3.
- The redesigned mixtures indicate that SAC-A RAP can significantly improve the DFT value of asphalt mixtures. For example, the DFT ranking among IH 20 mixtures was IH 20_30% RAP (SH 37) > IH 20_15% RAP (SH 37) > IH 20_0 RAP; the DFT ranking among IH 10 mixtures was IH_15% RAP (SH 37) > IH 10_20% RAP (Original) ≥ IH 10_0 RAP.
- The TxDOT blended DFT calculation method was applied in this research. The result shows that the FM 356 mixture had significantly higher blended DFT numbers than the other two mixtures. The blended DFT numbers ranking from high to low were FM 356 > IH 10 > IH 20 based on BMD, and FM 356 > IH 20 > IH 10 based on AMD. However, neither ranking was consistent with the lab-molded mixture slab test or the field test results. The DFT ranking of the mixture slab and field pavement surface was IH 20 > FM 356 > IH 10. This ranking implies that not only the coarse aggregate but also other factors such as fine aggregate, gradation, etc., may influence the mixture's DFT values.
- The redesigned (adjusting RAP percentage) mixture blended DFT results show that the blended DFT ranking was consistent with the mixture slab DFT ranking using the measured RAP aggregate DFT values. However, if using a constant DFT number for all RAP (e.g., 0.3), the blended DFT ranking was not consistent with the mixture slab DFT

ranking. This indicates that assuming a constant DFT value for all RAP may lead to unreasonable estimations on the mixture's skid resistance.

- For redesigned mixtures, although the blended DFT ranking (using the measured aggregate DFT) shows consistency with the mixture slab DFT ranking, the increase of blended DFT values seems much smaller than the increase of mixture slab DFT values when incorporating SAC-A RAP. One reason might be that the benefit of SAC-A RAP was underestimated when only accounting for coarse aggregate (retaining on the No. 4 or No. 8 sieve). For example, more than 50 percent of the SH 37 RAP aggregate component is the fine aggregate (76 percent passing No. 4 sieve and 56 percent passing No. 8 sieve), which might also increase the mixture slab DFT values but was ignored in the blended DFT calculation.

CHAPTER 5 LABORATORY EVALUATION OF IMPACT OF RAP ON SKID OF ASPHALT MIXTURES

This chapter describes the study of the impact of RAP on the skid resistance of asphalt mixes and the development of the SAC rating for RAP materials. The researchers considered the following factors: (a) two RAP types: SAC-A RAP (milled from SH 37) and SAC-B RAP (laboratory-produced with the same gradation as SH 37 RAP); (b) three RAP amounts: 0, 15 percent, and 30 percent; and (c) four surface mix types: Superpave C (redesigned FM 356 mixtures), Superpave C (redesigned IH 20 mixtures), dense-graded Type D (redesigned IH 10 mixtures), and Superpave D mixtures. Each mix type has five mixtures due to different RAP types and different RAP percentages: 0 RAP, 15 percent RAP (SAC-A), 30 percent RAP (SAC-A), 15 percent RAP (SAC-B), and 30 percent RAP (SAC-B).

Thus, the combination led to 20 different asphalt mixtures. For each mixture, two slabs were fabricated and investigated. Three-wheel polishing, DFT, laser texturing, ARTS, and CTM tests were performed on each slab. In addition, the blended DFT values based on raw aggregates of each mixture were determined and compared with the lab test values.

This chapter is organized into the following sections:

- Description of the mixture information, including the RAP characterization, the mixture designs, the raw aggregate DFT values, blended DFT values, etc.
- Presentation of the lab test results on mixture slabs, including the mixture DFT values and the laser texture measurement results (macrotexture and microtexture).
- Analysis and assembly of the RAP, raw aggregates, and mixture test information for all mixtures and recommendation of SAC rating methods for RAP materials.
- Summary of the findings and conclusions.

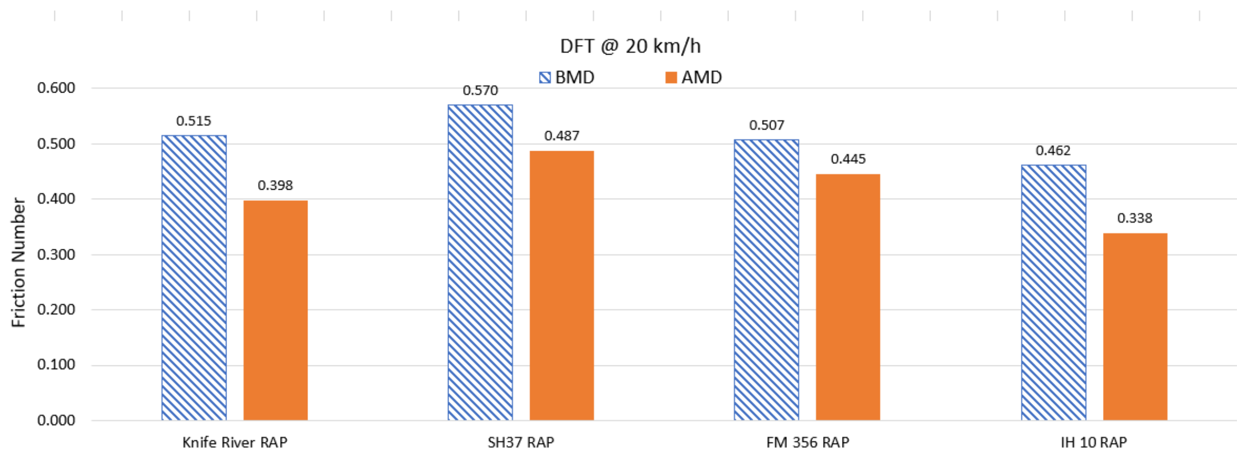
MIXTURE INFORMATION

This chapter describes the information of RAP, raw aggregate DFT values, mixture design, and aggregate blended DFT values.

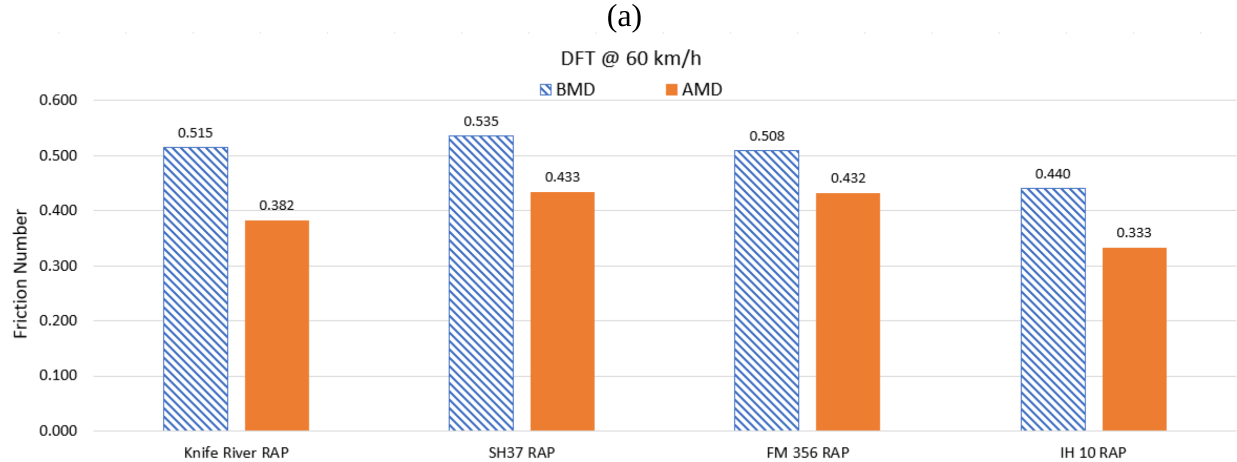
RAP Material from Stockpile or Milled Pavement Surface

As described in Chapters 3 and 4, the researchers characterized four types of RAP aggregate in terms of binder content, gradation, texture, and friction. The RAP materials characterized were from four sources: (a) RAP stockpile from Knife River Company, (b) RAP stockpile from Vulcan Materials Company (used in FM 356 surface mixture), (c) RAP stockpiles from El Paso County (used in IH 10 surface mixture), and (d) SH 37 surface-milled RAP. Among these RAP materials, the SH 37 RAP was milled directly from the SH 37 pavement surface mixture, and the other RAP materials may be a blend from different pavement surface mixtures. The researchers contacted the Paris District and RK Hall Construction and confirmed that the original SH 37 mixture designs have high percentages of sandstone (SAC-A stone).

Figure 5-1 shows the RAP aggregate DFT values. In this figure, BMD indicates the aggregate before Micro-Deval abrasion, and AMD indicates the aggregate after Micro-Deval abrasion. The SH 37 RAP has the highest DFT values among the four RAP materials for both BMD and AMD.



(a)



(b)

Figure 5-1. RAP Aggregate DFT Test Results at (a) 20 km/h and (b) 60 km/h.

Figure 5-2 and Table 5-1 show the RAP binder contents and aggregate gradations, respectively.

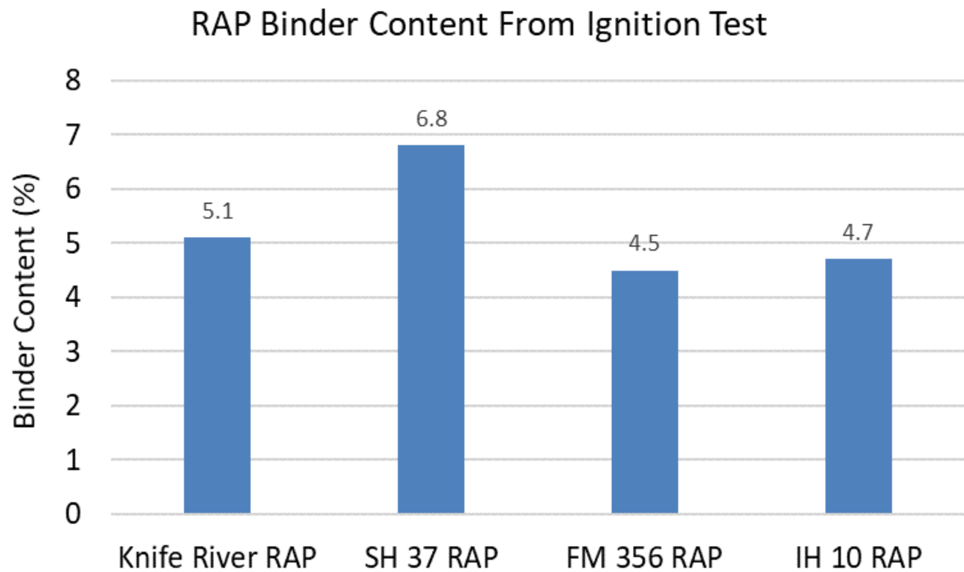


Figure 5-2. RAP Binder Contents.

Table 5-1. RAP Aggregate Sieve Analysis Results.

Sieve Size	Knife River RAP	SH 37 RAP	FM 356 RAP	IH 10 RAP
3/4	100	100	100	100
1/2	93.2	100	98.2	95.8
3/8	83.2	95	92.4	84.6
No. 4	58.6	76	70.5	60.4
No. 8	41.9	56	53.7	44.2
No. 16	32.6	43	43.5	34.4
No. 30	27.0	36	36.2	27.8
No. 50	20.4	30	23.2	20.3
No. 200	10.6	11.4	4.6	7.8

One purpose of this research is to evaluate the influence of RAP type on the mixture's skid resistance, which means the RAP type is the only changing factor in the mixture. To address this, the researchers used limestone-only aggregate to fabricate the SAC-B RAP in the laboratory according to the binder content and gradation of SH 37 RAP. More details are described in the following.

Laboratory-Produced RAP

A procedure described by McDaniel et al. (2012) was followed to produce the RAP in the laboratory. The researchers identified that combining two limestone stockpiles (one Type F Rock and one screenings stockpile) could produce the blends with the same gradation as SH 37 RAP. The aggregates were sieved into each sieve size and then blended according to the desired percentages. To obtain the designed percentage of passing No. 200 sieve, a grinding machine was employed to crush some screenings into a smaller size.

The aggregate blends and the binder (PG 70-22) were heated to a mixing temperature of 149ºC (300ºF) and mixed in a 5-gal bucket mixer. Next, the mix was conditioned for two hours at the compaction temperature (135°C or 275ºF) according to AASHTO R 30 (AASHTO 2020c). After conditioning, the mixture was left in an 85°C (185ºF) oven for 120 hours to simulate the aging over the pavement's service life. After this exposure, the mixture was cooled and remixed in the bucket mixer to be separated into smaller particles. The laboratory-produced RAP was then stored in closed containers for future use. Figure 5-3 shows the conditioning chamber and the mixer.

(a) (b)

Figure 5-3. Laboratory-Produced RAP of (a) Conditioning in 85°C Chamber for 120 Hours and (b) Mixing in a Bucket Mixer.

The Micro-Deval and aggregate ring tests such as CTM, ARTS, and DFT were conducted to characterize the laboratory-produced RAP aggregate. It has much lower DFT values (0.35 for BMD and 0.23 for AMD) than other RAP materials and can represent a "worse skid resistance" scenario and be used as SAC-B RAP.

Mixture Design Combinations

Four surface mix types—Superpave C (redesigned FM 356 mixtures), Superpave C (redesigned IH 10 mixtures), dense-graded Type D (redesigned IH 20 mixtures), and Superpave D (SP D)—were investigated in this research. Three RAP percentages (0, 15, and 30 percent) and two RAP types (SAC-A and SAC-B) were considered for each mix type. Thus, there were five different mixtures for each surface mix type (0 RAP, 15 percent SAC-A RAP, 15 percent SAC-B RAP, 30 percent SAC-A RAP, and 30 percent SAC-B RAP). For convenience, the researchers named the mixtures from Superpave C redesigned FM 356 mixtures as follows: FM 356_0 RAP, FM 356_15% RAP (SAC-A), FM 356_15% RAP (SAC-B), FM 356_30% RAP (SAC-A), and FM 356_30% RAP (SAC-B). For the other mixtures, only the FM 356 needed to be replaced with IH 10, IH 20, or SP D accordingly.

The combinations led to 20 (4 × 5) different asphalt mixtures. The combined gradation was designed to be the same (or similar) among different RAP percentages for each surface mix type. Since the SAC-A RAP (SH 37 RAP) and SAC-B RAP (laboratory-produced RAP) had the same gradation and binder content, the stockpile percentages were the same for the corresponding mixtures.

Figure 5-4, Figure 5-5, and Figure 5-6 show the mixture designs for FM 356_0 RAP, FM 356_15% RAP, and FM 356_30% RAP, respectively. In the figures, "RAP" means SAC-A RAP or SAC-B RAP.

	AGGREGATE BIN FRACTIONS														"RECYCLED MATERIALS"						
Aggregate	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		
Source:	Sandstone		mestone_Dolom		mestone_Dolom										Fractionated RAP						Material Type
Pit:	Brownlee		Marble Falls Quarry		Marble Falls Quarry										Pavers Supply						Material Source
Number:	1402704		1402702		1402702																RAS Type
Producer:	Capitol Aggregates		Oldcastle Materials Texas		Oldcastle Materials Texas		Pavers Supply		Austin White Lime												RAP/RAS Producer
Sample ID:							Washed Sand		Lime												Sample ID
															Recycled Asphalt Binder (%)						
															6.8						
Hydrated Lime?:															0.0	% of Tot.		% of Tot.		% of Tot.	Total Bin
Individual Bin (%):	35.0	Percent	10.0	Percent	36.0	Percent	18.0	Percent	1.0	Percent		Percent		Percent		% of Aggreg		% of Aggreg		% of Aggreg	100.0%
Sieve Size:	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum. % Passing
1"	100.0	35.0	100.0	10.0	100.0	36.0	100.0	18.0	100.0	1.0					100.0	0.0					100.0
3/4"	100.0	35.0	100.0	10.0	100.0	36.0	100.0	18.0	100.0	1.0					100.0	0.0					100.0
1/2"	99.0	34.7	58.2	5.8	100.0	36.0	100.0	18.0	100.0	1.0					100.0	0.0					95.5
3/8"	74.3	26.0	17.1	1.7	100.0	36.0	100.0	18.0	100.0	1.0					95.1	0.0					82.7
No. 4	5.9	2.1	1.8	0.2	99.8	35.9	100.0	18.0	100.0	1.0					75.8	0.0					57.2
No. 8	2.0	0.7	1.4	0.1	78.7	28.3	100.0	18.0	100.0	1.0					56.0	0.0					48.2
No. 16	2.0	0.7	1.4	0.1	56.0	20.2	100.0	18.0	100.0	1.0					43.3	0.0					40.0
No. 30	2.0	0.7	1.4	0.1	38.0	13.7	91.0	16.4	100.0	1.0					36.2	0.0					31.9
No. 50	2.0	0.7	1.4	0.1	24.9	9.0	61.0	11.0	100.0	1.0					29.9	0.0					21.8
No. 200	2.0	0.7	1.1	0.1	4.2	1.5	3.2	0.6	100.0	1.0					11.4	0.0					3.90

Figure 5-4. FM 356_0 RAP Mixture Design.

	AGGREGATE BIN FRACTIONS														"RECYCLED MATERIALS"						
Aggregate	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		
Source:	Sandstone		mestone_Dolom		mestone_Dolom										Fractionated RAP						Material Type
Pit:	Brownlee		Marble Falls Quarry		Marble Falls Quarry										Pavers Supply						Material Source
Number:	1402704		1402702		1402702																RAS Type
Producer:	Capitol Aggregates		Oldcastle Materials Texas		Oldcastle Materials Texas		Pavers Supply		Austin White Lime												RAP/RAS Producer
Sample ID:							Washed Sand		Lime												Sample ID
															Recycled Asphalt Binder (%)						
															6.8						
Hydrated Lime?:															15.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix	Total Bin
Individual Bin (%):	35.0	Percent	8.3	Percent	27.0	Percent	15.0	Percent	0.0	Percent		Percent		Percent	14.7	% of Aggreg		% of Aggreg		% of Aggreg	100.0%
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing
1"	100.0	35.0	100.0	8.3	100.0	27.0	100.0	15.0	100.0	0.0					100.0	14.7					100.0
3/4"	100.0	35.0	100.0	8.3	100.0	27.0	100.0	15.0	100.0	0.0					100.0	14.7					100.0
1/2"	99.0	34.7	58.2	4.8	100.0	27.0	100.0	15.0	100.0	0.0					100.0	14.7					96.2
3/8"	74.3	26.0	17.1	1.4	100.0	27.0	100.0	15.0	100.0	0.0					95.1	14.0					83.4
No. 4	5.9	2.1	1.8	0.1	99.8	26.9	100.0	15.0	100.0	0.0					75.8	11.1					55.3
No. 8	2.0	0.7	1.4	0.1	78.7	21.2	100.0	15.0	100.0	0.0					56.0	8.2					45.3
No. 16	2.0	0.7	1.4	0.1	56.0	15.1	100.0	15.0	100.0	0.0					43.3	6.4					37.3
No. 30	2.0	0.7	1.4	0.1	38.0	10.3	91.0	13.7	100.0	0.0					36.2	5.3					30.0
No. 50	2.0	0.7	1.4	0.1	24.9	6.7	61.0	9.2	100.0	0.0					29.9	4.4					21.1
No. 200	2.0	0.7	1.1	0.1	4.2	1.1	3.2	0.5	100.0	0.0					11.4	1.7					4.08

Figure 5-5. FM 356_15% RAP Mixture Design.

	AGGREGATE BIN FRACTIONS														"RECYCLED MATERIALS"						
Aggregate	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		
Source:	Sandstone		mestone_Dolom		mestone_Dolom										Fractionated RAP						Material Type
Pit:	Brownlee		Marble Falls Quarry		Marble Falls Quarry										Pavers Supply						Material Source
Number:	1402704		1402702		1402702																RAS Type
Producer:	Capitol Aggregates		Oldcastle Materials Texas		Oldcastle Materials Texas		Pavers Supply		Austin White Lime												RAP/RAS Producer
Sample ID:							Washed Sand		Lime												Sample ID
															Recycled Asphalt Binder (%)						
															6.8						
Hydrated Lime?:															30.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix	Total Bin
Individual Bin (%):	29.0	Percent	9.0	Percent	24.6	Percent	8.0	Percent	0.0	Percent		Percent		Percent	29.4	% of Aggreg		% of Aggreg		% of Aggreg	100.0%
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing
1"	100.0	29.0	100.0	9.0	100.0	24.6	100.0	8.0	100.0	0.0					100.0	29.4					100.0
3/4"	100.0	29.0	100.0	9.0	100.0	24.6	100.0	8.0	100.0	0.0					100.0	29.4					100.0
1/2"	99.0	28.7	58.2	5.2	100.0	24.6	100.0	8.0	100.0	0.0					100.0	29.4					95.9
3/8"	74.3	21.5	17.1	1.5	100.0	24.6	100.0	8.0	100.0	0.0					95.1	28.0					83.6
No. 4	5.9	1.7	1.8	0.2	99.8	24.6	100.0	8.0	100.0	0.0					75.8	22.3					56.7
No. 8	2.0	0.6	1.4	0.1	78.7	19.4	100.0	8.0	100.0	0.0					56.0	16.5					44.5
No. 16	2.0	0.6	1.4	0.1	56.0	13.8	100.0	8.0	100.0	0.0					43.3	12.7					35.2
No. 30	2.0	0.6	1.4	0.1	38.0	9.3	91.0	7.3	100.0	0.0					36.2	10.6					28.0
No. 50	2.0	0.6	1.4	0.1	24.9	6.1	61.0	4.9	100.0	0.0					29.9	8.8					20.5
No. 200	2.0	0.6	1.1	0.1	4.2	1.0	3.2	0.3	100.0	0.0					11.4	3.4					5.32

Figure 5-6. FM 356_30% RAP Mixture Design.

In addition, the blended gradations for 0 percent RAP, 15 percent RAP, and 30 percent RAP mixtures were designed to be very close, as listed in Table 5-2. This eliminated (or reduced to a minimum) the impact of other factors when evaluating the impact of RAP percentages.

Table 5-2. Blended Gradation of FM 356 Mixtures (Superpave C).

Sieve Size	FM 356_0 RAP	FM 356_15% RAP	FM 356_30% RAP
3/4	100	100	100
1/2	95.5	96.2	95.9
3/8	82.7	83.4	83.6
No. 4	57.2	55.3	56.7
No. 8	48.2	45.3	44.5
No. 16	40	37.3	35.2
No. 30	31.9	30	28
No. 50	21.8	21.1	20.5
No. 200	3.9	4.1	5.3

Figure 5-7, Figure 5-8, and Figure 5-9 show the mixture design for IH 20_0 RAP, IH 20_15% RAP, and IH 20_30% RAP, respectively. Similarly, Table 5-3 lists the blended gradation of IH 20 mixtures.

	AGGREGATE BIN FRACTIONS														"RECYCLED MATERIALS"						
	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		
Aggregate Source:	Igneous		Igneous		Igneous																Material Type
Aggregate Pit:	Jones Mill		Jones Mill		Jones Mill		SMITH PIT														Material Source
Aggregate Number:	0050122		0050122		0050122		LOCAL SOURCE														RAS Type
Sample ID:	1/2" C.A.		3-8" C.A.		SCREENINGS		FIELD SAND														Sample ID
															Recycled Asphalt Binder (%)						
Hydrated Lime?:																% of Tot. Mix		% of Tot. Mix		% of Tot. Mix	Total Bin
Individual Bin (%):	50.0	Percent	10.0	Percent	30.0	Percent	10.0	Percent		Percent		Percent		Percent		% of Aggreg		% of Aggreg		% of Aggreg	100.0%
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing
3/4"	100.0	50.0	100.0	10.0	100.0	30.0	100.0	10.0													100.0
1/2"	100.0	50.0	100.0	10.0	100.0	30.0	100.0	10.0													100.0
3/8"	90.4	45.2	100.0	10.0	100.0	30.0	100.0	10.0													95.2
No. 4	34.3	17.2	35.0	3.5	95.4	28.6	100.0	10.0													59.3
No. 8	9.6	4.8	7.8	0.8	71.2	21.4	100.0	10.0													36.9
No. 30	3.1	1.6	3.0	0.3	28.8	8.6	96.3	9.6													20.1
No. 50	2.5	1.3	2.6	0.3	19.6	5.9	72.1	7.2													14.6
No. 200	1.8	0.9	1.8	0.2	10.4	3.1	12.0	1.2													5.4

Figure 5-7. IH 20_0 RAP Mixture Design.

	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		
	AGGREGATE BIN FRACTIONS														"RECYCLED MATERIALS"						
Aggregate Source:	Igneous		Igneous		Igneous										Fractionated RAP						Material Type
Aggregate Pit:	Jones Mill		Jones Mill		Jones Mill		SMITH PIT														Material Source
Aggregate Number:	0050122		0050122		0050122		LOCAL SOURCE														RAS Type
Sample ID:	1/2" C.A.		3-8" C.A.		SCREENINGS		FIELD SAND								SH37 RAP						Sample ID
															Recycled Asphalt Binder (%)						
															6.8						
Hydrated Lime?:															15.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix	Total Bin
Individual Bin (%):	38.3	Percent	16.0	Percent	25.0	Percent	6.0	Percent		Percent		Percent		Percent	14.7	% of Aggreg		% of Aggreg		% of Aggreg	100.0%
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing
3/4"	100.0	38.3	100.0	16.0	100.0	25.0	100.0	6.0							100.0	14.7					100.0
1/2"	100.0	38.3	100.0	16.0	100.0	25.0	100.0	6.0							100.0	14.7					100.0
3/8"	90.4	34.6	100.0	16.0	100.0	25.0	100.0	6.0							95.1	14.0					95.6
No. 4	34.3	13.1	35.0	5.6	95.4	23.9	100.0	6.0							75.8	11.1					59.7
No. 8	9.6	3.7	7.8	1.2	71.2	17.8	100.0	6.0							56.0	8.2					37.0
No. 30	3.1	1.2	3.0	0.5	28.8	7.2	96.3	5.8							36.2	5.3					20.0
No. 50	2.5	1.0	2.6	0.4	19.6	4.9	72.1	4.3							29.9	4.4					15.0
No. 200	1.8	0.7	1.8	0.3	10.4	2.6	12.0	0.7							11.4	1.7					6.0

Figure 5-8. IH 20_15% RAP Mixture Design.

	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		
	AGGREGATE BIN FRACTIONS														"RECYCLED MATERIALS"						
Aggregate Source:	Igneous		Igneous		Igneous										Fractionated RAP						Material Type
Aggregate Pit:	Jones Mill		Jones Mill		Jones Mill		SMITH PIT														Material Source
Aggregate Number:	0050122		0050122		0050122		LOCAL SOURCE														RAS Type
Sample ID:	1/2" C.A.		3-8" C.A.		SCREENINGS		FIELD SAND								SH37 RAP						Sample ID
															Recycled Asphalt Binder (%)						
															6.8						
Hydrated Lime?:															30.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix	Total Bin
Individual Bin (%):	45.0	Percent	4.0	Percent	19.5	Percent	2.1	Percent		Percent		Percent		Percent	29.4	% of Aggreg		% of Aggreg		% of Aggreg	100.0%
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing
3/4"	100.0	45.0	100.0	4.0	100.0	19.5	100.0	2.1							100.0	29.4					100.0
1/2"	100.0	45.0	100.0	4.0	100.0	19.5	100.0	2.1							100.0	29.4					100.0
3/8"	90.4	40.7	100.0	4.0	100.0	19.5	100.0	2.1							95.1	28.0					94.2
No. 4	34.3	15.4	35.0	1.4	95.4	18.6	100.0	2.1							75.8	22.3					59.8
No. 8	9.6	4.3	7.8	0.3	71.2	13.9	100.0	2.1							56.0	16.5					37.1
No. 30	3.1	1.4	3.0	0.1	28.8	5.6	96.3	2.0							36.2	10.6					19.8
No. 50	2.5	1.1	2.6	0.1	19.6	3.8	72.1	1.5							29.9	8.8					15.3
No. 200	1.8	0.8	1.8	0.1	10.4	2.0	12.0	0.3							11.4	3.3					6.5

Figure 5-9. IH 20_30% RAP Mixture Design.

Table 5-3. Blended Gradation of IH 20 Mixtures (Dense-Graded Type D).

Sieve Size	IH 20_0 RAP	IH 20_15% RAP	IH 20_ 30% RAP
3/4	100	100	100
1/2	100	100	100
3/8	95.2	95.6	94.2
No. 4	59.3	59.7	59.8
No. 8	36.9	37	37.1
No. 30	20.1	20	19.8
No. 50	14.6	15	15.3
No. 200	5.4	6	6.5

Figure 5-10, Figure 5-11, and Figure 5-12 show the mixture design for IH 10_0 RAP, IH 10_15% RAP, and IH 10_30% RAP, respectively. The blended gradation of IH 10 mixtures is listed in Table 5-4.

	AGGREGATE BIN FRACTIONS							"RECYCLED MATERIALS"			
Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10	
Source:	mestone_Dolom	Igneous	mestone_Dolom	mestone_Dolomi				Fractionated RAP			Material Type
Pit:	Ned Finney Quarry	Padre Canyon	Ned Finney Quarry	Ned Finney Quarry				txdot			Material Source
Number:	2407220	2411613	2407220	2407220							RAS Type
Producer:											RAP/RAS Producer
Sample ID:	3/4 SAC B	3/4 SAC A	3/8	Fines							Sample ID
								Recycled Asphalt Binder (%)			
								6.8			
Hydrated Lime?:								0.0 % of Tot. Mix	% of Tot.	% of Tot.	Total Bin
Individual Bin (%):	Percent	27.5 Percent	34.5 Percent	38.0 Percent	Percent	Percent	Percent	% of Aggreg	% of Aggreg	% of Aggreg	100.0%

Sieve Size:	Bin 1 Cum.% Passing	Bin 1 Wtd Cum. %	Bin 2 Cum.% Passing	Bin 2 Wtd Cum. %	Bin 3 Cum.% Passing	Bin 3 Wtd Cum. %	Bin 4 Cum.% Passing	Bin 4 Wtd Cum. %	Bin 5 Cum.% Passing	Bin 5 Wtd Cum. %	Bin 6 Cum.% Passing	Bin 6 Wtd Cum. %	Bin 7 Cum.% Passing	Bin 7 Wtd Cum. %	Bin 8 Cum.% Passing	Bin 8 Wtd Cum. %	Bin 9 Cum.% Passing	Bin 9 Wtd Cum. %	Bin 10 Cum.% Passing	Bin 10 Wtd Cum. %	Cum. % Passing
1"			100.0	27.5	100.0	34.5	100.0	38.0							100.0	0.0					100.0
3/4"			100.0	27.5	100.0	34.5	100.0	38.0							100.0	0.0					100.0
1/2"			73.0	20.1	100.0	34.5	100.0	38.0							100.0	0.0					92.6
3/8"			45.0	12.4	89.0	30.7	100.0	38.0							97.0	0.0					81.1
No. 4			5.0	1.4	30.0	10.4	99.0	37.6							73.0	0.0					49.3
No. 8			4.0	1.1	4.0	1.4	83.0	31.5							47.0	0.0					34.0
No. 16			3.5	1.0	3.0	1.0	54.0	20.5							35.0	0.0					22.5
No. 30			3.0	0.8	2.0	0.7	37.3	14.2							27.0	0.0					15.7
No. 50			2.0	0.6	1.5	0.5	26.5	10.1							20.0	0.0					11.1
No. 200			1.8	0.5	1.0	0.3	13.6	5.2							8.0	0.0					6.0

Figure 5-10. IH 10_0 RAP Mixture Design.

	AGGREGATE BIN FRACTIONS														"RECYCLED MATERIALS"						
Aggregate	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		
Source:	mestone_Dolom		Igneous		mestone_Dolom		mestone_Dolomi								Fractionated RAP						Material Type
Pit:	Ned Finney Quarry		Padre Canyon		Ned Finney Quarry		Ned Finney Quarry								txdot						Material Source
Number:	2407220		2411613		2407220		2407220														RAS Type
Producer:																					RAP/RAS Producer
Sample ID:	3/4 SAC B		3/4 SAC A		3/8		Fines														Sample ID
															Recycled Asphalt Binder (%)						
															6.8						
Hydrated Lime?:															15.0	% of Tot. Mix		% of Tot.		% of Tot.	Total Bin
Individual Bin (%):		Percent	27.0	Percent	30.3	Percent	28.0	Percent		Percent		Percent		Percent	14.7	% of Aggreg		% of Aggreg		% of Aggreg	100.0%
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing
1"			100.0	27.0	100.0	30.3	100.0	28.0							100.0	14.7					100.0
3/4"			100.0	27.0	100.0	30.3	100.0	28.0							100.0	14.7					100.0
1/2"			73.0	19.7	100.0	30.3	100.0	28.0							100.0	14.7					92.7
3/8"			45.0	12.2	89.0	27.0	100.0	28.0							95.1	14.0					81.1
No. 4			5.0	1.4	30.0	9.1	99.0	27.7							75.8	11.1					49.3
No. 8			4.0	1.1	4.0	1.2	83.0	23.2							56.0	8.2					33.8
No. 16			3.5	0.9	3.0	0.9	54.0	15.1							43.3	6.4					23.3
No. 30			3.0	0.8	2.0	0.6	37.3	10.4							36.2	5.3					17.2
No. 50			2.0	0.5	1.5	0.5	26.5	7.4							29.9	4.4					12.8
No. 200			1.8	0.5	1.0	0.3	13.6	3.8							11.4	1.7					6.3

Figure 5-11. IH 10_15% RAP Mixture Design.

	AGGREGATE BIN FRACTIONS														"RECYCLED MATERIALS"						
Aggregate	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		
Source:	mestone_Dolom		Igneous		mestone_Dolom		mestone_Dolomi								Fractionated RAP						Material Type
Pit:	Ned Finney Quarry		Padre Canyon		Ned Finney Quarry		Ned Finney Quarry								txdot						Material Source
Number:	2407220		2411613		2407220		2407220														RAS Type
Producer:																					RAP/RAS Producer
Sample ID:	3/4 SAC B		3/4 SAC A		3/8		Fines														Sample ID
															Recycled Asphalt Binder (%)						
															6.8						
Hydrated Lime?:															30.0	% of Tot. Mix		% of Tot.		% of Tot.	Total Bin
Individual Bin (%):		Percent	25.2	Percent	30.0	Percent	15.5	Percent		Percent		Percent		Percent	29.3	% of Aggreg		% of Aggreg		% of Aggreg	100.0%
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing
1"			100.0	25.2	100.0	30.0	100.0	15.5							100.0	29.3					100.0
3/4"			100.0	25.2	100.0	30.0	100.0	15.5							100.0	29.3					100.0
1/2"			73.0	18.4	100.0	30.0	100.0	15.5							100.0	29.3					93.2
3/8"			45.0	11.3	89.0	26.7	100.0	15.5							95.1	27.9					81.4
No. 4			5.0	1.3	30.0	9.0	99.0	15.3							75.8	22.2					47.8
No. 8			4.0	1.0	4.0	1.2	83.0	12.9							56.0	16.4					31.5
No. 16			3.5	0.9	3.0	0.9	54.0	8.4							43.3	12.7					22.8
No. 30			3.0	0.8	2.0	0.6	37.3	5.8							36.2	10.6					17.7
No. 50			2.0	0.5	1.5	0.5	26.5	4.1							29.9	8.8					13.8
No. 200			1.8	0.5	1.0	0.3	13.6	2.1							11.4	3.3					6.2

Figure 5-12. IH 10_30% RAP Mixture Design.

Table 5-4. Blended Gradation of IH 10 Mixtures (Superpave C).

Sieve Size	IH 10_0 RAP	IH 10_15% RAP	IH 10_30% RAP
3/4	100	100	100
1/2	92.6	92.7	93.2
3/8	81.1	81.1	81.4
No. 4	49.3	49.3	47.8
No. 8	34	33.8	31.5
No. 16	22.5	23.3	22.8
No. 30	15.7	17.2	17.7
No. 50	11.1	12.8	13.8
No. 200	6	6.3	6.2

Figure 5-13, Figure 5-14, and Figure 5-15 show the mixture design for SP D_0 RAP, SP D_15% RAP, and SP D_30% RAP, respectively. The blended gradation of SP D mixtures is listed in Table 5-5.

	AGGREGATE BIN FRACTIONS							"RECYCLED MATERIALS"			
Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10	
Source:	Sandstone	imestone_Dolomit	imestone_Dolomit					Fractionated RAP			Material Type
Pit:	Brownlee	Servtex	Servtex	River Bend				Knife River			Material Source
Number:	1402704	1504603	1504603								RAS Type
Producer:	Capital	Hanson	Hanson	Knife River							RAP/RAS Producer
Sample ID:	D Rock	F Rock	Washed Screeings	Sand				RAP			Sample ID
								Recycled Asphalt Binder (%)			
								6.8			

	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		
Hydrated Lime?:															0.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix	Total Bin
Individual Bin (%):	26.0	Percent	37.0	Percent	37.0	Percent	0.0	Percent		Percent		Percent		Percent		% of Aggreg		% of Aggreg		% of Aggreg	100.0%
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing
3/4"	100.0	26.0	100.0	37.0	100.0	37.0	100.0	0.0							100.0	0.0					100.0
1/2"	99.8	25.9	100.0	37.0	100.0	37.0	100.0	0.0							100.0	0.0					99.9
3/8"	71.5	18.6	100.0	37.0	100.0	37.0	100.0	0.0							100.0	0.0					92.6
No. 4	11.4	3.0	58.9	21.8	95.7	35.4	99.2	0.0							80.2	0.0					60.2
No. 8	2.7	0.7	6.6	2.4	81.9	30.3	79.7	0.0							71.3	0.0					33.4
No. 16	1.9	0.5	1.8	0.7	59.7	22.1	59.2	0.0							52.0	0.0					23.2
No. 30	0.9	0.2	1.1	0.4	36.8	13.6	39.4	0.0							37.7	0.0					14.3
No. 50	0.8	0.2	1.0	0.4	22.9	8.5	14.7	0.0							27.2	0.0					9.1
No. 200	0.6	0.2	0.3	0.1	6.0	2.2	4.0	0.0							10.4	0.0					2.5

Figure 5-13. SP D_0 RAP Mixture Design.

	AGGREGATE BIN FRACTIONS														"RECYCLED MATERIALS"						
Aggregate	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		
Source:	Sandstone		Limestone_Dolomit		Limestone_Dolomit										Fractionated RAP						Material Type
Pit:	Brownlee		Servtex		Servtex		River Bend								Knife River						Material Source
Number:	1402704		1504603		1504603																RAS Type
Producer:	Capital		Hanson		Hanson		Knife River														RAP/RAS Producer
Sample ID:	D Rock		F Rock		Washed Screeings		Sand								RAP						Sample ID
															Recycled Asphalt Binder (%)						
															6.8						
Hydrated Lime?:															15.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix	Total Bin
Individual Bin (%):	22.0	Percent	38.0	Percent	25.3	Percent	0.0	Percent		Percent		Percent		Percent	14.7	% of Aggreg		% of Aggreg		% of Aggreg	100.0%
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing
3/4"	100.0	22.0	100.0	38.0	100.0	25.3	100.0	0.0							100.0	14.7					100.0
1/2"	99.8	22.0	100.0	38.0	100.0	25.3	100.0	0.0							100.0	14.7					100.0
3/8"	71.5	15.7	100.0	38.0	100.0	25.3	100.0	0.0							95.1	14.0					93.0
No. 4	11.4	2.5	58.9	22.4	95.7	24.2	99.2	0.0							75.8	11.1					60.2
No. 8	2.7	0.6	6.6	2.5	81.9	20.7	79.7	0.0							56.0	8.2					32.1
No. 16	1.9	0.4	1.8	0.7	59.7	15.1	59.2	0.0							43.3	6.4					22.6
No. 30	0.9	0.2	1.1	0.4	36.8	9.3	39.4	0.0							36.2	5.3					15.2
No. 50	0.8	0.2	1.0	0.4	22.9	5.8	14.7	0.0							29.9	4.4					10.7
No. 200	0.6	0.1	0.3	0.1	6.0	1.5	4.0	0.0							11.4	1.7					3.4

Figure 5-14. SP D_15% RAP Mixture Design.

	AGGREGATE BIN FRACTIONS														"RECYCLED MATERIALS"						
Aggregate	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		
Source:	Sandstone		Limestone_Dolomit		Limestone_Dolomit										Fractionated RAP						Material Type
Pit:	Brownlee		Servtex		Servtex		River Bend								Knife River						Material Source
Number:	1402704		1504603		1504603																RAS Type
Producer:	Capital		Hanson		Hanson		Knife River														RAP/RAS Producer
Sample ID:	D Rock		F Rock		Washed Screeings		Sand								RAP						Sample ID
															Recycled Asphalt Binder (%)						
															6.8						
Hydrated Lime?:															30.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix	Total Bin
Individual Bin (%):	20.0	Percent	34.5	Percent	16.0	Percent	0.0	Percent		Percent		Percent		Percent	29.5	% of Aggreg		% of Aggreg		% of Aggreg	100.0%
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing
3/4"	100.0	20.0	100.0	34.5	100.0	16.0	100.0	0.0							100.0	29.5					100.0
1/2"	99.8	20.0	100.0	34.5	100.0	16.0	100.0	0.0							100.0	29.5					100.0
3/8"	71.5	14.3	100.0	34.5	100.0	16.0	100.0	0.0							95.1	28.1					92.9
No. 4	11.4	2.3	58.9	20.3	95.7	15.3	99.2	0.0							75.8	22.4					60.3
No. 8	2.7	0.5	6.6	2.3	81.9	13.1	79.7	0.0							56.0	16.5					32.4
No. 16	1.9	0.4	1.8	0.6	59.7	9.6	59.2	0.0							43.3	12.8					23.3
No. 30	0.9	0.2	1.1	0.4	36.8	5.9	39.4	0.0							36.2	10.7					17.1
No. 50	0.8	0.2	1.0	0.3	22.9	3.7	14.7	0.0							29.9	8.8					13.0
No. 200	0.6	0.1	0.3	0.1	6.0	1.0	4.0	0.0							11.4	3.4					4.5

Figure 5-15. SP D_30% RAP Mixture Design.

Table 5-5. Blended Gradation of SP D Mixtures.

Sieve Size	SP D_0 RAP	SP D_15% RAP	SP D_30% RAP
3/4	100	100	100
1/2	99.9	100	100
3/8	92.6	93	92.9
No. 4	60.2	60.2	60.3
No. 8	33.4	32.1	32.4
No. 16	23.2	22.6	23.3
No. 30	14.3	15.2	17.1
No. 50	9.1	10.7	13
No. 200	2.5	3.4	4.5

Blended DFT Values

The blended DFT for each mixture can be determined based on the mixture design and aggregate DFT information. As discussed in Chapter 4, the blended DFT of the TxDOT method (Izzo 2020) was employed. According to the findings of Chapter 4, by using measured RAP aggregate DFT, the blended DFT values have better consistency with the mixture slab and field DFT measurements than using the constant value (0.3). Thus, the measured RAP aggregate DFT was suggested for use in this research.

The raw aggregate DFT values used for the blended DFT calculation are summarized in Table 5-6. More details about how to measure aggregate DFT, such as aggregate ring fabricating and testing, were described in Chapter 4.

Since there is no significant difference between DFT at 60 km/h and DFT at 20 km/h, only DFT at 20 km/h values (both BMD and AMD) are used hereafter.

Table 5-6. Summary of Raw Aggregate DFT Values.

Mix Type	Stockpile	Quarry	DFT of BMD at 20 km/h	DFT of BMD at 60 km/h	DFT of AMD at 20 km/h	DFT of AMD at 60 km/h
FM 356	Sandstone	Brownlee	0.61	0.58	0.45	0.39
FM 356	Limestone	Marble Falls	0.45	0.46	0.31	0.30
IH 20	Igneous	Jones Mill	0.47	0.44	0.32	0.31
IH 10	Limestone	Ned Finney	0.39	0.40	0.20	0.22
IH 10	Igneous	Padre Canyon	0.57	0.55	0.38	0.37
SP D	Sandstone	Brownlee	0.52	0.48	0.41	0.32
SP D	Limestone	Servtex	0.35	0.39	0.23	0.23

The blended DFT calculation was based on the stockpile gradation and the percentage of retaining on the No. 4 or No. 8 sieve. The DFT of fine aggregates was assigned the same value as the coarse aggregate if the aggregates were from the same quarry and had the same product code. More details can be found in Chapter 4. Figure 5-16 shows an example of the blended DFT calculation. In this example, the DFT values for the sand stockpile were arbitrarily assumed, and these values did not affect the result because the retaining of sand on sieve No. 4 or No. 8 was zero.

Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.8
Source:	Igneous	Igneous	Igneous	FIELD SAND	Fractionated RAP
Bin %	38.3	16	25	6	14.7
No. 4, Cum % Passing	34.3	35	95.4	100	75.8
Retained on No. 4, %	65.7	65	4.6	0	24.2
% Used	25.1631	10.4	1.15	0	3.5574
Normalized	62.49	25.83	2.86	0.00	8.83
Aggregate DFT (BMD) *100	47.00	47.00	47.00	40.00	57.00
Aggregate DFT (AMD) *100	32.00	32.00	32.00	30.00	49.00
Stockpile DFT (AMD) *100	29.37	12.14	1.34	0.00	5.04
Stockpile DFT (AMD)*100	20.00	8.26	0.91	0.00	4.33
Blended DFT (BMD) *100	**47.88**				
Blended DFT (AMD)*100	**33.50**				

(a)

Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.8
Source:	Igneous	Igneous	Igneous	FIELD SAND	Fractionated RAP
Bin %	38.3	16	25	6	14.7
No. 8, Cum % Passing	9.6	7.8	71.2	100	56
Retained on No. 8, %	90.4	92.2	28.8	0	44
% Used	34.6232	14.752	7.2	0	6.468
Normalized	54.92	23.40	11.42	0.00	10.26
Aggregate DFT (BMD) *100	47.00	47.00	47.00	40.00	57.00
Aggregate DFT (AMD) *100	32.00	32.00	32.00	30.00	49.00
Stockpile DFT (AMD) *100	25.81	11.00	5.37	0.00	5.85
Stockpile DFT (AMD)*100	17.57	7.49	3.65	0.00	5.03
Blended DFT (BMD) *100	**48.03**				
Blended DFT (AMD)*100	**33.74**				

(b)

Figure 5-16. IH 20_15% RAP (SAC-A) Mixture Blended DFT Results Based on the Retaining of (a) the No. 4 Sieve and (b) the No. 8 Sieve.

The researchers performed the blended DFT calculations for the 20 mixtures, and Table 5-7 summarizes the findings.

Table 5-7. Summary of Blended DFT Values Using Measured RAP DFT.

Mixture Name	Blended DFT * 100 (BMD, +#4)	Blended DFT * 100 (BMD, +#8)	Blended DFT * 100 (AMD, +#4)	Blended DFT * 100 (AMD, +#8)
FM 356_0 RAP	57.3	55.6	41.8	40.3
FM 356_15% RAP (SAC-A)	57.7	56.5	42.8	41.9
FM 356_30% RAP (SAC-A)	57.1	56	42.8	42.4
FM 356_15% RAP (SAC-B)	56	53.9	40.7	38.8
FM 356_30% RAP (SAC-B)	53.4	50.9	38.5	36.3
IH 20_0 RAP	47.0	47.0	32.0	32.0
IH 20_15% RAP (SAC-A)	47.9	48	33.5	33.7
IH 20_30% RAP (SAC-A)	48.8	49.1	35.1	35.6
IH 20_15% RAP (SAC-B)	45.9	45.8	31.2	31.1
IH 20_30% RAP (SAC-B)	44.8	44.5	30.4	30.1
IH 10_0 RAP	48.3	46.2	29.3	27.2
IH 10_15% RAP (SAC-A)	49.4	47.8	31.1	29.9
IH 10_30% RAP (SAC-A)	49.7	48.7	32.2	31.8
IH 10_15% RAP (SAC-B)	47.8	45.7	29.3	27.3
IH 10_30% RAP (SAC-B)	46.7	44.6	28.7	26.9
SP D_0 RAP	44.3	41.1	33.4	29.8
SP D_15% RAP (SAC-A)	44.8	42.1	34.2	31.2
SP D_30% RAP (SAC-A)	46.1	43.8	35.7	33.2
SP D_15% RAP (SAC-B)	42.8	40	31.8	28.7
SP D_30% RAP (SAC-B)	42.1	39.6	31	28.2

SLAB TEST RESULTS

Below presents the test results of the slab tests. For each mixture, at least two slabs were fabricated. Each slab was polished by a three-wheel polish machine and eventually went through

115,000 cycles. The researchers stopped the polishing at 500, 1,500, 3,000, 6,000, 10,000, 15,000, 25,000, 40,000, 60,000, 85,000 and 115,000 cycles to conduct the DFT, CTM (for macrotexture determination), and ARTS test (for macrotexture and microtexture determination). The changing of the texture (micro- and macro-MPD) and the DFT friction number during polishing were then investigated.

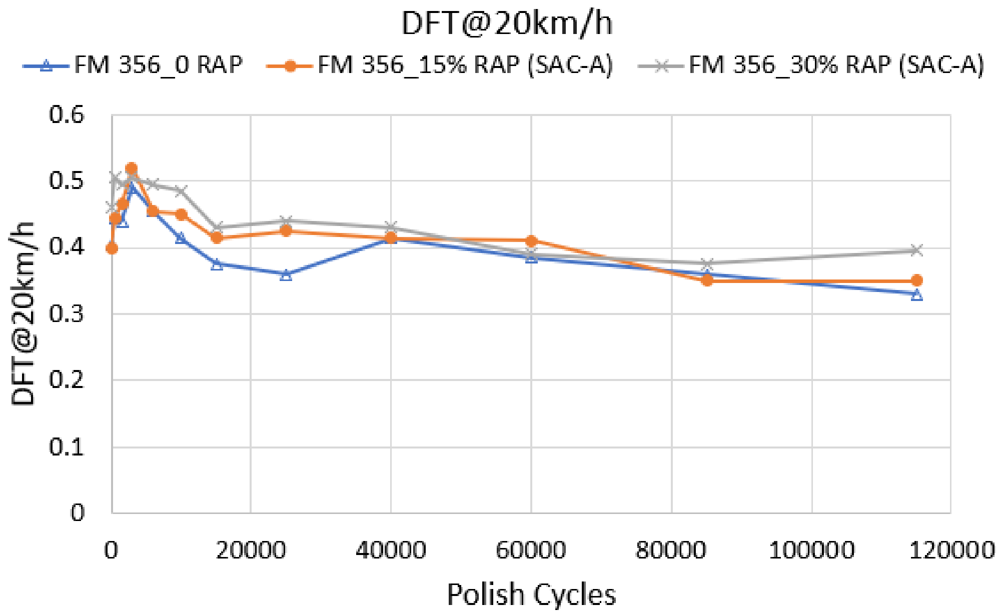
The test results are summarized below. For the convenience of comparison, the curves of 0 RAP, 15 percent RAP, and 30 percent RAP are plotted together in one figure, and each curve was plotted based on the averaged values of two slabs.

FM 356 Mixture Slab DFT Results

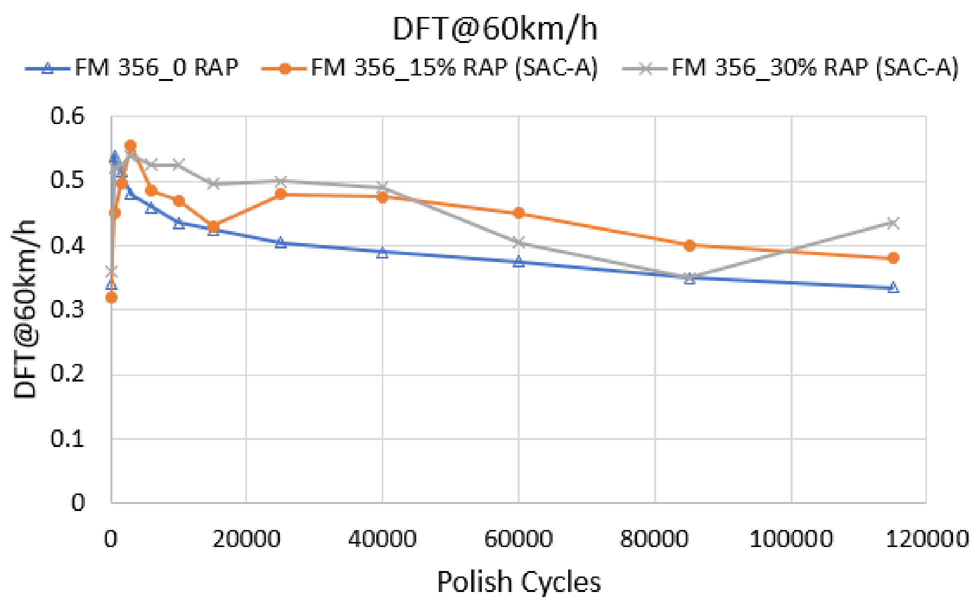
Figure 5-17 and Figure 5-18 show the DFT results of FM 356 mixtures with SAC-A RAP and SAC-B RAP, respectively.

Each curve shows that the DFT values on the mixture slabs first increased, and the maximum DFT values occurred at approximately 500–3,000 polish cycles. This increase was due to removing the excess binder from the surface and exposing the aggregate. After reaching the peak point, the DFT values decreased as the polish cycle increased. The DFT values reached a relatively stable number at around 100,000 cycles.

Overall, the addition of SAC-A RAP increases the mixture slab DFT values, while SAC-B RAP decreases the slab DFT values.

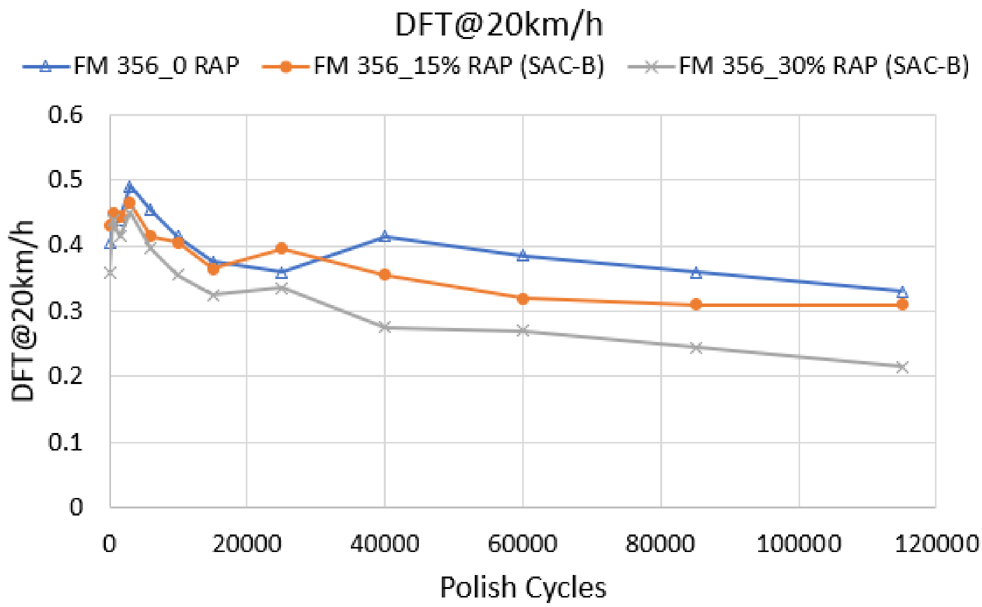


(a)

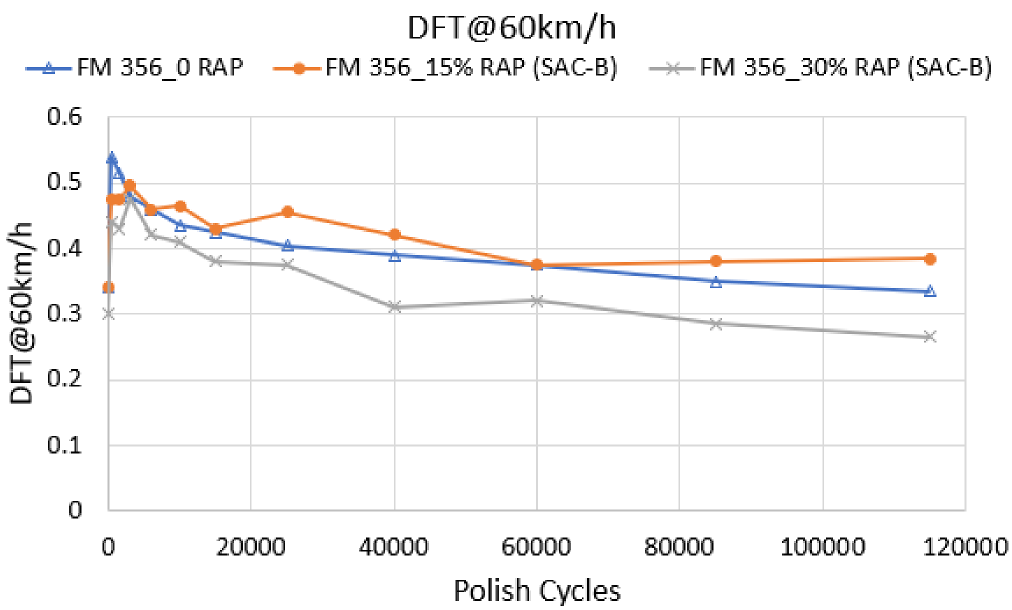


(b)

Figure 5-17. DFT Test Results on FM 356 Mixture with SAC-A RAP Slabs at (a) 20 km/h and (b) 60 km/h.



(a)

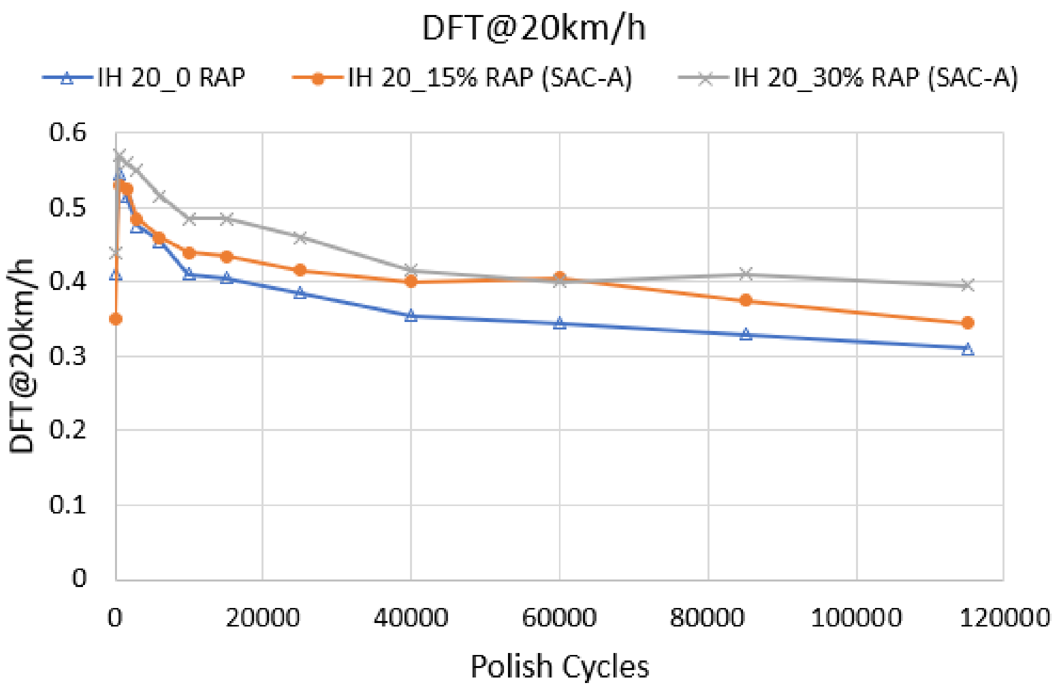


(b)

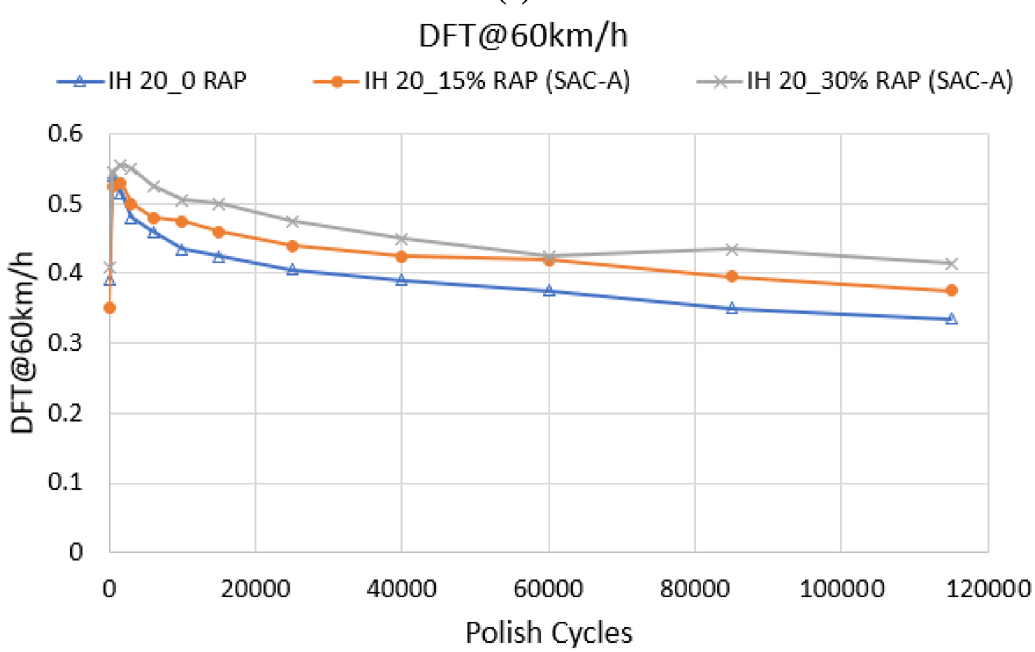
Figure 5-18. DFT Test Results on FM 356 Mixture with SAC-B RAP Slabs at (a) 20 km/h and (b) 60 km/h.

IH 20 Mixture Slab DFT Results

Figure 5-19 and Figure 5-20 show the DFT results of IH 20 mixtures with SAC-A RAP and SAC-B RAP, respectively. These figures show a clear trend that IH 20_30% RAP (SAC-A) > IH 20_15% RAP (SAC-A) > IH 20_0 RAP > IH 20_15% RAP (SAC-B) > IH 20_30% RAP (SAC-B) in terms of both DFT @ 20 km/h and DFT @ 60 km/h values.

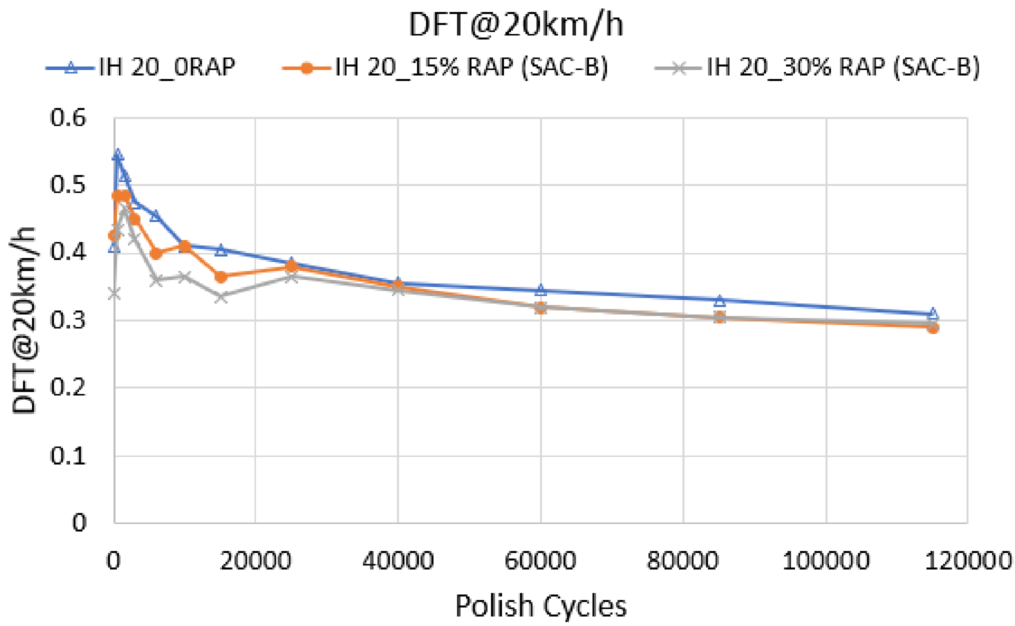


(a)

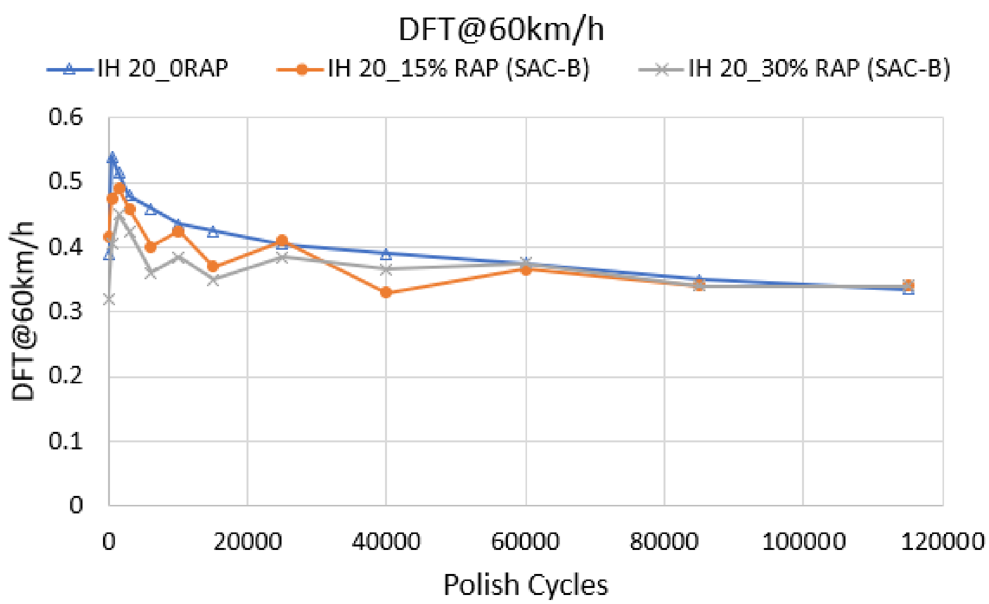


(b)

Figure 5-19. DFT Test Results on IH 20 Mixture with SAC-A RAP Slabs at (a) 20 km/h and (b) 60 km/h.



(a)

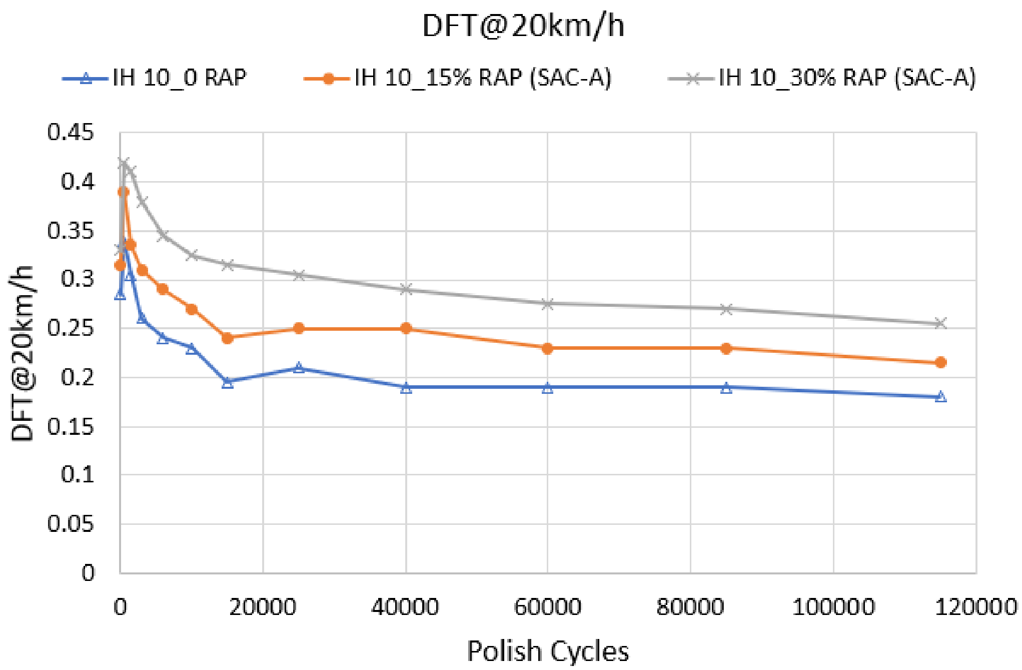


(b)

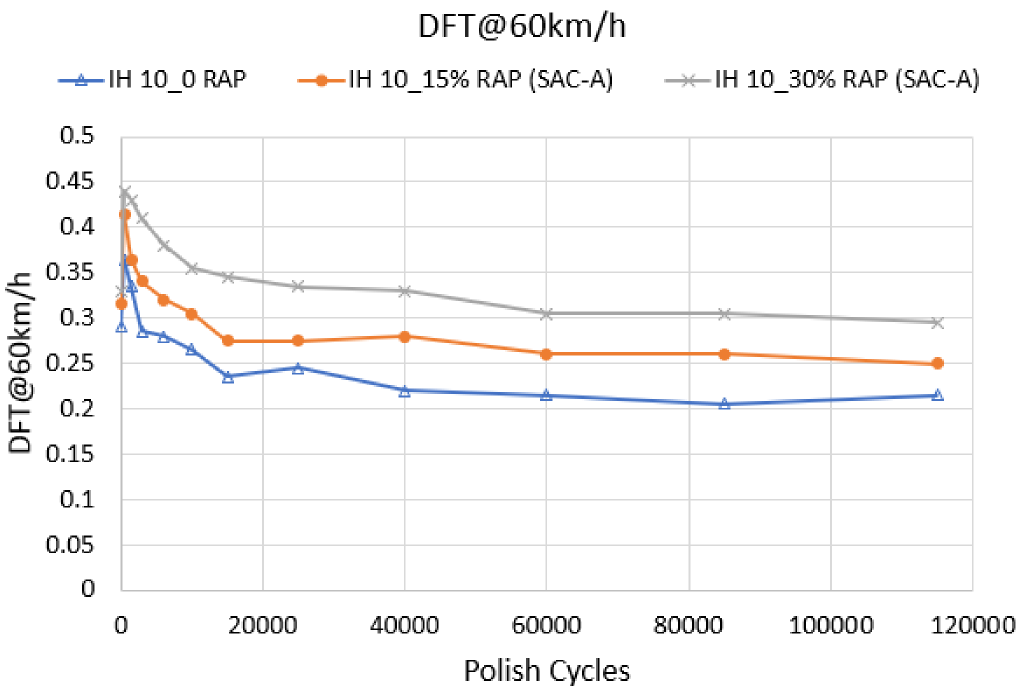
Figure 5-20. DFT Test Results on IH 20 Mixture with SAC-B RAP Slabs at (a) 20 km/h and (b) 60 km/h.

IH 10 Mixture Slab DFT Results

Figure 5-21 and Figure 5-22 show the DFT results of IH 10 mixtures with SAC-A RAP and SAC-B RAP, respectively. Figure 5-21 clearly shows that IH 10_30% RAP (SAC-A) > IH 10_15% RAP (SAC-A) > IH 10_0 RAP in terms of both DFT @ 20 km/h and DFT @ 60 km/h values. It indicates that the addition of SAC-A RAP increases the slab DFT values. Figure 5-22 shows that the ranking is IH 10_15% RAP (SAC-B) > IH 10_0 RAP > IH 10_30% RAP (SAC-B), which indicates that the addition of SAC-B RAP decreases the slab DFT values.

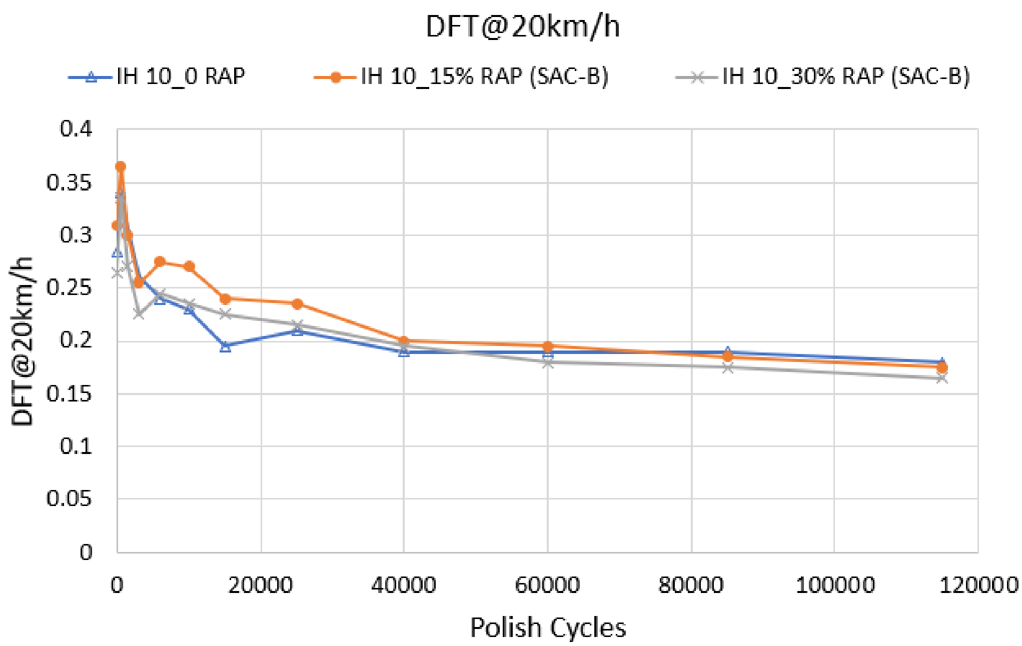


(a)

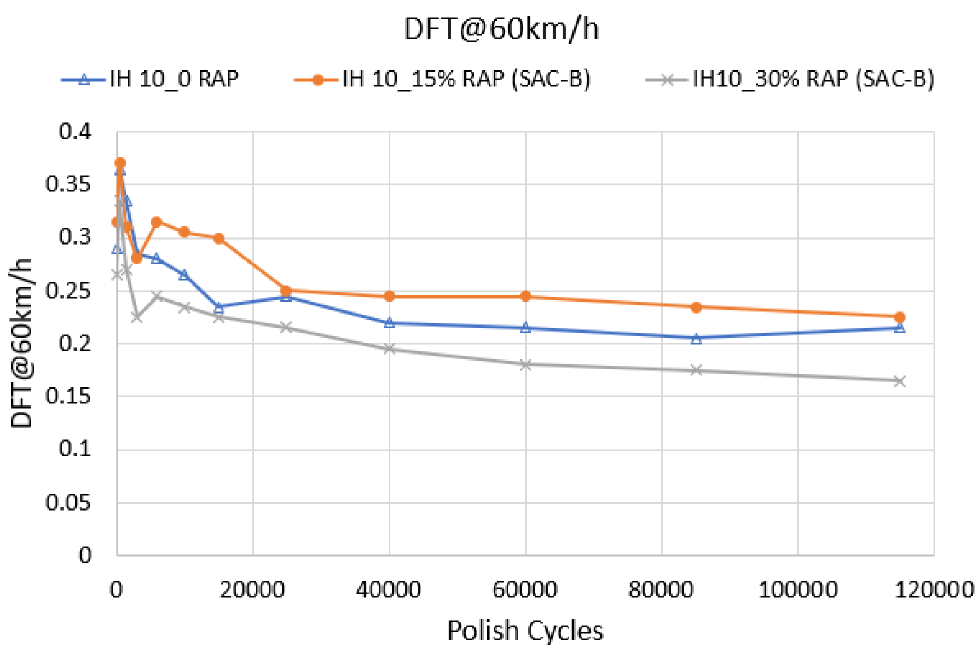


(b)

Figure 5-21. DFT Test Results on IH 10 Mixture with SAC-A RAP Slabs at (a) 20 km/h and (b) 60 km/h.



(a)



(b)

Figure 5-22. DFT Test Results on IH 10 Mixture with SAC-B RAP Slabs at (a) 20 km/h and (b) 60 km/h.

SP D Mixture Slab DFT Results

Figure 5-23 and Figure 5-24 show the DFT results of SP D mixtures with SAC-A RAP and SAC-B RAP, respectively. The addition of SAC-A RAP increases the slab DFT values, while the addition of SAC-B RAP decreases the slab DFT values. The trend shows that SP D_30% RAP (SAC-A) > SP D_15% RAP (SAC-A) > SP D_0 RAP > SP D_15% RAP (SAC-B) > SP D_30% RAP (SAC-B) in terms of both DFT @ 20 km/h and DFT @ 60 km/h values.

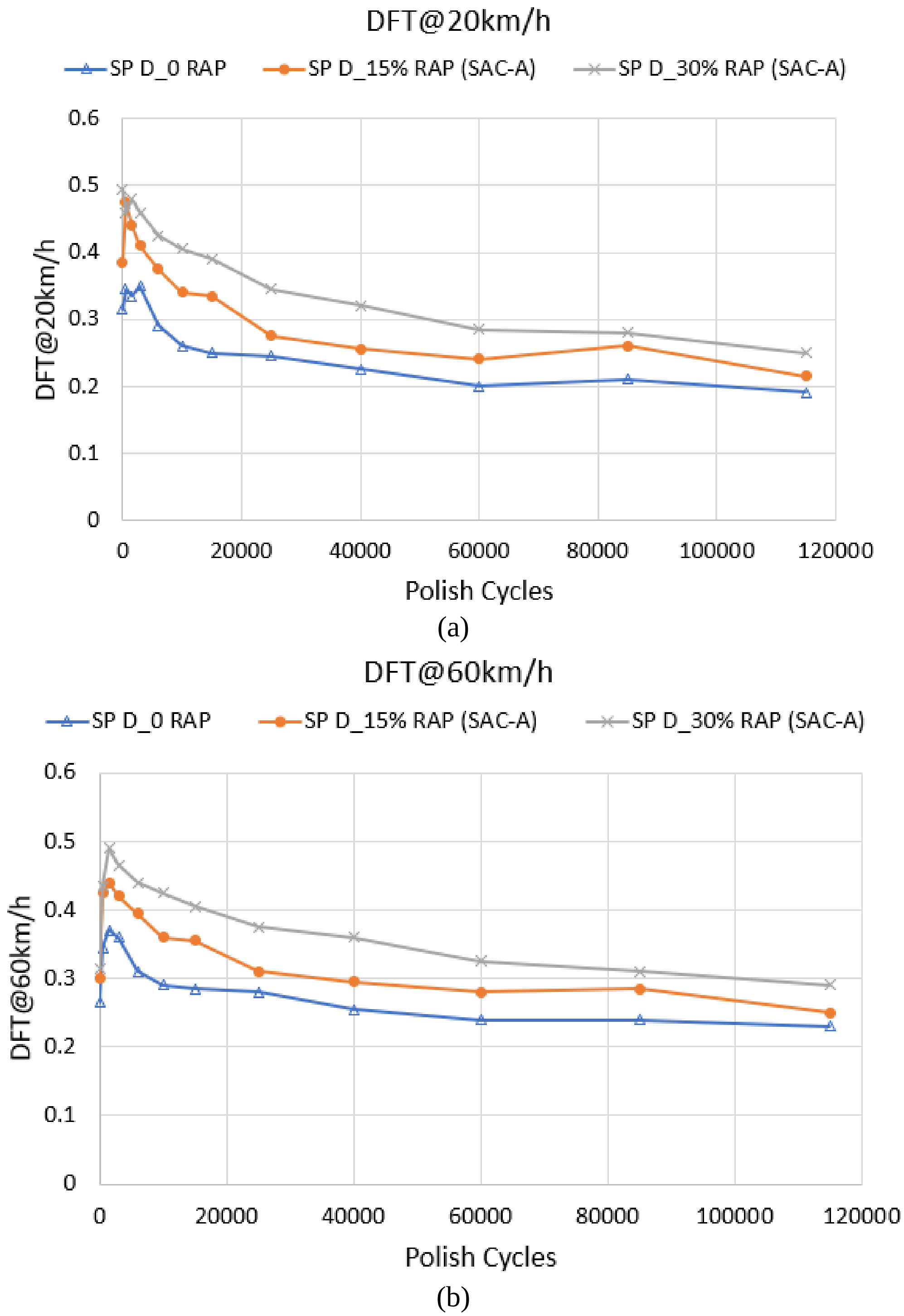
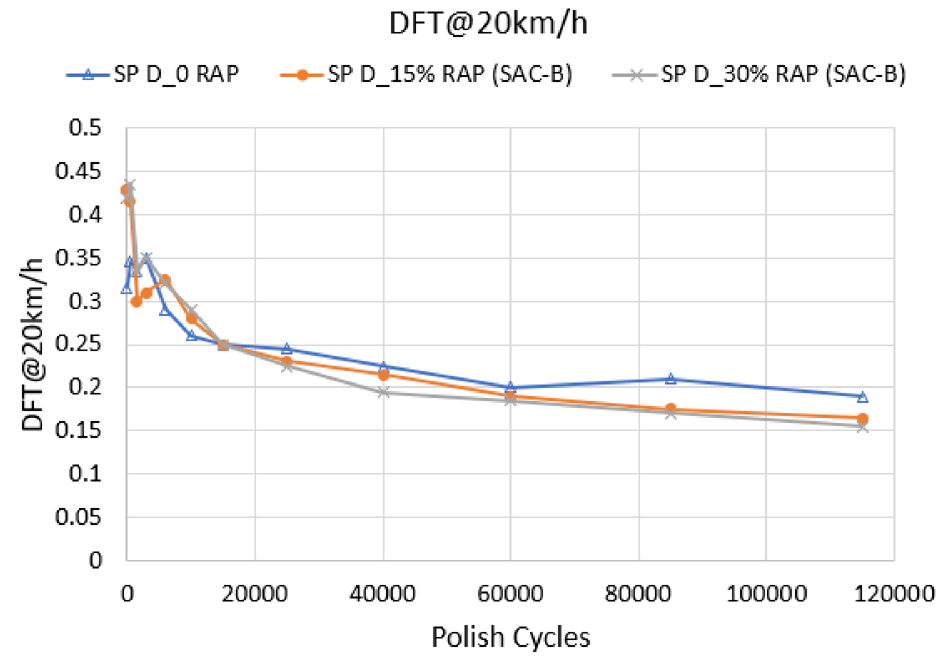
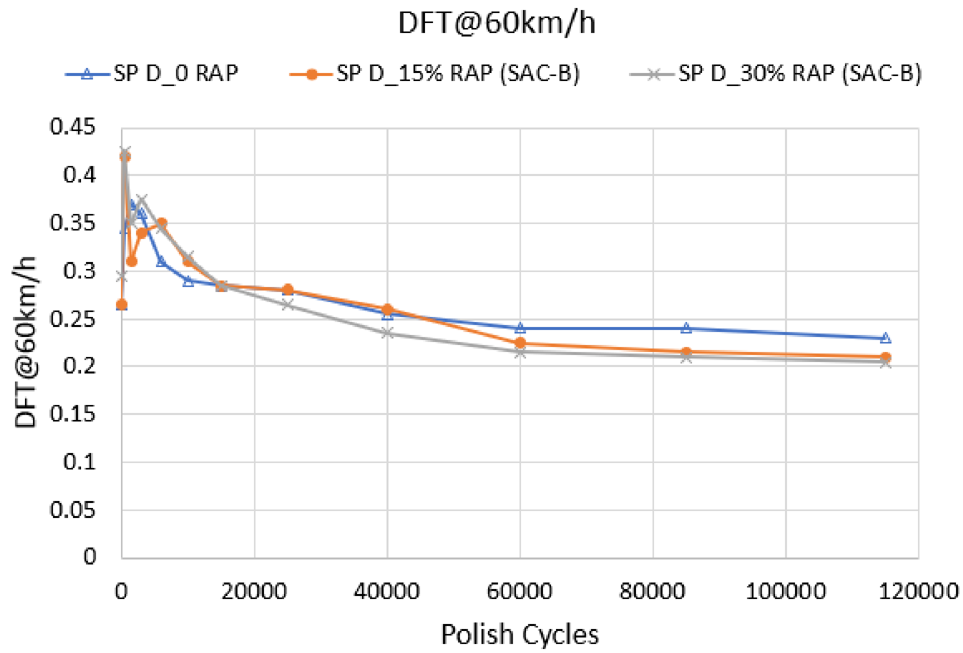


Figure 5-23. DFT Test Results on SP D Mixture with SAC-A RAP Slabs at (a) 20 km/h and (b) 60 km/h.



(a)



(b)

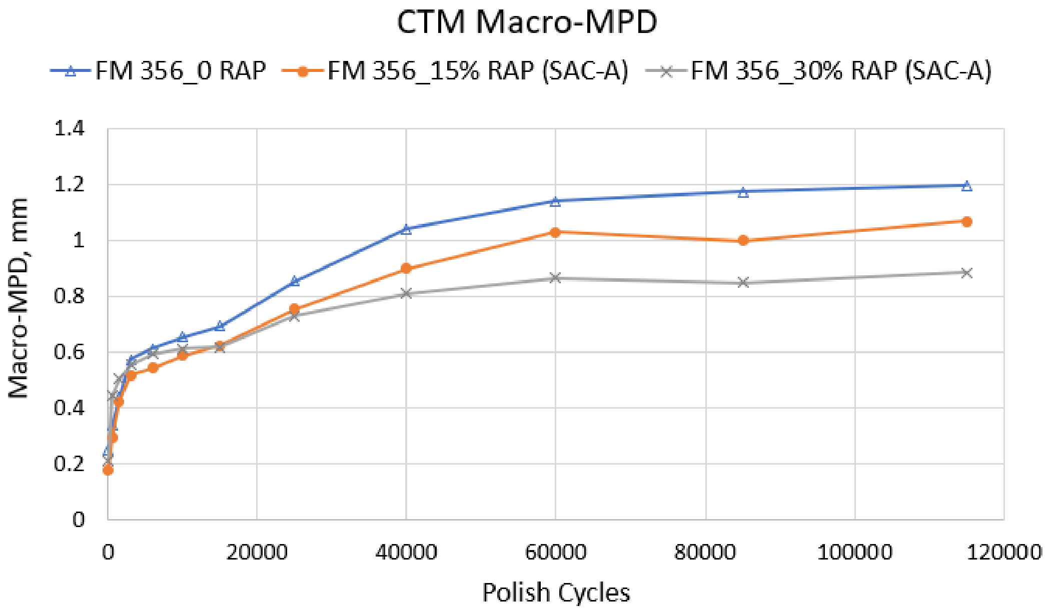
Figure 5-24. DFT Test Results on SP D Mixture with SAC-B RAP Slabs at (a) 20 km/h and (b) 60 km/h.

FM 356 Mixture Slab Texture Results

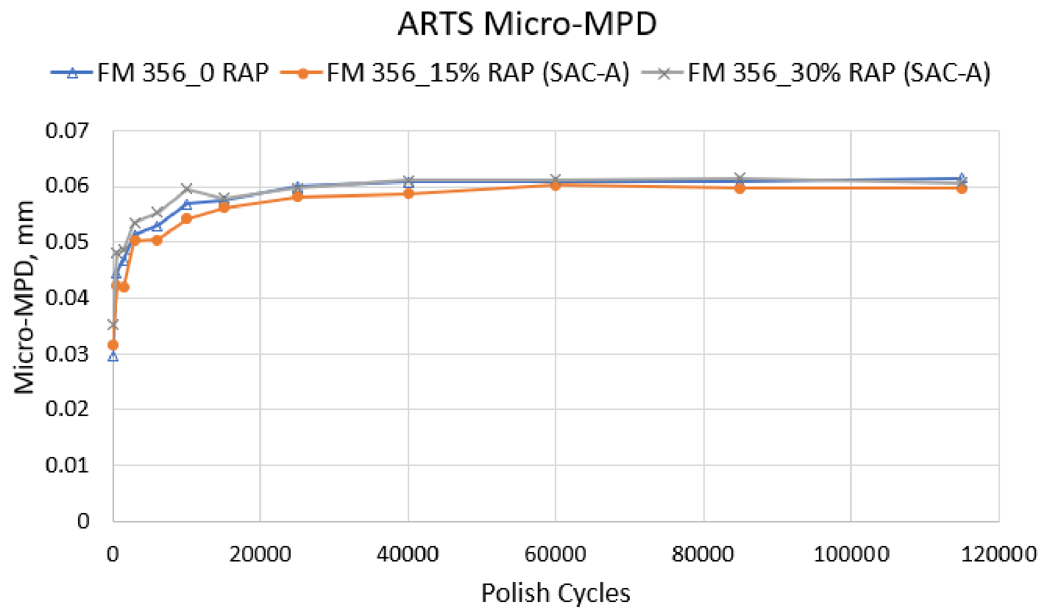
As explained in Chapter 4, the CTM test was used to determine the mixture slab surface macro-MPD, while the ARTS test was used to determine both macro-MPD and micro-MPD. The previous research findings show that the CTM macro-MPD values have a good relationship with the ARTS macro-MPD values. Their value differences are not significant (usually less than

10 percent). Thus, only CTM macro-MPD and ARTS micro-MPD results are presented in this report.

Figure 5-25 and Figure 5-26 show the macro-MPD and micro-MPD results of FM 356 mixtures with SAC-A RAP and SAC-B RAP, respectively. Neither macro-MPD nor micro-MPD ranking is consistent with DFT ranking among the mixtures with different RAP percentages.

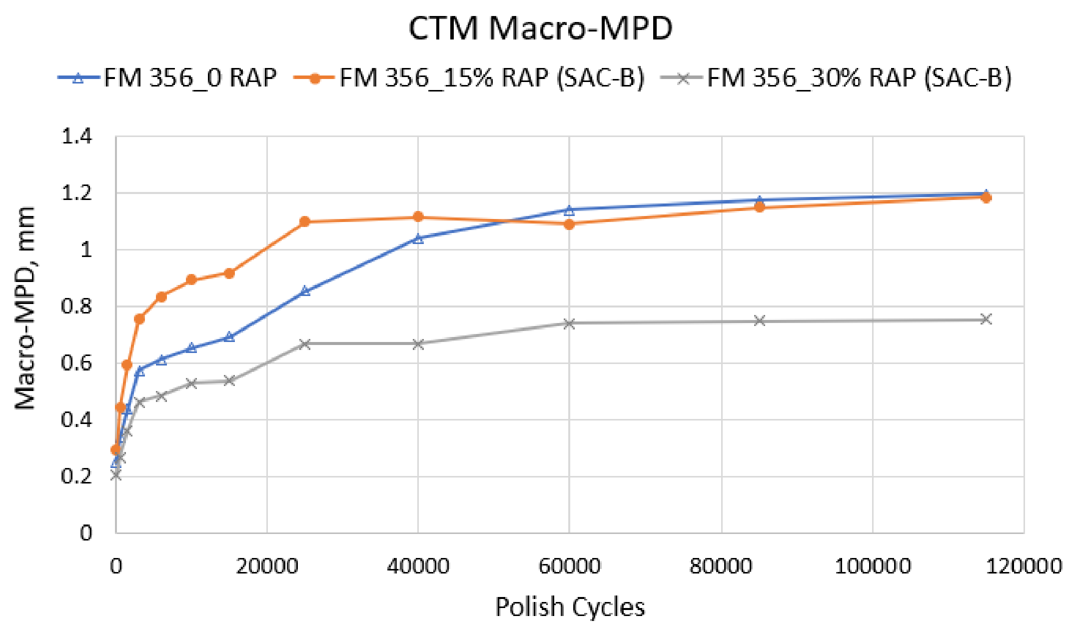


(a)

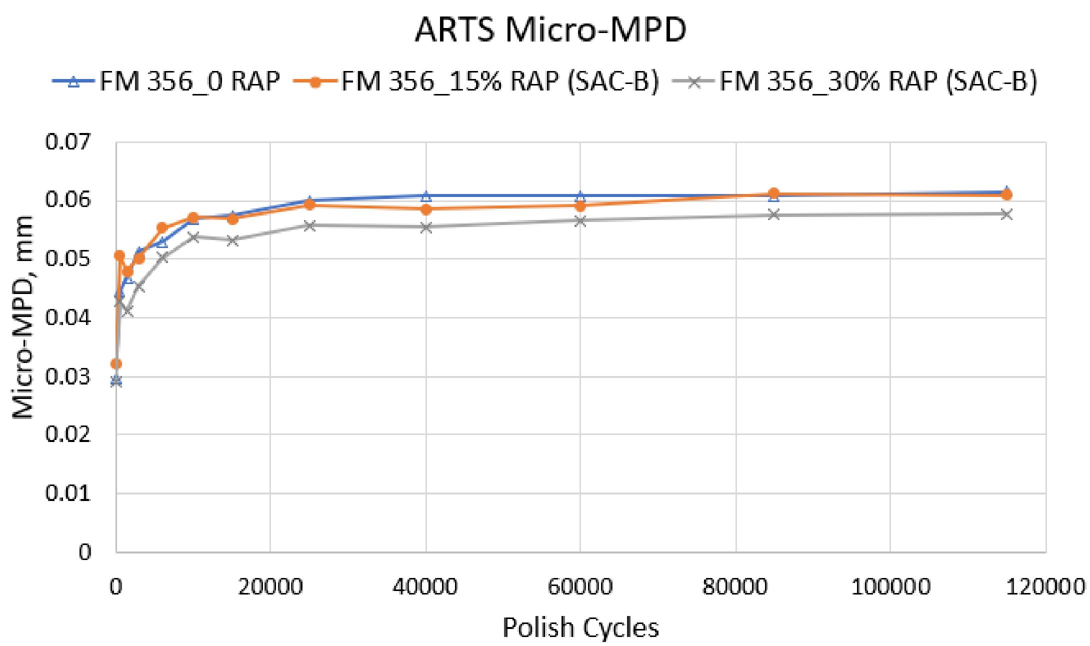


(b)

Figure 5-25. Texture Test Results on FM 356 Mixture with SAC-A RAP Slabs at (a) CTM Macro-MPD and (b) ARTS Micro-MPD.



(a)

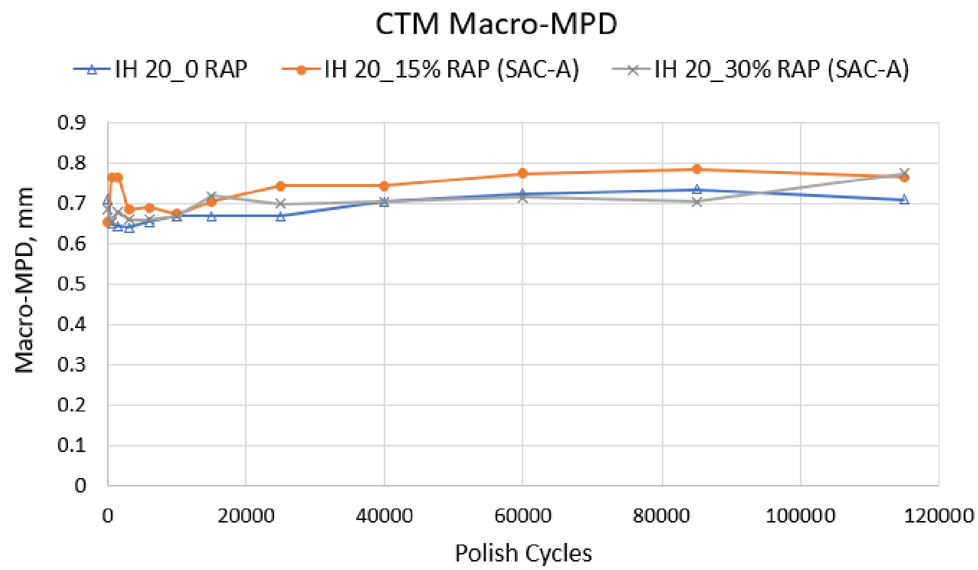


(b)

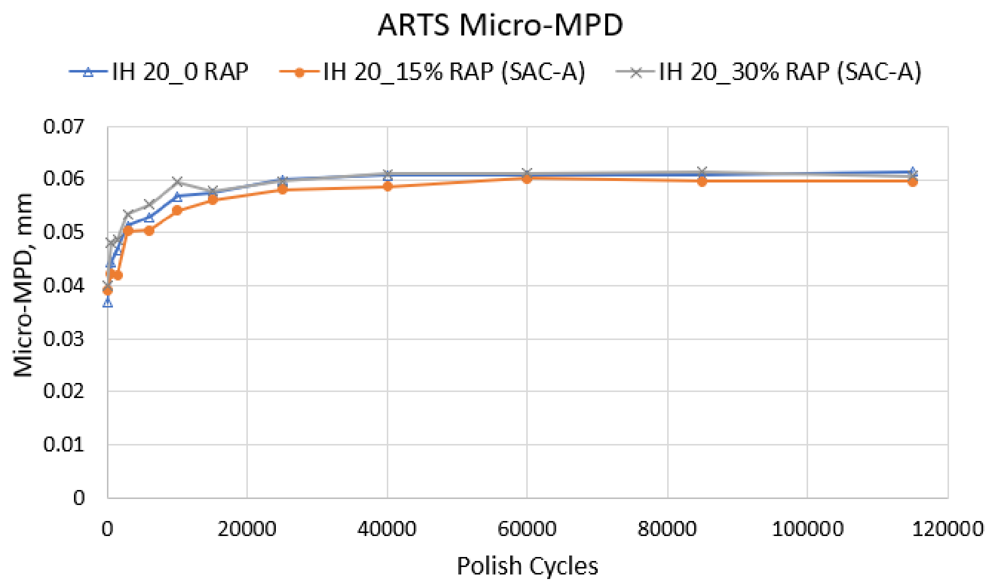
Figure 5-26. Texture Test Results on FM 356 Mixture with SAC-B RAP Slabs at (a) CTM Macro-MPD and (b) ARTS Micro-MPD.

IH 20 Mixture Slab Texture Results

Figure 5-27 and Figure 5-28 show the macro-MPD and micro-MPD results of IH 20 mixtures with SAC-A RAP and SAC-B RAP, respectively. Only Figure 5-28a shows IH 20_0 RAP > IH 20_15% RAP (SAC-B) > IH 20_30% RAP (SAC-B) in terms of CTM macro-MPD. Other rankings are not consistent with DFT rankings.

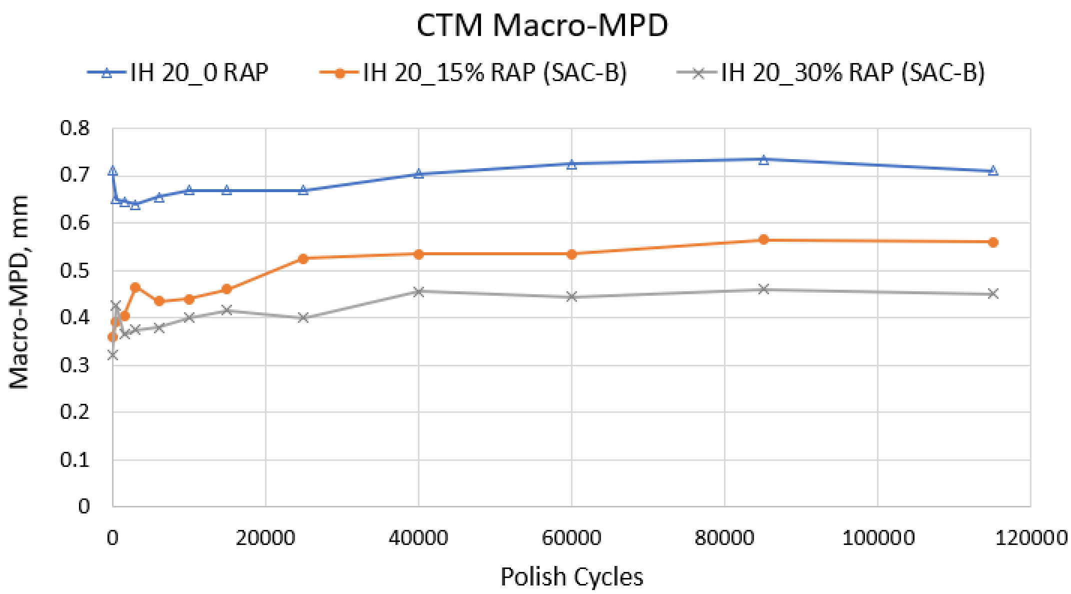


(a)

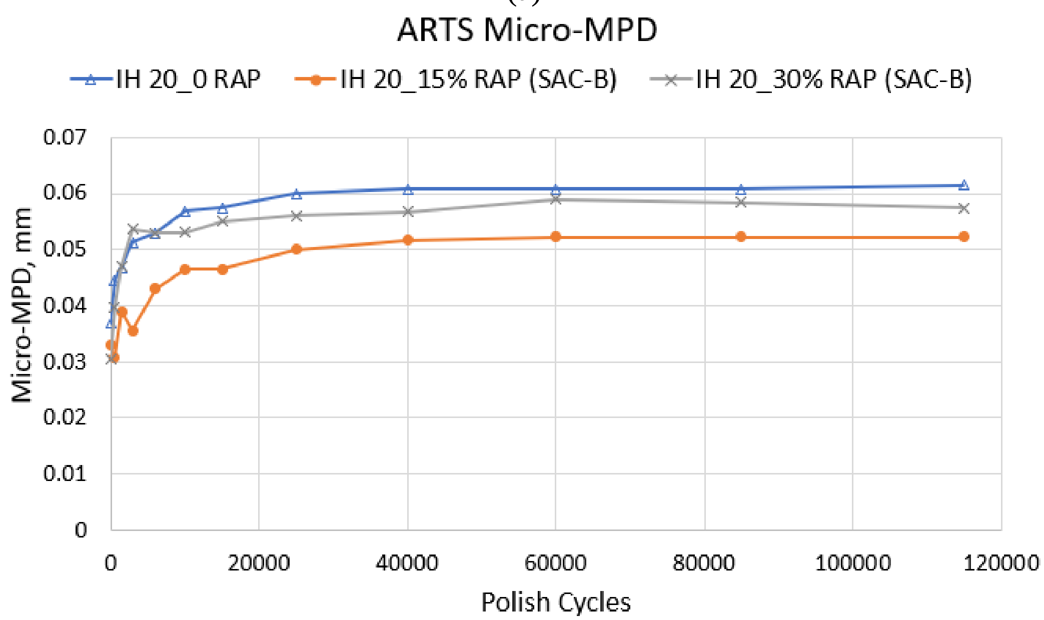


(b)

Figure 5-27. Texture Test Results on IH 20 Mixture with SAC-A RAP Slabs at (a) CTM Macro-MPD and (b) ARTS Micro-MPD.



(a)

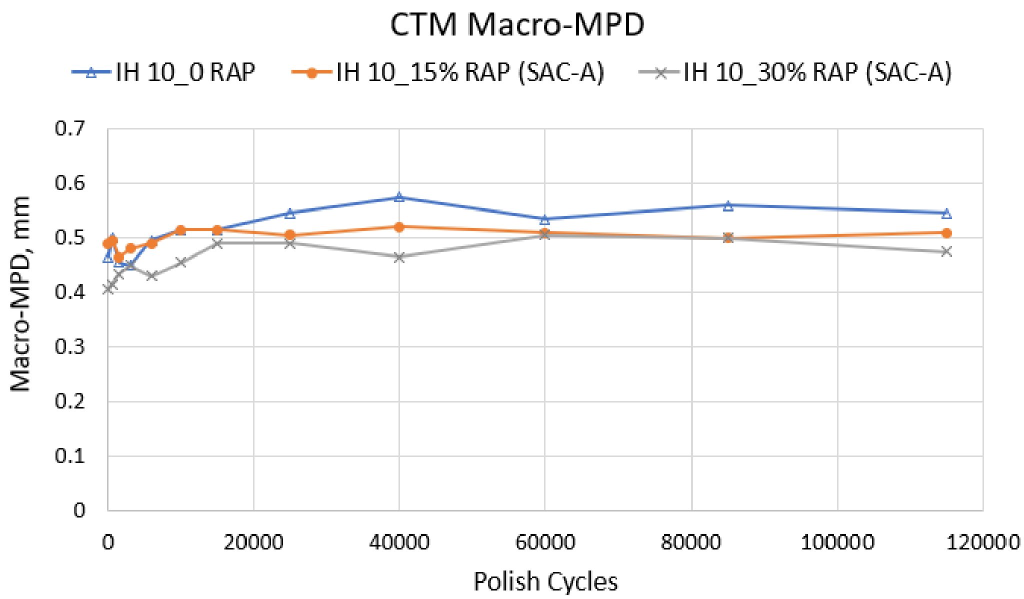


(b)

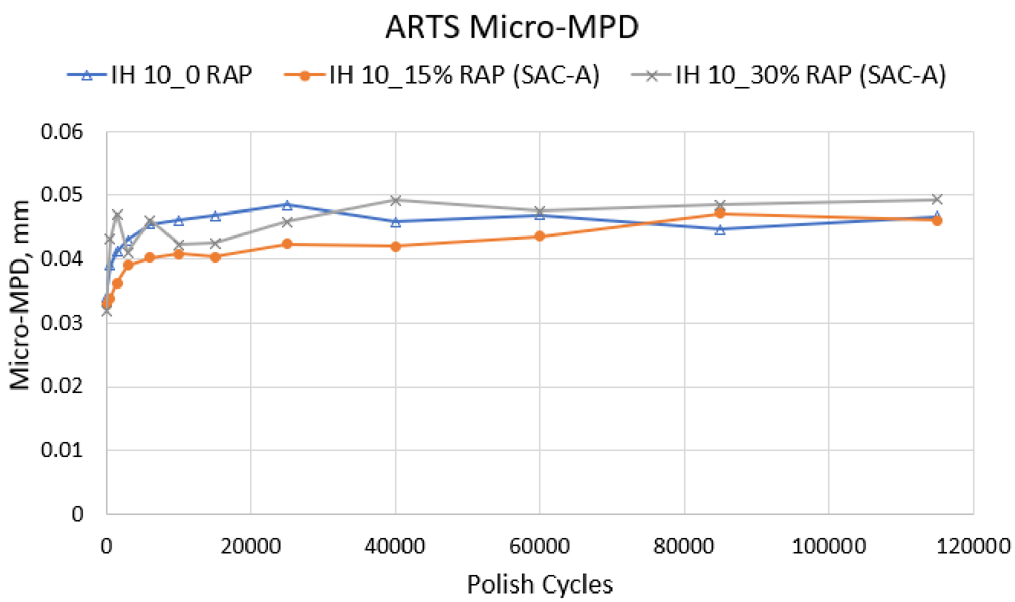
Figure 5-28. Texture Test Results on IH 20 Mixture with SAC-B RAP Slabs at (a) CTM Macro-MPD and (b) ARTS Micro-MPD.

IH 10 Mixture Slab Texture Results

Figure 5-29 and Figure 5-30 show the macro-MPD and micro-MPD results of IH 20 mixtures with SAC-A RAP and SAC-B RAP, respectively. Neither macro-MPD nor micro-MPD has a consistent ranking with DFT rankings.

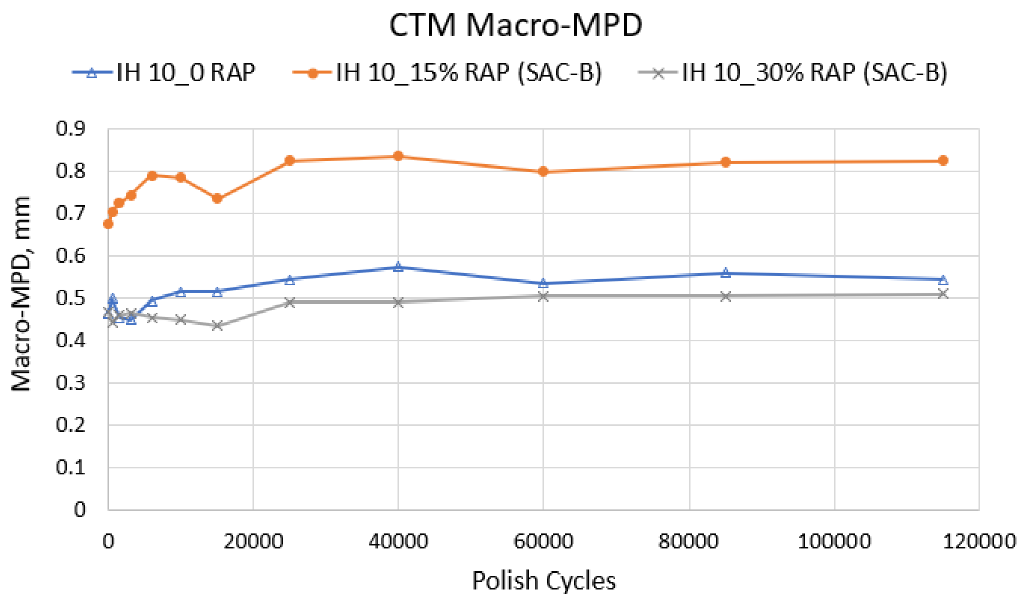


(a)

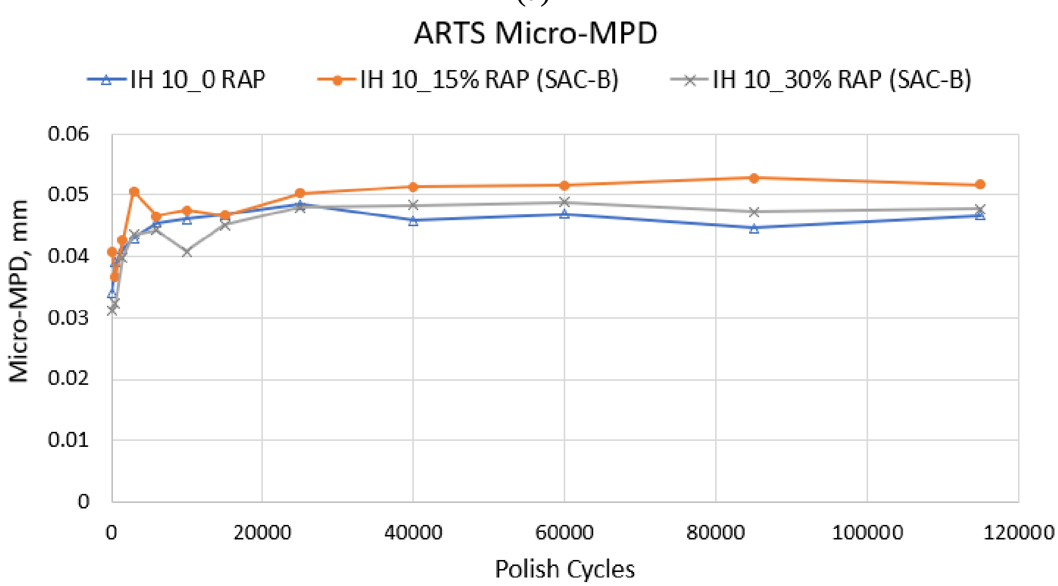


(b)

Figure 5-29. Texture Test Results on IH 10 Mixture with SAC-A RAP Slabs at (a) CTM Macro-MPD and (b) ARTS Micro-MPD.



(a)

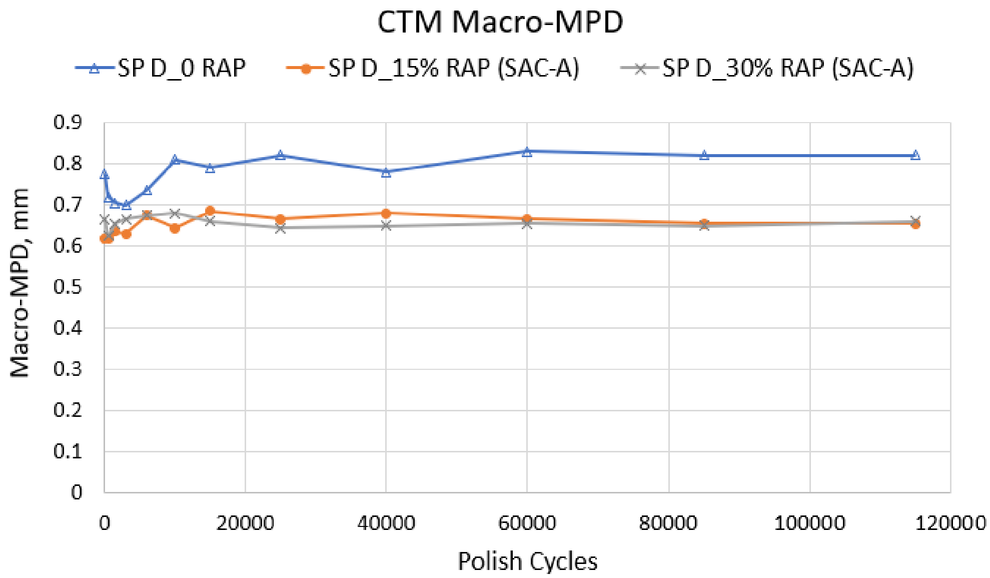


(b)

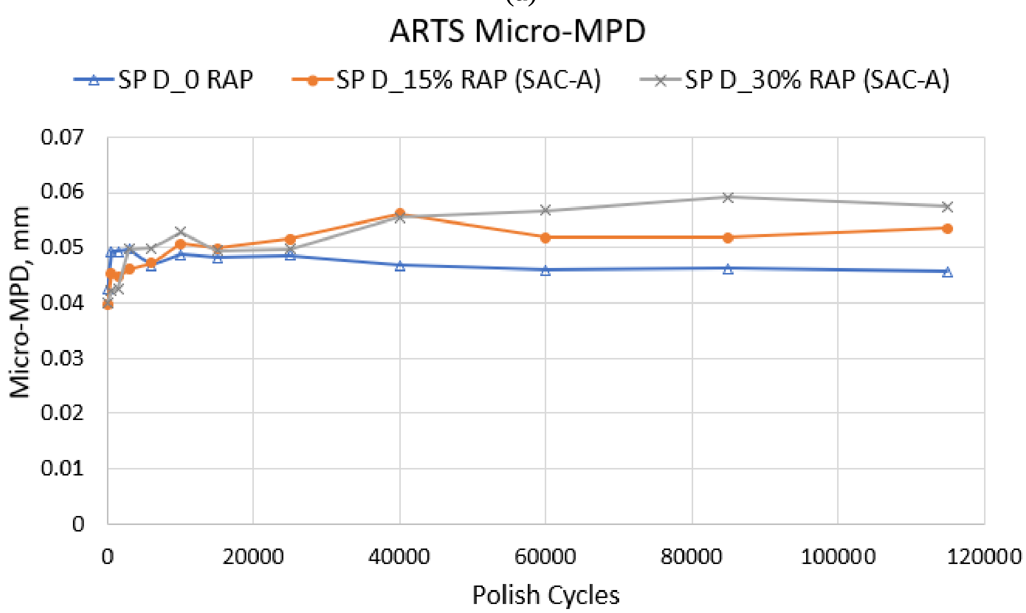
Figure 5-30. Texture Test Results on IH 10 Mixture with SAC-B RAP Slabs at (a) CTM Macro-MPD and (b) ARTS Micro-MPD.

SP D Mixture Slab Texture Results

Figure 5-31 and Figure 5-32 show the macro-MPD and micro-MPD results of SP D mixtures with SAC-A RAP and SAC-B RAP, respectively. The micro-MPD ranking of mixtures with different SAC-A RAP percentages (Figure 5-31b) and the macro-MPD ranking of mixtures with different SAC-B RAP percentages are consistent with corresponding DFT rankings.

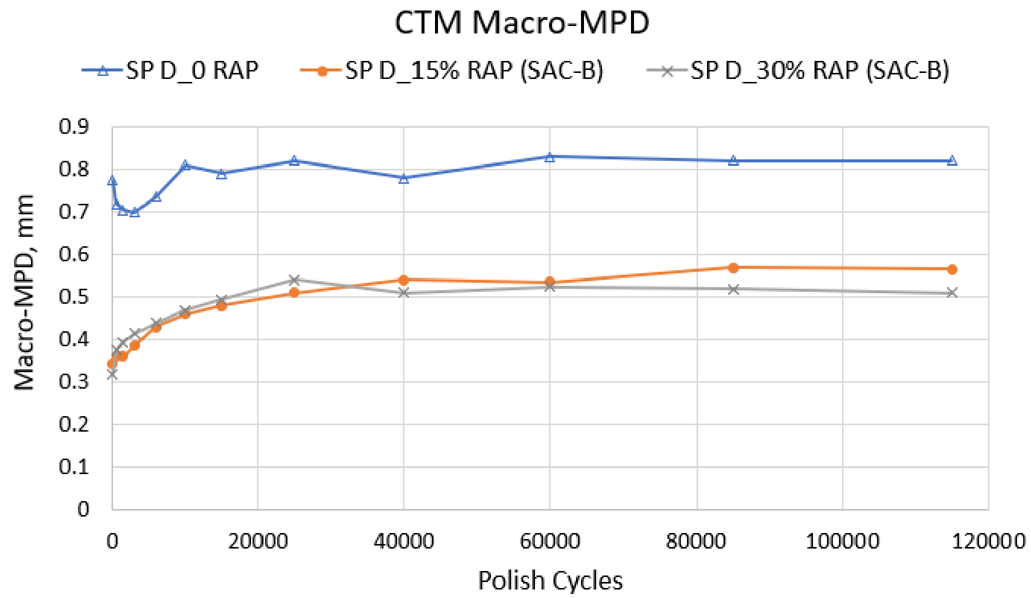


(a)

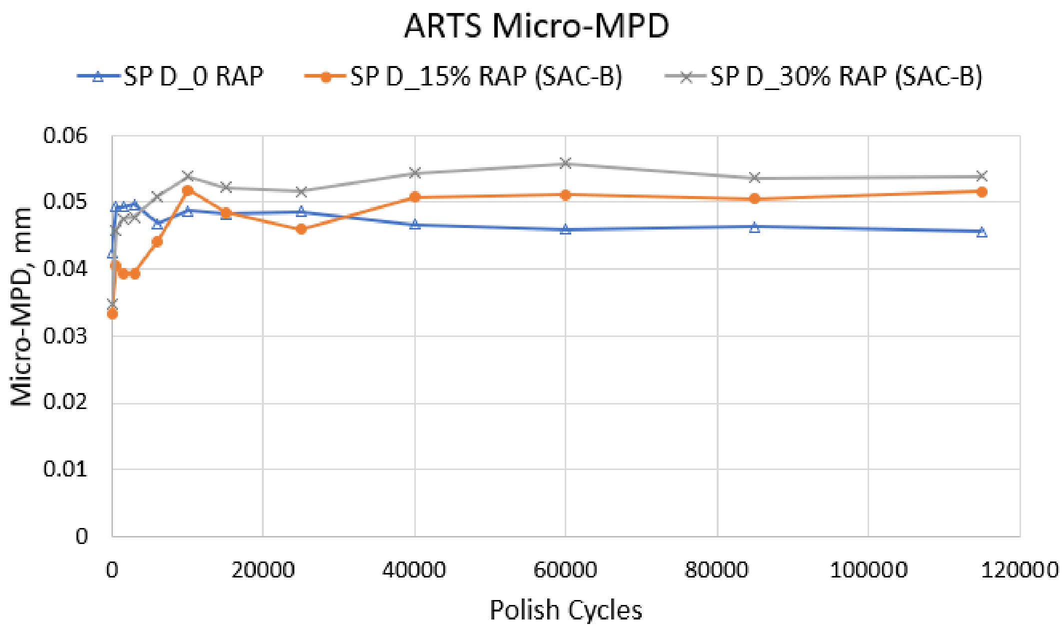


(b)

Figure 5-31. Texture Test Results on SP D Mixture with SAC-A RAP Slabs at (a) CTM Macro-MPD and (b) ARTS Micro-MPD.



(a)



(b)

Figure 5-32. Texture Test Results on SP D Mixture with SAC-B RAP Slabs at (a) CTM Macro-MPD and (b) ARTS Micro-MPD.

ANALYSIS

The relationship between the aggregate blended DFT value and the mixture slab DFT value was investigated below. For simplicity and clarity, the aggregate blended DFT values determined based on the retaining of the No. 4 Sieve (both BMD and AMD) were selected. The slab DFT values (@ 20 km/h) at 3,000 and 115,000 polish cycles were selected to represent the maximum and minimum mixture DFT values and compare with the aggregate BMD and AMD DFT values, respectively. Details are described below.

FM 356 Mixtures

Figure 5-33 shows the aggregate blended DFT and mixture slab DFT values of FM 356 mixtures with SAC-A RAP and SAC-B RAP. In general, both blended DFT and slab DFT rankings show that 30 percent SAC-A RAP > 15 percent SAC-A RAP > 0 percent RAP > 15 percent SAC-B RAP > 30 percent SAC-B RAP. Figure 5-33a shows a different trend in which the FM 356_15% RAP (SAC-A) mixture has the highest blended and slab DFT values.

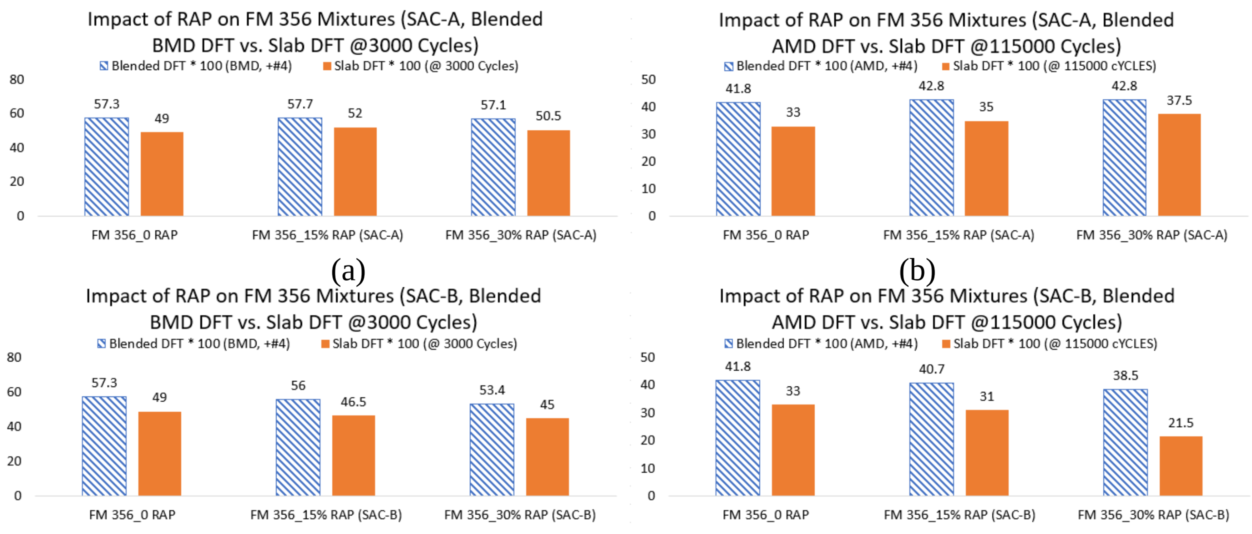


Figure 5-33. Impact of RAP on FM 356 Mixtures: (a) SAC-A RAP, Blended BMD DFT, and Slab DFT at 3,000 Cycles; (b) SAC-A RAP, Blended AMD DFT, and Slab DFT at 115,000 Cycles; (c) SAC-B RAP, Blended BMD DFT, and Slab DFT at 3,000 Cycles; and (d) SAC-B RAP, Blended AMD DFT, and Slab DFT at 115,000 Cycles.

IH 20 Mixtures

Figure 5-34 shows the aggregate blended DFT and mixture slab DFT values of IH 20 mixtures with SAC-A RAP and SAC-B RAP. Again, the ranking is 30 percent SAC-A RAP > 15 percent SAC-A RAP > 0 percent RAP > 15 percent SAC-B RAP > 30 percent SAC-B RAP for both aggregate blended DFT and mixture slab DFT values.

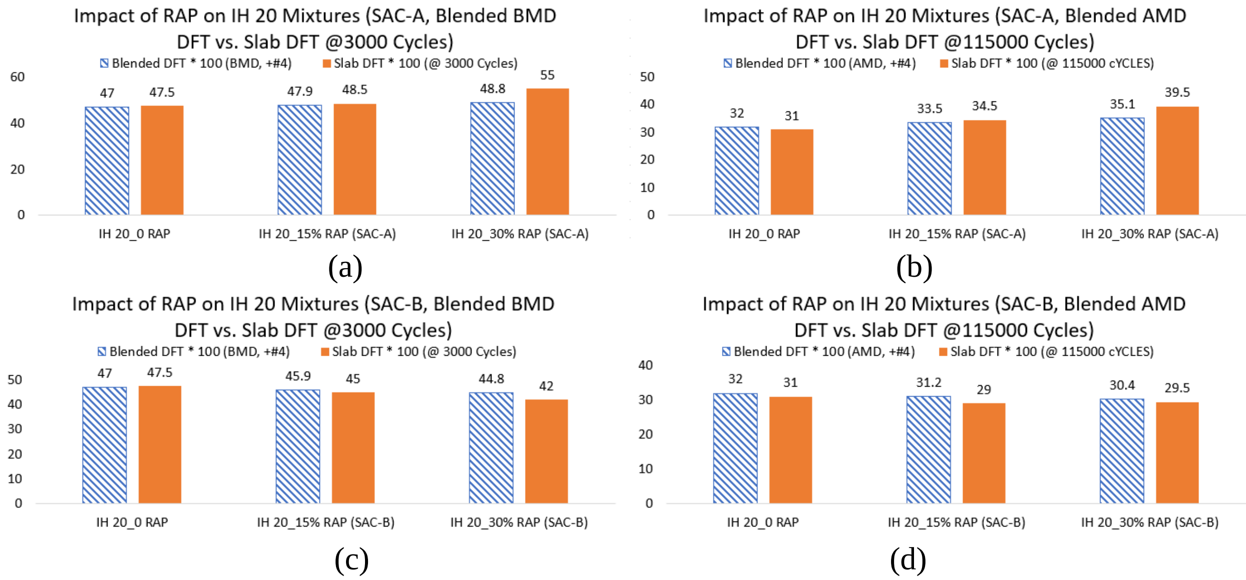


Figure 5-34. Impact of RAP on IH 20 Mixtures: (a) SAC-A RAP, Blended BMD DFT, and Slab DFT at 3,000 Cycles; (b) SAC-A RAP, Blended AMD DFT, and Slab DFT at 115,000 Cycles; (c) SAC-B RAP, Blended BMD DFT, and Slab DFT at 3,000 Cycles; and (d) SAC-B RAP, Blended AMD DFT, and Slab DFT at 115,000 Cycles.

IH 10 Mixtures

Figure 5-35 shows the aggregate blended DFT and mixture slab DFT values of IH 10 mixtures with SAC-A RAP and SAC-B RAP. Again, the rankings are 30 percent SAC-A RAP > 15 percent SAC-A RAP > 0 percent RAP > 15 percent SAC-B RAP > 30 percent SAC-B RAP for both aggregate blended DFT and mixture slab DFT values.

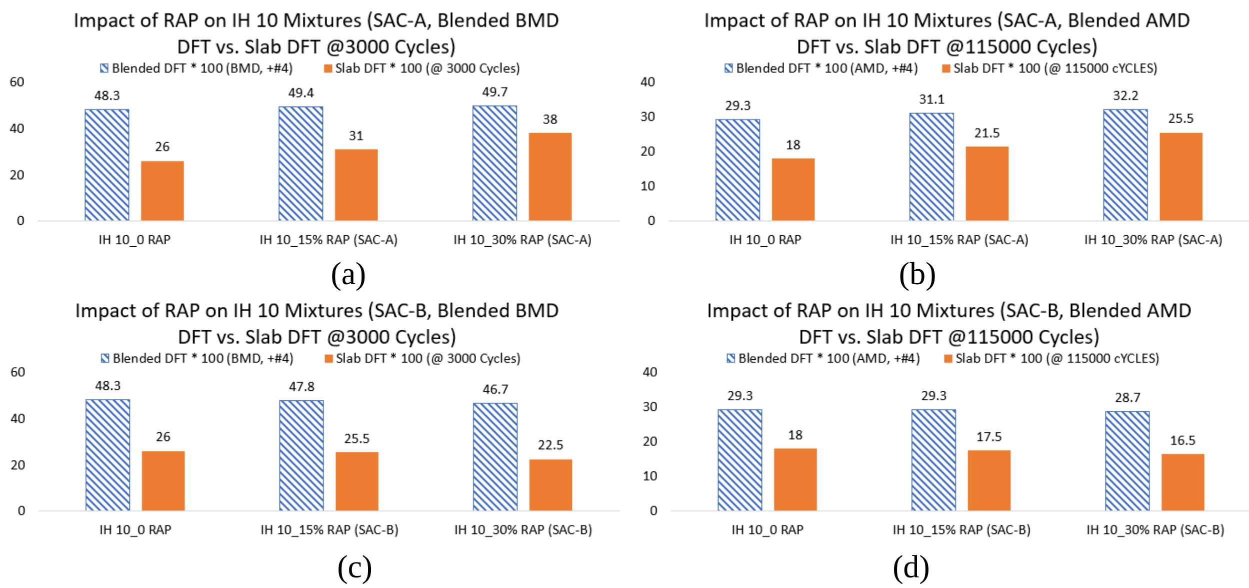


Figure 5-35. Impact of RAP on IH 10 Mixtures: (a) SAC-A RAP, Blended BMD DFT, and Slab DFT at 3,000 Cycles; (b) SAC-A RAP, Blended AMD DFT, and Slab DFT at 115,000 Cycles; (c) SAC-B RAP, Blended BMD DFT, and Slab DFT at 3,000 Cycles; and (d) SAC-B RAP, Blended AMD DFT, and Slab DFT at 115,000 Cycles.

SP D Mixtures

Figure 5-36 shows the aggregate blended DFT and mixture slab DFT values of SP D mixtures with SAC-A RAP and SAC-B RAP. Except for Figure 5-36c, where the SP D_15 percent RAP shows the smallest slab DFT value, the rankings are 30 percent SAC-A RAP > 15 percent SAC-A RAP > 0 percent RAP > 15 percent SAC-B RAP > 30 percent SAC-B RAP for both aggregate blended DFT and mixture slab DFT values.

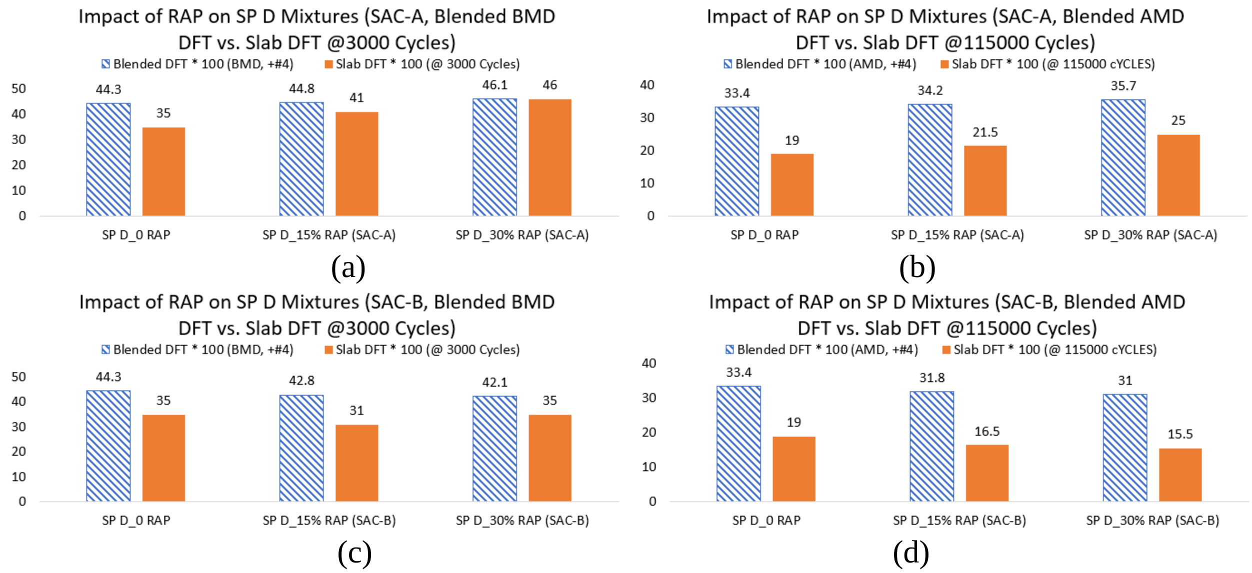


Figure 5-36. Impact of RAP on SP D Mixtures: (a) SAC-A RAP, Blended BMD DFT, and Slab DFT at 3,000 Cycles; (b) SAC-A RAP, Blended AMD DFT, and Slab DFT at 115,000 Cycles; (c) SAC-B RAP, Blended BMD DFT, and Slab DFT at 3,000 Cycles; and (d) SAC-B RAP, Blended AMD DFT, and Slab DFT at 115,000 Cycles.

Relationship between Aggregate Blended DFT and Mixture Slab DFT Values

The above results confirm a correlation between the aggregate blended DFT and the mixture slab DFT. By combining all the mixtures, the relationships between the aggregate blended DFT and the mixture slab DFT are shown in Figure 5-37. The AMD aggregate blended DFT and the mixture slab DFT at 3,000 polish cycles has the best relationship and the highest R^2 value (Figure 5-37b). Therefore, the researchers suggested using the relationship between the AMD aggregate DFT and the AMD blended DFT to develop the SAC rating for RAP materials.

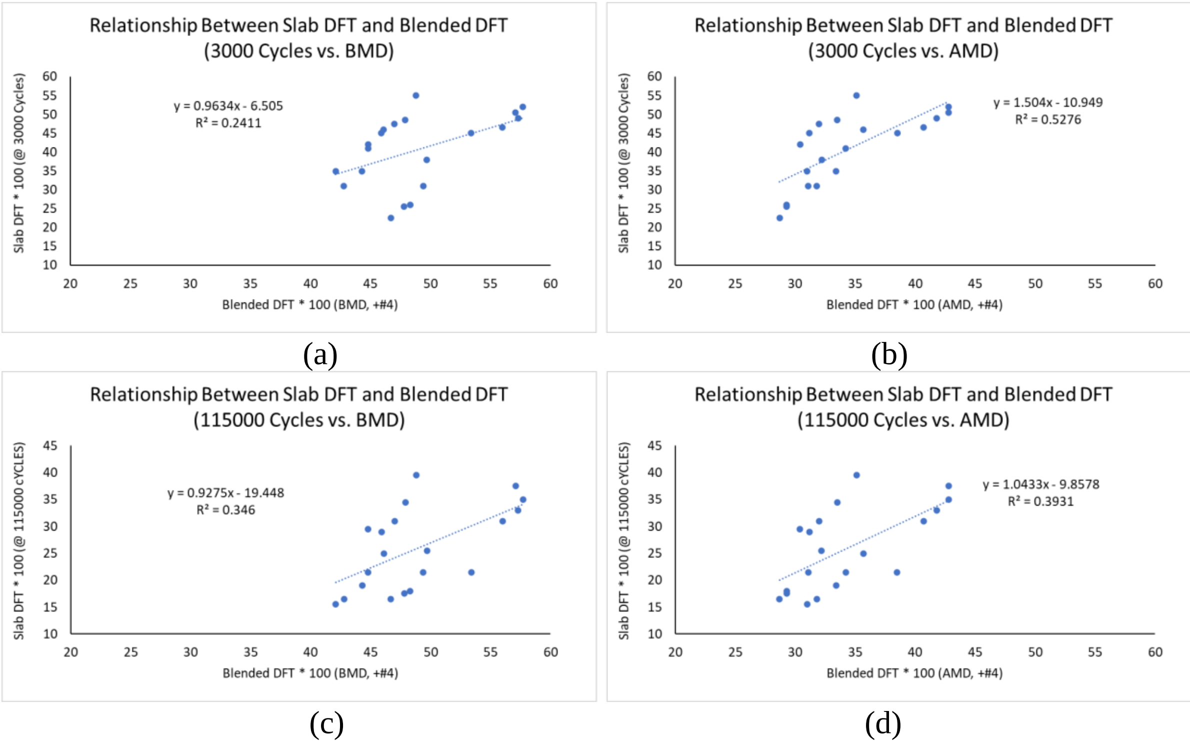


Figure 5-37. Relationship between Aggregate Blended DFT and Mixture Slab DFT: (a) 3,000 Cycles vs. BMD, (b) 3,000 Cycles vs. AMD, (c) 115,000 Cycles vs. BMD, and (d) 115,000 Cycles vs. AMD.

SUMMARY AND CONCLUSIONS

Different RAP materials were characterized by the ignition oven test, sieving analysis, Micro-Deval test, aggregate ring tests, including the CTM, ARTS, and DFT test (before and after Micro-Deval). In addition, the laboratory-produced RAP was fabricated to obtain a SAC-B RAP with the same gradation and binder content of the SAC-A RAP. To study the impact of RAP (different types and different percentages), twenty asphalt mixtures were designed. For each mixture, at least two slabs were fabricated. Each slab was polished by a three-wheel polish machine and eventually went through 115,000 cycles. The researchers stopped the polishing at 500, 1,500, 3,000, 6,000, 10,000, 15,000, 25,000, 40,000, 60,000, 85,000, and 115,000 cycles to conduct the DFT, CTM (for macrotexture determination), and ARTS test (for macrotexture and microtexture determination). The changing of the texture (micro- and macro-MPD) and the DFT friction number during polishing were then investigated.

By assembling the slab test results, raw aggregate information, aggregate blended DFT values, and RAP test results, the conclusions and findings are summarized as follows:

- RAP has a significant influence on the skid resistance of the asphalt mixture. In general, the addition of SAC-A RAP increases the mixture slab DFT values, while SAC-B RAP decreases the slab DFT values.
- According to the slab DFT test result of the 20 mixtures, the dominant ranking is 30 percent SAC-A RAP > 15 percent SAC-A RAP > 0 percent RAP > 15 percent SAC-B RAP > 30 percent SAC-B RAP for each surface mix type.

- Neither macro-MPD nor micro-MPD has a consistent DFT ranking among the mixtures with different RAP percentages.
- The blended DFT ranking was consistent with the mixture slab DFT ranking using the measured RAP aggregate DFT values. It confirms the conclusion in Chapter 4 that assuming a constant DFT value (e.g., 0.3) for all RAP may lead to unreasonable estimations on the skid resistance of the mixture.
- The AMD blended DFT (determined based on AMD aggregate DFT values) has a stronger relationship with mixture slab DFT than BMD blended DFT. Thus, the RAP aggregate AMD DFT is suggested to develop the SAC rating for RAP materials.

In general, the addition of SAC-A RAP increases the mixture slab DFT values, while SAC-B RAP decreases the slab DFT values. The texture test results (macro-MPD and micro-MPD) do not show this trend. The DFT values, such as aggregate blended DFT values and mixture slab DFT values, will be combined and analyzed in the next chapter. The findings of Chapters 3, 4, and 5 will be combined to develop guidelines for using RAP in surface mixes.

CHAPTER 6 PRELIMINARY CRITERIA AND GUIDELINES FOR USING RAP IN SURFACE MIXES

The researchers have presented field evaluation, RAP and raw aggregate characterization, RAP mixture design, and RAP mixture slab testing results in previous chapters. These investigations focused on the skid resistance and texture of the aggregate, mixture, and pavement surface. Based on the research results and findings, the researchers determined the potential of using RAP to conserve SAC-A resources and evaluated the impact of RAP on mixtures' skid resistance. According to quantified test results and regression relationships between aggregate and mixture, the researchers developed preliminary criteria and guidelines for using RAP in surface mixes to enhance skid resistance.

This chapter is organized into the following sections:

- Rationales for the guideline development by summarizing the previous findings.
- Developed criteria and guidelines.
- Application of the criteria and guidelines.
- Summary of the findings and conclusions.

RATIONALE

This section briefly summarizes the previous investigation and findings and provides rationales for the guideline development.

Field Test Section Evaluation

For field evaluation, the researchers identified three districts reporting low field skids in their corresponding SAC-A sections: the Lufkin District (FM 356), Atlanta District (IH 20), and El Paso District (IH 10). DFT, MPD, and ARTS tests were performed on the field sections. The researchers also collected and characterized all the raw aggregates and RAP aggregates used in FM 356, IH 20, and IH 10 mixtures. The aggregate tests included sieving analysis, Micro-Deval, and aggregate ring tests (DFT and ARTS tests). The corresponding mixture slabs were fabricated for the three-wheel polishing, DFT, and laser texturing tests (ARTS and CTM) at certain polished cycles.

Figure 6-1 shows each mixture's SAC-A aggregate stockpile percentages (percent SAC-A) and the coarse SAC-A percentages (percent plus #4 from SAC-A). The FM 356 section surface mixture is Superpave C with 29 percent sandstone (SAC-A); the coarse SAC-A (retaining on the No. 4 sieve from the SAC-A) aggregate is 63.8 percent on total coarse aggregate. The IH 20 section surface mixture is dense-graded Type D with 90 percent igneous aggregates (SAC-A, coarse and fine) and 10 percent sand; the coarse SAC-A (retaining on the No. 4 sieve from the SAC-A) aggregate is 100 percent on total coarse aggregate. The IH 10 section surface mixture is Superpave C with 28 percent igneous (SAC-A); the coarse SAC-A (retaining on the No. 4 sieve from the SAC-A) aggregate is 53.4 percent on total coarse aggregate.

The FM 356 and IH 10 mixture have 20 percent RAP, and the IH 10 mixture has no RAP. In the current specification, RAP is always categorized as SAC-B aggregate. *Standard Specifications* *for Construction and Maintenance of Highways, Streets, and Bridges* (TxDOT, 2014) specifies that "Class B aggregate may be blended with a Class A aggregate to meet requirements for Class A materials. Ensure that at least 50% by weight, or volume if required, of the material retained on the No. 4 sieve comes from the Class A." Since the coarse SAC-A percentages of the three test sections are all larger than 50 percent, all three mixtures belong to SAC-A materials.

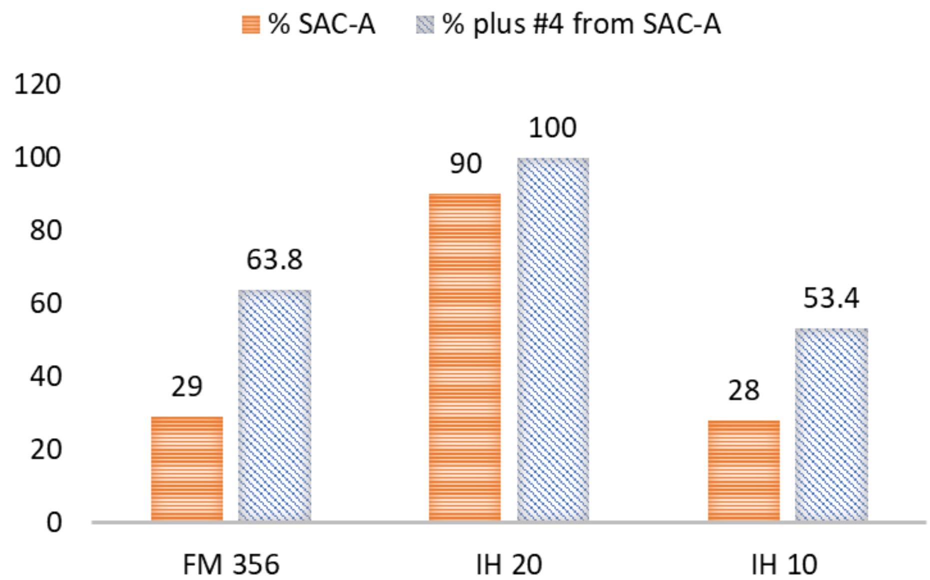


Figure 6-1. Stockpile Percentages of SAC-A Aggregates (% SAC-A) and Coarse SAC-A Percentages (% plus #4 from SAC-A) of Three Test Sections.

The surface DFT results of field pavements and mixture slabs are shown in Figure 6-2 and Figure 6-3, respectively. The results show IH 20 > FM 356 > IH 10 regarding the DFT ranking.

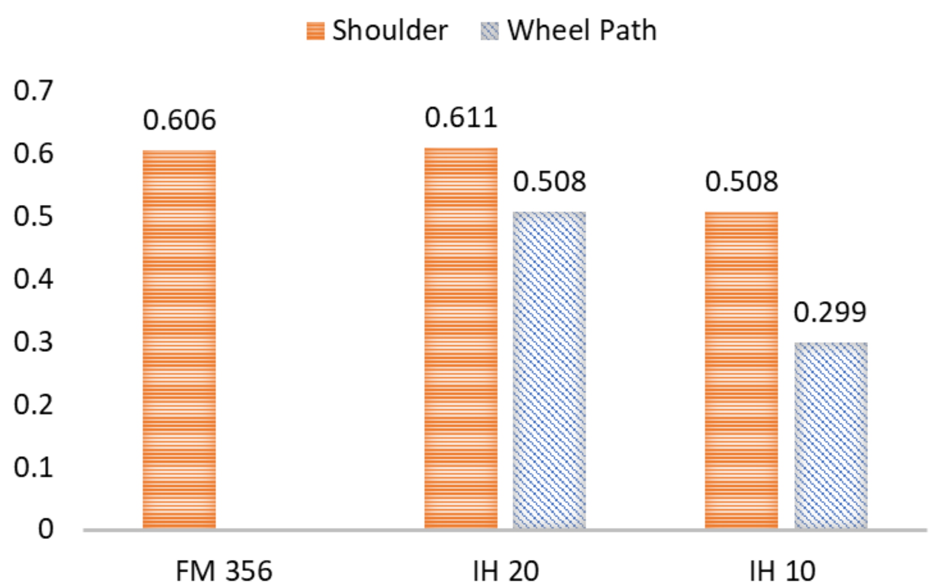


Figure 6-2. Pavement Surface DFT (@ 20 km/h) Results of Three Test Sections.

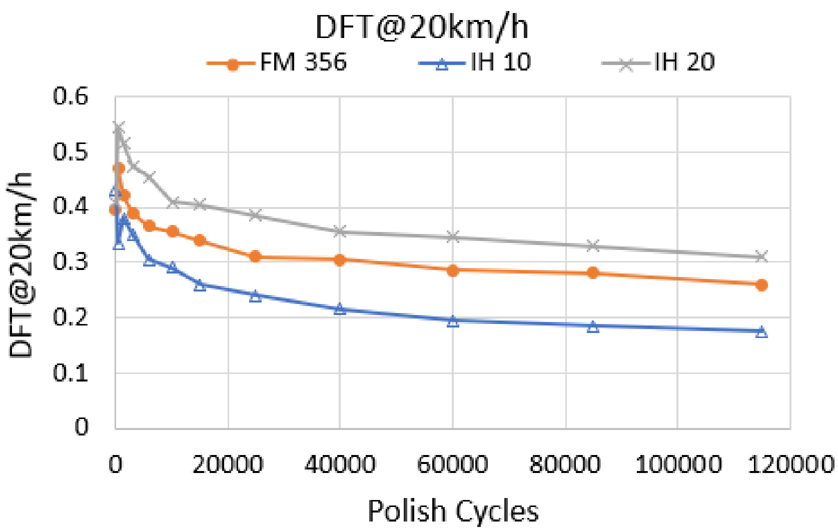


Figure 6-3. Mixture Slab Surface DFT (@ 20 km/h) Results of Three Test Sections.

Neither the micro-MPD ranking nor the macro-MPD ranking is consistent with the DFT ranking of the field pavements or lab-molded mixture slabs. As seen in Figure 6-4, the ranking is IH 10 > IH 20 > FM 356 in terms of macro-MPD and FM 356 > IH 10 > IH 20 in terms of micro-MPD. Thus far, no consistent relationships have been developed for pavement texture and friction, so the criteria proposed in this research will mainly rely on DFT results.

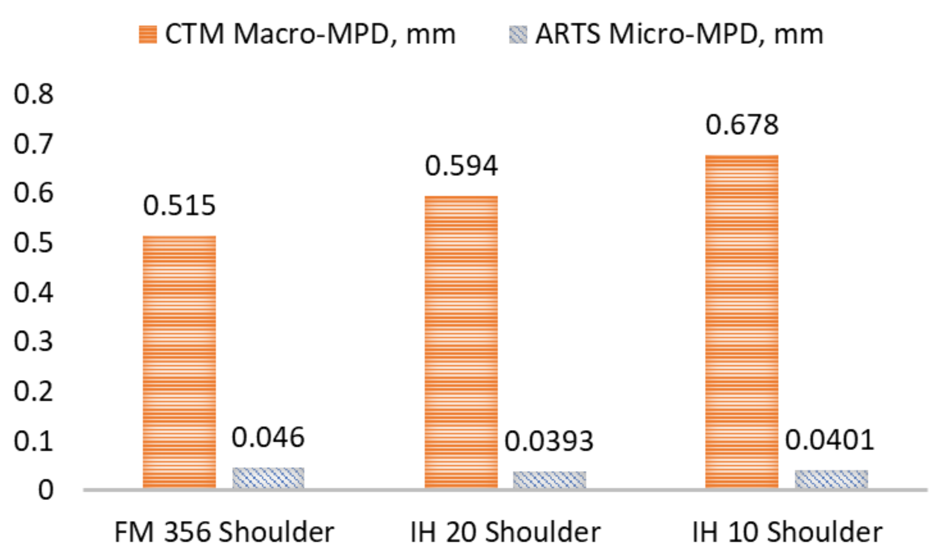


Figure 6-4. Pavement Surface CTM Macro-MPD and ARTS Micro-MPD Results of Three Test Sections.

RAP and Virgin Aggregate Characterization

In this study, the researchers characterized virgin and RAP aggregates through sieve analysis, Micro-Deval, aggregate ring DFT, and texturing (ARTS micro-MPD) tests. The RAP materials include RAP stockpile from Knife River Company, RAP stockpile from Vulcan Materials Company (used in FM 356 surface mixture), RAP stockpiles from El Paso County (used in IH 10 surface mixture), SH 37 (SAC-A pavement surface-milled RAP), and lab-produced RAP using SAC-B aggregates. Among these RAP materials, the SH 37 RAP was milled directly from SH 37 pavement surface mixture, and the other RAP materials may be a blend from different pavement surface mixtures.

Figure 6-5 shows the Micro-Deval test results (percent loss) for 12 types of aggregates, including virgin and RAP aggregates. The aggregate ring DFT test results are shown in Figure 6-6. In this figure, BMD indicates the aggregate before Micro-Deval abrasion, and AMD indicates the aggregate after Micro-Deval abrasion. The SH 37 RAP has the highest DFT values among the five RAP materials for BMD and AMD, and the lab-produced RAP has the lowest DFT values.

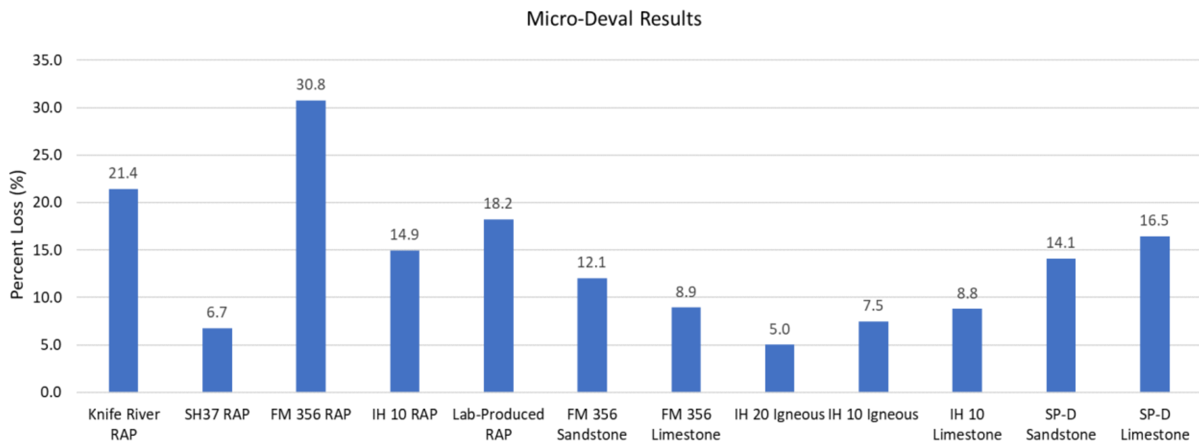


Figure 6-5. Aggregate Micro-Deval Test Results.

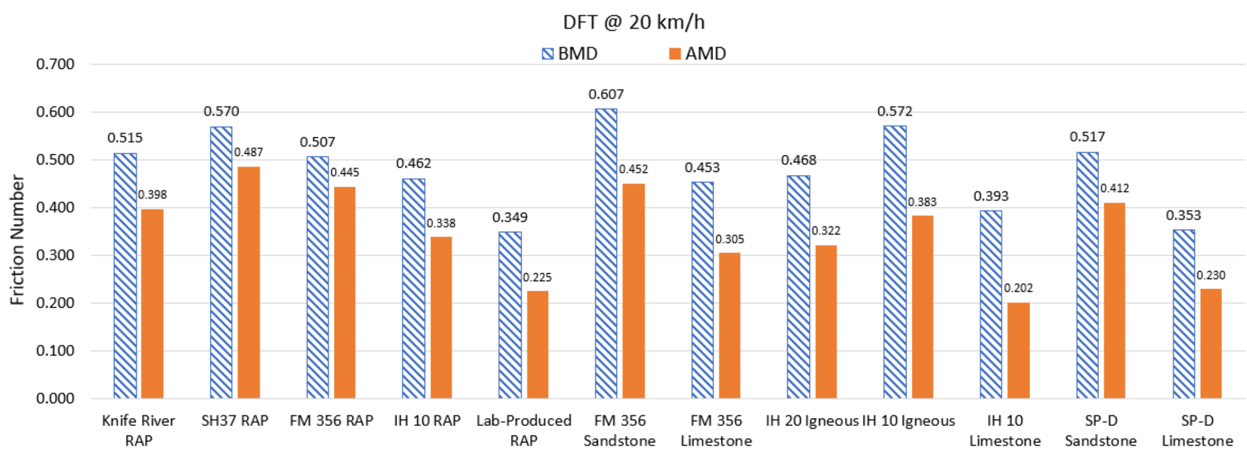


Figure 6-6. Aggregate Ring DFT Test Results.

Blended DFT Calculation

The blended DFT calculation method in this research is similar to that used by MDOT (MDOT 2012a, 2012b, and 2016) and TxDOT Soils and Aggregates Section (Izzo 2020). The main difference is incorporating RAP: this research proposes using the measured RAP aggregate DFT value rather than 0.3 for all RAP.

The calculation is based on the stockpile percentages and the percentage of coarse components (retained on the No. 4 sieve) of each stockpile. The DFT of fine aggregates was assigned the same value as the coarse aggregate if the aggregates were from the same quarry and had the same product code. More details can be found in Chapter 4.

Figure 6-7 shows the blended DFT results for the mixtures from the three test sections. The blended DFT ranking is FM 356 > IH 20 > IH 10 for both BMD and AMD, inconsistent with the DFT ranking of pavement surface or mixture slabs. One potential reason is that blended DFT considers only coarse aggregate, while mixture slab DFT may be impacted by coarse aggregate and fine aggregate components. The portions and the types of the fine aggregate components in FM 356, IH 20, and IH 10 mixtures are different.

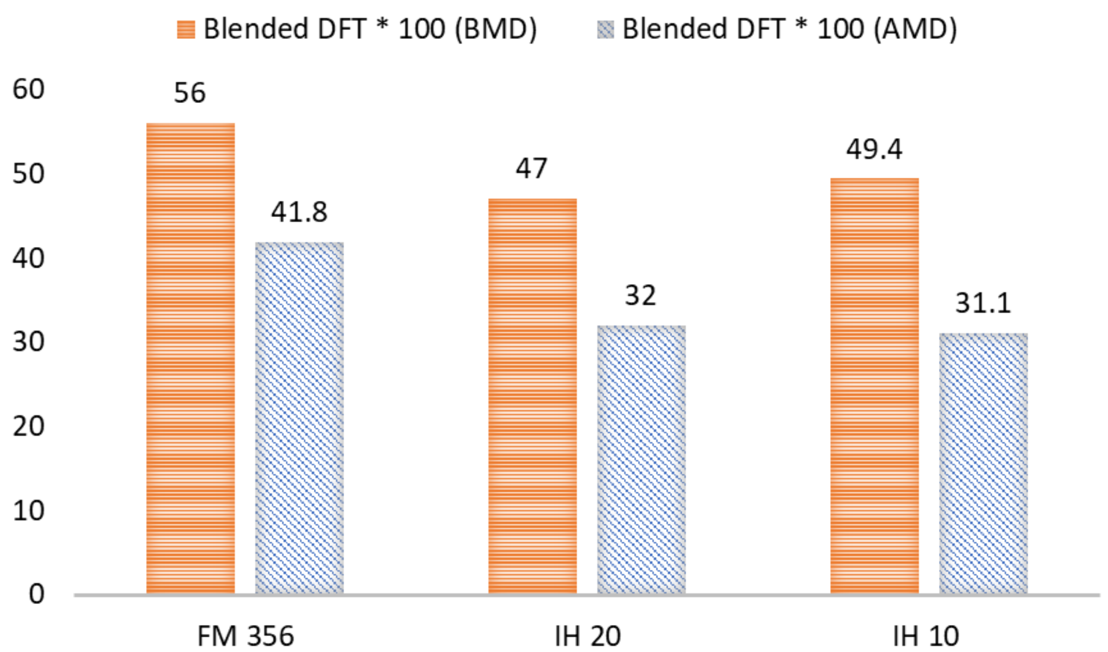


Figure 6-7. Blended DFT Results Based on BMD and AMD Aggregate for Three Test Sections.

The researchers also redesigned mixtures by adjusting RAP percentages and compared the blended DFT ranking with the corresponding mixture slab DFT ranking. The result shows that for a given mixture type (or gradation type), the blended DFT ranking is consistent with the mixture slab DFT ranking using the measured RAP aggregate DFT values. However, if using a constant DFT number for all RAP (e.g., 0.3), the blended DFT ranking was not consistent with the mixture slab DFT ranking. It indicates that assuming a constant DFT value for all RAP may lead to unreasonable estimations on the skid resistance of mixtures.

Impact of RAP on the Skid Resistance of Asphalt Mixtures

Four surface mix types—Superpave C (redesigned FM 356 mixtures), Superpave C (redesigned IH 10 mixtures), dense-graded Type D (redesigned IH 20 mixtures), and Superpave D (SP D mixtures)—were investigated in this research. Three RAP percentages (0, 15, and 30 percent) and two RAP types (SAC-A [milled from SH 37] and SAC-B [lab-produced]) were considered for each mix type.

Thus, there were five different mixtures for each surface mix type (0 RAP, 15 percent SAC-A RAP, 15 percent SAC-B RAP, 30 percent SAC-A RAP, and 30 percent SAC-B RAP). For convenience, the researchers named the redesigned FM 356 mixtures as follows: FM 356_0 RAP, FM 356_15% RAP (SAC-A), FM 356_15% RAP (SAC-B), FM 356_30% RAP (SAC-A), and FM 356_30% RAP (SAC-B). Accordingly, for the other mixtures, only the "FM 356" needed to be replaced with other names, such as "IH 10", "IH 20", or "SP D."

The combination led to 20 (4 × 5) different asphalt mixtures. The combined gradation was designed to be the same (or very close) among different RAP percentages for each surface mix type. For each mixture, two slabs were fabricated and investigated. Three-wheel polishing, DFT, and laser texturing tests ARTS and CTM were performed on each slab. The polishing on each slab went through 115,000 cycles. The researchers stopped the polishing at 500, 1,500, 3,000, 6,000, 10,000, 15,000, 25,000, 40,000, 60,000, 85,000, and 115,000 cycles to conduct the DFT and texturing tests.

The researchers found that the DFT values on the mixture slabs first increased, and the maximum DFT values occurred at approximately 500–2,000 polish cycles. This increase was due to removing the excess binder from the surface and exposing the aggregate. After reaching the peak point, the DFT values decreased as the polish cycle increased. The DFT values reached a relatively stable number at around 100,000 cycles (close to the minimum DFT values).

Table 5-7 lists the aggregate blended DFT and slab DFT values for the 20 mixtures. The slab DFT value at 3,000 polish cycles is usually close to the peak value to simulate the initial condition of pavement surface (e.g., half or one year after the pavement construction). The slab DFT value at 115,000 polish cycles is usually the lowest. The blended DFT values based on the aggregates (both BMD and AMD) of each mixture were determined and listed in Table 6-1.

Table 6-1. Summary of Aggregate Blended DFT and Slab DFT Values.

Mixture Name	Blended DFT * 100 (BMD)	SLAB DFT * 100 (@ 3,000 cycles)	Blended DFT * 100 (AMD)	SLAB DFT * 100 (@ 115,000 cycles)
FM 356_0 RAP	57.3	49	41.8	33
FM 356_15% RAP (SAC-A)	57.7	52	42.8	35
FM 356_30% RAP (SAC-A)	57.1	50.5	42.8	37.5
FM 356_15% RAP (SAC-B)	56	46.5	40.7	31
FM 356_30% RAP (SAC-B)	53.4	45	38.5	21.5
IH 20_0 RAP	47.0	47.5	32.0	31
IH 20_15% RAP (SAC-A)	47.9	48.5	33.5	34.5
IH 20_30% RAP (SAC-A)	48.8	55	35.1	39.5
IH 20_15% RAP (SAC-B)	45.9	45	31.2	29
IH 20_30% RAP (SAC-B)	44.8	42	30.4	29.5
IH 10_0 RAP	48.3	26	29.3	18
IH 10_15% RAP (SAC-A)	49.4	31	31.1	21.5
IH 10_30% RAP (SAC-A)	49.7	38	32.2	25.5
IH 10_15% RAP (SAC-B)	47.8	25.5	29.3	17.5
IH 10_30% RAP (SAC-B)	46.7	22.5	28.7	16.5
SP D_0 RAP	44.3	35	33.4	19
SP D_15% RAP (SAC-A)	44.8	41	34.2	21.5
SP D_30% RAP (SAC-A)	46.1	46	35.7	25
SP D_15% RAP (SAC-B)	42.8	31	31.8	16.5
SP D_30% RAP (SAC-B)	42.1	35	31	15.5

Figure 6-8 shows the slab DFT results for IH 20 redesigned mixtures. Overall, the slab DFT ranking is 30 percent RAP (SAC-A) > 15 percent RAP (SAC-A) > 0 RAP > 15 percent RAP (SAC-B) > 30 percent RAP (SAC-B). This ranking is consistent with the blended DFT ranking using the measured RAP aggregate DFT values for calculation.

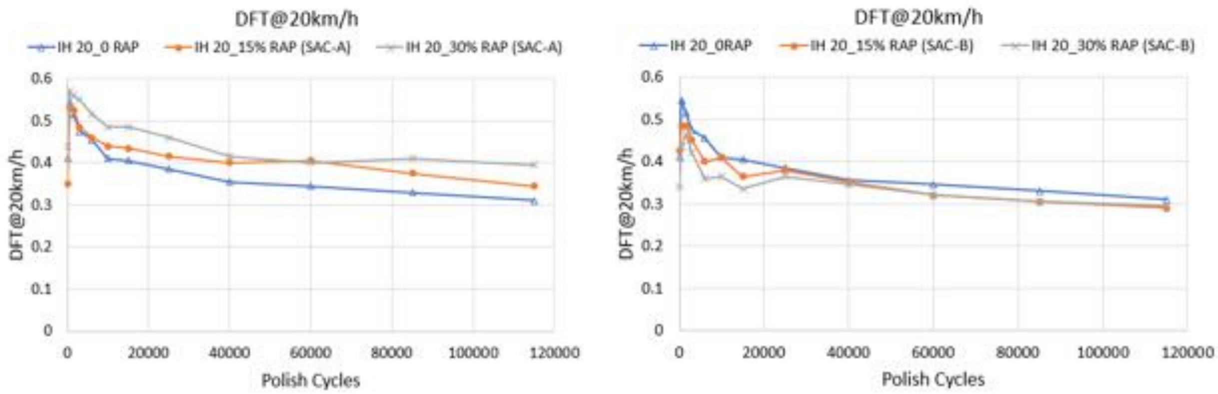


Figure 6-8. Mixture Slab DFT (@ 20 km/h) Results of IH 20 Redesigned Mixtures.

According to the results in Chapter 5, the researchers found that there is a stronger relationship between the aggregate blended DFT (AMD) and the mixture slab DFT at 3,000 polish cycles than other combinations (e.g., blended DFT [BMD] vs. slab DFT at 3,000 polish cycles). The following regression equation was developed to predict the mixture slab DFT at 3,000 cycles based on the aggregate blended DFT (AMD).

$$DFT_{slab} = 1.896 * DFT_{Blended} - 0.221 + G \qquad (6\text{-}1)$$

where DFT_{slab} is the DFT values measured on mixture slab surface at 20 km/h and after 3,000 polish cycles, $DFT_{Blended}$ is the aggregate blended DFT value (AMD) of the corresponding mixture, and G is the gradation adjusting factor (−0.07 for Superpave C, −0.033 for SP D, and 0.082 for Type D).

According to Equation 6-1, the DFT_{slab} for 20 mixtures in Table 6-1 can be predicted based on the corresponding $DFT_{Blended}$ (AMD) values. Figure 6-9 compares the measured and predicted slab DFT values of the 20 mixtures.

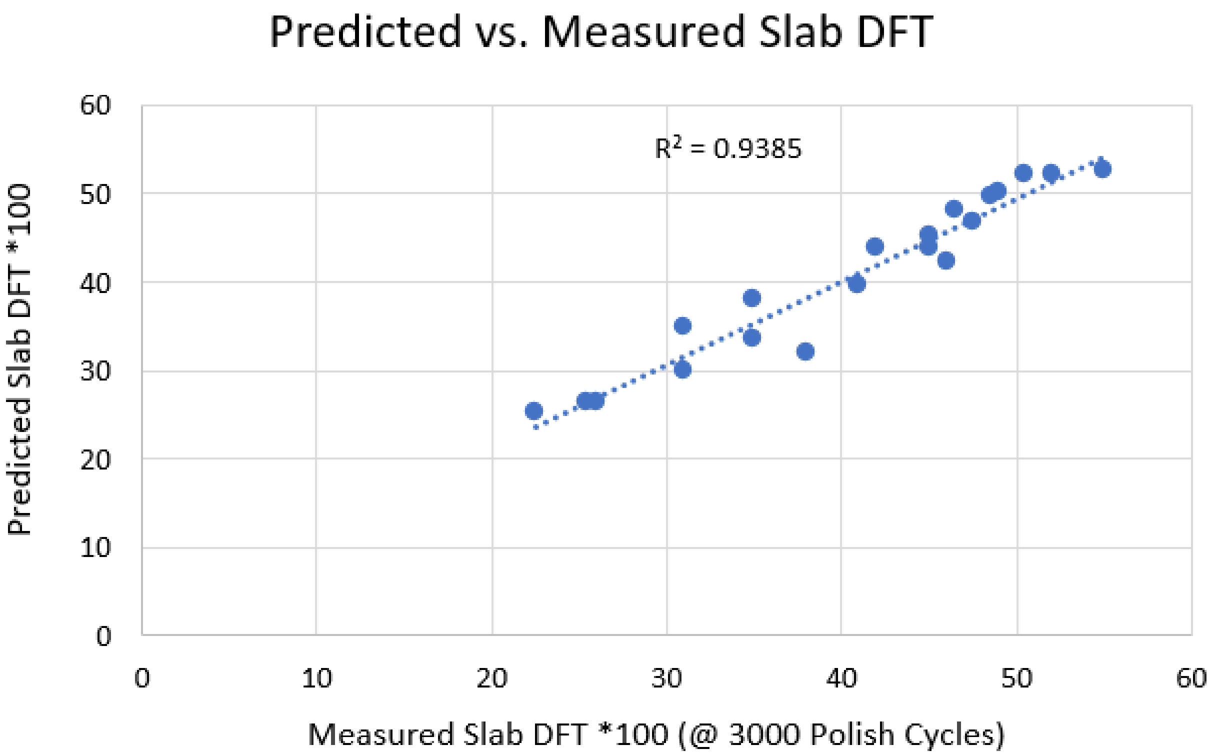


Figure 6-9. Comparison Between the Measured and Predicted Slab DFT Values.

PIARC has developed the IFI as a universal method for reporting pavement friction characteristics and harmonizing the results from different devices for measuring pavement surface friction. The model incorporates DFT at 20 km/h (DFT_{20}) and CTM measurements (macro-MPD). The IFI is calculated according to ASTM E1960: Standard Practice for Calculating International Friction Index of a Pavement Surface (ASTM 2015b), as follows:

$$S_p = 14.2 + 89.7\,MPD \quad (6\text{-}2)$$

$$IFI = 0.081 + 0.732 DFT_{20} e^{\frac{-40}{S_p}} \quad (6\text{-}3)$$

where S_p is the speed constant parameter, *MPD* is the macro-MPD measured using CTM, and DFT_{20} is the coefficient of friction at 20 km/h measured by the DFT.

In the TxDOT Project 0-6746, a model was developed to predict the skid number SN (50) of the asphalt pavement surface (Chowdhury et al. 2017):

$$SN\,(50) = 4.81 + 140.32(IFI - 0.045)e^{\frac{-20}{S_p}} \quad (6\text{-}4)$$

where *SN* (50) is the skid number measured at 50 mph (80 km/h). This measurement is conducted by locking the trailer's left wheel at periodic intervals while a metered amount of water is sprayed on the pavement ahead of the left tire (TxDOT 2021).

After incorporating the slab DFT values (at 3,000 cycles) and the CTM macro-MPD values into Equations 6-2, 6-3, and 6-4, the IFI and SN (50) for each mixture were determined and listed in Table 6-2.

Table 6-2. Summary of IFI and SN (50) Values.

Mixture Name	Slab DFT * 100 (@ 3,000 cycles)	Blended DFT * 100 (AMD, +#4)	Macro-MPD, mm	IFI	SN (50)
FM 356_0 RAP	49	41.8	0.748	0.261	26.3
FM 356_15% RAP (SAC-A)	52	42.8	0.661	0.278	28.4
FM 356_30% RAP (SAC-A)	50.5	42.8	0.641	0.270	27.3
FM 356_15% RAP (SAC-B)	46.5	40.7	0.865	0.247	24.7
FM 356_30% RAP (SAC-B)	45	38.5	0.537	0.239	23.7
IH 20_0 RAP	47.5	32	0.682	0.253	25.3
IH 20_15% RAP (SAC-A)	48.5	33.5	0.730	0.259	26.0
IH 20_30% RAP (SAC-A)	55	35.1	0.694	0.296	30.5
IH 20_15% RAP (SAC-B)	45	31.2	0.473	0.239	23.7
IH 20_30% RAP (SAC-B)	42	30.4	0.408	0.223	21.8
IH 10_0 RAP	26	29.3	0.513	0.147	13.2
IH 10_15% RAP (SAC-A)	31	31.1	0.500	0.169	15.6
IH 10_30% RAP (SAC-A)	38	32.2	0.460	0.202	19.4
IH 10_15% RAP (SAC-B)	25.5	29.3	0.772	0.144	12.9
IH 10_30% RAP (SAC-B)	22.5	28.7	0.473	0.132	11.7
SP D_0 RAP	35	33.4	0.775	0.188	17.7
SP D_15% RAP (SAC-A)	41	34.2	0.653	0.218	21.2
SP D_30% RAP (SAC-A)	46	35.7	0.657	0.245	24.3
SP D_15% RAP (SAC-B)	31	31.8	0.462	0.169	15.6
SP D_30% RAP (SAC-B)	35	31	0.460	0.188	17.7

The SN (50) can be predicted based on the aggregate blended DFT values after combining Equations 6-1 through 6-4. Figure 6-10 shows the SN (50) prediction based on assumed aggregate blended DFT values (0.1–0.6) for Superpave C, SP D, and Type D mixtures.

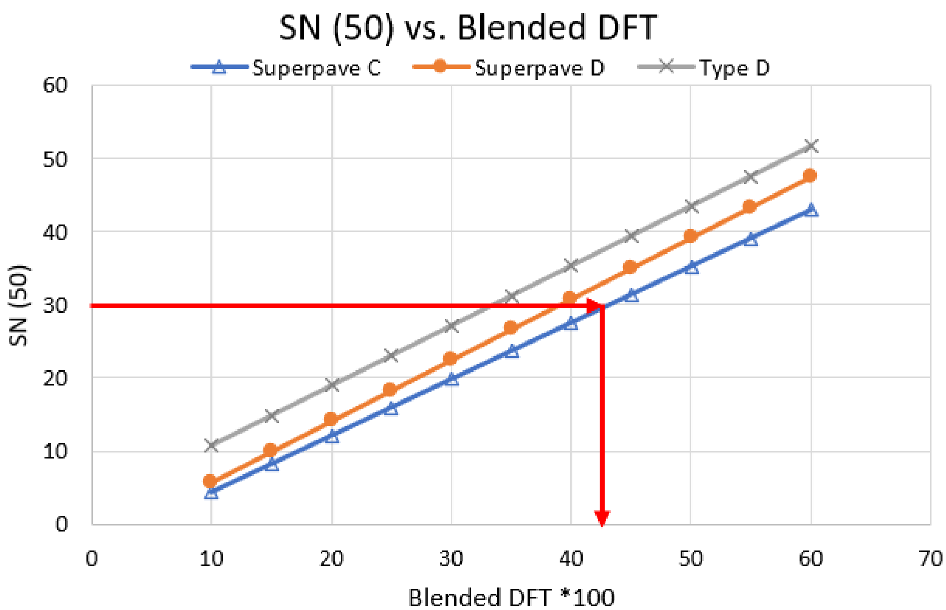


Figure 6-10. Prediction of SN (50) Based on Aggregate Blended DFT Values.

The researchers also made the SN (50) prediction by combining all mixtures, as seen in Figure 6-11.

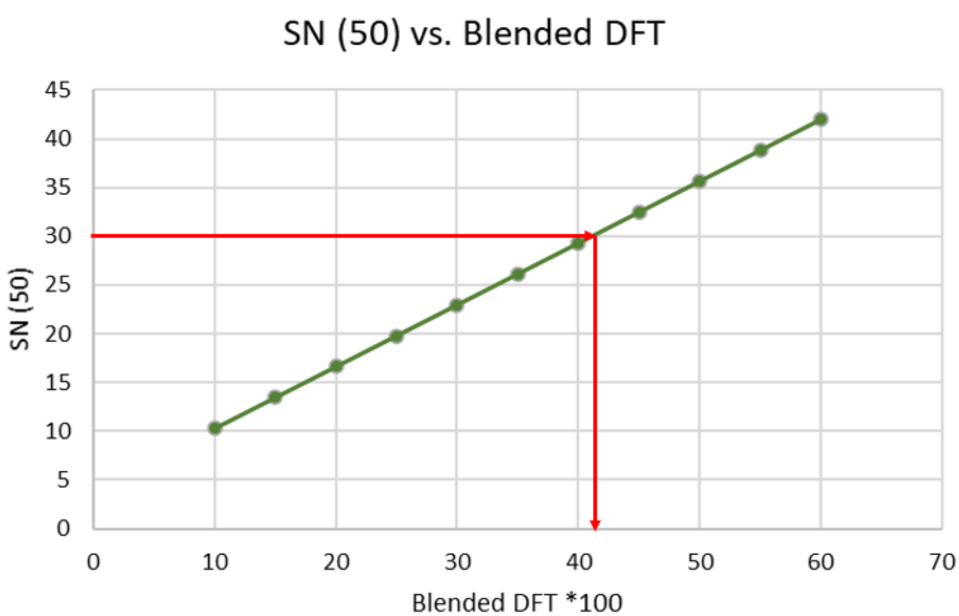


Figure 6-11. Prediction of SN (50) by Combining All Mixtures.

As seen in Figure 6-10 and Figure 6-11, if using 30 as a threshold of SN (50), the corresponding aggregate blended DFT ($DFT_{Blended}$) after times 100 is 43 for Superpave C mixture and 41.5 if mixtures are combined.

CRITERIA AND GUIDELINES

Below describes the criteria and guidelines for using RAP in the surface mixes to meet skid requirements. The criteria and guidelines include SAC criteria for virgin aggregate, RAP aggregate, and blended aggregate. The details are below.

TxDOT Form 2088

TxDOT Form 2088 (TxDOT 2021) provides the current guideline for selecting the aggregates for HMA surfacing. In this guideline, users can fill the table to estimate the demand for friction (or frictional demand) and friction supply (or friction available) based on the specific level of requirements. Figure 6-12 shows an example of using Form 2088 to determine the SAC requirement. As seen in the figure, since the total frictional demand is 18, users must choose SAC-A aggregate to make the total friction available equal to 20 to meet the requirement (the total available friction equals or exceeds the total frictional demand).

Selection Guidelines for Bituminous Surface Aggregate Classification (SAC) — **DESIGNER'S RATING**

Demand for Friction	Low (1)	Moderate (2)	High (3)	1	2	3
Rain Fall (inches/year)	≤20	>20 ≤40	>40	☐	☒	☐
Traffic (ADT)	≤5000	>5000 ≤15,000	>15,000	☐	☐	☒
Speed (mph)	≤35	>35 ≤60	>60	☐	☐	☒
Trucks (%)	≤8	>8 ≤15	>15	☐	☒	☐
Vertical Grade (%)	≤2	>2 ≤5	>5	☐	☒	☐
Horizontal Curve (º)	≤3	>3 ≤7	>7	☒	☐	☐
Driveways (per mile)	≤5	>5 ≤10	>10	☐	☒	☐
Intersecting Roadways (ADT)	≤500	>500 ≤750	>750	☐	☒	☐
Wet Surface Crashes (%)	≤5	>5 <15	≥15	☒	☐	☐
Summary of Total Frictional Demand					18	
***Available Friction**	**Low (2)**	**Moderate (5)**	**High (8)**	**2**	**5**	**8**
Cross Slope (%)	<2	2 - 3	3 - 4	☐	☒	☐
Surface Design Life (years)	>10	>5 ≤10	≤5	☒	☐	☐
Macro Texture of proposed surface	Fine (Such as: HMAC Type 'D' and 'F')	Medium (Such as: HMAC Type 'C', CMHB, SuperPave, Microsurface)	Coarse (Such as: PFC, SMA, Seal Coat, NovaChip)	☐	☒	☐
Aggregate MicroTexture	SAC C	SAC B	SAC A	☐	☐	☒
Summary of Total Friction Available					20	
Does total available friction equal or exceed total frictional demand?				☒ Yes		☐ No

Figure 6-12. Example of Using Form 2088 to Determine the SAC Requirement.

SAC Criteria for Virgin Aggregate

TxDOT uses procedures in *Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges* (TxDOT 2014) to select aggregates for pavement surfacing. The aggregate sources supplied to TxDOT projects are subject to sampling and testing at least twice a year to publish the BRSQC catalog. The catalog divides the aggregate types mainly into sandstone, limestone-dolomites, gravels, and igneous rocks and provides producer information and rated values. The TxDOT MTD/SA assigns a SAC to all bituminous coarse aggregate sources based on rated statistical values, according to the criteria shown in Table 6-3.

Table 6-3. SAC Criteria for Virgin Aggregate.

Property	Test Method	SAC-A	SAC-B	SAC-C
Acid-insoluble residue, % min	Tex-612-J	55	—	—
5-cycle Mg, % max	Tex-411-A	25	30	35
Crushed faces, 2 or more, % min	Tex-460-A	85	85	85

Note: — means not applicable

According to comparison and statistical analysis, the researchers of TxDOT Project 0-6959 (Lee et al. 2020) found that the rated source Micro-Deval can be used as an additional criterion to initiate an additional aggregate classification for surface mixes. They recommend that the maximum Micro-Deval loss percentages allowed for SAC-A, SAC-B, and SAC-C are 15, 30, and 45, respectively. The proposed SAC criteria for virgin aggregate are shown in Table 6-4.

Table 6-4. Proposed SAC Criteria for Virgin Aggregate.

Property	Test Method	SAC-A	SAC-B	SAC-C
Acid-insoluble residue, % min	Tex-612-J	55	—	—
5-cycle Mg, % max	Tex-411-A	25	30	35
Crushed faces, 2 or more, % min	Tex-460-A	85	85	85
Micro-Deval loss, % max	*Tex-461-A*	*15*	*30*	*45*

Note: — means not applicable

SAC Criteria for RAP Aggregate

Currently, MTD/SA specifies that all RAP aggregates belong to SAC-B. According to the findings of this research, the researchers proposed new SAC criteria for RAP aggregate, as listed in Table 6-5.

It means if the RAP aggregate meets the criteria in Table 6-5, the RAP may be categorized into SAC-A RAP and be treated the same as other virgin SAC-A aggregate when determining the SAC for the blended aggregate.

Table 6-5. Proposed SAC Criteria for RAP Aggregate.

Property	Test Method	SAC-A
Micro-Deval loss, % max	*Tex-461-A*	*15*
*DFT*100 (after Micro-Deval), min*	*ASTM E1911 (ASTM 2019) on TxDOT Aggregate Ring*	*43*

SAC Criteria for Blended Aggregate

Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges (TxDOT 2014) specifies that “Class B aggregate may be blended with a Class A aggregate to meet requirements for Class A materials. Ensure that at least 50% by weight, or volume if required, of the material retained on the No. 4 sieve comes from the Class A.” Table 6-6 shows the current criteria. The “Plus No.4 from SAC-A, % min” means the percentage of SAC-A coarse (retained on No. 4 sieve) aggregate to all coarse (retained on No. 4 sieve) aggregate.

Table 6-6. Current SAC Criteria for Blended Aggregate.

Property	Method	SAC-A
Plus No.4 from SAC-A, % min	Based on the percentages of aggregate stockpiles; RAP belongs to SAC-B	50

According to the findings of this research, the researchers proposed new SAC criteria for blended aggregate, as listed in Table 6-7.

Table 6-7. Proposed SAC Criteria for Blended Aggregate.

Property	Method	SAC-A
Plus No.4 from SAC-A, % min	*Based on the percentages of aggregate stockpiles; RAP belongs to SAC-A or SAC-B (Table 6-5)*	*50*
$DFT_{Blended} \times 100$ *(after Micro-Deval), min*	*Blended DFT calculation*	*43*

APPLICATION

The FM 356 mixture was employed to demonstrate the application of the criteria and guidelines developed in this research.

FM 356 Mixture Design

As seen in Figure 6-13, according to the current specification, the mixture (or blended aggregate) belongs to the SAC-A category because the portion of coarse aggregate from SAC-A is 63.8 percent (larger than 50 percent) of the total coarse aggregate.

Aggregate Classification

		Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8
Individual Bin (%):		Bin No.1 = 29 %	Bin No.2 = 10 %	Bin No.3 = 24.9 %	Bin No.4 = 15 %	Bin No.5 = 1 %			Bin No.8 = 20.1 %
Aggregate Source:		Sandstone	Limestone_Dolomite	Limestone_Dolomite					Fractionated RAP
Aggregate Number:		1402704	1402702	1402702					
Class (A) Rock (Y/N):		Yes	No	No					
Sieve Size:		Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %
Passing	Retained								
-	1"	0.0	0.0	0.0	0.0	0.0			0.0
1"	3/4"	0.0	0.0	0.0	0.0	0.0			0.0
3/4"	1/2"	0.3	4.2	0.0	0.0	0.0			0.0
1/2"	3/8"	7.2	4.1	0.0	0.0	0.0			0.8
3/8"	No. 4	19.8	1.5	0.0	0.0	0.0			4.8
No. 4	No. 8	1.1	0.0	5.3	0.0	0.0			4.4
No. 8	No. 16	0.0	0.0	5.7	0.0	0.0			1.8
No. 16	No. 30	0.0	0.0	4.5	1.4	0.0			1.8
No. 30	No. 50	0.0	0.0	3.3	4.5	0.0			1.8
No. 50	No. 200	0.0	0.0	5.2	8.7	0.0			3.4
No. 200	Pan	0.6	0.1	1.0	0.5	1.0			1.2
Total:		29.0	10.0	24.9	15.0	1.0			20.1
Percent of plus No. 4		27.3	9.8	0.0	0.0	0.0			5.6
Percent of plus No. 8:		28.4	9.8	5.3	0.0	0.0			10.1

Percent of plus No. 4 from class (A) Rock:	27.3
Total Percent of plus No. 4	42.8
Percent of plus No. 4 from class (A) Rock	63.8

Percent of plus No. 8 from class (A) Rock:	28.4
Total Percent of plus No. 8:	53.6
Percent of plus No. 8 from class (A) Rock:	53.0

Figure 6-13. FM 356 Mixture Design.

FM 356 RAP Aggregate SAC Category

Table 6-8 shows the FM 356 RAP aggregate test results (the Micro-Deval loss and the aggregate DFT) and the corresponding criteria. The percentage of Micro-Deval loss is 30.8, and the maximum allowable value is 15. Thus, the FM 356 RAP aggregate cannot meet the SAC-A requirement and is determined to be SAC-B.

Table 6-8. Determine the FM 356 RAP Aggregate SAC Category.

Property	Result	SAC-A Criteria	Meet Requirement?
Micro-Deval loss, %	30.8	15 (Max)	No
DFT × 100 (after Micro-Deval)	45	43 (Min)	Yes

FM 356 Bended DFT

Figure 6-14 shows the aggregate blended DFT value calculation according to the FM 356 mixture design. Three rows in this figure have the term “Plus No.4, %,” and the explanation for each is below.

- The “Plus No.4, % based on stockpile” is the percentage of coarse aggregate for each stockpile, which equals 100 minus the percentage of passing No. 4 sieve.

- The “Plus No.4, % based on all aggregate” is the percentage of the coarse aggregate of each stockpile to all aggregate, which equals the stockpile percentage (Bin %) times the “Plus No.4, % based on stockpile.”
- The “Plus No.4, % based on coarse aggregate” is the percentage of the coarse aggregate of each stockpile to total coarse aggregate, which equals the individual “Plus No.4, % based on all aggregate” divided by the sum of “Plus No.4, % based on all aggregate” of all the stockpiles.

The sand and lime have nothing retained on the No. 4 sieve; their contribution to blended DFT is zero regardless of their aggregate DFT values.

Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.8
Source:	Sandstone	Limestone_ Dolomite	Limestone_ Dolomite	Washed Sand	Lime	Fractionated RAP
Bin %	29	10	24.9	15	1	20.1
No. 4, Cum % Passing	5.9	1.8	99.8	100	100	72
Plus No. 4, % based on stockpile	94.1	98.2	0.2	0	0	28
Plus No. 4, % based on all aggregate	27.3	9.8	0.0	0.0	0.0	5.6
Plus No. 4, % based on coarse aggregate	63.8	23.0	0.1	0.0	0.0	13.2
Aggregate DFT (AMD) *100	45	31	31	30	0	45
Stockpile DFT (AMD)*100	28.70	7.11	0.04	0.0	0.0	5.92
Blended DFT (AMD)*100	41.8					

Figure 6-14. FM 356 Aggregate Blended DFT Calculation.

FM 356 Blended Aggregate SAC Category

Table 6-9 shows the FM 356 percentage of SAC-A coarse aggregate to total coarse aggregate (Plus No.4 from SAC-A, %) and the blended DFT ($DFT_{Blended}$) result. The FM 356 blended aggregate does not meet the SAC-A requirement according to the corresponding criteria. FM 356 mixture may need to be redesigned by selecting different virgin aggregate or RAP to meet the SAC-A requirement. For example, using SAC-A aggregate to replace Bin No. 2 or using RAP with a higher DFT value.

Table 6-9. Determine the FM 356 Blended Aggregate SAC Category.

Property	Result	SAC-A Criteria	Meet Requirement?
Plus No.4 from SAC-A, %	63.8	50 (Min)	Yes
$DFT_{Blended} \times 100$ (after Micro-Deval)	41.8	43 (Min)	No

SUMMARY AND CONCLUSIONS

This document describes preliminary criteria and guidelines for using RAP in surface mixes to enhance skid resistance. The researchers have conducted field evaluations, RAP and raw aggregate characterization, RAP mixture design, and RAP mixture slab testing. These investigations focused on the skid resistance and texture of the aggregate, mixture, and pavement surface. Based on the research results and findings, the researchers determined the potential of using RAP to conserve SAC-A resources and evaluated the impact of RAP on mixtures' skid resistance. The rationale, description, and application of the criteria and guidelines were presented in this document. The conclusions and findings are summarized as follows:

- RAP may significantly influence the skid resistance of the asphalt mixture, depending on the RAP percentage and the relative DFT values to the virgin aggregate.
- In general, the addition of high skid-resistant RAP increases the mixture slab DFT values, while low skid-resistant RAP decreases the slab DFT values. It confirms the potential of using high skid-resistant RAP (e.g., reclaimed from the previous high skid-resistant SAC-A pavement) to conserve SAC-A virgin aggregate resource.
- The aggregate blended DFT provides a good indication of the corresponding mixture slab (or pavement) surface DFT. For a given gradation, a higher aggregate blended DFT usually leads to a higher mixture DFT. However, it is not always true when comparing two mixtures with different gradations. One potential reason is that blended DFT considers only coarse aggregate, while mixture slab DFT may be impacted by coarse aggregate and fine aggregate.
- The relationship between the aggregate blended DFT and the mixture slab DFT values were developed based on the test results of 20 mixtures. Further, the blended DFT values were used to predict SN (50).
- The preliminary criteria and guidelines for determining the SAC of virgin aggregate, RAP aggregate, and blended aggregate were proposed based on the above findings.
- The current research covers limited types of material (virgin aggregate, RAP, and mixture) and only considers the impact of coarse aggregate on the skid resistance. Further investigation is needed to refine the criteria and guidelines.

CHAPTER 7 SUMMARY AND RECOMMENDATIONS

Pavement skid resistance is critical for public safety in wet-weather conditions. Crashes on wet pavements are related to inadequate pavement skid resistance. To improve pavement skid resistance, the use of SAC-A aggregate has increased significantly to meet pavements' friction demand. TxDOT needs to develop specifications, methods, and means to conserve existing SAC-A resources. TxDOT specifications allow the use of RAP to conserve natural resources and save costs. The unknown is the contribution of RAP to the skid resistance and friction of the pavement surface, especially when pavements constructed with SAC-A are reclaimed and used for production. RAP may potentially help reduce the need for SAC-A aggregates. Intuitively RAP must have some contribution to friction, but this contribution has not been evaluated and quantified.

This report mainly focuses on the skid resistance and texture of aggregates, mixtures, and pavement surfaces. The investigations include field evaluations, RAP and raw aggregate characterization, RAP mixture design, and RAP mixture slab testing. Based on the work presented in the previous chapters, the conclusions and recommendations are provided in the following sections.

SUMMARY

The summary and conclusion are listed in the following:

- According to the extensive literature review, various states have their guidelines for RAP usage and the percentage allowed to be used in the surface mixes, along with the aggregate gradation policy. Numerous studies have concluded that the friction and durability performance of asphalt surface courses with 10 to 25 percent RAP performed well under low traffic. However, no research was currently found to investigate the skid resistance (or texture) of RAP aggregate itself or categorize RAP aggregates (e.g., SAC-A or SAC-B). The potential positive impact of high skid-resistant RAP on surface mixtures was unknown or not quantitatively studied.
- Three test sections were identified: (1) FM 356 in the Lufkin District, (2) IH 20 in the Atlanta District, and (3) IH 10 in the El Paso District. The test sections were reported to have low field skids, although the surface mixtures belong to SAC-A materials. Three types of tests were performed on the test sections: (1) the CTM laser test for macro-MPD determination, (2) the ARTS laser test for micro- and macro-MPD determination, and (3) the DFT test for friction number determination. The findings are summarized as follows:
    - The pavement shoulder DFT values (at 60 km/h and 20 km/h) are larger than the wheel path DFT values. The difference is statistically significant. These findings confirm that the traffic polish makes the pavement surface smoother and less skid-resistant.
    - The pavement shoulder micro-MPD values are larger than the wheel path DFT values. The difference is statistically significant. These findings confirm that the aggregate surface microtexture gets polished by the traffic and contributes to the lower skid resistance of the main-lane wheel path.

- The pavement shoulder macro-MPD values are not statistically different from the main-lane wheel-path macro-MPD values. This result implies traffic polish does not significantly change the macrotexture in these sections. This lack of change is reasonable since the macrotexture mainly depends on the arrangement of the aggregates (both coarse and fine), and this arrangement will not change much if no significant distress (such as bleeding, cracking, stripping, etc.) appears on the pavement surface.
- The CTM macro-MPD values have a good relationship with the ARTS macro-MPD values. Their value difference for each station is usually less than 10 percent. Since ARTS is equipped with a line laser and provides a 3D profile rather than a CTM 2D profile, the ARTS macro-MPD might be more representative to describe the surface macrotexture. In addition, ARTS can determine the micro-MPDs based on the same 3D profile. Due to these features, ARTS is considered a very convenient tool for pavement texture analysis.
- The DFT ranking (from high to low values) among the three sections is IH 20 > FM 356 > IH 10. The field DFT ranking is consistent with the ranking of lab DFT tests on mixture slabs. Neither the micro-MPD ranking nor the macro-MPD ranking is consistent with the DFT ranking of the field pavements or lab-molded mixture slabs. It is widely agreed that pavement macrotexture and microtexture are the primary contributors to pavement friction performance. However, there is no unique relationship between texture and friction; though strong and statistically significant, the relationship is different for each pavement surface type. Thus far, no consistent relationships have been developed for pavement texture and friction.

- A series of aggregate testing and mixture tests were performed, such as the ignition test, sieve analysis test, Micro-Deval test, DFT and ARTS tests on aggregate rings, three-wheel polishing test on mixture slabs, DFT test, and laser texturing tests (ARTS and CTM) at certain polished cycles on mixture slabs, etc. The materials included FM 356, IH 20, and IH 10 mixture raw aggregates and RAP aggregates. In addition, some mixtures were redesigned by adding/removing RAP to evaluate if RAP is the cause of the low skid resistance. By assembling all the lab test and field test information, the conclusions and findings are summarized as follows:
    - The aggregate sieve analysis results confirm that the raw aggregates for each mixture were correctly collected, and the gradations agree with the original design.
    - The aggregate ring DFT results show that some RAP has higher DFT values than limestone (SAC-B) aggregate. For example, the RAP milled from SH 37 has a similar DFT value to other SAC-A aggregates, such as sandstone.
    - Both DFT and ARTS micro-MPD on the aggregate ring test results clearly show that the BMD values are significantly larger than the AMD values. These results are reasonable since the Micro-Deval test removes some texture on the aggregate surface; accordingly, the skid resistance drops.
    - The DFT values on the mixture slabs first increased, and the maximum DFT values occurred at approximately 500–2,000 polish cycles. This increase was due to removing the excess binder from the surface and exposing the aggregate. After reaching the peak point, the DFT values decreased as the polish cycle increased. The DFT values reached a relatively stable number at around 100,000 cycles.

- The ranking of the DFT number on the mixture slabs is IH 20 > FM 356 > IH 10, which is consistent with the DFT results on the field pavements. Neither the macro-MPD nor micro-MPD rankings were consistent with the DFT ranking. This difference in rankings confirms the field observation findings.
- The redesigned mixtures indicate that some RAP (e.g., SH 37 RAP) can significantly improve the DFT value of asphalt mixtures. For example, the DFT ranking among IH 20 mixtures was IH 20_30% RAP (SH 37) > IH 20_15% RAP (SH 37) > IH 20_0 RAP (original IH 20 mixture); the DFT ranking among IH 10 mixtures was IH_15% RAP (SH 37) > IH 10_20% RAP (original IH 10 mixture) ≥ IH 10_0 RAP.
- A blended DFT calculation method was applied in this research to estimate the skid resistance of the final combined aggregate. The result shows that the FM 356 mixture had significantly higher blended DFT numbers than the other two mixtures. The blended DFT numbers ranking from high to low were FM 356 > IH 10 > IH 20 based on BMD and FM 356 > IH 20 > IH 10 based on AMD. However, neither rankings were consistent with the lab-molded mixture slab DFT test or the field DFT test results. The DFT ranking of the mixture slab and field pavement surface was IH 20 > FM 356 > IH 10. This ranking implies that not only the coarse aggregate DFT but also other factors such as fine aggregate, gradation, etc., may influence the mixture's DFT values.
- The redesigned (adjusting RAP percentage) mixture blended DFT results show that the blended DFT ranking was consistent with the mixture slab DFT ranking using the measured RAP aggregate DFT values. However, if using a constant DFT number for all RAP (e.g., 0.3), the blended DFT ranking was not consistent with the mixture slab DFT ranking. This indicates that assuming a constant DFT value for all RAP may lead to unreasonable estimations on the skid resistance of mixtures.
- For redesigned mixtures (e.g., IH 20 redesigned mixtures), although the blended DFT ranking (using the measured aggregate DFT) shows consistency with the mixture slab DFT ranking, the increase of blended DFT values seems much smaller than the increase of mixture slab DFT values when incorporating good RAP (e.g., SH 37 RAP). One reason might be that the benefit of good RAP was underestimated if only accounting for coarse aggregate (retaining on the No. 4 or No. 8 sieve). For example, more than 50 percent of the SH 37 RAP aggregate component is the fine aggregate (76 percent passing No. 4 sieve and 56 percent passing No. 8 sieve), which might also increase the mixture slab DFT values but was ignored in the blended DFT calculation.

- Twenty asphalt mixtures were designed and investigated to study the impact of RAP (different types and percentages) on the mixtures' skid resistance. The following factors were considered in these mixtures: (a) two RAP types: SAC-A RAP (milled from SH 37) and SAC-B RAP (laboratory-produced with the same gradation as SH 37 RAP); (b) three RAP amounts: 0 percent, 15 percent and 30 percent; and (c) four surface mix types: Superpave C (redesigned FM 356 mixtures), Superpave C (redesigned IH 20 mixtures), dense-graded Type D (redesigned IH 10 mixtures), and SP D mixtures. For each mixture, at least two slabs were fabricated. Each slab was polished by a three-wheel polish machine and eventually went through 115,000 cycles. The researchers stopped the polishing at 500, 1,500, 3,000, 6,000, 10,000, 15,000, 25,000, 40,000, 60,000, 85,000 and 115,000 cycles to conduct the DFT, CTM (for macrotexture determination), and ARTS tests (for macrotexture and microtexture determination). The changing of the texture (micro- and macro-MPD) and the DFT friction number during polishing were then investigated. By assembling the slab test results, raw aggregate information, aggregate blended DFT values, and RAP aggregate test results, the conclusions and findings are summarized as follows:

  - In general, the addition of SAC-A RAP increases the mixture slab DFT values, while SAC-B RAP decreases the slab DFT values.
  - According to the slab DFT test result of the 20 mixtures, the dominant ranking is 30 percent SAC-A RAP > 15 percent SAC-A RAP > 0 RAP > 15 percent SAC-B RAP > 30 percent SAC-B RAP for each surface mix type. Neither macro-MPD nor micro-MPD has a consistent DFT ranking among the mixtures with different RAP percentages.
  - The blended DFT ranking was consistent with the mixture slab DFT ranking using the measured RAP aggregate DFT values. This ranking confirms the previous conclusion that assuming a constant DFT value (e.g., 0.3) for all RAP may lead to unreasonable estimations on the skid resistance of the mixture.
  - The AMD blended DFT (determined based on AMD aggregate DFT values) has a stronger relationship with mixture slab DFT than BMD blended DFT. Thus, the RAP aggregate AMD DFT is suggested to develop the SAC rating for RAP materials.

In general, RAP may significantly influence the skid resistance of the asphalt mixture, depending on the RAP percentage and the relative DFT values to the virgin aggregate. The addition of high skid-resistant RAP increases the mixture slab DFT values, while low skid-resistant RAP decreases the slab DFT values. These results confirm the potential of using high skid-resistant RAP (e.g., reclaimed from the previous high skid-resistant SAC-A pavement) to conserve SAC-A virgin aggregate resources.

RECOMMENDATIONS

The blended DFT provides a good indication of the corresponding mixture slab (or pavement) surface DFT. A higher aggregate blended DFT usually leads to a higher mixture DFT for a given gradation or mixture type. Therefore, the aggregate blended DFT values and mixture slab DFT values were combined and analyzed to develop guidelines for using RAP in surface mixes. The findings and recommendations are summarized as follows:

- The measured RAP aggregate AMD DFT is suggested to be employed to develop RAP material SAC rating. The blended aggregate AMD DFT is suggested to be used to develop the criteria for mixture SAC rating.
- The relationship between the aggregate blended DFT and the mixture slab DFT values were developed based on the test results of 20 mixtures. Further, the blended DFT values were used to predict SN (50).
- Based on the above relationships, the minimum required DFT values for RAP aggregate and blended aggregate was determined and recommended. Accordingly, the preliminary criteria and guidelines for determining RAP and blended aggregate SAC were proposed.

- The proposed criteria and guidelines provide a quantitative way to evaluate and compare the aggregate and mixture skid resistance.
- The current research covers limited types of material (virgin aggregate, RAP, and mixture) and only considers the impact of coarse aggregate on the skid resistance. Further investigation is needed to refine the criteria and guidelines.

REFERENCES

AASHTO (2012). *AASHTO T327 Standard Method of Test for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus*, Washington, DC.

AASHTO (1990). *AASHTO T278 Standard Method of Test for Surface Frictional Properties Using the British Pendulum Tester,* Washington, DC.

AASHTO (1996). *AASHTO T279 Standard Method of Test for Accelerated Polishing of Aggregates Using the British Wheel*, Washington, DC.

AASHTO (2016). *AASHTO R76 Standard Practice for Reducing Samples of Aggregate to Testing Size*, Washington, DC.

AASHTO (2019). *AASHTO T96-02 Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*, Washington, DC.

AASHTO (2020a). *AASHTO T104-99 Standard Method of Test for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate,* Washington, DC.

AASHTO (2020b). *AASHTO PP 104 Sample Preparation and Polishing of Asphalt Mixture for Dynamic Friction Testing*, Washington, DC.

AASHTO (2020c). *AASHTO R30 Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA),* Washington, DC.

Arámbula-Mercado, E., E. Fernando, S. Hu, and W. Crockford (2018). *Application of A Laser Scanning System to Dynamic Friction Test Specimens: Correlation Between Texture and Friction,* FHWA/TX-18/5-6921-01-R1, Texas A&M Transportation Institute.

ASTM (2015a). *ASTM E2157 Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter,* ASTM International, West Conshohocken, PA.

ASTM (2015b). *ASTM E1960-07 Standard Practice for Calculating International Friction Index of a Pavement Surface,* ASTM International, West Conshohocken, PA.

ASTM (2016). *ASTM E1845 Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth*, ASTM International, West Conshohocken, PA.

ASTM (2017a). *ASTM D3042-17 Standard Test Method for Insoluble Residue of Carbonate Aggregates*, ASTM International, West Conshohocken, PA.

ASTM (2017b). *ASTM C131-01 Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*, ASTM International, West Conshohocken, PA.

ASTM C88 (2017c). *Standard Method of Test for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate*, ASTM International, West Conshohocken, PA.

ASTM (2017d). *ASTM D8079 Standard Practice for Preparation of Compacted Slab Asphalt Mix Samples Using a Segmented Rolling Compactor,* ASTM International, West Conshohocken, PA.

ASTM (2018). *ASTM E303-93 Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester,* ASTM International, West Conshohocken, PA.

ASTM (2019). *ASTM E1911 Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester*, ASTM International, West Conshohocken, PA.

ASTM (2020a). *ASTM E274 Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire*, ASTM International, West Conshohocken, PA.

ASTM (2020b). *ASTM E501 Standard Specification for Standard Rib Tire for Pavement Skid-Resistance Tests*, ASTM International, West Conshohocken, PA.

ASTM (2020c). *ASTM E524 Standard Specification for Standard Smooth Tire for Pavement Skid-Resistance Tests*, ASTM International, West Conshohocken, PA.

Cairney, P. (1997). *Skid Resistance and Crashes: A Review of the Literature*, No. ARR 311.

Chowdhury, A., E. Kassem, S. Aldagari, and E. Masad (2017). *Validation of Asphalt Mixture Pavement Skid Prediction Model and Development of Skid Prediction Model for Surface Treatments*, FHWA/TX-17/0-6746-01-1, Texas Department of Transportation, Austin, TX.

Crouch, L., J. Gothard, G. Head, and W. Goodwin (1995). Evaluation of Textural Retention of Pavement Surface Aggregates, *Transportation Research Record*, No. 1486, Transportation Research Board, Washington, DC.

Dahir, S. H., and J. J. Henry (1978). *Alternatives for the Optimization of Aggregate and Pavement Properties Related to Friction and Wear Resistance*, No. FHWA-RD-78-209.

Doyle, J. D. and I. L. Howard (2010). *Laboratory Investigation of High RAP Content Pavement Surface Layers*, Report No. FHWA/MS-DOT-RD-10-212.

Dunford, A. (2013). *Friction and the Texture of Aggregate Particles Used in the Road Surface Course*, Doctoral dissertation, University of Nottingham.

FHWA (1990). *Nationwide Personal Transportation Survey, NPTS Databook,* Report FHWA-PL-94-010, Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

Galambos, V., B. Hegmon, and K. Rice (1997). *Pavement Texture and Available Skid Resistance. Federal Highway Administration*, U.S. Department of Transportation, Washington, DC.

Hall, J. W., K. L. Smith, L. Titus-Glover, J. C. Wambold, T. J. Yager, and Z. Rado (2009). *Guide for Pavement Friction*, NCHRP Project.

Han, J., S. C. Thakur, O. Chong, R. L. Parsons (2011). *Laboratory Evaluation of Characteristics of Recycled Asphalt Pavement in Kansas*, Report K-TRAN: KU-09-2, University of Kansas, Topeka, KS.

Heitzman, M., F. Gu, and A. Welderufael (2019). *Three Wheel Polishing Device and Dynamic Friction Tester Accelerated Laboratory Friction Testing Repeatability and Reproducibility Study*, NCAT Report 19-05, Auburn, AL.

Henry, J. J. (2000). *NCHRP Synthesis of Highway Practice 291: Evaluation of Pavement Friction Characteristics*, Transportation Research Board, National Research Council, Washington, DC.

Hogervorst, D. (1974). *Some Properties of Crushed Stone for Road Surfaces*, Bulletin of the International Association of Engineering Geology, Vol. 10, No. 1.

Ivey, D. L., D. L. Bullard, J. R. Lock, and L. I. Griffin III (1992). *Texas Skid Initiated Accident Reduction Program: Final Report*, Report 910-1F, TTI: 2-18-89/910, TX-92/910-1F, Texas Department of Transportation.

Izeppi, E., G. Flintsch, and K. McGhee (2010). *Field Performance of High Friction Surfaces*. FHWA/VTRC 10-CR6. Federal Highway Administration, U.S. Department of Transportation.

Izzo, R. (2020). *Measuring Microtexture of Aggregates Using the Dynamic Friction Tester (DFT)*. 2020 Virtual Transportation Short Course, Texas. https://static.tti.tamu.edu/conferences/tsc20/presentations/materials/izzo.pdf

Kowalski, K. J., R. S. McDaniel, and J. Olek (2010). *Identification of Laboratory Technique to Optimize Superpave HMA Surface Friction Characteristics*, FHWA/IN/JTRP-2010/6, Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, IN. doi: 10.5703/1288284314265.

Kassem, E., A. Awed, E. Masad, and D. Little (2013). “Development of Predictive Model for Skid Loss of Asphalt Pavements,” *Transportation Research Record: Journal of the Transportation Research Board*, No. 2372.

Lee, S., A. Prakoso, D. Goehl, T. Blackmore, M. Souliman, and L. F. Walubita (2020). *Documenting The Impacts of Aggregate Quality on Hot Mix Asphalt (HMA) Performance: Technical Report,* FHWA/TX-19/0-6959-R1, Texas Department of Transportation, Austin, TX.

Lizárraga, J. M., A. Ramirez, P. Díaz, J. R. Marcobal, and J. Gallego (2018). “Short-term performance appraisal of half-warm mix asphalt mixtures containing high (70%) and total RAP contents (100%): From laboratory mix design to its full-scale implementation,” *Construction and Building Materials*, Vol. 170, pp. 433-445.

Masad, E., A. Luce, E. Mahmoud, and A. Chowdhury (2007). *Relationship of Aggregate Texture to Asphalt Pavement Skid Resistance Using Image Analysis of Aggregate Shape*, Final Report for Highway IDEA Project.

Masad, E., A. Rezaei, A. Chowdhury, and T. J. Freeman (2010). *Field Evaluation of Asphalt Mixture Skid Resistance and Its Relationship to Aggregate Characteristics,* No. 0-5627-3. Texas A&M Transportation Institute.

Mayes, G., M. McCain, and T. Murphy (1998). “RAP Merges with Superpave Asphalt,” *Asphalt, Spring/Summer*, Vol. 12, No. 2, pp. 24–26.

McQuaid, G., P. Millar, and D. Woodward (2014). *A Comparison of Techniques to Determine Surface Texture Data*, In Civil Engineering Research in Ireland Conference, Belfast, Ireland.

McDaniel S. R., K. J. Kowalski, A. Shah (2012). *Evaluation of Reclaimed Asphalt Pavement for Surface Mixtures*, FHWA/IN/JTRP-2012/03, Indiana Department of Transportation and Purdue University.

MDOT (2012a). *Laboratory Method of Polishing Aggregates Using the Circular Track Polishing Machine*, MSMT 215, Maryland Department of Transportation.

MDOT (2012b). *Measuring Frictional Properties of Aggregates Using the Dynamic Friction Tester*, MSMT 216, Maryland Department of Transportation.

MDOT (2016). *Laboratory Method of Predicting Frictional Resistance of a Blend of Aggregate*, MSMT 416, Maryland Department of Transportation.

Mustaffar, M., O. bin Che Puan, and L. T. Chai (2004, August). *Application of Digital Photogrammetry to Quantification of Road Surface Distresses,* In the 6th Malaysian Road Conference, Kuala Lumpur, Malaysia.

NHTSA (2014). *A compilation of motor vehicle crash data from the fatality analysis reporting system and the general estimates system*, Traffic Safety Facts, Report No. DOT HS 812 261, National Highway Traffic Safety Administration, Washington, DC.

NHTSA (2016). *Early estimate of motor vehicle traffic fatalities for 2015*, Brief Statistical Summary, Report No. DOT HS 812 269, National Highway Traffic Safety Administration, Washington, DC.

Serigos, P.A., A. De Fortier Smit, and J.A. Prozzi (2014). "Incorporating Surface Microtexture in the Prediction of Skid Resistance of Flexible Pavements." *Transportation Research Record*, No. 2457, Washington, DC, pp. 105–113.

Smith, H. A. (1977). "Pavement Contributions to Wet-Weather Skidding Accident Reduction." *Transportation Research Record*, No. 622.

Solaimanian, M. T., and T. W. Kennedy (1996). "Production Variability Analysis of Hot-Mix Asphalt Concrete Containing Reclaimed Asphalt Pavement," *Transportation Research Record*, No. 1543, Washington, DC, pp. 89–96.

Stroup-Gardiner, M., and C. Wagner (1999). "Use of Reclaimed Asphalt Pavement in Superpave Hot Mix Asphalt Applications," *Transportation Research Record*, No. 1681, Washington, DC, pp. 1–9.

TxDOT (1999a). *Tex-438-A Accelerated Polish Test for Coarse Aggregate*, Texas Department of Transportation, Austin, TX.

TxDOT (1999b). *Tex-410-A Abrasion of Coarse Aggregate Using The Los Angeles Machine*, Texas Department of Transportation, Austin, TX.

TxDOT (1999c). *Tex-411-A Soundness of Aggregate Using Sodium Sulfate or Magnesium Sulfate*, Texas Department of Transportation, Austin, TX.

TxDOT (2000). *Tex-612-J Acid Insoluble Residue for Fine Aggregate*, Texas Department of Transportation, Austin, TX.

TxDOT (2014). *Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges*, Texas Department of Transportation, Austin, TX.

TxDOT (2016a). *Tex-200-F Sieve Analysis of Fine and Coarse Aggregates*, Texas Department of Transportation, Austin, TX.

TxDOT (2016b). *Tex-461-A Micro-Deval Abrasion of Aggregate*, Texas Department of Transportation, Austin, TX.

TxDOT (2019). *Tex-236-F Determining Asphalt Content from Asphalt Paving Mixtures by the Ignition Method*, Texas Department of Transportation, Austin, TX.

TxDOT (2021). *Pavement Manual*, Texas Department of Transportation, Austin, TX.

White, G. (2019). "Quantifying the impact of reclaimed asphalt pavement on airport asphalt surfaces," *Construction and Building Materials*, Vol. 197, pp. 757–765.

Williams, B. A., J. R. Willis, and T. C. Ross (2019). *Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2018*, National Asphalt Pavement Association, 2019, Information Series 138 (9th edition).

Wu, Z., B. King, C. Abadie, and Z. Zhang (2012). "Development of Design Procedure to Predict Asphalt Pavement Skid Resistance," *Transportation Research Record*, No. 2306.

Wu, Z., B. King, and Y. P. Subedi (2016). *Evaluation of LADOTD Aggregate Friction Rating Table by Field Measurements*, Report HWA/LA.15/554, Louisiana Transportation Research Center, Baton Rouge, LA.

Zuniga-Garcia, N., and J.A. Prozzi (2019). "High-Definition Field Texture Measurements for Predicting Pavement Friction," *Transportation Research Record*, No. 2673, Washington, DC, pp. 246–260.