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Impact of Reclaimed Asphalt Pavement and Recycled Asphalt Shingles on Laboratory and Field Performance of Texas Asphalt Concrete Pavements

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Dedication

This thesis is dedicated to my parents, my sisters and my grandmother.

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by

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Abstract

The use of recycled materials in Asphalt Concrete (AC) mixes is highly promoted in the transportation industry. Recycled materials minimize the use of virgin materials, reduce the consumption of resources, and cut costs for new construction or rehabilitation projects. The incorporation of Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS) in the AC mixture is promoted as long as equal or improved performance is achieved. The Texas Department of Transportation (TxDOT) is currently placing asphaltic concrete (AC) mixes that are lasting less than their expected performance life when recycled materials are used.

The objective of this thesis is to present a performance comparison between virgin mixes and recycled mixes placed in Texas. The study includes a network level analysis that contains merged data from four different TxDOT databases at a statewide level from 2008 to 2015. Results from the Hamburg Wheel Tracking Test (HWTT) and Indirect Tensile Strength (IDT) were used in order to better understand the impact of the recycled materials in the laboratory performance. Similarly, life predictions in terms of fatigue cracking were incorporated into the study. At project level, results from the HWTT, IDT and Overlay Tester (OT) were used to characterize the performance of the AC mixtures in the laboratory. Field performance results were obtained through the collection of condition surveys that include cracking and rutting surveys.

The data merging process from different databases permitted the evaluation of the impact of RAP and RAS in the AC mix performance. The integration of the network and project level data lead to a better understanding of the use of recycled materials in Texas, their laboratory performance and their susceptibility to fatigue cracking and rutting.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Background

With increasing demand to implement sustainable design practices for highway construction, environmental responsibility has become a significant concern for the transportation industry. Over the last decades, transportation agencies and States Department of Transportation (DOT) have incorporate recycled asphalt in their mix design process. The use of recycled materials has increased due to the minimized consumption of resources, low environmental impact and economic benefits. There are more than 94% asphalt paved roads in the United States and the demand for new construction and rehabilitation projects is continuously increasing. The asphalt industry remains the country's most diligent recycler with more than 99% reclaimed asphalt pavement being put back to use (Hansen and Copeland, 2017). From a wide variety of options in recycled materials the most commonly used are reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS).

One of the most common processes to obtain RAP is through milling, or cold planning. This method collects the asphalt pavement directly from the existing pavement surface by removing from 3 in. to 4 in. by a single pass of the milling machine. The collected material normally is transported for processing or processed and placed in situ. This process alters the properties of the asphalt mix aggregate and modifies the virgin binder, which are the two main components of the asphalt mix. The aggregate can be crushed and graded to then be re-incorporated into the mixture. The asphalt binder is reactivated and mixed with virgin binder, which is usually softer to reduce the aging effects of the recycled binder. The collection of RAS can be achieved through two different methods. One of them is from the tear-off shingles and the other is from the

manufacturer waste. The properties of the recycled shingles contribute to the asphalt content and the aggregates of the mix design.

The incorporation of RAP and RAS into the mix should be cautiously measured due to the fact that RAP contains graded asphalt binder and RAS does not. RAP contains aged binder and even though RAS contains asphalt cement its properties are different. Because of this, the properties of the two materials can have different effects in AC mixtures. The addition of the recycled materials change the mechanistic properties of the mix affecting the performance and the cracking responses to traffic loads. Several studies have shown that the addition of RAP and RAS can have a direct effect on the resistance to deformation, cracking and strength of the AC. Therefore, the use of RAP and RAS is promoted as long as the same or improved field performance is obtained.

In general highway agencies and DOT's have established a criteria for the incorporation of these materials into the AC mixture. TxDOT limits the use of RAP to a maximum of 20% and the use of RAS to 5% for surface mixes. Several studies have investigated the effects of RAP and RAS in the laboratory using the Hamburg Wheel Tracking Test (HWTT), Indirect Tensile Test (IDT), Overlay Tester (OT), and Dynamic Modulus (DM). Some of this research studies indicate that the inclusion of recycled materials can have a detrimental effect on the field performance of flexible pavements.

To quantify the impact of the RAP and RAS on AC performance three different data sources were used. TxDOT database SiteManager was used to collect statewide data regarding the characteristics of the AC mix designs. Research Project 0-6679 "Performance Life of Various HMA Mixes in Texas" conducted at The University of Texas at El Paso (UTEP) developed an online tool called PERMIT that provides information regarding the predicted life of mixes in

Texas. SiteManager and PERMIT were merged to determine how recycled materials affect the performance of the AC. Similarly, Research Project 0-6658 "Collection of Materials and Performance Data for Texas Flexible Pavements and Overlays" conducted also at UTEP was used to determine the effects of recycled materials on the project level AC performance. The study was carried at a network level which consisted of an extensive road network, and a project level that contained a limited number of road sections.

1.2 Problem Statement

TxDOT is currently placing recycled AC mixes that are perceived to last less than their intended performance life. Recycled materials like RAP and RAS are used and promoted by transportation agencies because of the minimized environmental impact and cost reduction. However, recycled materials should be carefully used to minimize their negative aspects in terms of fatigue cracking and rutting. Results from HWTT, IDT and OT were used to characterize the performance of AC mixes in the laboratory. Performance life predictions from PERMIT and access to condition surveys offered a better understanding of the actual performance of recycled AC mixes in the field. With the combination of a network level and a project level information, the impact of RAP and RAS in AC mixes can be evaluated more quantitatively and objectively.

1.3 Objectives

The objective of this research is to compare the laboratory and field performance between virgin mixes and comparable mixes with recycled asphalt. The following items were addressed:

1. Establish a linking process within the SiteManager forms to identify the virgin and recycled mixes and their laboratory performance results.

2. Develop a merging process between SiteManager and PERMIT to assign a performance life prediction to the sections.
3. Use data from TxDOT Research Project 0-6658 "Collection of Materials and Performance Data for Texas Flexible Pavements and Overlays" to select relevant sections and obtain their respective laboratory and field performance results.
4. Evaluate the impact of RAP and RAS on laboratory results and field performance for AC mixes in Texas.
5. Integrate the network and project level results to provide a final recommendation.

1.4 Thesis Organization

This thesis is organized in six chapters. This introductory chapter presents the main objectives of the project as well as a background overview. Chapter 2 presents a literature review of the AC mixes in Texas, the test equipment used to characterize mixes in the laboratory and the results from previous studies that have investigated the impact of RAP and RAS in performance. Chapter 3 explains the linking process within SiteManager and between SiteManager and PERMIT. This chapter also presents a network level statistical analysis. Chapter 4 explains the structure of the DSS and the results obtained from the laboratory testing. Chapter 5 presents the field performance data collection and a correlation analysis to the results from the laboratory tests. Chapter 6 contains the summary of the study, conclusions and recommendations for future work.

Chapter 2: Literature Review

2.1 Recycled Materials

The use of recycled materials in asphalt mixtures began in earnest in the 1970s in response to the oil embargo. The embargo banned petroleum exports to several nations, including the United States, and introduced cuts in oil productions (Weiner, 1999). The importance of oil lead to an effort from the transportation industry to reduce material consumption and other major issues in transportation planning. Nowadays, with increasing demand to build new roads and maintain existing highway infrastructure, transportation professionals have continue incorporating recycled materials in their mix design practices.

From a wide variety of recycled materials, the most commonly used are reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS). RAP is salvaged, milled, pulverized, broken, or crushed so that particles pass the 2-in. sieve (Texas Department of Transportation, 2014). RAS is defined as processed asphalt shingle material from manufacturing of asphalt roofing shingles or from re-roofing residential structure and all particles must pass the 3/8 in. sieve (Texas Department of Transportation, 2014). TxDOT allows the use of recycled materials only when it is specified in the construction plans. When using recycled materials, the contractor must ensure that the material is free of contamination and must comply with TxDOT's Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges specifications book.

Zhou et al. (2010) documented the practice of RAP stockpile management and processing in Texas. The study recommended the elimination of RAP stockpiles contamination, to keep RAP stockpiles separate, and to avoid over processing and moisture. These recommendations aimed to improve RAP variability and its blending process. A more recent study by Zhou et al. (2013) documented the use of RAS in Texas. The researchers conducted a comprehensive investigation

in the use of tear-off asphalt shingles (TOAS) and manufacture was asphalt shingles (MWAS). They reported that the TOAS binders are much stiffer than MWAS. The authors recommended that it is important to differentiate between TOAS and MWAS when used in asphalt mixtures. This study also documented that the contractor can save from $4.00 to $7.00 per ton of HMA by using 5% RAS in HMA. Similarly, they found that the net energy requirement associated with recycling shingles into HMA is less than the requirement associated with disposing of those shingles in a landfill and using all virgin materials for HMA production.

The use of recycled materials is promoted by several DOT’s because it reduces project costs and because of its positive environmental impact. The last survey conducted by the National Asphalt Pavement Association (NAPA) in 2015 reported that the total estimated tons of RAP used reached 74.2 million which was estimated to reduce the need of 3.7 million tons of asphalt binder and nearly 70.5 million tons of aggregates. The total estimated tons of RAS were estimated to be 1.93 million, saving 386,200 tons of asphalt binder and 965,500 tons of aggregate (Hansen and Copeland, 2017).

2.2 AC MIXES IN TEXAS

Transportation agencies limit the use of recycled materials in flexible pavements because of the RAP and RAS variability and because of their potential negative impact in terms of premature cracking due to the stiff binder from the recycled materials. However, the use of recycled materials is also promoted because it reduces the rutting potential of the AC mixtures.

Table 2.1 illustrates the most common AC mixtures used in Texas by the item number and mix type as well as the recommended limits for the use of RAP and RAS in surface mixtures. Higher amounts of RAP are permitted for base course layers. The common applications for each item are also presented in this table. Mixes that comply with Items 340 and 341 are dense graded. The main

difference between these two items is that Item 340 is used for small projects where no QC/QA is needed, while Item 341 is used for high-volume construction and follows QC/QA specifications. Item 342 is used for high speed roadways since are known to reduce tire noise. Items 344 and 346 are typically used for high volume roads. The allowable RAP content for Item 346 is 15% since SMA mixes are already good at resisting rutting, adding too much RAP might impact the mix resistance to cracking.

Table 2.1 AC Mixes in Texas (Texas Department of Transportation, 2014)

Item No.	Mixture	Types	RAP (%)	RAS (%)	Applications
Item 340	Dense Graded Mixture (Small Quantities)	A, B, C, D & F.	20	5	For projects with less than 5,000 tons of HMA. No QC&QA specifications.
Item 341	Dense Graded Mixture	A, B, C, D & F.	20	5	Used from high to low volume, new construction or overlays.
Item 342	Permeable Friction Course	PFC_PG and PFC_A-R	10	5	Commonly used for high speed roadways.
Item 344	Performance Design Mixtures	SP A, B, C & D. CMHB C & D.	20	5	Used from medium to high demand roads in new construction or overlays.
Item 346	Stone Matrix Asphalt Mixtures	SMA C, D & F. SMAR C & F.	15	5	Used typically in high volume roads.

2.3 Fatigue Cracking and Rutting- Laboratory and Field Performance

One of the main concerns when recycled materials are used is how RAP and RAS impact rutting and fatigue cracking. Table 2.2 demonstrates a portion of a rankings table developed by TxDOT Flexible Pavements Branch (2004). The table provides the mixture characteristics by mix

type from a 0 to 5 scale, with 5 being the best. The factors that determine the behavior of the mixes are also listed in this table.

Table 2.2 AC Mixes Performance in Texas (TxDOT Flexible Pavements Branch, 2004)

Mixture Characteristic	Dense Grade (Item 340/341)	PFC (Item 342)	Performance Design Mixes (Item 344)	SMA (Item 346)	Determining Factors
Resistance to Rutting	2-5	4-5	3-5	4-5	Stone to stone contact and binder stiffness
Resistance to Cracking	1-4	3-5	2-4	4-5	Total volume of asphalt in mix, binder film thickness
Resistance to Segregation	1-4	5	3-4	4-5	Gradation, uniformity and aggregate size
Resistance to Raveling	2-4	2-4	3-4	4-5	Toughness of mastic and resistance to segregation
Ability to resist high shear forces (hard turning motions)	2-4	2-4	3-4	4-5	Toughness of mastic and resistance to raveling
Resistance to Moisture Damage	2-4	3-5	3-4	4-5	Binder film thickness and potential to adverse permeability
Resistance to Freeze/Thaw Damage	3-4	2-4	3-4	4-5	Binder film thickness and potential permeability
Long Term Durability	2-3	3-4	3-4	4-5	Binder film thickness and toughness

Figure 2.1 illustrates two of the main distresses observed during the data collection process for this study. Rutting is a longitudinal surface depression in the wheel path (Miller and Bellinger, 2003). This distress can occur due to excessive deformation in any layer of the pavement structure, HMA, base or subgrade. Fatigue cracking, also known as alligator cracking, occurs in areas subjected to repeated traffic loadings in the wheel paths (Miller and Bellinger, 2003). This distress

is identified by a series of interconnected cracks which visually represent an alligator pattern in high severity cases. The low severity cases are often confused with longitudinal cracking. However, alligator cracking can be distinguished because it presents a non-linear path, as the example presented in Figure 2.1-b.

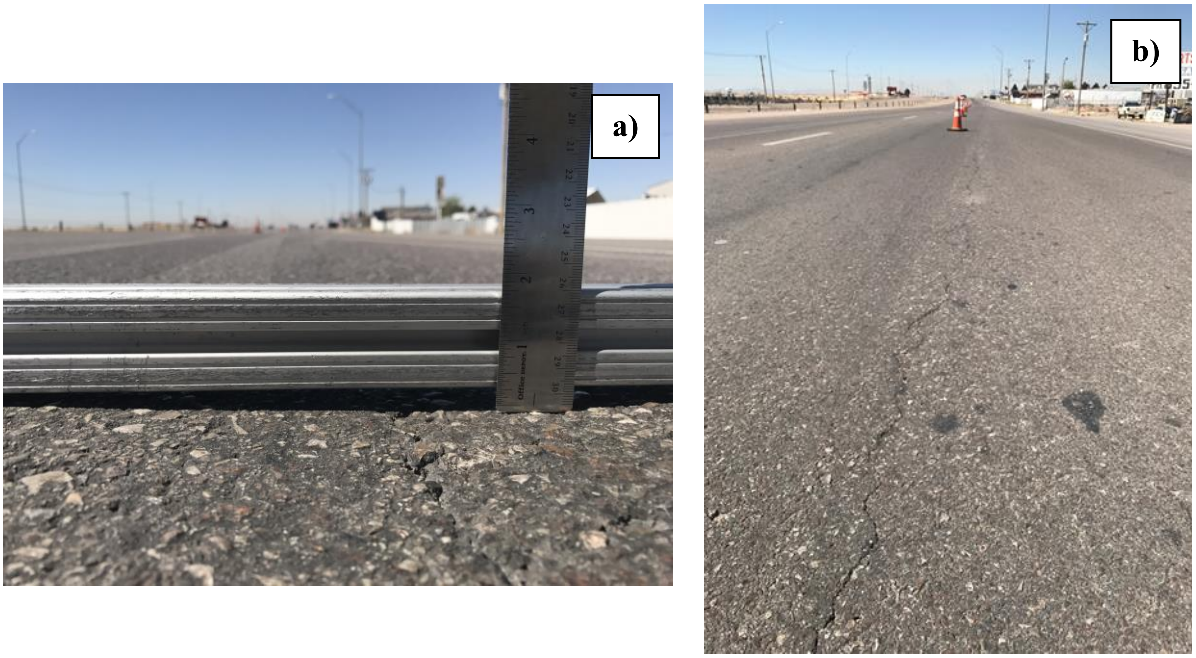


Figure 2.1 a) Rutting b) Fatigue (Alligator) Cracking

From the information presented in Table 2.2, the performance of the dense graded mixes, Items 340 and 341, is variable and could be categorized with the poorest performance. Item 342 mixes present improved and less variable performance, when compared to the dense graded mixes. The ranges for the Performance Design mixes, Item 344, appear to show less variability and good cracking resistance. Item 346 mixes are commonly seen as superior mixtures that have particularly high resistance to cracking and rutting.

Different laboratory tests are currently used to predict these failure distresses. TxDOT uses different testing equipment and parameters, depending on the mix type, to accept or reject mixtures based on these performance predictions. For the purpose of this study, only the results from the

Hamburg Wheel Tracking Test (HWTT), Indirect Tensile Strength (IDT) and Overlay Tester (OT) will be evaluated. The testing equipment is presented in Figure 2.2.

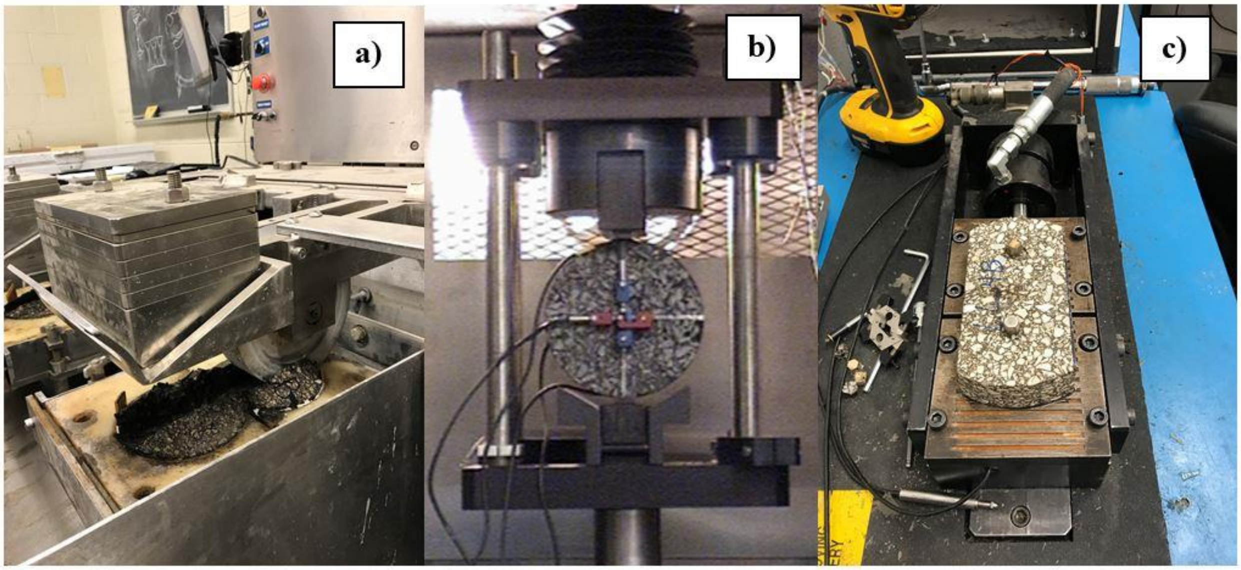


Figure 2.2 a) Hamburg Wheel Tracking Test, b) Indirect Tensile Strength, and c) Overlay Tester

The HWTT is a torture tests used to evaluate the rutting potential and moisture susceptibility of the asphalt mixtures. This test simulates a traffic load by repeatedly moving a steel wheel over the asphalt sample. According to TxDOT (2014) Items 340, 341, 344 and 346 mixes require HWTT number of cycles based on their PG grades. The requirements are as follows: PG 64 or less, PG 70, and PG 76 or higher require 10,000, 15,000 or 20,000 wheel passes, respectively. A mixture is considered failed if it does not comply with the number of passes requirements or if it exceeds 0.5 in. (12.5 mm) in rut depth. The parameter from the HWTT results used for this study was the rut depth.

The IDT is conducted by loading a cylindrical specimen across its vertical diametral plane at a specified rate of deformation and test temperature. The peak load at failure is recorded and used to calculate the IDT strength of the specimen. IDT results are used to evaluate the cracking characteristics of the mixes. When used in conjunction with laboratory mix design this test is

helpful to estimate the potential of rutting. TxDOT recommends an IDT strength that falls between 85 psi to 200 psi. There are some cases when more than 200 psi are allowed based on the Engineer's recommendation and the HWTT results.

TxDOT employs the OT to determine the susceptibility of AC mixes to fatigue cracking. The OT operates by applying repeated direct tension loads to specimens. TxDOT and many other state DOT's evaluate the OT results based on the number of cycles. Garcia, et al (2016) proposed a new methodology to assess the crack initiation and crack propagation potentials of the AC mixes. This method estimates the resistance of AC mixtures to initiate a crack by using the critical fracture energy from the first cycle of the OT. The crack progression rate that is defined as the rate of decrease in the measured load with the number of cycles, was used to characterize the resistance of AC mixes to delay the propagation of a crack.

The design interaction plot proposed by Garcia et al. (2016) is depicted in Figure 2.3. The parameters used to evaluate the improved OT are the critical fracture energy (Crack Initiation Property) and crack progression rate (Crack Propagation Property). The acceptance limits are used to delineate the cracking performance of the AC mixes. Mixes than fall within the shaded area are perceived to exhibit good cracking resistance, and those located outside these limits are categorized as poor cracking resistant mixes.

Behnia et al. (2011) investigated the effects of RAP in the low-temperature cracking performance of asphalt mixtures. Among other tests, the IDT strength tests were conducted on HMA specimens that contained 20% and 40% RAP. The 20% RAP mixtures performed better than the 40% RAP in terms of handling and relaxing thermally induced stress in pavement.

Jo and Walaa (2010) evaluated three different RAP percentages 10%, 25% and 40% and a control section with 0%. They found that the average IDT strength of RAP mixtures did not change significantly from 0% to 10%, RAP but it was significantly different at 25% and 40% RAP.

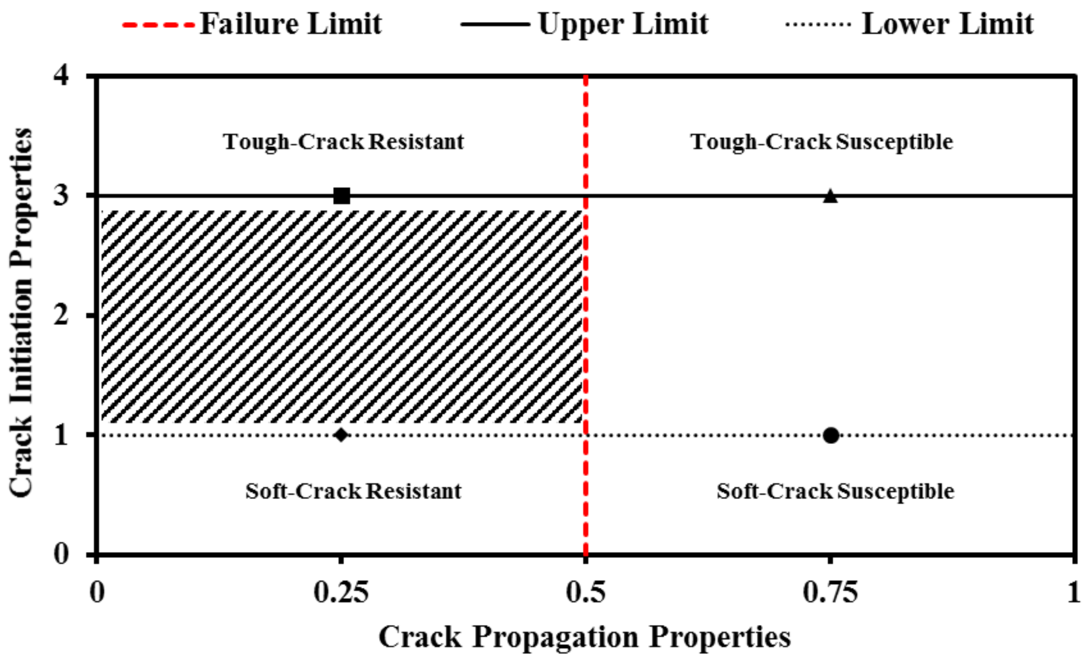


Figure 2.3 OT Interaction Plot (Garcia et al. 2016)

Wen, et al. (2013) investigated two control sections without RAS and two sections with 3% RAS, all four sections contained 15% RAP. After three years of service, minimal rutting was observed for all four sections. Low severity longitudinal cracks were found in two sections, one with RAS and one without RAS. Eight cores from each section were obtained to conduct different laboratory tests. The results from the ANCOVA statistical analysis for the HWTT indicated that the rutting depths of the mixtures with RAS are less than the virgin mixes, suggesting that the use of RAS increases the rutting resistance of HMA mixes.

Zhou, et al. (2011) studied the impact of high-RAP contents in three different test sections in Texas. In all three cases, RAP improved the rutting and moisture resistance but worsened the

cracking resistance when more than 30% RAP or a combination of RAP and RAS were used. This study also documented three different mixes with different variations in RAP contents in order to propose a balanced mix design using the OT as a direct measure for cracking resistance. The cracking requirements in terms of OT cycles varied depending on the climate, traffic level and existing pavement conditions. The research team concluded that more work was needed in order to develop criteria that accounted for these factors.

Tran et al. (2012) evaluated the impact of rejuvenator on the performance of HMA mixtures with high RAP and RAS contents. A statistical analysis indicated that virgin control mixtures had the highest number of cycles to failure and differed from those with recycled materials. The mixture with 20% RAP and 5% RAS with rejuvenator had the highest number of OT cycles to failure, followed by the 50% RAP with rejuvenator, then the 20% RAP with 5% RAS, and finally the 50% RAP mix. However, the results for the statistical analysis of the recycled mixtures were not statistically significant.

Zhou et al. (2013) collected field performance results on US 87, Amarillo Texas of two 3-in. thick asphalt overlay sections to validate the effectiveness of increasing the design density and the impact in cracking resistance of RAS mixes. Increasing the design density improved the reflective cracking performance of the RAS sections. They indicated that the use of RAS did not significantly influence the dynamic moduli of the HMA but improved their rutting and moisture damage. However, the RAS mixes had poor cracking resistance.

Goh and You (2011) evaluated the rutting of 5% and 10% RAS mixes along with a control mix using the asphalt pavement analyzer (APA). All mixtures were compacted at 86 gyrations under different temperatures. The 10% RAS mixture had significantly lower rutting depth when

compared to the control mixture. The use of RAS could significantly improve the rutting resistance of mixes, likely due to the aged nature of the RAS binder.

Four test sections were constructed in Highway 10 in Iowa Sioux County as part of the Transportation Pooled Fund (TPF) 5-213 in Iowa. The experimental plan included a control mixture with 0% RAS and three sections with 4%, 5% and 6% RAS. Williams et al. (2013) reported the presence of transverse cracking after two years of service. The control section with 0% RAS contained the greatest amount of transverse cracking, followed by the 5%, 6% and 4%. They indicated that the addition of RAS to the Iowa DOT mix design increases its ability to resist cracking.

Zhou et al. (2013) also evaluated the use of RAP and RAS in rutting and cracking performance. The study investigated the impact of soft binders in terms of dynamic modulus, HWTT rut depth, and OT cycles. The results indicated that the use of soft and modified asphalt binders can effectively improve cracking resistance of RAP and RAS mixes without compromising the rutting resistance. The dynamic modulus was not a good indicator or cracking resistance for the evaluated mixes.

In conclusion, the addition of recycled materials, such as RAP and RAS, are used to improve the rutting resistance of the AC. This is due to the aged binder found in the recycled materials. The use of aged binder may impact the flexibility of the mixture, therefore increase its cracking potential. For this reason, mixes should be carefully designed otherwise too much stiffness can provoke premature cracking. Rutting and cracking are a major performance concern in the flexible pavement community. Researchers are continuously conducting studies to evaluate a perfect mix that can balance the rutting and cracking potential.

Chapter 3: Network Level Analysis

3.1 BACKGROUND

Based on previous projects, UTEP research team was in a unique position to quantify the impact of the RAP and RAS on AC performance. The objective of Research Project 0-6679 "Performance Life of Various HMA Mixes in Texas" conducted at UTEP was to rationally propose the representative service lives of various HMA mixes in Texas. The outcome of that project was an online web-based application called PERMIT (Performance Life of HMA Mixes in Texas). That platform contained built-in algorithms that allowed the overall performance of the AC mixes in Texas. PERMIT utilizes and merges the following three databases:

1. Pavement Management Information System (PMIS): a collection of visual distress rating, scores, GPS coordinates, and traffic information that is gather annually and biannually.
2. Design and Construction Information System (DCIS): contains information about construction, reconstruction, and maintenance of Texas' roads.
3. Letting Database: documents the HMA-let jobs.

PERMIT is an online tool that takes different elements from each database to estimate the longevity, serviceability state, performance information and life predictions of thousands of road sections in Texas (Rodriguez et al. 2014). As shown in Figure 3.1, PERMIT provides a visual representation of these sections with an Interactive Google Maps® representation. The sections are color-coded based on the service life and distress condition.

Due to interest expressed by TxDOT engineers, a link between PERMIT and TxDOT SiteManager database was prototyped through another online tool named Pavement Analysis and Statistics (PASS). SiteManager includes quality control/quality assurance (QC/QA), construction administration, and field record keeping, contract record maintenance, contractor payment

processing, materials management, and civil rights monitoring data. PASS allows users to analyze and visualize all the available information from the planning to the archival stage of a project from historical data.

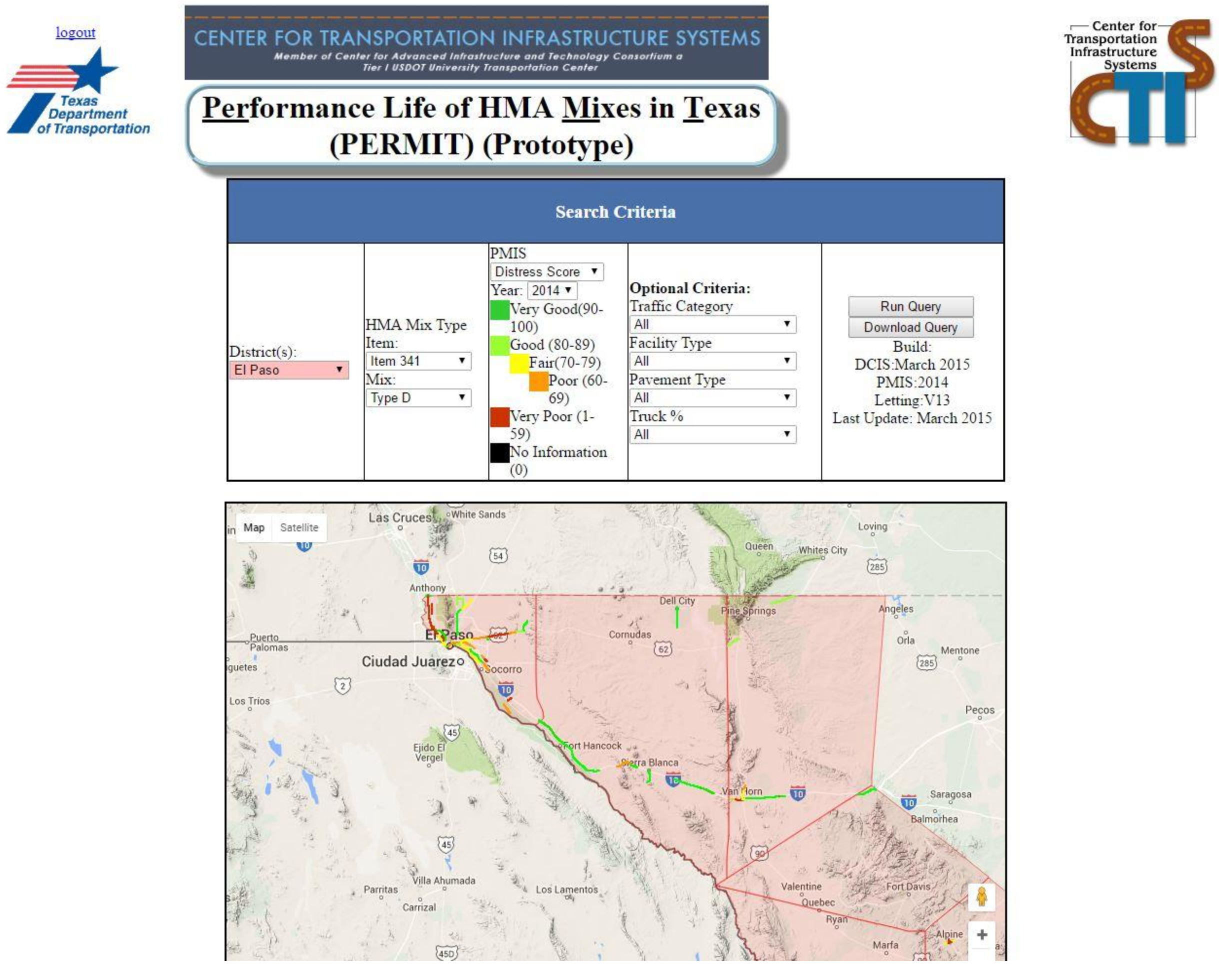


Figure 3.1 Graphical User Interface of PERMIT

As seen on Figure 3.2, PASS graphical user interface (GUI) was designed to be very similar to the SiteManager forms for the convenience of the users. PASS is currently capable to provide data from sixteen different SiteManager forms; one of them is the form TX2MIXDE (HMAC Mixture Design) that provides the information pertaining to mix design variables.

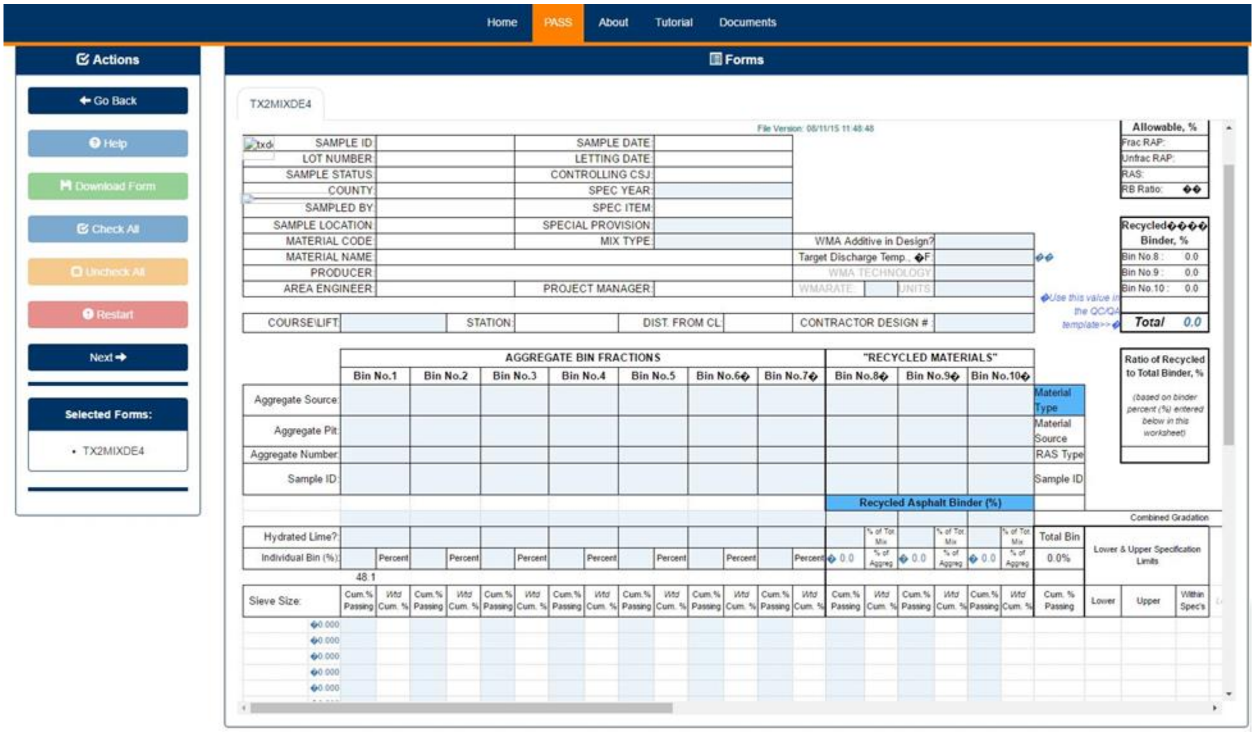


Figure 3.2-Graphical User Interface of PASS

3.1 DATA MINING PROCESS USING SITEMANAGER

SiteManager is a software program that automates and streamlines the management of highway construction projects and contains more than 38 million records. In this study, the information from 2008 through 2015 was used. Since the main objective of this project was to study the impact of recycled asphalt in the performance of flexible pavements, two sets of data were generated from the TX2MIXDE forms to differentiate projects with virgin mixes and with RAP/RAS mixes.

Figure 3.3 illustrates the Combined Gradation tab of the SiteManager form TX2MIXDE4. The data obtained from this form can be identified by a colored square around the field. The description for each box is provided below.

- Box 1: this field indicates the form version, date and time.

- Box 2: contains the unique sample ID that is automatically generated by SiteManager based on the username and the entry date.
- Box 3: contains the control section job (CSJ) number. This is a nine-digit number that serves as a unique key descriptor used to identify every project.
- Box 4: contains the information about the mix type used. Note that a CSJ might contain more than one mix type that can be differentiated by the sample ID.
- Box 5: this field serves as a description to separate the recycled materials section of the form. Most of the information regarding the use of recycled materials is contained in this section.
- Box 6: this field was retrieved to identify the location of the field value within the form and to cross reference the data retrieved from box 7 and 9.
- Box 7: this field provides the description of the type of recycled material (i.e. Fractionated RAP, Unfractionated RAP or RAS).
- Box 8: contains the value of the asphalt binder percentage from the recycled material.
- Box 9: contains the value of the percentage of recycled asphalt in the mix. This field comes with the description % of Total Mix.
- Box 10: this field contains the value for the asphalt binder percent in the total mix.
- Box 11: contains the value for the percentage of antistripping agent.

The first step to obtain information about the use of recycled asphalt was to merge three different fields from TX2MIXDE form. These fields are highlighted in Boxes 6, 7 and 9 in Figure 3.3. The elements used to match these three fields were the CSJ, Sample ID, and Mix Type. The bin number (Box 6) was used to identify the location of the material type and the recycled asphalt data within the form. The material type (Box 7) contained the description of the type of recycled

asphalt used in the mix design. Currently, the options to fill this portion of the form are: Fractionated RAP, Unfractionated RAP, and RAS. It is important to keep in mind that other descriptions for this field may be found within SiteManager due to changes in versions.

The recycled asphalt binder stores two values, one is the percentage of recycled binder (Box 8) and the other is the percentage of recycled asphalt (Box 9), which contains the description “% of total mix.” For this study the value needed to evaluate the AC mixes was the recycled asphalt content (Box 9), along with its description key.

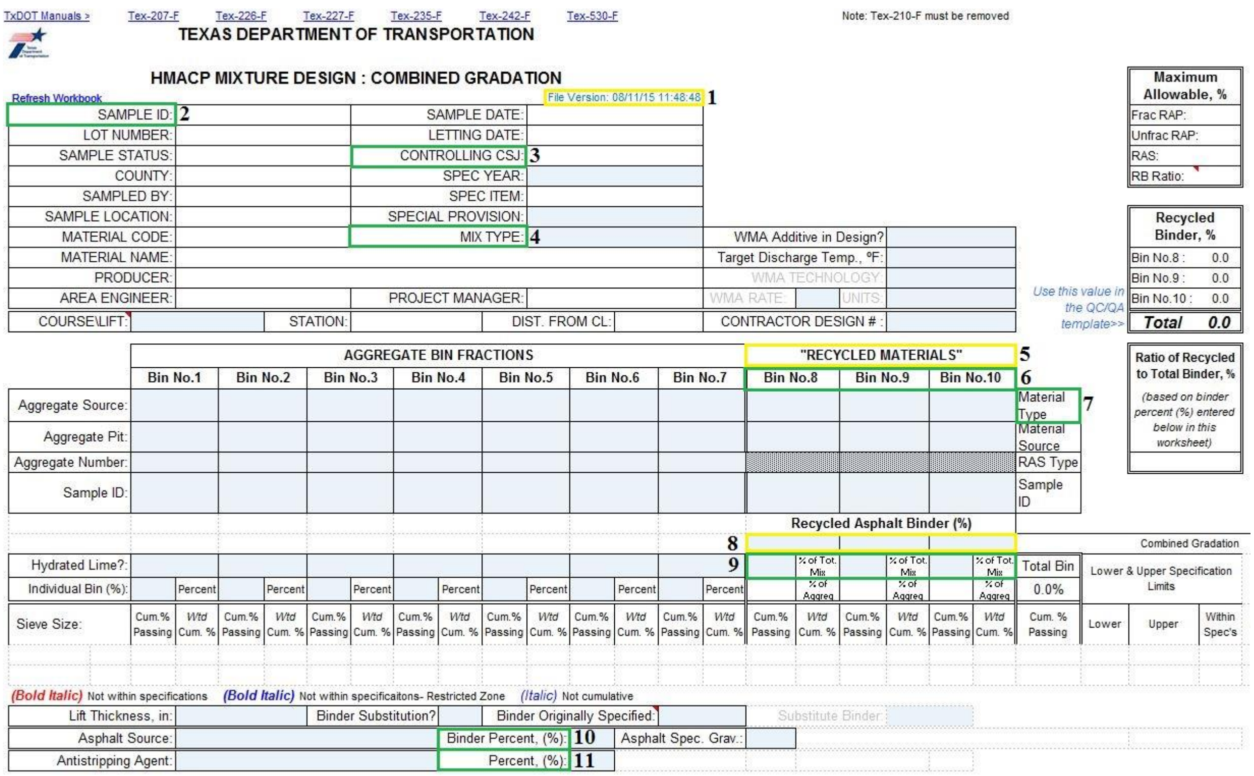


Figure 3.3 TX2MIXDE Combined Gradation

Further complexity was encountered with form versioning and the availability of data with changing versions. This became one of the main challenges while using SiteManager and affected the process to identify mixes with content of RAP or RAS for the 2008-2012 data set. The information stored in Box 8 and Box 9 is extracted together under the recycled asphalt binder (%)

field. After retrieving data from those two fields it was observed that there was no parameter or description key to identify the location of the field value within the form. Because of the absence of this description key there was no way to differentiate the percentage of recycled binder (Box 8) from the percentage of recycled asphalt (Box 9).

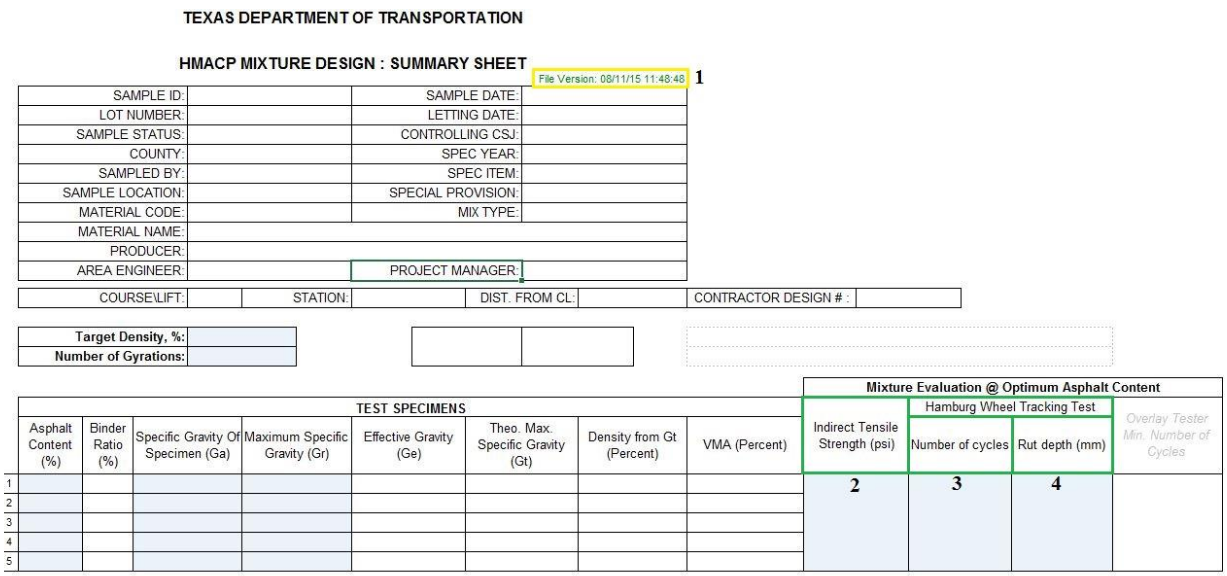
TxDOT constantly updates the templates used to collect information by adding, revising or removing fields in the forms. TxDOT removes the old template from SiteManager and uses only the most recent version to upload or retrieve data. All SiteManager forms have a revision tab that keeps track of the date and the type of changes that were made. These new forms have embedded equations that define the version and make changes according to the version number. In order to ensure consistency between forms, the form version code changes calculations, conditional formatting and display of sheets and rows.

Old templates need to be backward compatible with new forms to be able to provide accurate information according to current specifications. After December 2012, the description key "% of total mix" was added to the TX2MIXDE form to identify the field value stored in Box 9. Updated data from 2008-2015 was received from TxDOT during the merging process. The description key was part of the new data set since SiteManager automatically back calculates the values for the new forms. The new database contained the description key "% of total mix" for the complete data set from 2008 to 2015 which was used to distinguish the values from Box 8 and Box 9.

The data from the Combined Gradation tab was merged to the Summary tab of form TX2MIXDE. Figure 3.4 illustrates the information retrieved from this portion of the form. The description of each field is provided below:

- Box 1: this field indicates the form version, date and time.

- Box 2: this field contains the Indirect Tensile (IDT) strength in psi units.
- Box 3: contains information for the Hamburg Wheel Tracking Test (HWTT) number of cycles.
- Box 4: contains information for the Hamburg Wheel Tracking Test (HWTT) rut depth in millimeters.


TEXAS DEPARTMENT OF TRANSPORTATION

HMACP MIXTURE DESIGN : SUMMARY SHEET

File Version: 08/11/15 11:48:48 1

SAMPLE ID:		SAMPLE DATE:	
LOT NUMBER:		LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY:		SPEC YEAR:	
SAMPLED BY:		SPEC ITEM:	
SAMPLE LOCATION:		SPECIAL PROVISION:	
MATERIAL CODE:		MIX TYPE:	
MATERIAL NAME:			
PRODUCER:			
AREA ENGINEER:		PROJECT MANAGER:	

COURSE\LIFT: | STATION: | DIST. FROM CL: | CONTRACTOR DESIGN # :

Target Density, %:
Number of Gyrations:

	TEST SPECIMENS								Mixture Evaluation @ Optimum Asphalt Content			
										Hamburg Wheel Tracking Test		
	Asphalt Content (%)	Binder Ratio (%)	Specific Gravity Of Specimen (Ga)	Maximum Specific Gravity (Gr)	Effective Gravity (Ge)	Theo. Max. Specific Gravity (Gt)	Density from Gt (Percent)	VMA (Percent)	Indirect Tensile Strength (psi)	Number of cycles	Rut depth (mm)	Overlay Tester Min. Number of Cycles
1									2	3	4	
2												
3												
4												
5												

Figure 3.4 TX2MIXDE Summary

TxDOT personnel uses the Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges manual to accept or reject AC mixes in the laboratory. During the mix design process the results from the laboratory tests are stored in the TX2MIXDE form under the Summary tab. First, the IDT test is used to determine the tensile strength or stiffness properties of the mix. The HWTT is used to predict the rutting resistance and moisture susceptibility of AC mixes through an assessment of the rut depth. The number of cycles from the HWTT results were retrieved but excluded from the analysis of this report. During the data mining process, it was found that some sections lack information in those fields. Therefore, the sample size from the Summary tab was different from the extracted data of the Combined Gradation tab.

3.2 Data Mining Process Between SiteManager and PERMIT

PERMIT is capable of calculating the historical performance data of road sections and provides a probabilistic service life for AC mixtures as discussed by Rodriguez et al. (2014). To associate and identify sections with recycled asphalt materials, PERMIT had to be connected to SiteManager. The various issues faced during the section identification process are discussed next. In the original version of PASS, PERMIT and SiteManager were linked only by CSJ. The query was defined to add the same mix type to all samples under the same CSJ. This linking process was inadequate because it did not allow to correctly identify different mixes under the same CSJ. Therefore, a different method to link SiteManager with PERMIT was established. The first step was to find a common field between the two databases besides CSJ. Linking by sample ID was the first unsuccessful method since the entries in SiteManager does not have the same sample ID as those from Letting or PMIS. An effective strategy was to link by CSJ and mix type. If a job in SiteManager happened to have more than one mix type, an entry would be generated for each mix type under the same CSJ.

Another challenge was the difference in mix type designation between SiteManager and PERMIT. For example, SiteManager mixes are described as ITEM341_B_LevelUp and PERMIT designates the mix as 341b. Therefore, a list of all the available mix types in SiteManager was obtained and then cross-referenced to the ones from PERMIT. For example, ITEM341_D_Fine_Surface and ITEM341_D_LevelUp were both designated as Type D. Special specifications mixes such as SS3224 and SS3268 were also cross-referenced to the mixes from PERMIT. Mix designation for all PERMIT mixes is presented in Figure 3.5. The mixes highlighted in gray show the mixture designation that PERMIT uses, and the rest are the different mix types found in SiteManager. This simple operation allowed to correctly link sections by CSJ and mix

type. MySQL was used to cross reference the mix types from both databases. During this process, 79 mix types found in SiteManager were consolidated to only 19 mixes. PERMIT excludes all records for Item 340 since these mixtures are not typically placed as surface courses. Due to sample size issues this portion of the study will presents results only for Item 341, 344 and 346.

341a
ITEM341_A_Coarse_Base
SS3224_A_Coarse_Base
SS3268_A_Coarse_Base
Type A

341b
ITEM341_B_Fine_Base
ITEM341_B_LevelUp
SS3224_B_Fine_Base
SS3224_B_LevelUp
SS3268_B_Fine_Base
SS3268_B_LevelUp
Type B

341c
ITEM341_C_Coarse_Surface
ITEM341_C_LevelUp
SS3224_C_Coarse_Surface
SS3224_C_LevelUp
SS3268_C_Coarse_Surface
SS3268_C_LevelUp
Type C

341d
ITEM341_D_Fine_Surface
ITEM341_D_LevelUp
SS3224_D_Fine_Surface
SS3224_D_LevelUp
SS3268_D_Fine_Surface
SS3268_D_LevelUp
Type D

341f
ITEM341_F_Fine_Mixture
ITEM341_F_LevelUp
SS3224_F_Fine_Mixture
SS3224_F_LevelUp
SS3268_F_Fine_Mixture
SS3268_F_LevelUp
Type F

CAM
CAM

CMHB_C
CMHB C
ITEM344_CMHB_C_Coarse_Surface

CMHB_F
CMHB F
ITEM344_CMHB_F_Fine_Surface

PFC
PFC_AR
PFC_PG

SMAR_F
SMAR F
SS3271_SMAR_F_Fine
SS3271_SMAR_F_LevelUp

SMA_C
ITEM346_SMA_C_Coarse
SMA C
SS3271_SMA_C_Coarse
SS3271_SMA_C_LevelUp

SMA_D
ITEM346_SMA_D_Medium
SMA D
SS3271_SMA_D_LevelUp
SS3271_SMA_D_Medium

SMA_F
ITEM346_SMA_F_Fine
ITEM346_SMAR_F_Fine
SS3271_SMA_F_Fine
SS3271_SMA_F_LevelUp
SMA F

SP-A
SP A
SS3270_SP_A_Base
SS3270_SP_A_LevelUp
ITEM344_SP_A_Base

SP-B
ITEM344_SP_B_Intermediate
SP B
SS3270_SP_B_Intermediate
SS3270_SP_B_LevelUp

SP-C
ITEM344_SP_C_Surface
SP C
SS3270_SP_C_LevelUp
SS3270_SP_C_Surface

SP-D
ITEM344_SP_D_Fine_Mixture
SP D
SS3270_SP_D_Fine_Mixture
SS3270_SP_D_LevelUp

TBPFC
TBPFC_AR
TBPFC_PG76

UTBWC
ITEM3142_UTBWC_A
ITEM3142_UTBWC_B
ITEM3142_UTBWC_C
SS3142_UTBWC_A
SS3142_UTBWC_B
SS3142_UTBWC_C

Figure 3.5 PERMIT to SiteManager Mix Type Designation

Mix design forms from TxDOT Research Project 0-6658 “Collection of Materials and Performance Data for Texas Flexible Pavements and Overlays” were used to verify the accuracy of the merged data. The parameters of interested such as mix type, recycled asphalt content, and laboratory data were manually verified from the section form. If the merged data was inconsistent

with form TX2MIXDE, the query was rewritten to solve the problem. The extraction process was repeated several times until the data was validated.

3.3 SiteManager and PERMIT Database Dimensions

The accessed version of the SiteManager database contained 7,500 unique sample ID's from 2008 to 2015. Each entry in SiteManager represents an actual project that was designed and built. The research team was able to merge within the two SiteManager forms approximately 85% of the data, that is 6,408 unique sample ID's. About 22% of that data could not be used since it did not contain mix type description, which reduce the sample size to 5,765 unique sample ID's. Because of the requirements of the study, these unique sample ID's were further separated into virgin mixes and recycled asphalt mixes. The sections with recycled asphalt were initially divided into four different categories: Fractionated RAP, Unfractionated RAP, RAP with addition of RAS, and RAS. Fractionated RAP is defined as two or more RAP stockpiles, divided into coarse and fine fractions (TxDOT, 2014). Unfractionated RAP is not commonly used in AC mixes, and some mixtures do not allow its use in the mix design. There were only 71 entries for Unfractionated RAP which were combined with the Fractionated RAP entries. This decision did not represent a significant change in the statistical analysis of the Fractionated RAP.

The SiteManager sample size by mix type is illustrated in Figure 3.6. Due to their small sample size and lack of relevant information the following mixes were excluded from the study: Item 340: Type A and B, Item 341: Type A and B, Item 342: PFC-AR and PFC-PG, Item 344: CMHB_F, Item 346: SMA-F and SMAR-F, and the other category. Item 340: Type B and Item 341: Type B have a good sample size, but were excluded from the study because these are not typically placed as surface mixes. The rest of the mixes were eliminated simply because there was not sufficient data to compare virgin mixes to RAP/RAS mixes. The final sample size used in the

study was 4,058 entries and are presented in Table 3.1 under the unique sample ID row. This table also presents the percentages for HWTT rut depth, IDT tensile strength and PERMIT, with respect to the total unique sample ID's. As previously mentioned, some irregularities were found within the database, hence the difference in retrieved data. The percentages presented under the PERMIT category do not represent the number of sections stored in PERMIT, but instead the sample size of the sections that were merged with SiteManager.

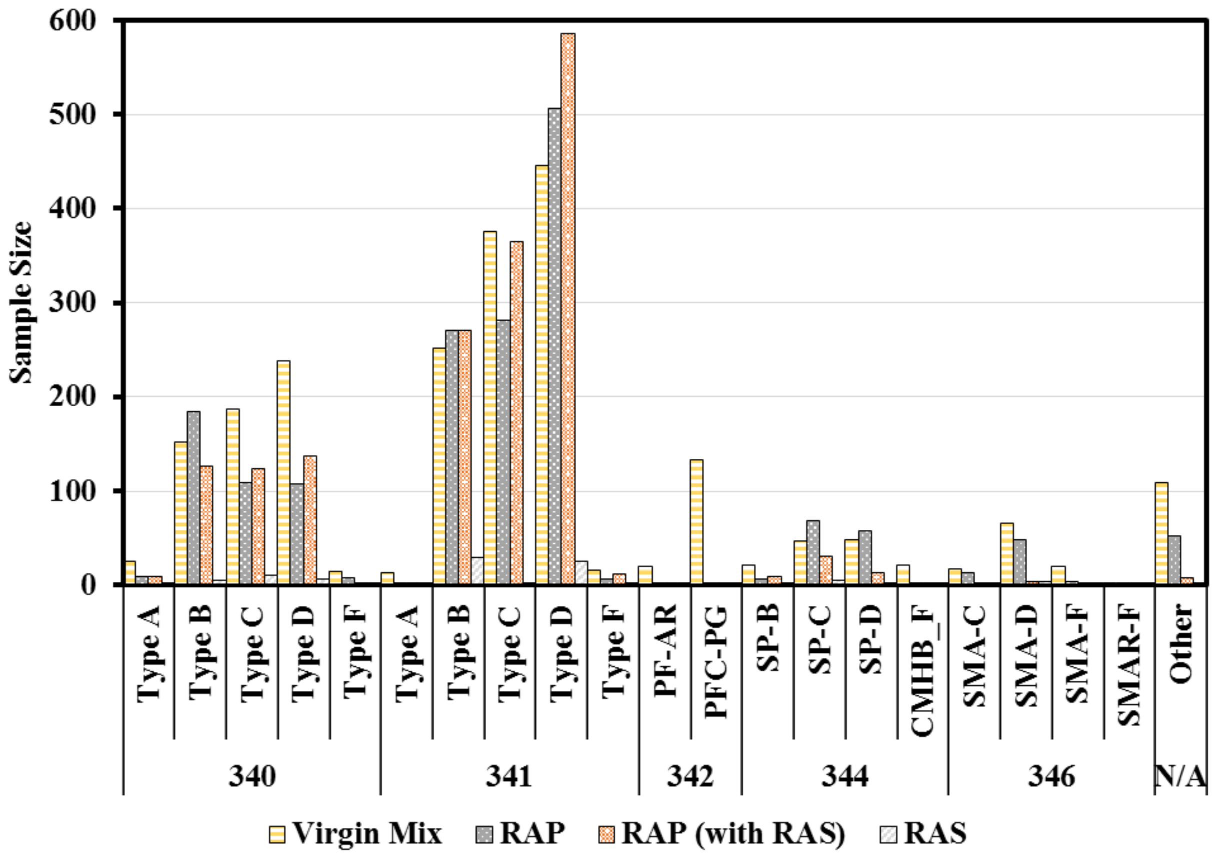


Figure 3.6- Frequency of Test Sections by Mix Type

One of the reasons why the SiteManager results might be larger than PERMIT is that several sample ID's can belong to a single CSJ. This should be taken into consideration when comparing the two data sets. Another reason for having a smaller sample size might be attributed to the way the data is stored in the four different databases. For example, if a particular CSJ does

not have mix type information in any of the PERMIT databases (DCIS, PMIS or Letting) then no match will be found when trying to link it to SiteManager. During the development process, it was observed that there are deficiencies within SiteManager and that in some cases some of the important information was blank. In some cases, the retrieved data did not include information in the CSJ, Sample ID, or Mix Type fields which were essential to identify and cross-reference the sections. One of the main factors that specifically impacted the sections with laboratory data is that not all the districts have access to testing equipment and their mix design process does not consider testing results to accept or reject AC mixtures. A stricter uploading process might be implemented to improve the sample size and quality of future data.

Table 3.1 SiteManager Sample Sizes by Unique Sample ID

SiteManager	Virgin Mixes	Recycled Asphalt			Total
		RAP	RAP and RAS	RAS	
Unique Sample ID	1,498	1,218	1,285	58	4,059
HWTT Rut Depth	55%	44%	55%	74%	52%
IDT Tensile Strength	64%	48%	58%	76%	58%
to PERMIT	23%	28%	25%	34%	25%

3.4 SiteManager Laboratory Performance

The results presented in this section were summarized by item number. Item 340 and Item 341 mixes possess the largest sample sizes, which can be assessed with more confidence. Superpave (SP) and Stone Matrix Asphalt (SMA) mixes were combined and represent Items 344 and 346, respectively. The merged data was summarized in box plots that are presented in terms of the median with the error bars represented by the minimum and the maximum. The box plot is divided in four equal parts. The distance between the minimum (lowest whisker) and the first box (first quartile) represents the distribution of the first 25% of the data. The bottom box represents the data distribution from the fist quartile to the median of the data set. The difference between the

median and the end of the second box (third quartile) represent another 25% of the data. Finally, the distance from the top box and the maximum (top whisker) represent the distribution of the final 25% of the data set. The secondary axis denotes the number of unique sample ID’s.

Figure 3.7 presents the box plot distributions for the amount of recycled asphalt content by item and type of recycled material. The results presented for the RAP with RAS category illustrate only the RAP content. This category was added to account for the impact of RAS since samples with only RAS were very limited throughout the study. The maximum sample size for sections with only RAS was 28 for Item 341. The box plot distributions for Item 340 and Item 341 with RAP illustrate that these mixtures usually use 20% recycled asphalt since in both cases the third quartile is equal to the mean.

When RAP and RAS are used in AC mixtures, the amount of RAP usually decreases. This pattern can be clearly observed in the RAP with RAS category for Items 340 and 341 were RAP contents range from 13% to 17%. Item 344: RAP illustrates a symmetric distribution between 10% to 20% recycled asphalt content. Whereas the distribution of RAP with RAS for Item 344 presents the use of RAP from 10% to 18%, higher variability is involved as presented by the whiskers. Finally, for Item 346: RAP the first quartile and the mean are the same with 10% RAP. Item 346: SMA mixes are not commonly designed with RAS or with a combination of RAP and RAS, each of these two categories have only four samples.

Figure 3.8 presents the HWTT rut depth results for Items 340, 341, 344 and 346. The median of Item 340 exhibits slightly greater rutting depths for virgin mixes than for any of the three recycled asphalt categories (RAP, RAP with RAS, and RAS). Item 340: RAP and Item 340: RAP with RAS exhibit similar distributions. The distribution of the Item 340 RAS sections indicate that the third quartile and the median are the same, but the sample size is very small when

compared to the rest of the categories. Item 341 exhibits very similar medians for all four categories, however the RAP sections have slightly greater rut depths when compared to the rest of the categories. The sample size retrieved indicates that it is a very common practice to use a combination of RAP and RAS for Item 341 mixes. Items 344 and 346 display improved rutting resistance when recycled asphalt is used. However, the error bars corroborate that some samples under Item 344 virgin exceeded the maximum rut depth of 12.7 mm (0.5 in.) established by TxDOT. Overall, Items 340, 344 and 346 present greater medians for virgin sections. This can be seen as an indication that the addition of recycled materials have a direct impact in rutting resistance.

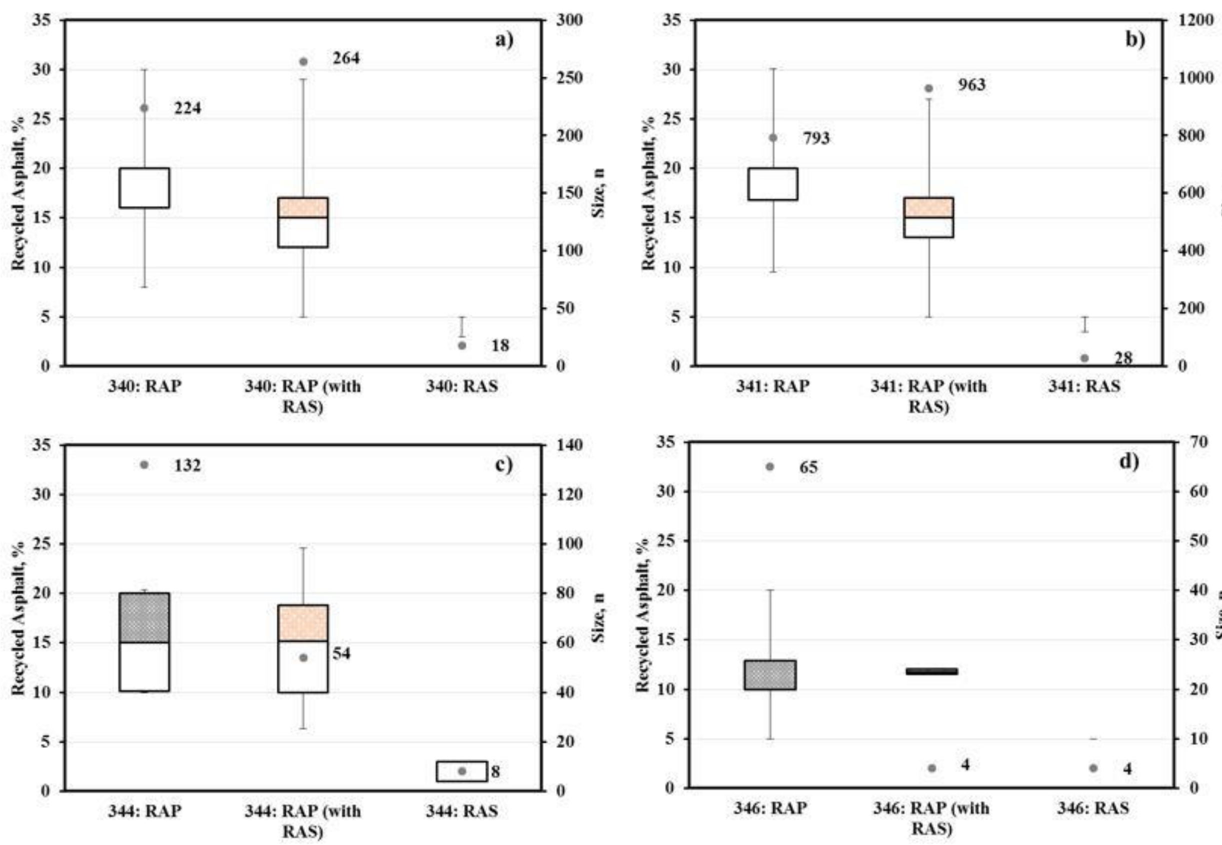


Figure 3.7 Box Plot Results for Recycled Asphalt Content a) Item 340, b) Item 341, c) Item 344 and d) Item 346.

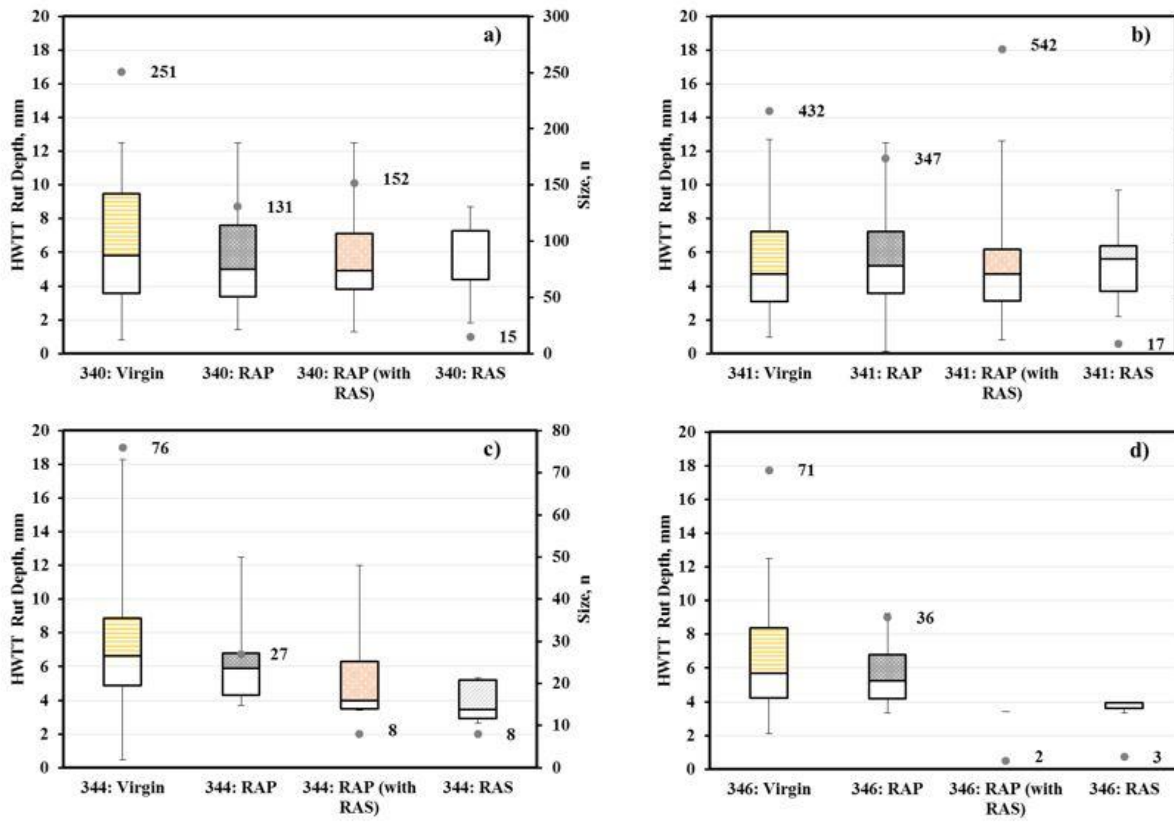


Figure 3.8 Box Plot Results for HWTT Rut Depth a) Item 340, b) Item 341, c) Item 344 and d) Item 346.

Figure 3.9 illustrates the IDT tensile strength summary for the four different items. A similar trend is observed in all four items where the medians for the recycled asphalt categories either improved or remained the same as the virgin mixes. These results indicate that the addition of recycled materials improved the IDT strength. Information for optimum asphalt binder, antistripping content, and HWTT number of cycles were also retrieved from SiteManager. No significant results were found at a general level, but the box plots are presented in Appendix A for informational purposes.

The medians from each item and recycled category from the HWTT Rut Depth and IDT Tensile Strength results were correlated as presented in Figure 3.10. The addition of RAP to Item 340 improved its rutting resistance but did not impact its IDT strength. The combination of RAP

and RAS to Item 340 improved its strength but not its rutting. For Item 341, the addition of RAP affected the resistance to deformation and the combination of RAP and RAS improved only in IDT strength when compared to the corresponding virgin mix. The virgin mix of Item 344 exhibits greater rutting when compared to the recycled asphalt categories. For this case, the addition of RAP clearly improved rutting deformation but not in terms of strength. The combination of RAP and RAS presents improvements in both strength and rutting resistance. The lowest median IDT strength is presented by the virgin mix of Item 346. The addition of RAP improved in terms of rutting and strength when compared to the virgin mix. The addition of RAP and RAS had a significant impact in both rutting and strength. Finally, it is observed that high variability is involved with the use of RAS for all Items.

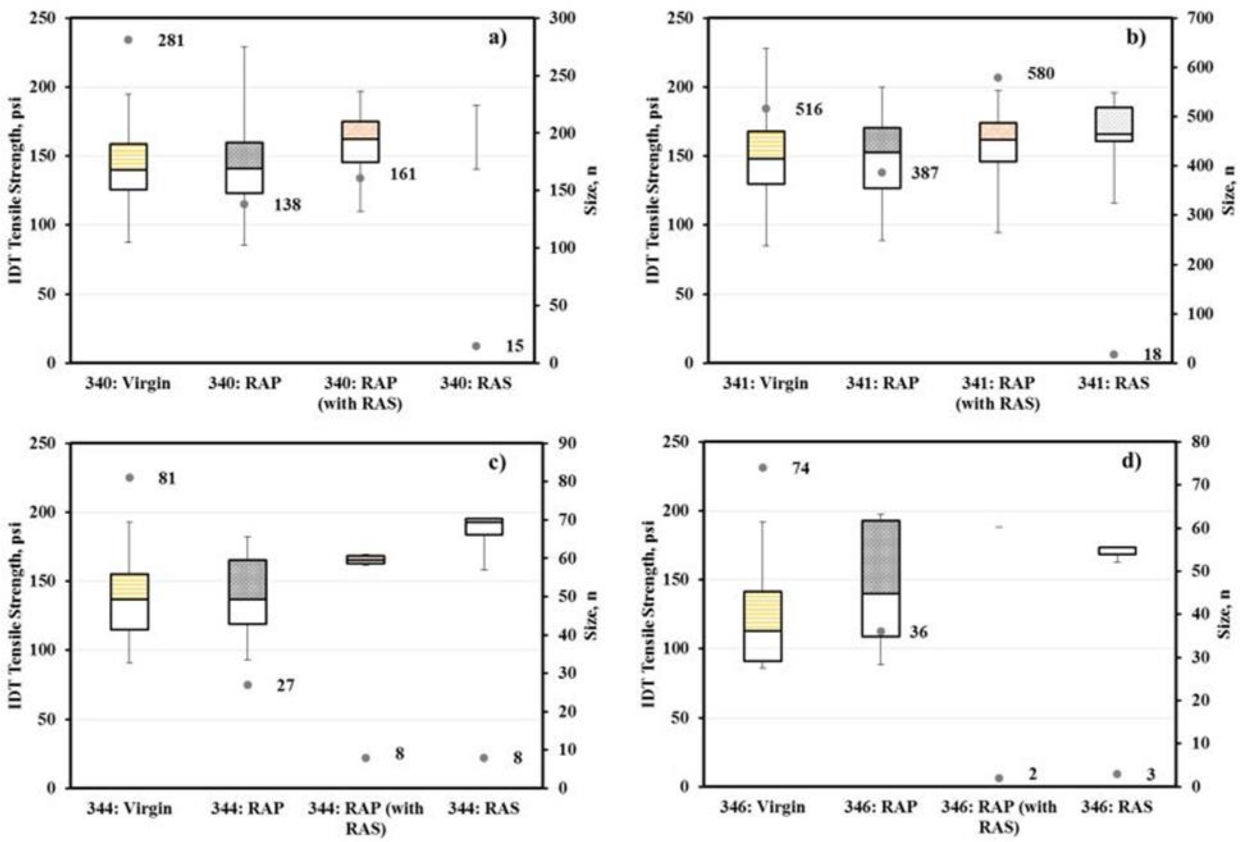


Figure 3.9 Box Plot Results for IDT Tensile Strength a) Item 340, b) Item 341, c) Item 344 and d) Item 346.

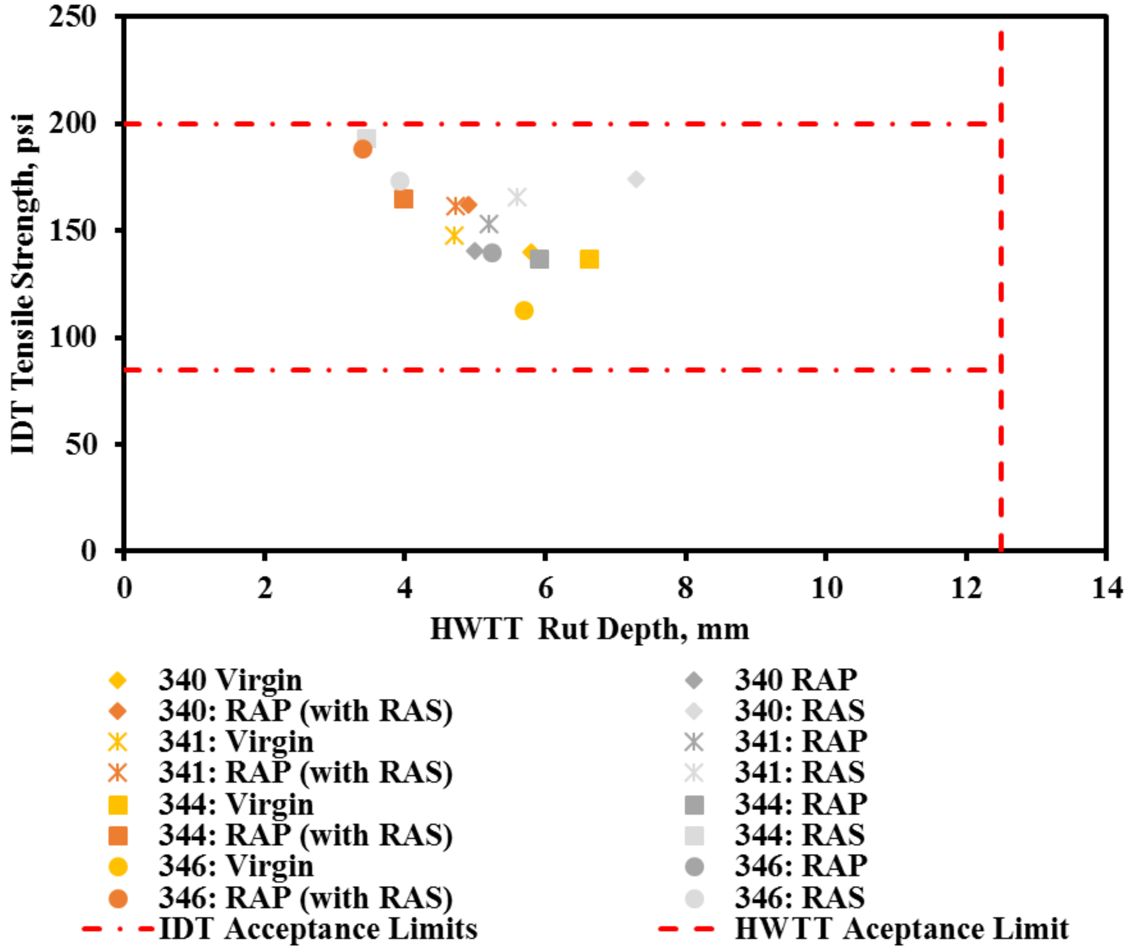


Figure 3.10 IDT Tensile Strength to HWTT Rut Depth Median Correlation

When RAP and RAS are used in the same mix, the amount of RAP usually decreases. As previously presented in Figure 3.7, there is great variability involved in the use of recycled materials. In order to investigate how the different amounts of recycled asphalt affect performance, Item 344 was selected as a case study. Sections that were designed with exactly 10%, 15% and 20% RAP were retrieved from the data set. Sections with RAP and RAS were divided into three different categories where the amount of RAS varies from 1% to 2% and 2% to 4%. The results are presented in Figure 3.11 in terms of IDT Tensile Strength and HWTT Rut Depth.

Sections with RAP and RAS from 1% to 2% exhibited improved rutting and strength characteristics when compared to virgin mixes. Sections with 10% RAP and 20% RAP present similar strength values as virgin mixes but are less vulnerable to rutting. Unexpectedly, sections with 15% RAP, and RAP with RAS ranging from 2% to 4% exhibited increased strength but were more susceptible to rutting. After the refinement criteria was applied, only 102 samples contained significant information, where 75% of the data belonged to virgin mixes. A more balanced sample size is needed to further investigate the impact of recycled materials in Superpave mixtures.

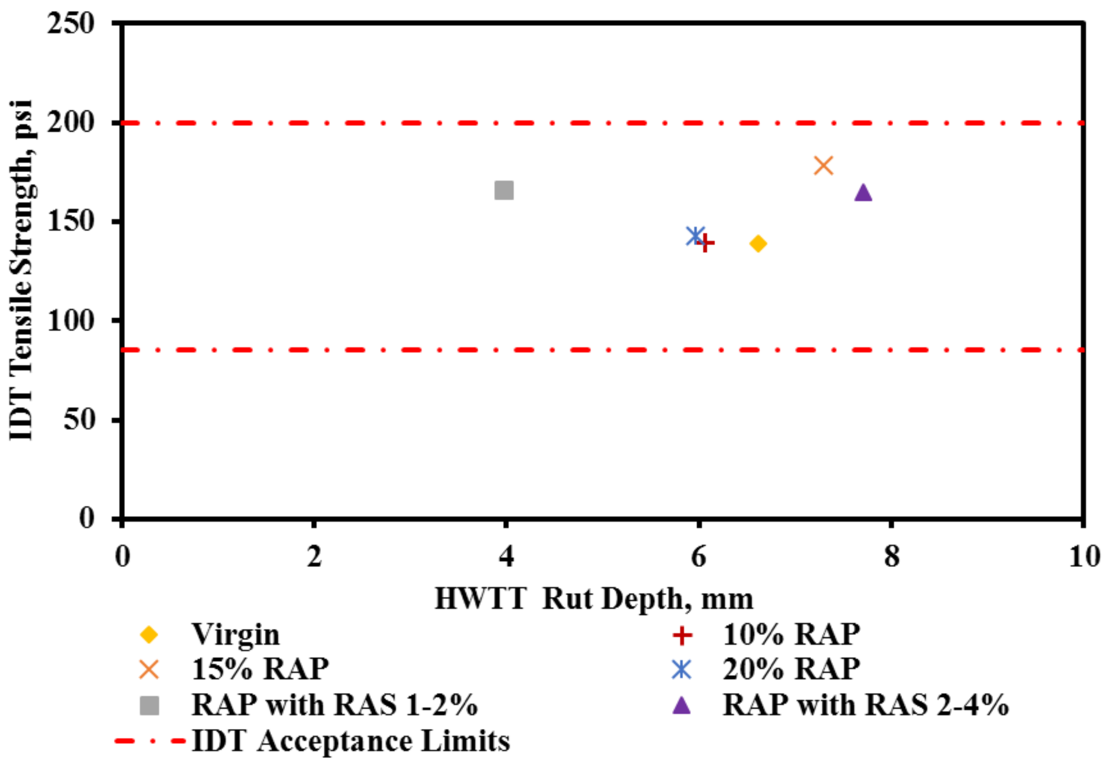


Figure 3.11 IDT Tensile Strength to HWTT Rut Depth Correlation for Item 344: SP Mixes

TxDOT also employs the Overlay Tester (OT) to estimate the reflective and fatigue cracking susceptibility of the AC mixes. The number of OT test results retrieved from SiteManager were low, since only 83 sample ID's contained information for this field. The main reason for having such a low number of entries might be that not all districts require OT tests and not all

districts own an OT testing device. These results could not be incorporated into this portion of the study because a different OT methodology was followed and raw data were not available to analyze the results. Overlay Tester results will be discussed at the project level analyses.

3.5 Pavement Performance from PERMIT

PERMIT contains the estimated performance lives of in-service roads, the actual lives of historical roads and the predicted in-service lives of the road sections. The in-service roads refer to PMIS sections that have not experienced significant distress or maintenance at the time of preparing this report. The historical sections refer to those that had been reconstructed in the past. However, the historical sections had to be disregarded from the study due to their small sample size. PERMIT estimates predicted in-service life of the sections using the annual distress ratings, scores and traffic data.

To predict the total section life, PERMIT uses the progression of the annual fatigue cracking of the road section from the PMIS database. PERMIT generates a pavement performance curve (PPC) for each section, by fitting a Weibull survival function. The Weibull function is capable of predicting the life of the section as long as the fatigue cracking is increasing (Rodriguez et al. 2014). Figure 3.12 illustrates the PCC and the Weibull function where D is the level of damage, T is the number of accumulated traffic to reach D, and α and β are statistically determined parameters. More information about this process can be found in the Technical Report TxDOT 0-6679-1 that can be accessed through the following link: http://ctis.utep.edu:5153/6679/.

PERMIT excludes Item 340 from the study because these mixes are typically used for maintenance projects without QC/QA checks (Rodriguez et al. 2014). Therefore, the average lives of Items: 341, 344 and 346 of the in-service sections are summarized in Figure 3.13. These results were also summarized as box plots in terms of median, minimum and maximum. The box plots on

the left illustrate the in-service life for each item. The box plots on the right illustrate the predicted in-service lives for the AC mixtures. RAS mixtures represent a very small sample size and cannot be assessed with enough confidence. All three items present higher in-service lives for virgin mixes when compared to recycled asphalt mixes. For this reason, longer predicted in-services lives are estimated for virgin mixes. However, the differences among the four different categories for each Item are less pronounced, with a maximum difference of 1.5 years.

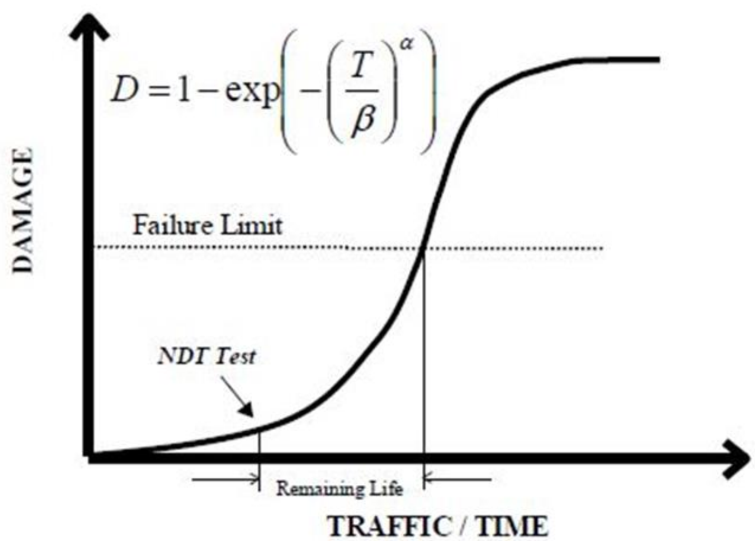


Figure 3.12 PERMIT Pavement Performance Curve (Rodriguez et al, 2014)

PERMIT calculates the predicted lives in terms of fatigue cracking and the results indicate that in terms of cracking virgin mixes perform better. These results seem to be consistent with the SiteManager laboratory testing results where mixes with recycled materials exhibited better performance in terms of rutting. PERMIT results are presented in terms of fatigue cracking and can be interpreted as an alternative to OT results.

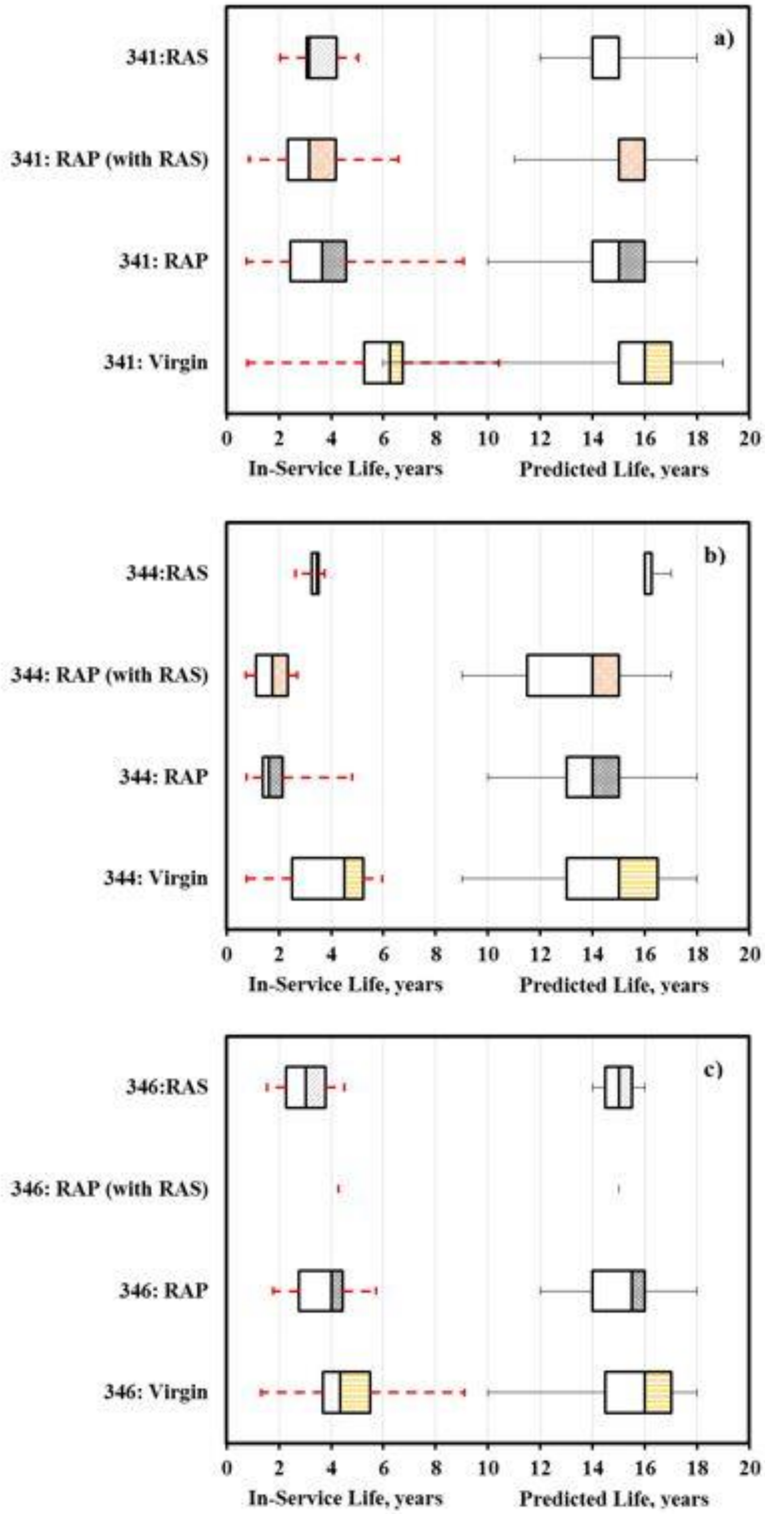


Figure 3.13 PERMIT Results based on Fatigue Cracking a) Item 341, b) Item 344, c) Item 346.

Chapter 4: Project Level

4.1 Background

As part of TxDOT Research Project 0-6658 titled "Collection of Materials and Performance Data for Texas Flexible Pavements and Overlays," a data storage system (DSS) has been developed to incorporate data collected at more than 100 test sections around Texas. The main objective of this DSS is to provide adequate and tangible data that can be used to calibrate any mechanistic-empirical (M-E) performance model. Figure 4.1 shows the main screen and main category tables of the DSS. The DSS contains more than 38,000 entries so far, ranging from (1) environmental and climatic data, (2) traffic data, (3) laboratory and field data and (4) performance history. During the past six years, the research team has sampled and monitored the selected 500-ft test sections from the start of construction to present.

Figure 4.2 illustrates the location of the test sections and the type of construction/treatment applied to each section. These test sections were selected based on their climatic zones, traffic volumes, pavement types, and expected service lives. At the beginning of Research Project 0-6658, pertinent data were gathered from different districts. These data included pavement plans, typical details and mix design sheets (form TX2MIXDE from SiteManager). Once the test sections were selected the information from the plans and the forms was stored in DSS. The main parameters retrieved from mix design sheets included mix type, binder performance grade, recycled asphalt content (RAP and RAS), asphalt content and antistripping content.

The DSS contains actual laboratory test results of the asphalt binder, asphalt concrete, base and subgrade. Laboratory testing for AC was performed on mixes sampled from the test sections during construction. The research team received loose mix or cored samples obtained right after construction. The dynamic shear rheometer (DSR) and the bending beam rheometer (BBR), were

used to determine the performance grade (PG) of the asphalt binders. Laboratory tests for HMA mixes included HWTT, OT, OT fracture properties, IDT, Dynamic Modulus (DM), and repeated load permanent deformation (RLPD). Finally, several tests were performed on the base and subgrade materials, including sieve analysis, resilient modulus, permanent deformation, unconfined compressive strength (UCS), among many others.

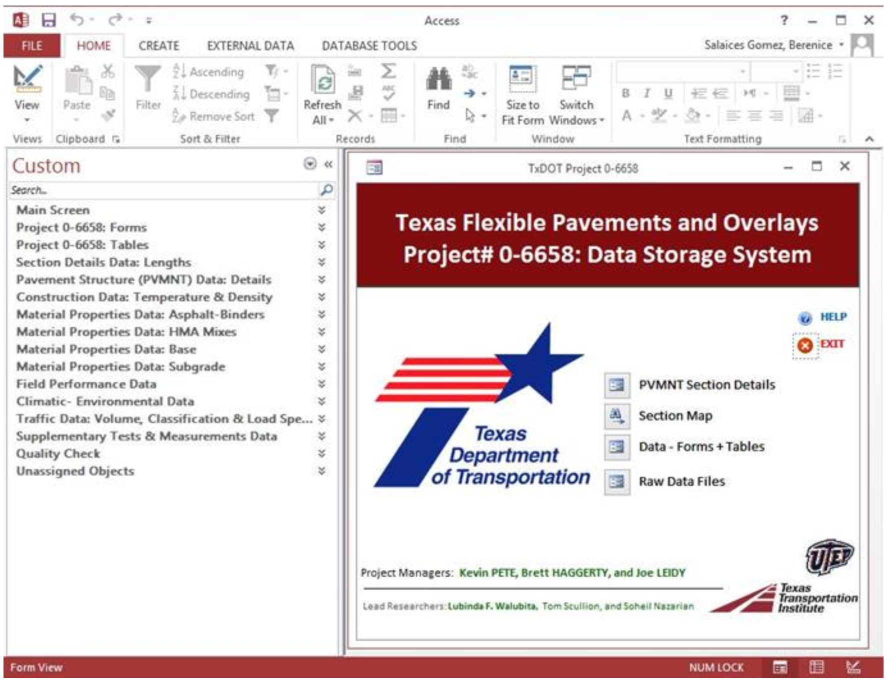


Figure 4.1 Main Screen of DSS

Each test section is being monitored in six-month intervals to collect pavement performance data. These periodic visits involve the documentation and collection of existing pavement conditions, such as visual crack survey and rut measurements. Additional functional and structural data, including photographs and video, Falling Weight Deflectometer (FWD) and high speed profiling are obtained. The FWD deflections are used to evaluate the structural capacity and layer moduli and the high-speed profile data provides the smoothness and quality of ride in terms of the International Roughness Index (IRI). Shortly after construction, a Ground Penetrating Radar

(GPR) was used to document the initial layer thicknesses and to identify any construction defects. Although DSS contains extensive information to characterize the performance of asphalt mixtures, only the mix design properties, HWTT, IDT and OT results were used for this study.

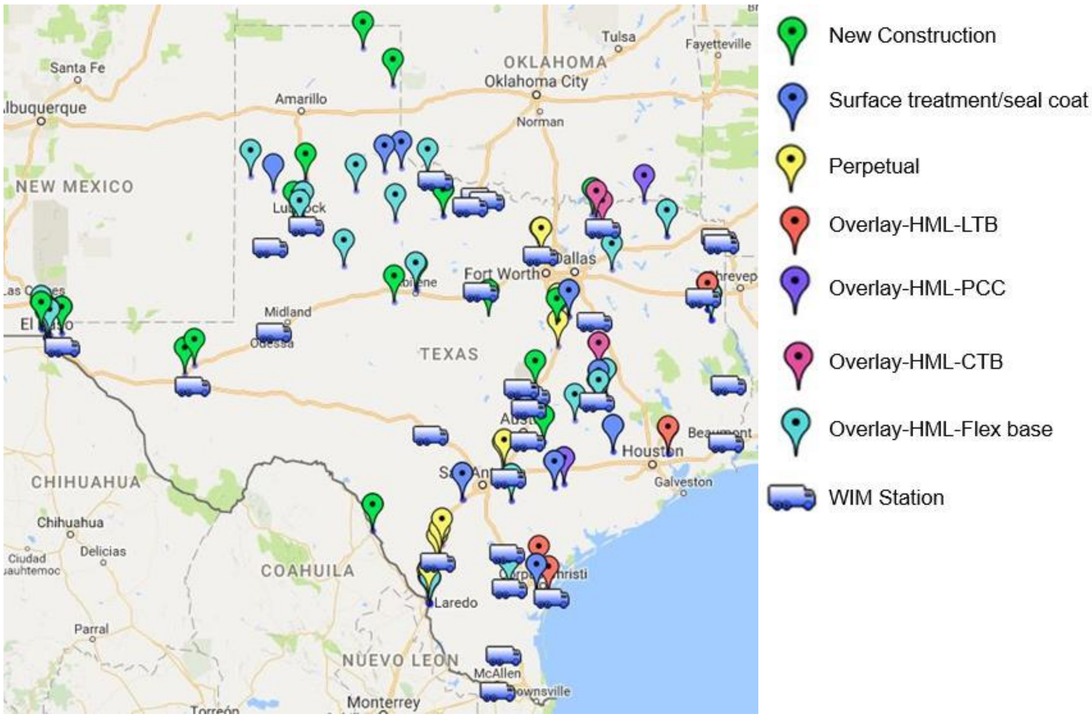


Figure 4.2 Location of Test Sections in Texas

4.2 DSS DIMENSIONS

Figure 4.3 presents the sample size distribution for the AC mixes stored in the database. About 73% of the test sections contained data useful for this study. Some AC mixtures were excluded from the study due to their small sample size or because they did not contain relevant information to compare virgin mixes to recycled mixes. Item 341: Type B mixes were excluded because they are not typically placed as surface mixes. Only three sections of Item 341: Type D were designed with RAS and were excluded from the study because of sample size limitations.

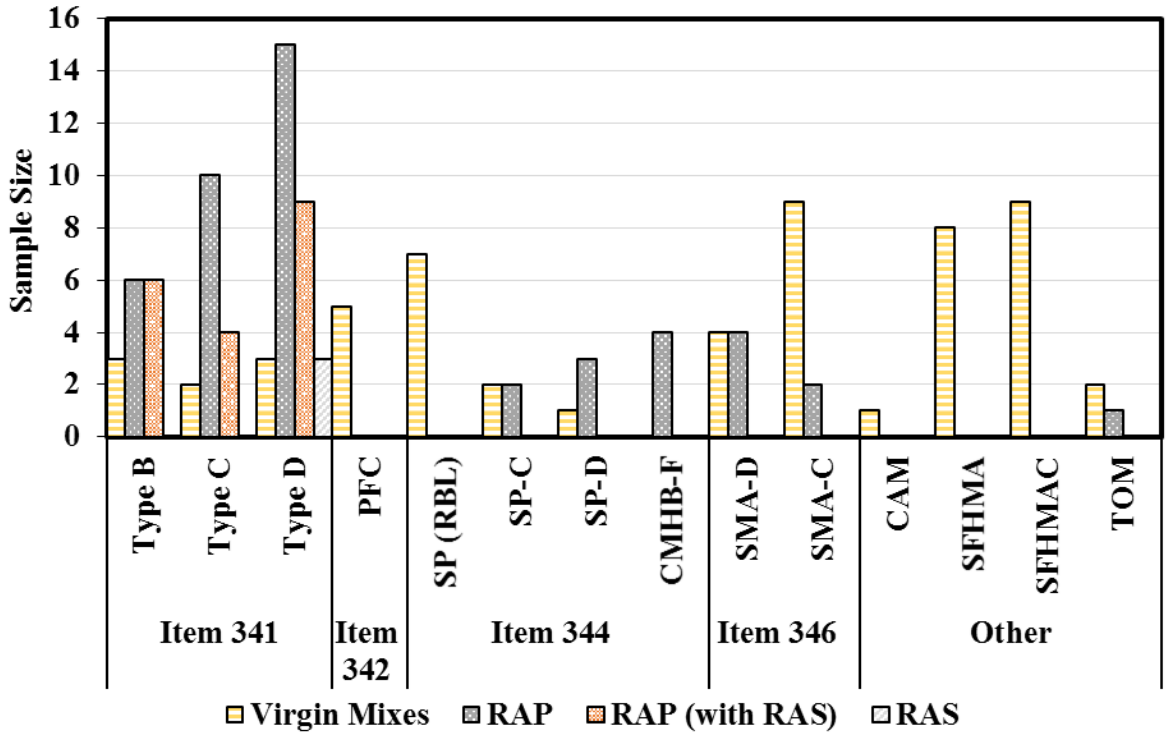


Figure 4.3 Distribution of Sections by Mix Type

Some of the 100 test sections had existing underlying mixtures or were designed with two different asphalt mixtures. Because of this, the available data was separated into unique test sections and unique sample ID. A unique test section can have more than one AC mixture that can be identify by the unique sample ID. Laboratory results were identified by unique sample ID and field performance results were only assigned to the unique test section. Table 4.1 presents the sample size evaluated for the laboratory results and the corresponding percentages by type of test. Some sections have not completed laboratory testing at the time of this study and therefore sample sizes vary from test to test. The Overlay Tester (OT) sample size is considerably smaller because these results were analyzed with a different OT methodology. This analysis requires raw data and its access was limited. Table 4.2 presents the field performance results by unique test section and the percentage of sections that have presented distresses at the time of preparing this report.

Table 4.1 DSS Laboratory Sample Sizes by Unique Sample ID

DSS Laboratory Testing	Virgin Mixes	Recycled Asphalt			Total
		RAP	RAP and RAS	RAS	
Unique Sample ID	56	47	19	3	125
HWTT Rut Depth	89%	96%	100%	100%	94%
IDT Tensile Strength	30%	85%	95%	100%	62%
Overlay Tester	27%	55%	63%	100%	45%

Table 4.2 DSS Field Sample Sizes by Unique Section ID

DSS Field Performance	Virgin Mixes	Recycled Asphalt			Total
		RAP	RAP and RAS	RAS	
Unique Test Section	23	34	13	3	73
Fatigue Cracking	4%	38%	23%	0%	23%
Transverse Cracking	17%	32%	0%	33%	22%
Longitudinal Cracking	4%	38%	15%	33%	23%
Field Rutting	74%	62%	38%	0%	59%

4.3 Analysis of DSS Laboratory Testing

The box plots for the recycled asphalt content, optimum asphalt content, antistripping content, HWTT rut depth, HWTT number of cycles and IDT tensile strength for Items 341, 344 and 346 are presented in *Appendix A*. The results for this portion of the study are presented as a correlation analysis using the HWTT, IDT and OT results to estimate the laboratory performance of the AC mixes as discussed below.

The variation of IDT strength with HWTT rut depth is shown in Figure 4.4. These two parameters are not strongly correlated when RAP and RAS are used. The IDT and HWTT results for Item 341: Type C mixes that contained RAP and RAP with RAS stayed within, or close to their corresponding acceptance limits imposed by TxDOT. The results for Item 341: Type D present high unpredictability when any type or combination of recycled materials are used. Three samples with RAP exhibited very high HWTT rut depth, while the rest of the RAP samples performed very well with no more than 7 mm HWTT rutting. Only one sample with RAP and RAS exhibited high

HWTT rut depth, two samples are within the HWTT acceptance limit, while the remaining sections are exactly at the acceptance limit. Surprisingly, the virgin mixes performed very well in both strength and rutting. All test samples under this item performed within the acceptance limits of the IDT strength.

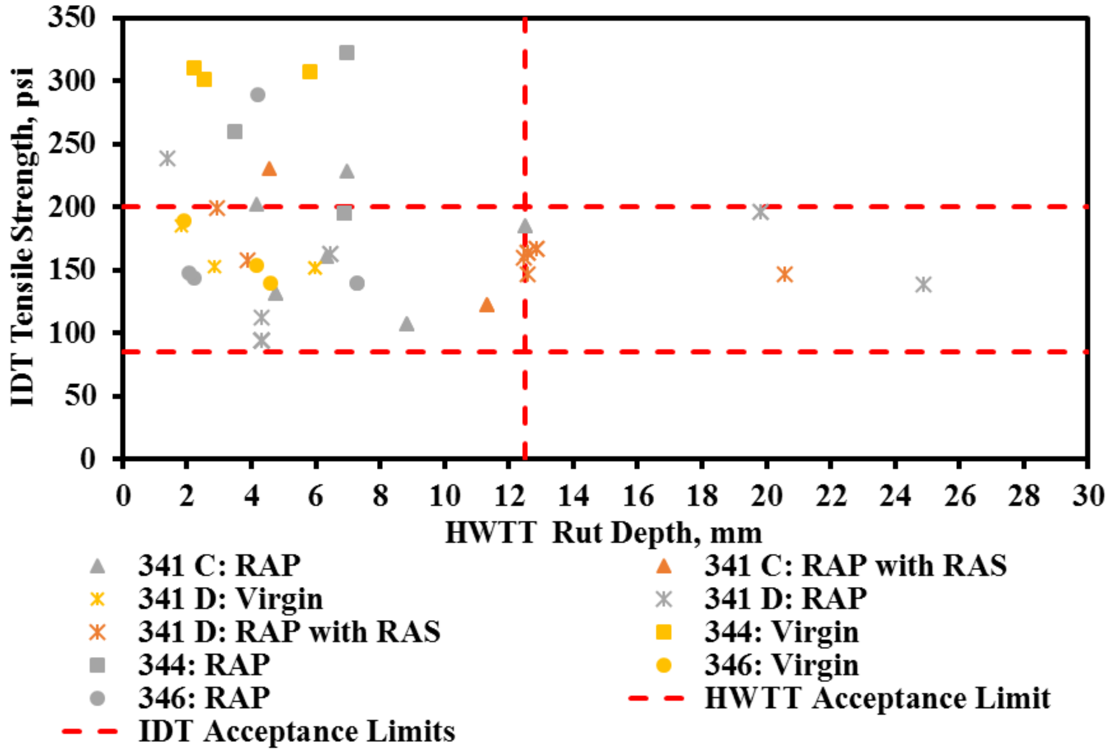


Figure 4.4 IDT Tensile Strength to HWTT Rut Depth Correlation of AC Mixes

Superpave mixes are perceived as high rut resistant but are more susceptible to cracking. The results from Figure 4.4 support this statement since virgin and RAP mixes for Item 344 have very high strength and performed fairly well in terms of rutting deformation. These results indicate that the high IDT tensile strength did not affect the rutting susceptibility of Item 344 mixes. The results for Item 346 demonstrate that only one sample with RAP is located above the IDT acceptance limit. The rest of the RAP and virgin mixes are located within the limits of the IDT and HWTT and performed well in both parameters. These results present acceptable rutting resistance for virgin and RAP mixes of Item 346 mixes.

Figure 4.5 illustrates the OT interaction plot. As a general statement, virgin mixes appear to cluster closer to the acceptance limit. AC mixtures with RAP appear to be close to the OT acceptance limit but a gradual movement to the right of the plot is observed. The sections with a combination of RAP and RAS move further away from the proposed OT acceptance limit. These preliminary results indicate that the combination of RAP and RAS modifies the stiffness of the virgin mix, which affects the cracking performance.

In specific, two mixes for Item 341: Type C with RAP fall within the accepted limits of the OT. The rest of the RAP mixes failed in crack propagation with values that range from 0.6 to 1.5. Similarly, the virgin sample failed in crack progression rate, along with the rest of the RAP and RAP with RAS mixes. Type C mixes with a combination of RAP and RAS present some of the highest crack progression rates when compared to the rest of the mixes. The results for Item 341: Type D demonstrate that all the virgin samples passed the OT interaction plot. Only one section with RAP falls within the OT acceptance limits, but the remaining two samples failed in crack progression rate, with one sample failing also in critical fracture energy. Mixes with a combination of RAP and RAS present variable results, with one mixture passing the OT interaction plot while the rest of the sections failed with results that vary from 0.6 to 2 in the crack progression axis.

The results for Item 344 indicate that virgin mixes performed very well in the OT interaction plot. The addition of RAP worsen the cracking performance of the mix and the remaining samples failed in the crack progression rate, with one sample failing also in critical fracture energy. The addition of RAP for Item 344 clearly affects crack retardation. In the contrary, all three samples with RAP for Item 346 performed well in terms of cracking. Only two virgin samples were available for this mix, where one passed and one failed in the OT interaction plot. In this case, the addition of RAP seems to improve the cracking resistance of the mixes.

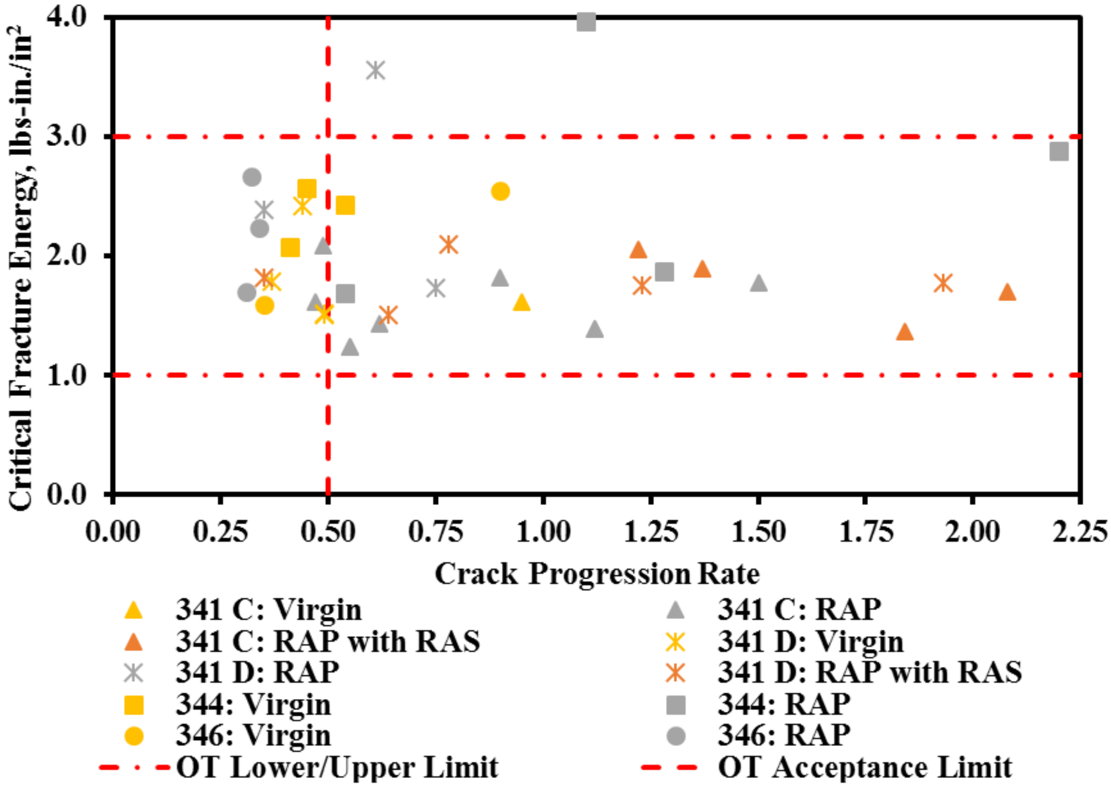


Figure 4.5 OT Design Interaction Plot of AC Mixes

This chapter covered the results for the project level analysis in terms of HWTT, IDT and OT. The refinement criteria and the available OT raw data affected the sample sizes evaluated for this portion of the study. Item 341: Type C and D hold the greatest sample sizes and the majority of the samples contained recycled materials. On the other hand, the test sections for Item 344 and Item 346 were mainly virgin and RAP mixes, therefore the impact of RAP and RAS was not evaluated for SP and SMA mixtures.

Based on the results presented in Figure 4.5 adding RAP to Item 341 mixes increases the crack propagation rate, and when RAP is combined with RAS this effect is more significant. Overall, these results confirm that mixes with RAP and with a combination of RAP and RAS tend to underperform relative to the virgin mixes in cracking. Because Item 341 is a very common

mixture in Texas it is recommended to re-evaluate the use of this combination when cracking resistance is a concern.

The outcomes from the IDT and HWTT correlation showed that in some cases adding RAP or a combination of RAP and RAS increases IDT strength and reduces HWTT rutting. However, since some samples with recycled content underperformed in HWTT further evaluation is needed. The correlation results from Figure 4.4 indicated that Item 344 virgin and RAP mixes have a very high IDT strength and good rutting resistance. The results from the OT interaction plot demonstrated that the high strength did not affect the cracking susceptibility of virgin mixes, but it did for the recycled mixes. Finally, it is not possible to draw a conclusion for Item 346 in terms of HWTT and IDT. However, the results from the OT interaction plot demonstrated that the addition of RAP improved the crack propagation rate.

Chapter 5: Relating Laboratory Results to Field Performance

5.1 Field Performance Results

One of the main advantages of Research Project TxDOT 0-6658 is that routine field performance data are collected. The test sections are relatively new with three to five years lives and have not exhibited severe distress yet. However, the performance data were retrieved to draw preliminary conclusions about the performance of the virgin and recycled mixes in terms of fatigue cracking and rutting.

Figure 5.1 illustrates the extents of fatigue (alligator) cracking that have been identified in the field. Mixes with recycled materials (RAP or a combination of RAP and RAS) have exhibited more extensive cracking as compared to the virgin mixes. As reflected in Figure 5.2, it is premature to draw a conclusion about the rutting performance of the mixes. While the addition of recycled materials intends to improve the rutting resistance, these results illustrate that this might not always be the case.

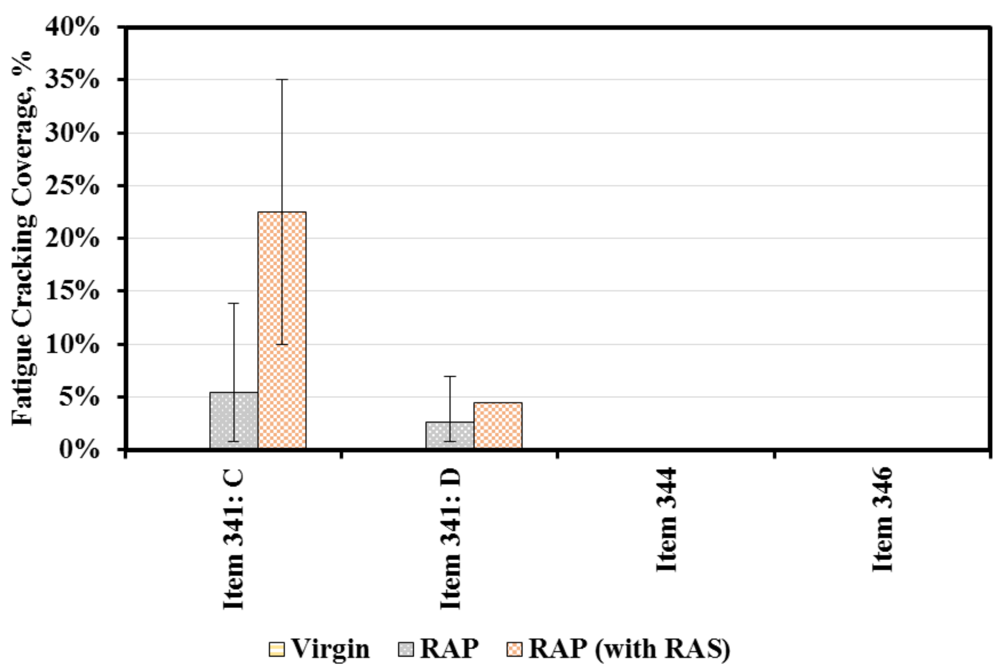


Figure 5.1 Average Fatigue Cracking Field Performance Results by Item

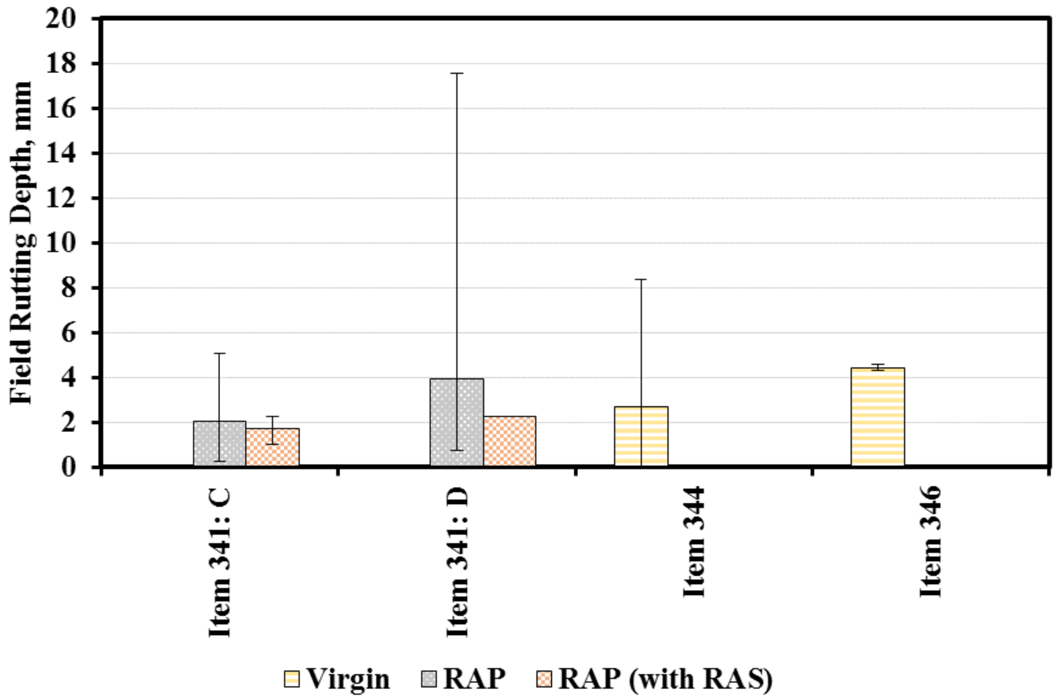


Figure 5.2 Average Rutting Field Performance Results by Item

5.2 COMPARISON OF FIELD PERFORMANCE WITH LABORATORY TESTING RESULTS

A correlation analysis of laboratory to field performance results was done for both fatigue cracking and rutting. Figure 5.3 presents the cross-plot of the extent of fatigue cracking and the OT crack progression rate for sections that have experienced fatigue cracking. The majority of the recycled asphalt sections are located to the right of the OT acceptance limit, which indicate greater cracking potential. Only two sections with RAP within the OT acceptance limit have experienced fatigue cracking. On the other hand, seven sections with recycled materials that are outside the OT acceptance limit have experienced this type of distress. The crack progression rates of these mixes vary from 0.5 to 1.25.

Two samples for Item 341: Type C and two samples for Item 341: Type D, both with RAP and RAP with RAS were selected based on their location in the OT interaction plot. The four different sections marked in Figure 5.3 were selected to evaluate their yearly crack progressions

as shown in Figure 5.4. Item 341: Type C and Type D mixes with RAP are located within the recommended zone of the OT interaction plot, while Item 341 Type C and Type D with RAP and RAS are located outside of the OT acceptance limits.

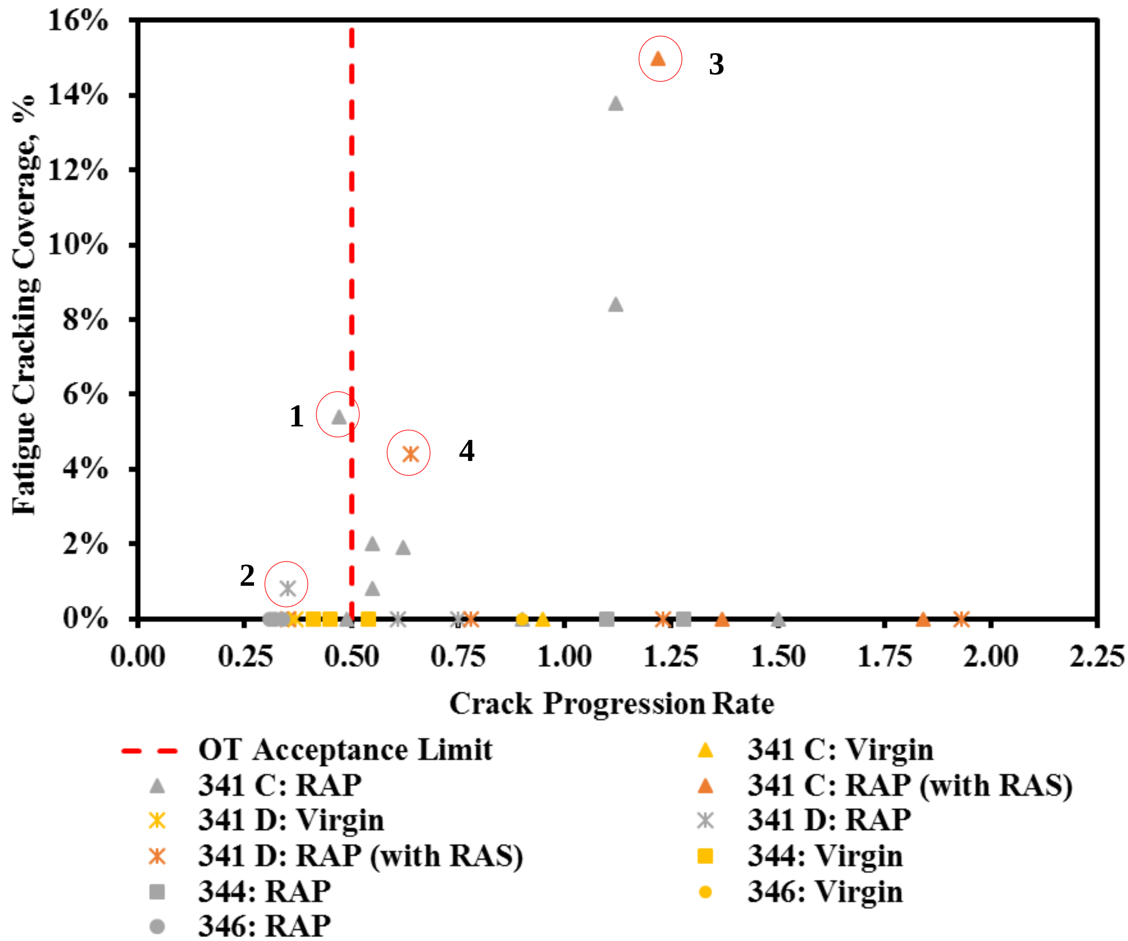


Figure 5.3 Field Fatigue Cracking to OT Crack Progression Rate

Each point presented in Figure 5.4 represents a field visit where a condition survey was documented. Item 341: Type C with RAP exhibited cracking by the second field visit; but during more than four years of monitoring no more than 5% cumulative cracking over the 500-ft section has been observed. Item 341: Type D with RAP presented minor cracking after approximately three years of service. These two sections have presented gradual increase in fatigue cracking over the years. Item 341: Type C with RAP and RAS exhibited 10% cracking approximately six months

after the first condition survey and by the third visit fatigue cracking increased to 15%. The first condition survey for Item 341: Type D with RAP and RAS found no cracking in the section. However, minor cracks were found by the fourth field evaluation that propagated very quickly within the following six-month period.

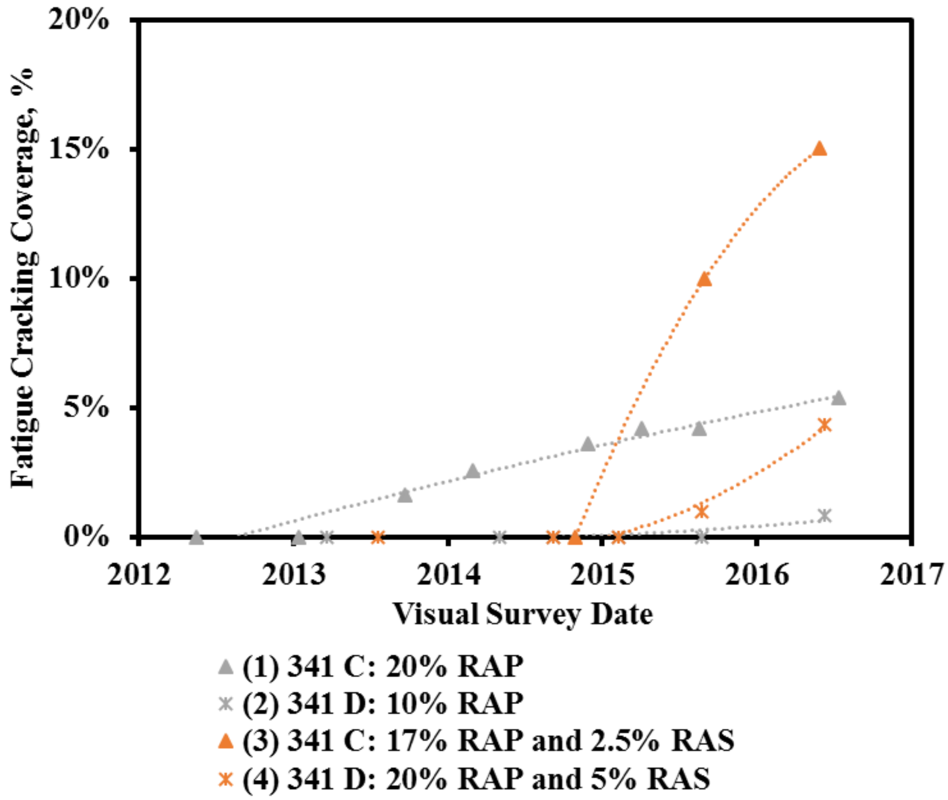


Figure 5.4 Yearly Fatigue Cracking Propagation

The number of sections that exhibited fatigue cracking for AC mixtures that contained RAP appear to have gradually increased over the years. On the other hand, sections with a combination of RAP and RAS have experienced considerable damage that propagated very quickly from one visit to another. These results indicate that the sections whose OT results are outside the acceptance limits on the interaction plot have presented higher crack progression rates. Therefore, the addition of RAS appears to directly impact the crack propagation susceptibility of AC mixtures. These

trends indicate that some sections located far outside the OT acceptance limit in Figure 5.3 that have not exhibited cracking as yet might experience a sudden increase in cracking since they are seen as crack susceptible mixes.

Figure 5.5 illustrates a cross-plot between the HWTT rut depth and field rut depth. The results for Item 341: Type C show that samples for all three categories (virgin, RAP, and RAP with RAS) have presented similar field rutting. Only one sample under Item 341: Type D with RAP has experienced extensive field rutting. Some of the remaining samples for the Type D mix have presented rutting in the field, although they performed very well in terms of HWTT rut depth. Samples with a combination of RAP and RAS have shown improved performance since only one sample has rutted in the field. Samples that exhibited very high HWTT rut depth in the lab have not yet presented field rutting.

Item 344 and 346 mixes are perceived to have high rutting resistance. However, the results from the rut field measurements indicate that virgin sections rutted excessively in the field when compared to sections with RAP. None of the Superpave or SMA sections with RAP have presented rutting at the time of preparing this report. These results indicate that the addition of RAP improves the rutting resistance of Item 344 and 346 mixes.

In conclusion, the addition of recycled materials have a negative effect on the cracking resistance of the AC mixes, especially when the combination of RAP and RAS in used. In terms of fatigue cracking and OT crack progression rate mixes with a combination of RAP and RAS appear to propagate cracks faster than RAP mixes. The results from the rutting surveys suggest that the addition of recycled materials does not always improve the rutting resistance of the mixes. Other factors such as underlying pavement structure, type of construction and traffic loads need to be considered.

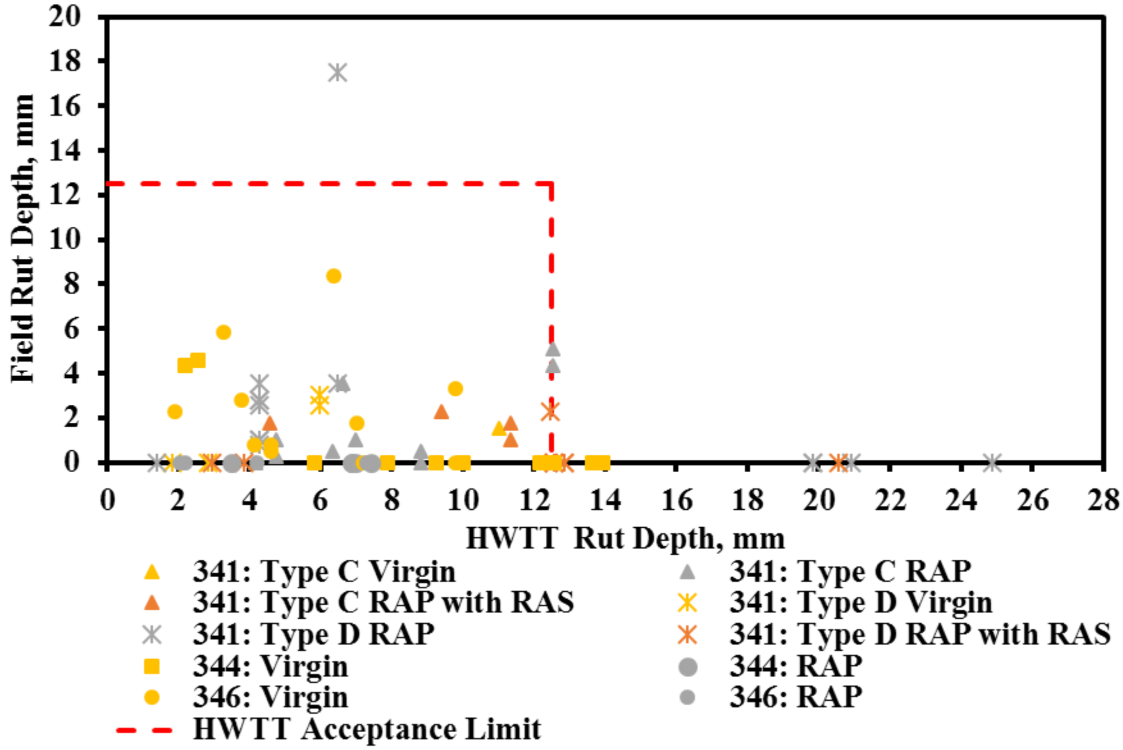


Figure 5.5 Field Rutting to HWTT Rut Depth

Chapter 6: Summary and Conclusion

6.1 Summary

This thesis presented a comparative study of the performance of AC mixes in Texas when RAP and RAS are used. To that end, the network level and a project level impact of recycled materials on the performance of AC mixes was evaluated. The network level analysis was carried out using TxDOT SiteManager database from 2008 through 2015. The rutting performance was evaluated using the statewide data from the HWTT rut depth and the cracking performance through the results of the IDT strength and the PERMIT performance predictions. The results from PERMIT encompass information from PMIS, DCIS and Letting and are calculated based on annual fatigue cracking performance.

The project level analysis was carried out using a database that contains laboratory test results and the documentation of the condition surveys of over 100 test sections. Laboratory results were presented in terms of HWTT rut depth, IDT strength and OT interaction plot. Rutting was assessed through the use of HWTT results and the field rutting observations. Cracking susceptibility was analyzed through the use of IDT and OT. The OT results were correlated to the fatigue cracking identified on the field in order to determine the influence of RAP and RAS in field performance. Similarly, the results from the field measurements were correlated to the HWTT rut depth results.

6.2 Conclusion

The use of SiteManager and PERMIT were useful in understanding the behavior of virgin mixes and recycled mixes in the state of Texas. The following conclusions can be drawn from the network level study:

- A larger sample size is needed to reliably evaluate the impact of RAS in the AC performance.
- The HWTT results illustrated that the addition of RAS and the combination of RAP with RAS improved the rutting resistance of the AC mixes.
- The results from the IDT tests indicated that all mixes exhibited greater tensile strengths with the inclusion of RAP, RAS or a combination.
- Mixes with the combination of RAP and RAS exhibited the highest median IDT strengths and demonstrated improved performance in terms of HWTT rut depth, followed by the RAP and virgin mixes.
- The in-service and predicted lives from PERMIT exhibited longer lasting fatigue lives for the virgin mixes.
- The results for the network level analysis are consistent in terms of rutting and cracking. Improved HWTT laboratory performance is observed for recycled asphalt mixes in terms of rutting while greater service lives for virgin mixes are predicted in terms of fatigue cracking.

The DSS laboratory and field performance results were used to compare the performance of virgin and recycled mixes. The following conclusions can be drawn from the project level analysis:

- The OT results indicated that virgin mixes are less susceptible to cracking, followed by mixes containing RAP. Particularly, the combination of RAP and RAS for Item 341 underperformed in cracking.

- The addition of RAP to Item 344 negatively affected the crack progression rate. Overall, these results suggested that the addition of recycled materials may have a negative impact in the cracking resistance of most mixes.
- The results from the field performance surveys indicate that only sections with mixes containing RAP and a combination of RAP and RAS have exhibited fatigue cracking. The mixes with the combination of RAP and RAS have higher crack progression rates in the field as well as OT tests when compared to mixes that contained only RAP.
- It is premature to draw a conclusion based on the rutting results from the condition surveys. Rutting has been observed in both virgin and recycled mixes. Samples for Item 341 that performed the worse in terms of HWTT rut depth have not yet presented rutting in the field.

6.3 RECOMMENDATIONS AND FUTURE WORK

Based on the results from this study it is recommended that TxDOT evaluates the maximum permitted RAP when used in combination with RAS. The use of RAP and RAS has been proven to be detrimental to the cracking performance of the AC mixes. It is recommended that if cracking is the concern, recycled materials should be avoided during the design process especially for Item 341 and Item 344. Further evaluation is needed to investigate the results from the condition surveys. The documentation of field performance indicates that sections with recycled materials have presented rutting, although the objective of using RAP and RAS is to improve the rutting resistance.

The incorporation of more records stored in SiteManager and the DSS is needed to evaluate other parameters that affect performance. It is advised to evaluate in more depth other mix design parameters such as asphalt content, PG- grading, aggregate gradation and additives. To further explore the impact of recycled materials in the AC performance continuous monitoring of the DSS

test sections is essential. In order to better understand the impact of recycled materials in the AC field performance, it is recommended to investigate other elements such as climate, traffic and layer structure.

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Appendix A-SiteManager

Appendix A contains the remaining box plots from the statistical analysis at a Network Level.

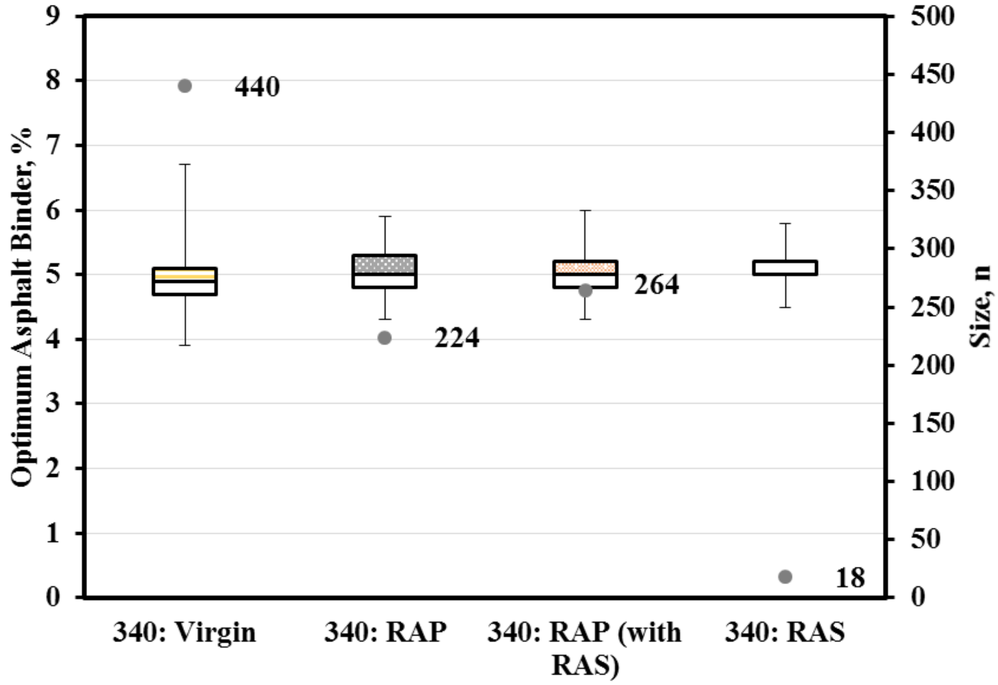

Figure A.1 Optimum Asphalt Binder Box Plot for Item 340

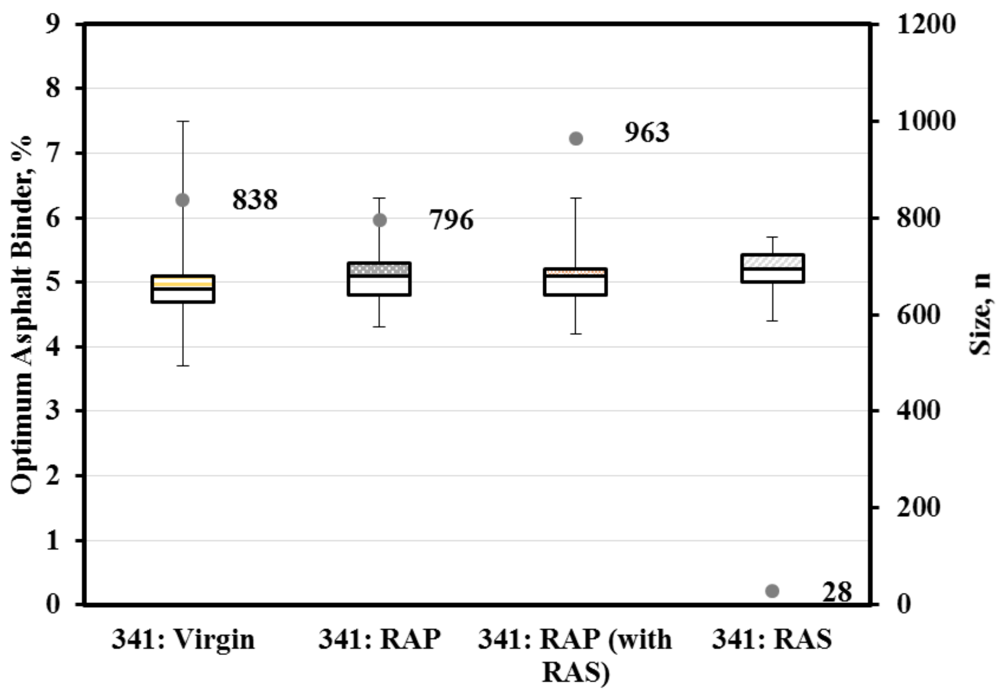

Figure A.2 Optimum Asphalt Binder Box Plot for Item 341

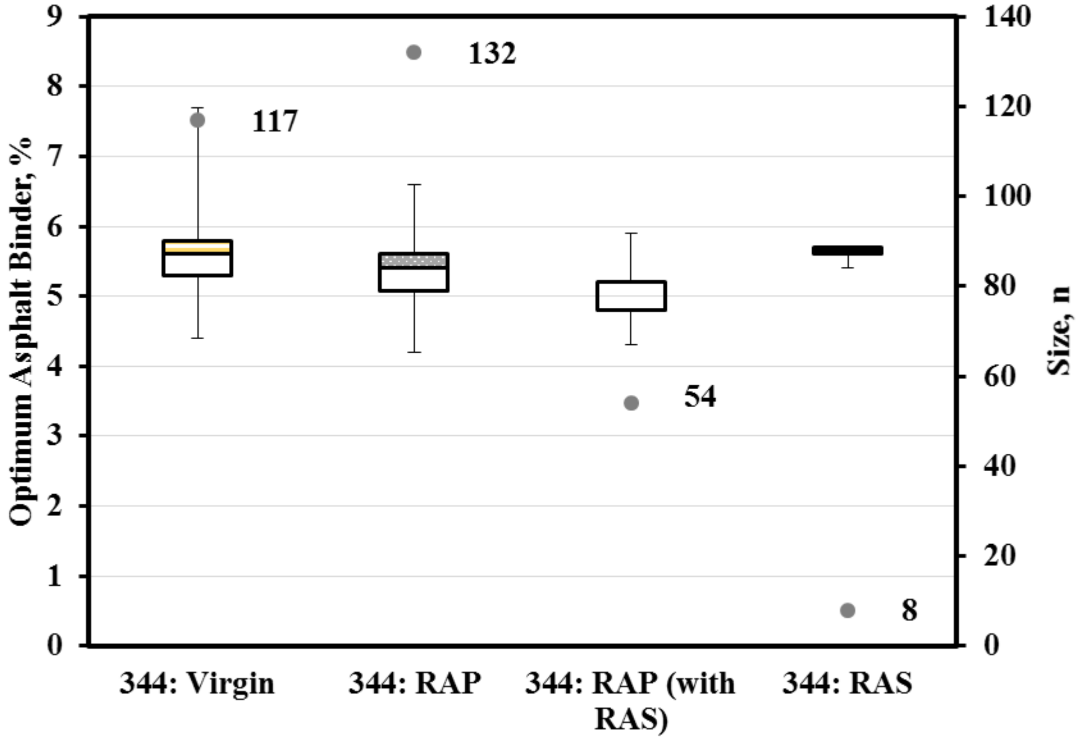

Figure A.3 Optimum Asphalt Binder Box Plot for Item 344

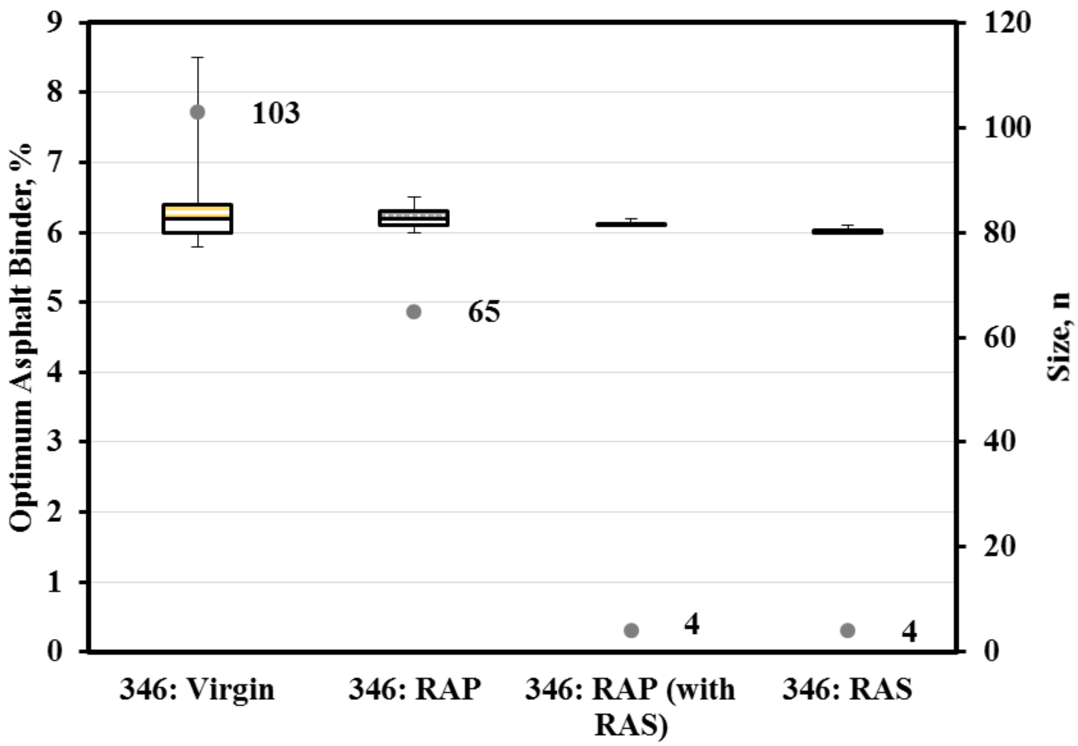

Figure A.4 Optimum Asphalt Binder Box Plot for Item 346

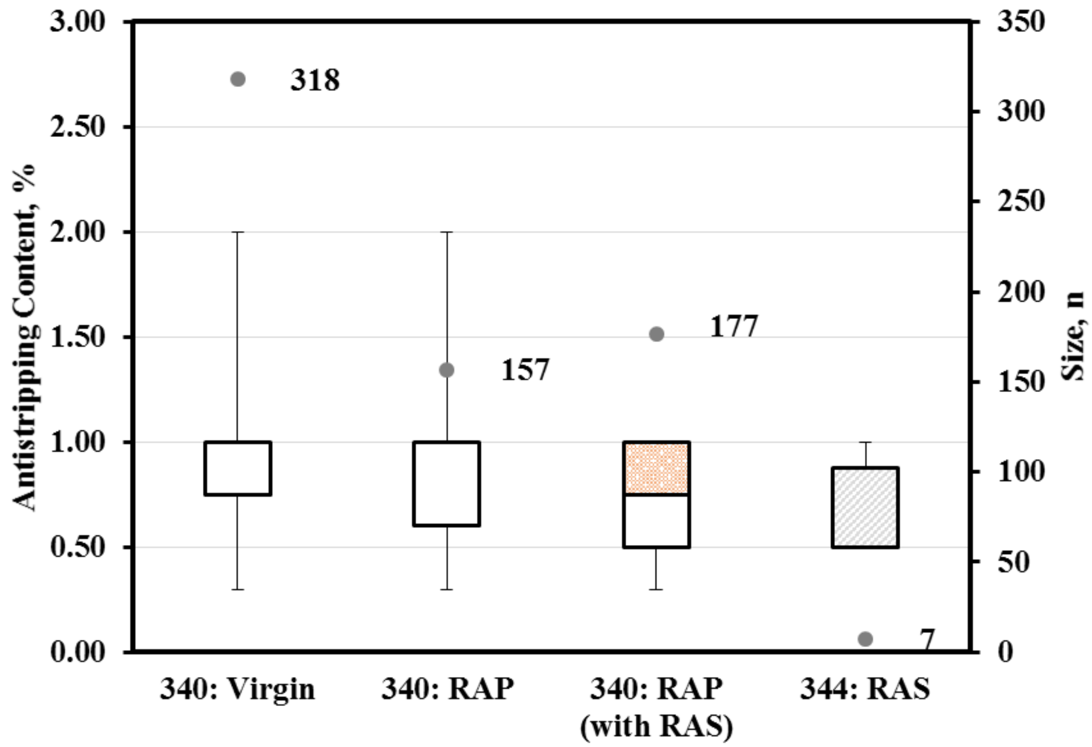

Figure A.5 Antistripping Content Box Plot for Item 340

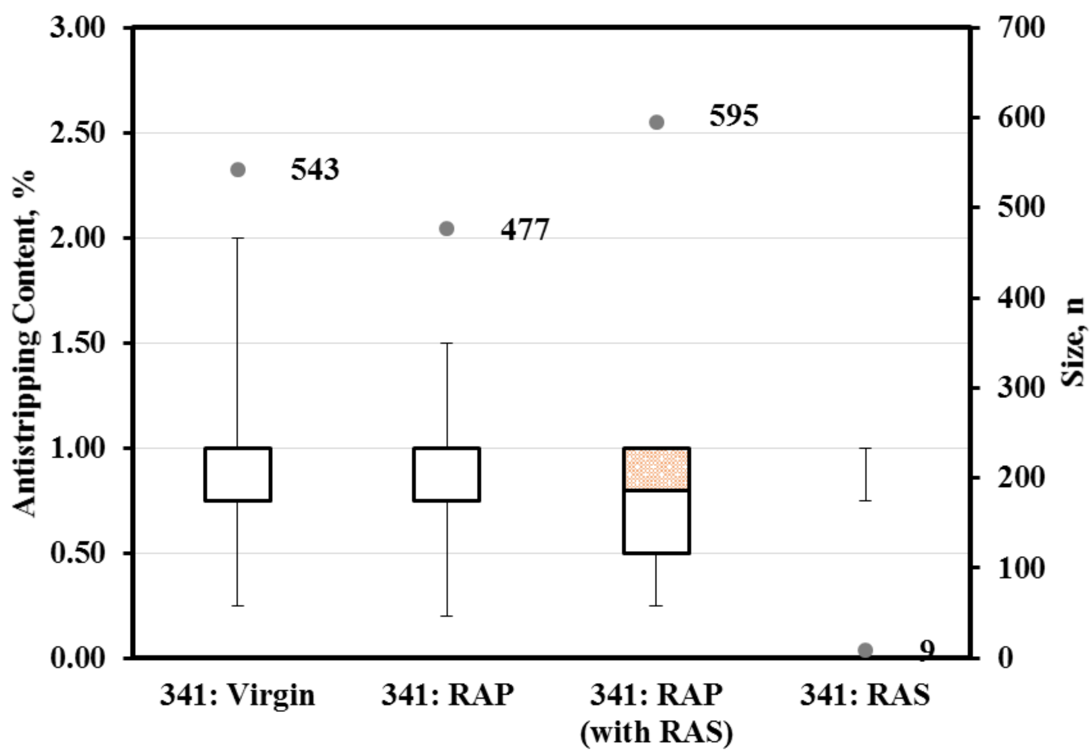

Figure A.6 Antistripping Content Box Plot for Item 341

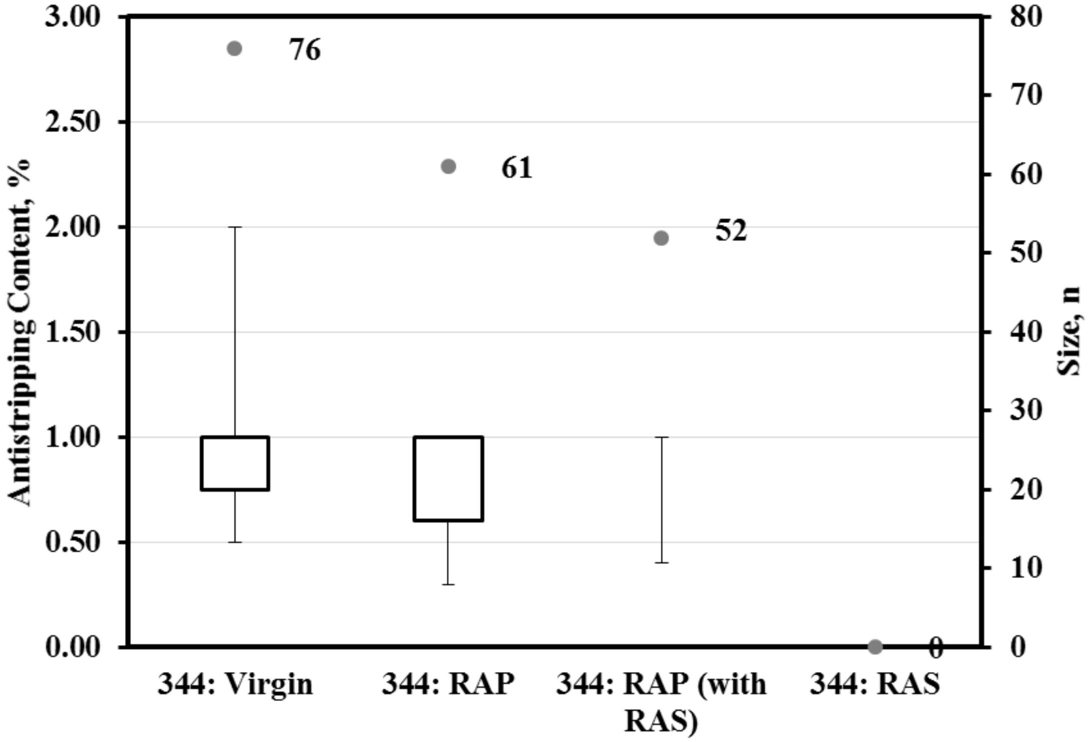

Figure A.7 Antistripping Content Box Plot for Item 344

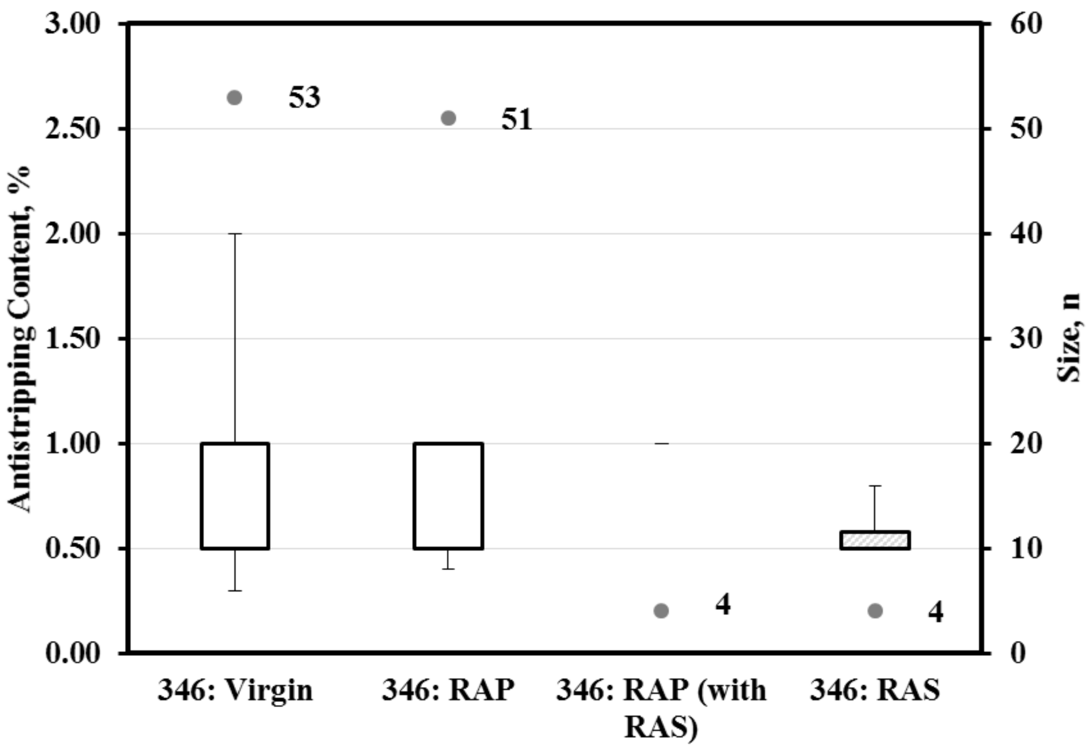

Figure A.8 Antistripping Content Box Plot for Item 346

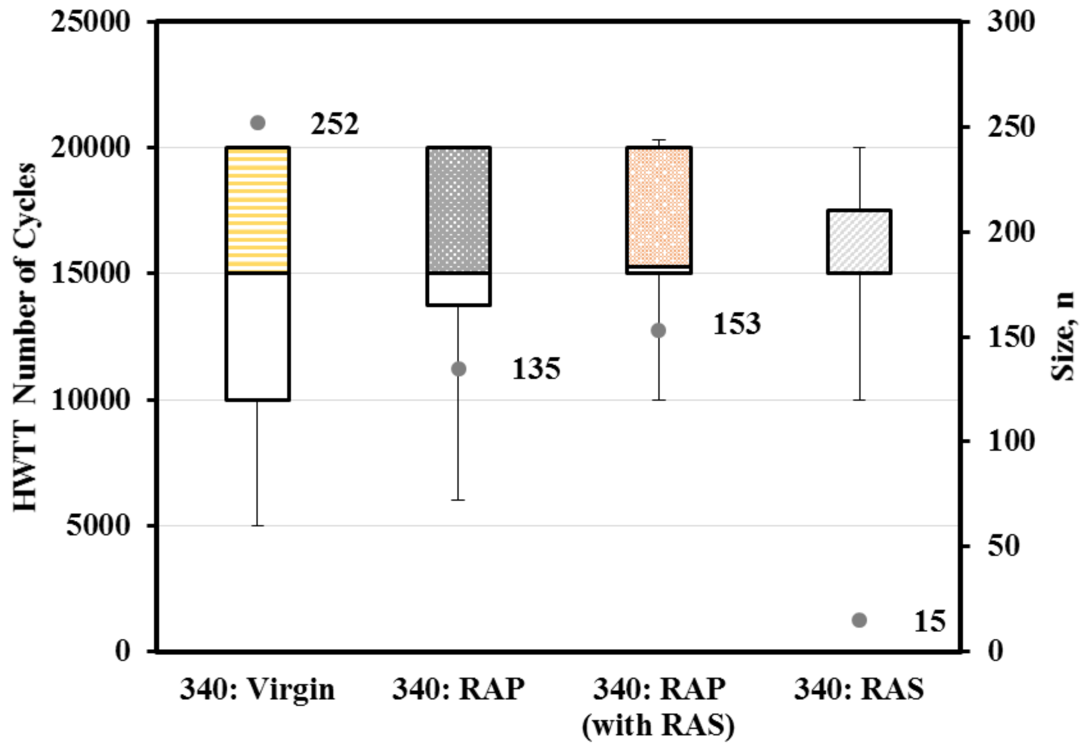

Figure A.9 HWTT Number of Cycles Box Plot for Item 340

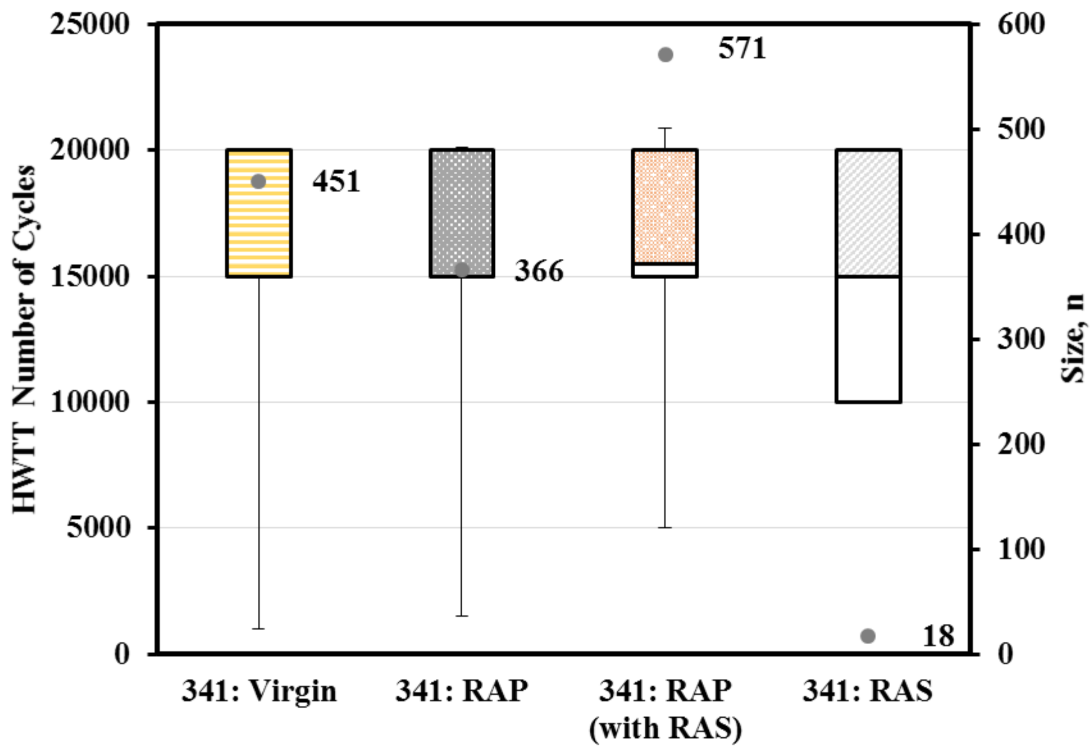

Figure A.10 HWTT Number of Cycles Box Plot for Item 341

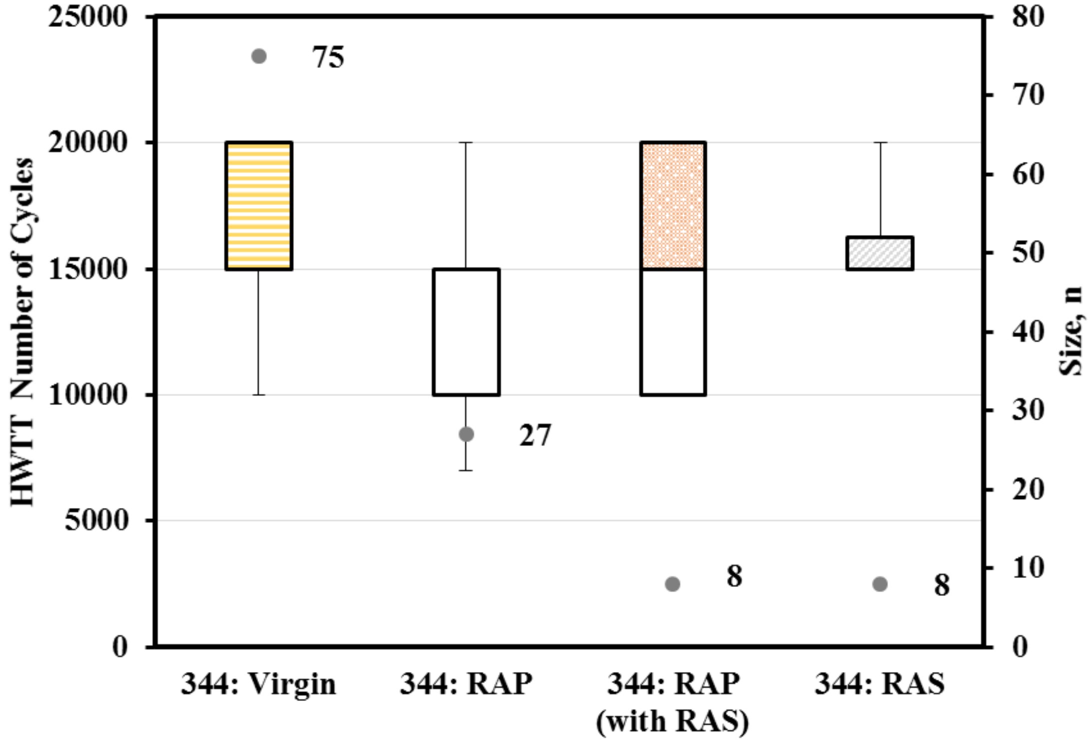

Figure A.11 HWTT Number of Cycles Box Plot for Item 344

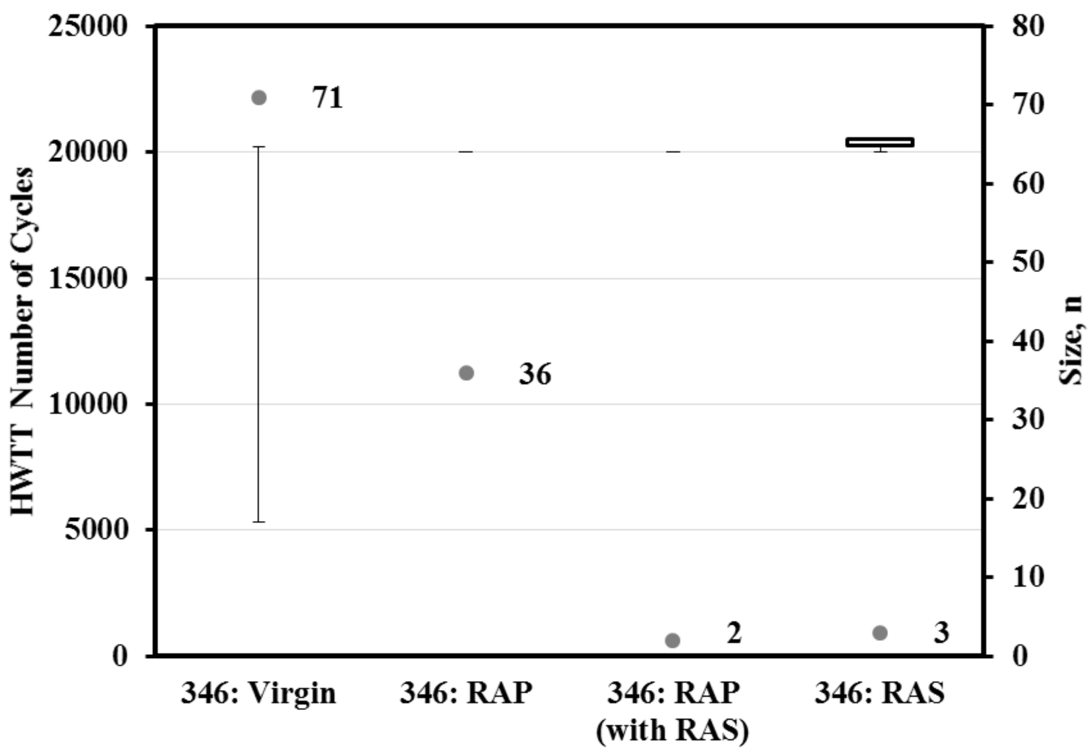

Figure A.12 HWTT Number of Cycles Box Plot for Item 346

Appendix B- Database Storage System (DSS)

Appendix B contains the box plots results from the statistical analysis at a Project Level.

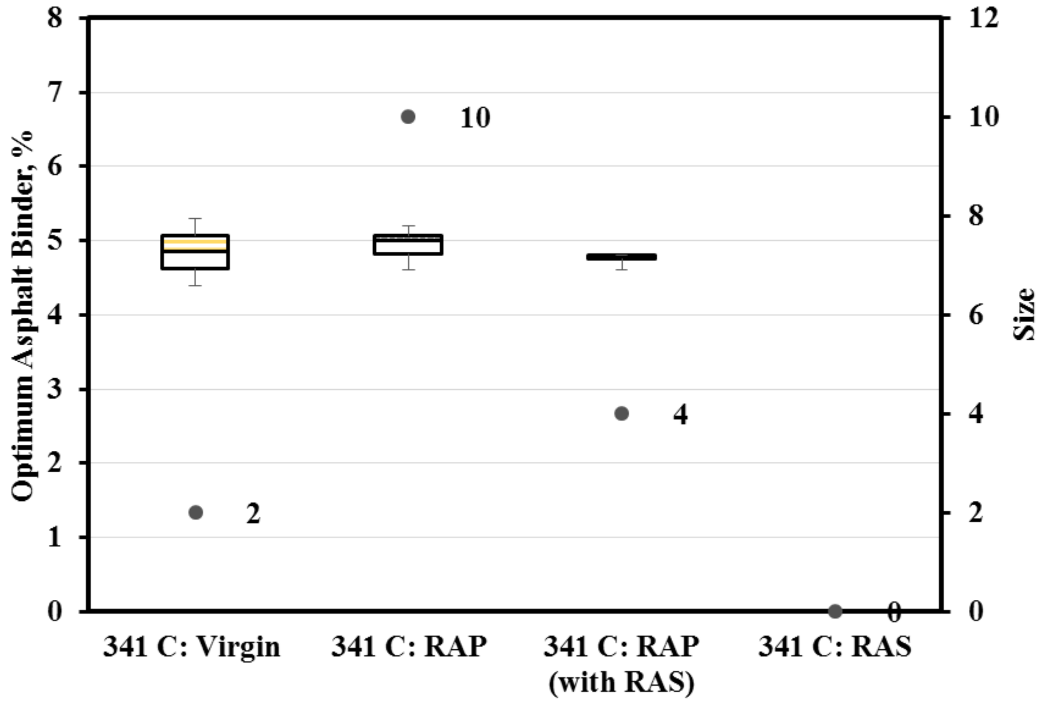

Figure B.1 Optimum Asphalt Binder Box Plot for Item 341: Type C

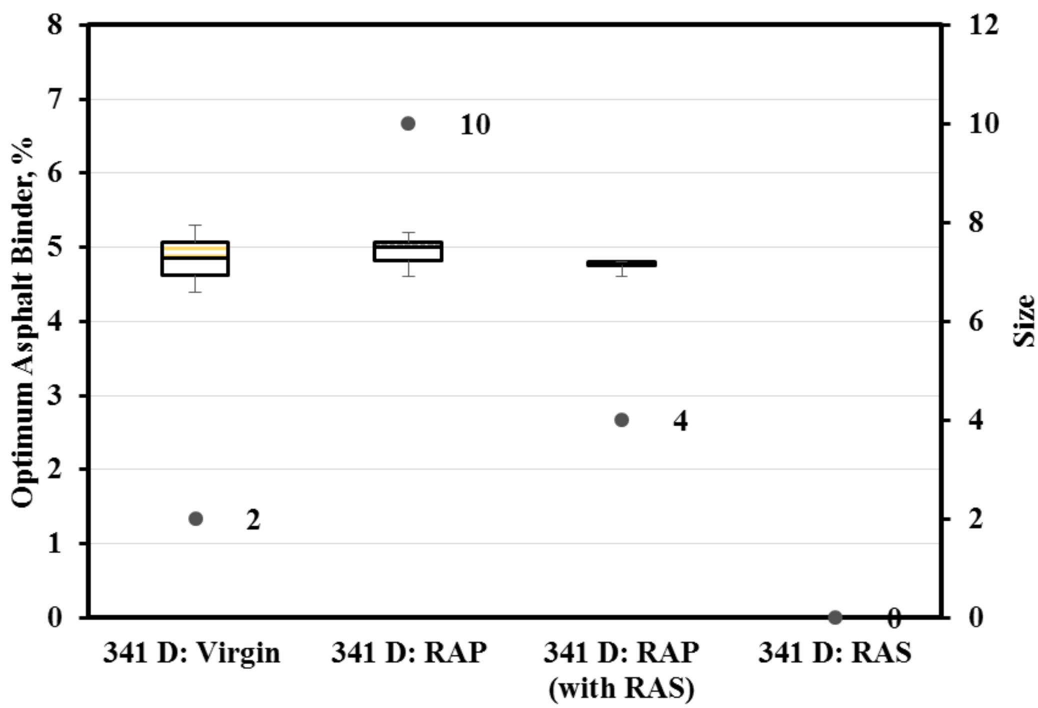

Figure B.2 Optimum Asphalt Binder Box Plot for Item 341: Type D

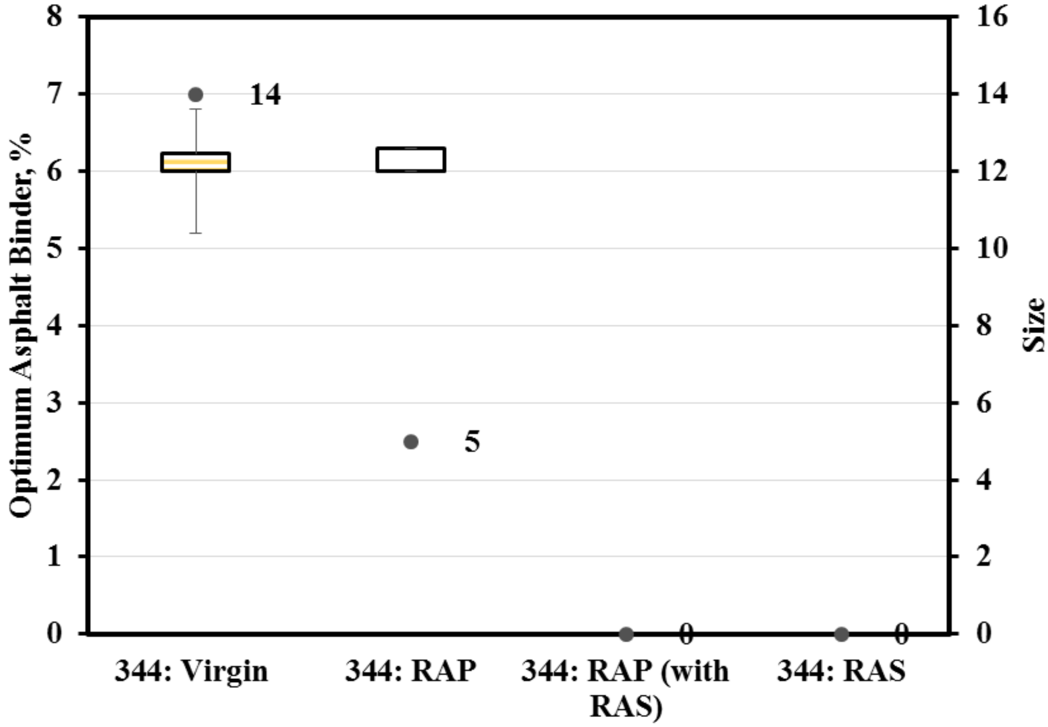

Figure B.3 Optimum Asphalt Binder Box Plot for Item 344

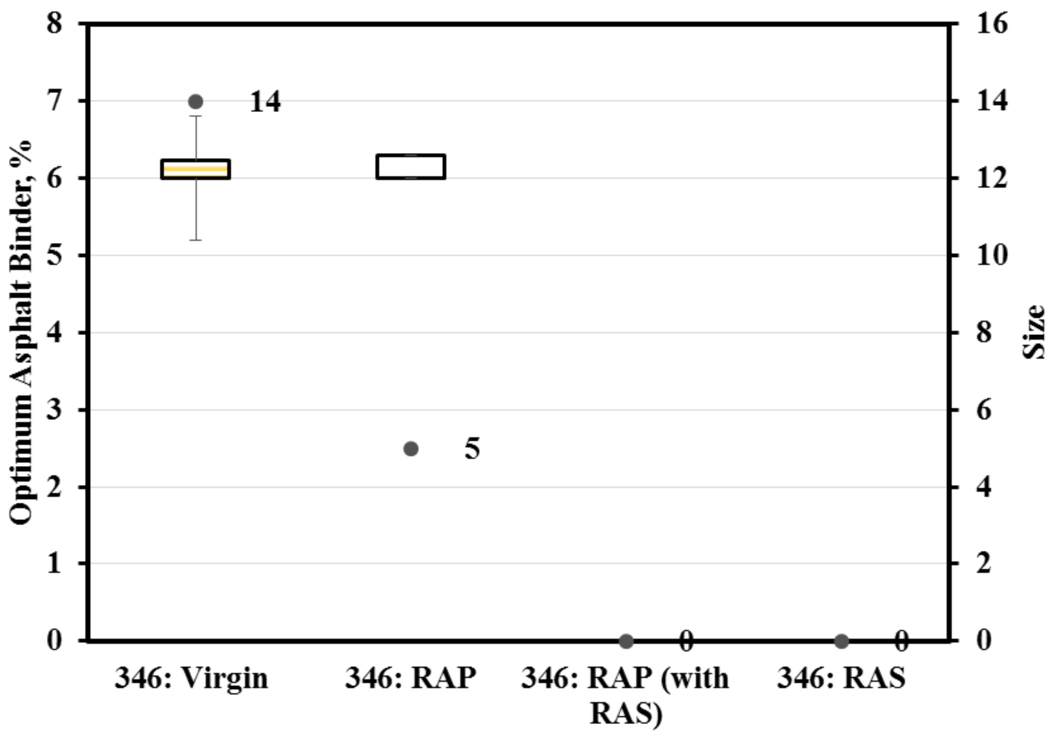

Figure B.4 Optimum Asphalt Binder Box Plot for Item 346

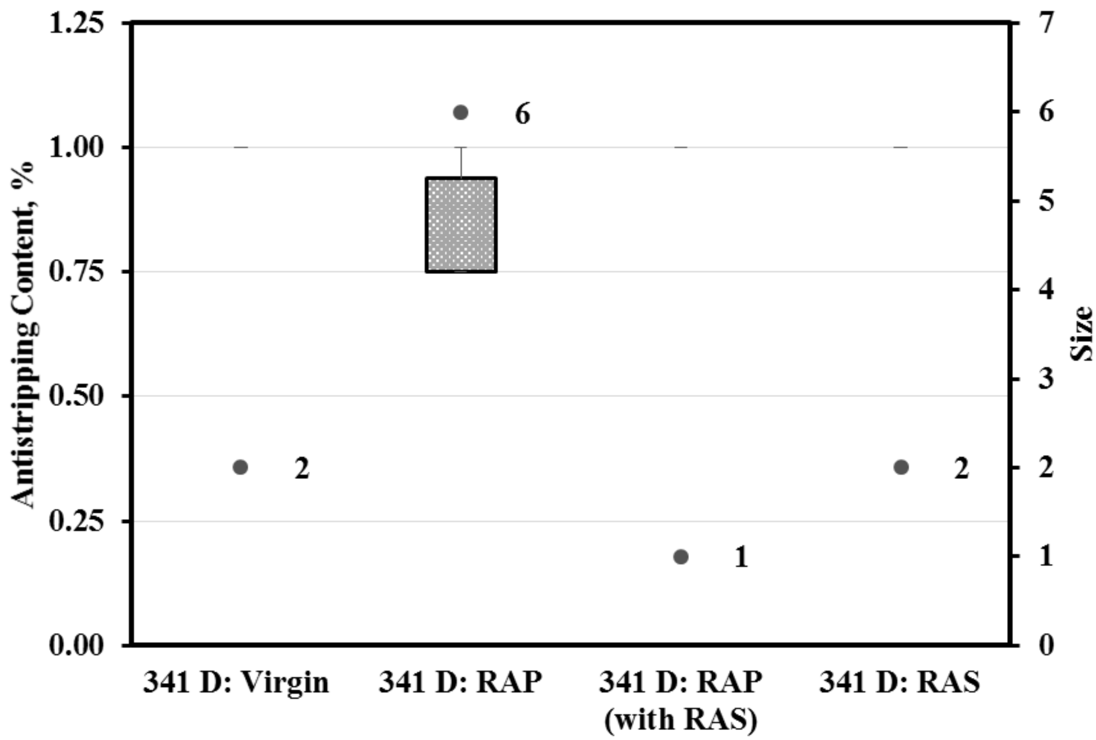

Figure B.5 Antistripping Content Box Plot for Item 341: Type D

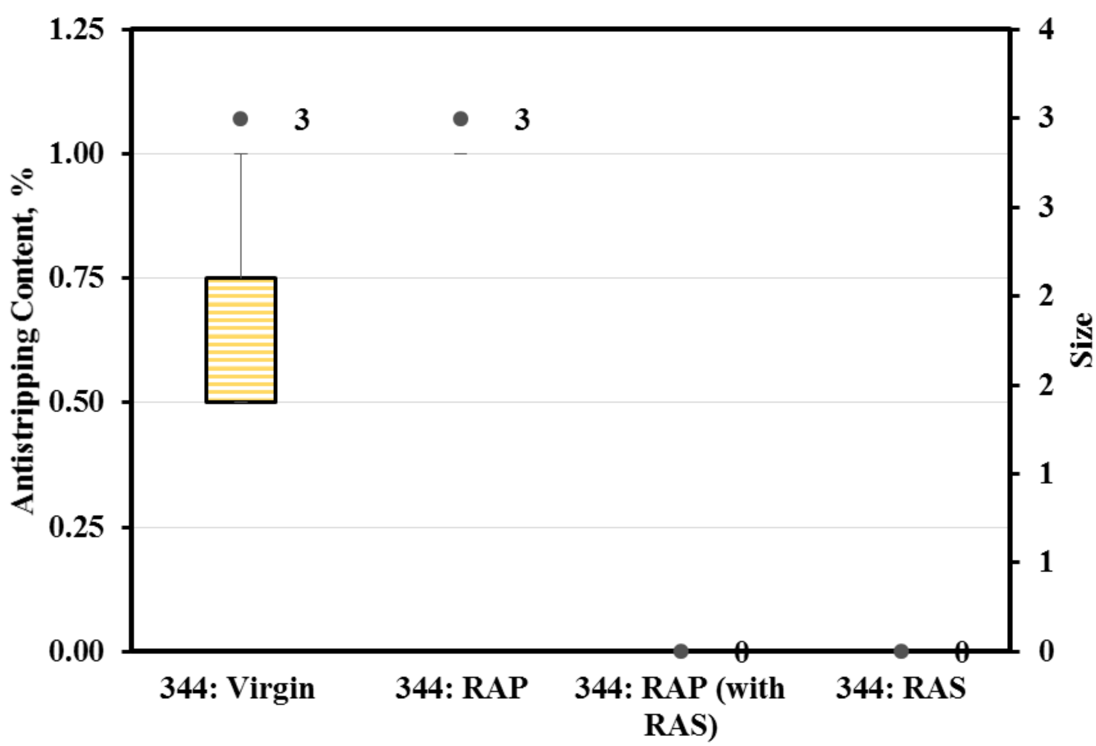

Figure B.6 Antistripping Content Box Plot for Item 344

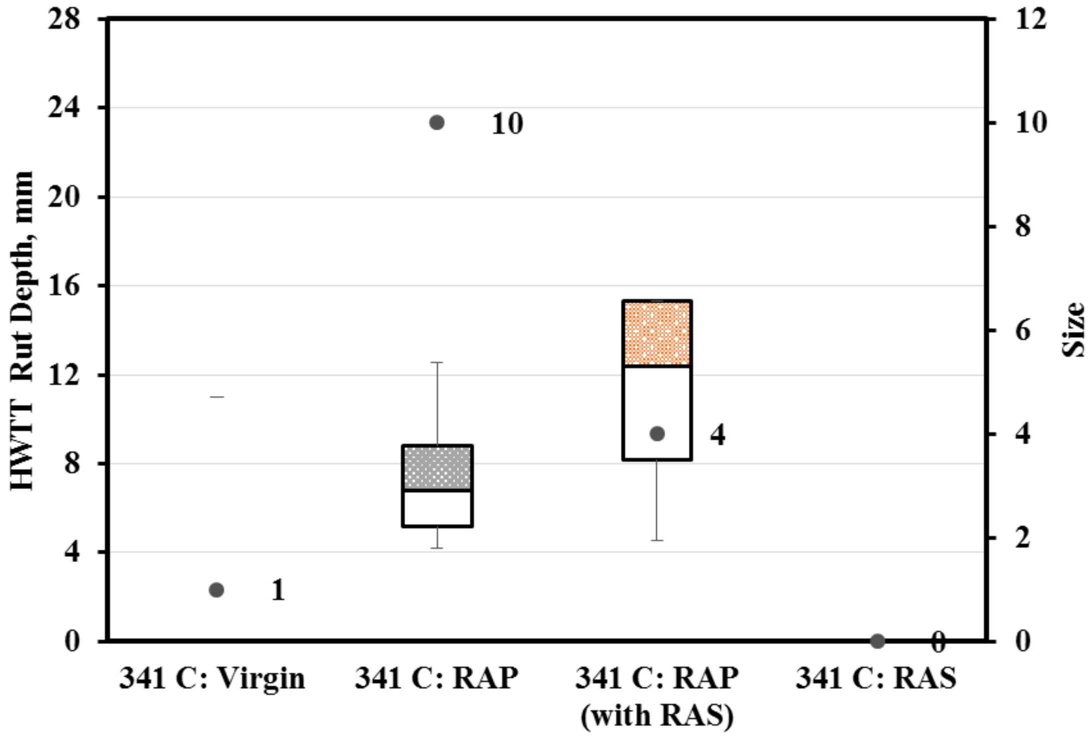

Figure B.7 HWTT Rut Depth Box Plot for Item 341: Type C

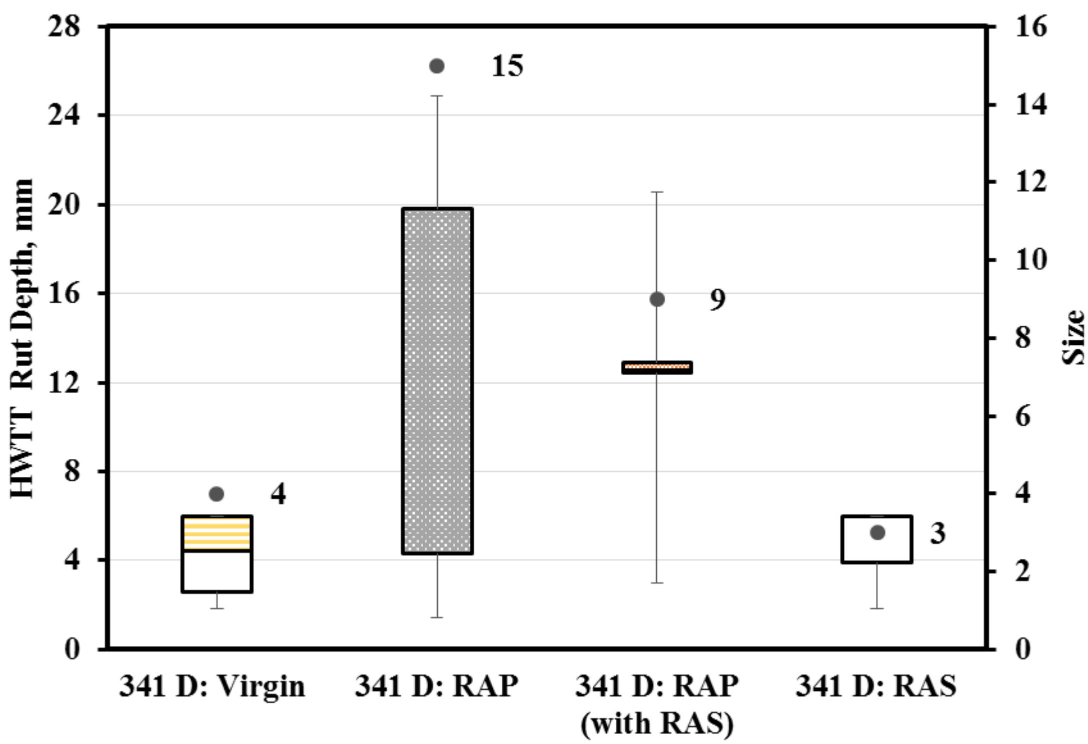

Figure B.8 HWTT Rut Depth Box Plot for Item 341: Type D

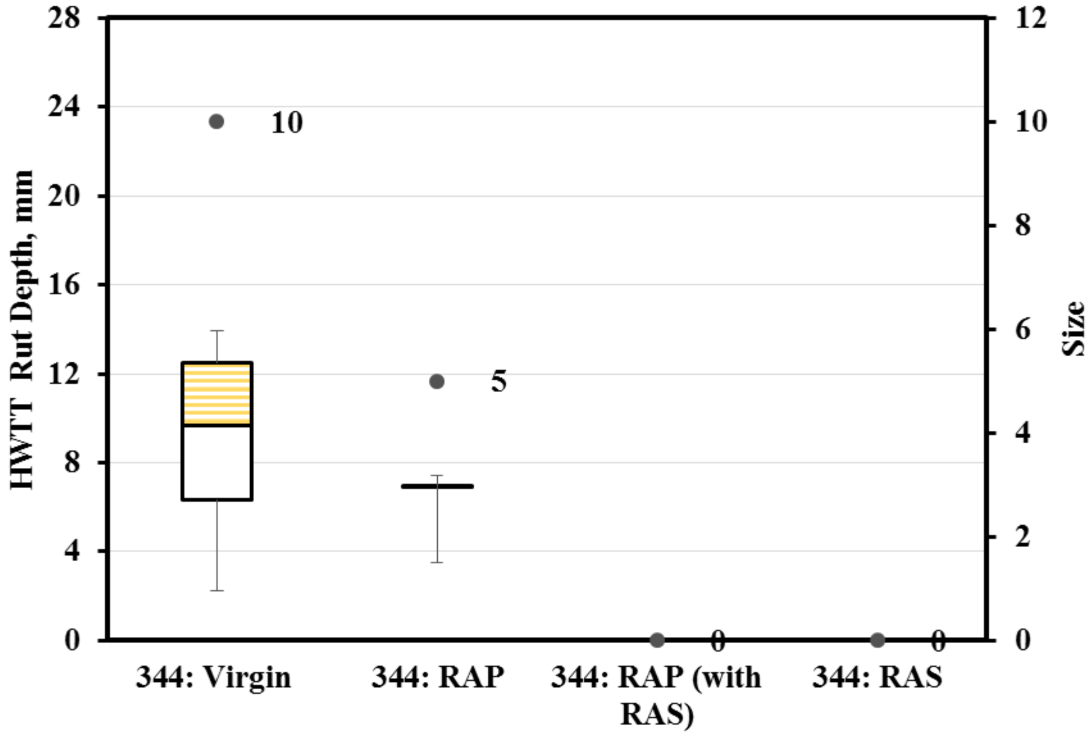

Figure B.9 HWTT Rut Depth Box Plot for Item 344

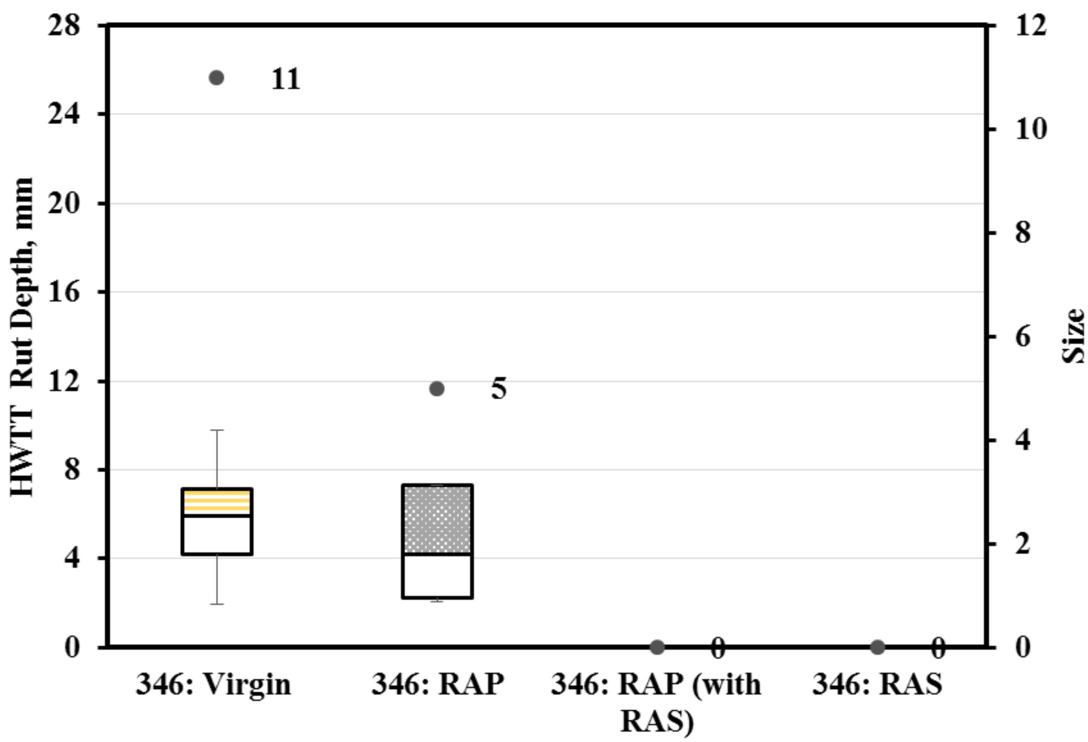

Figure B.10 HWTT Rut Depth Box Plot for Item 346

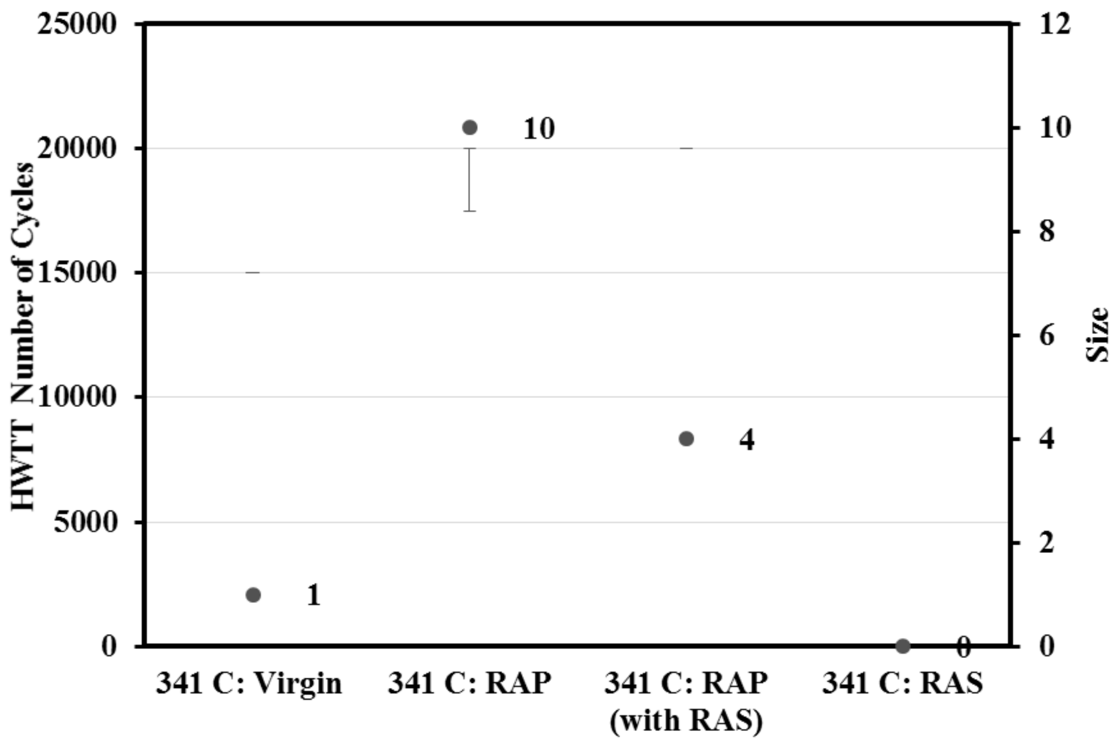

Figure B.11 HWTT Number of Cycles Box Plot for Item 341: Type C

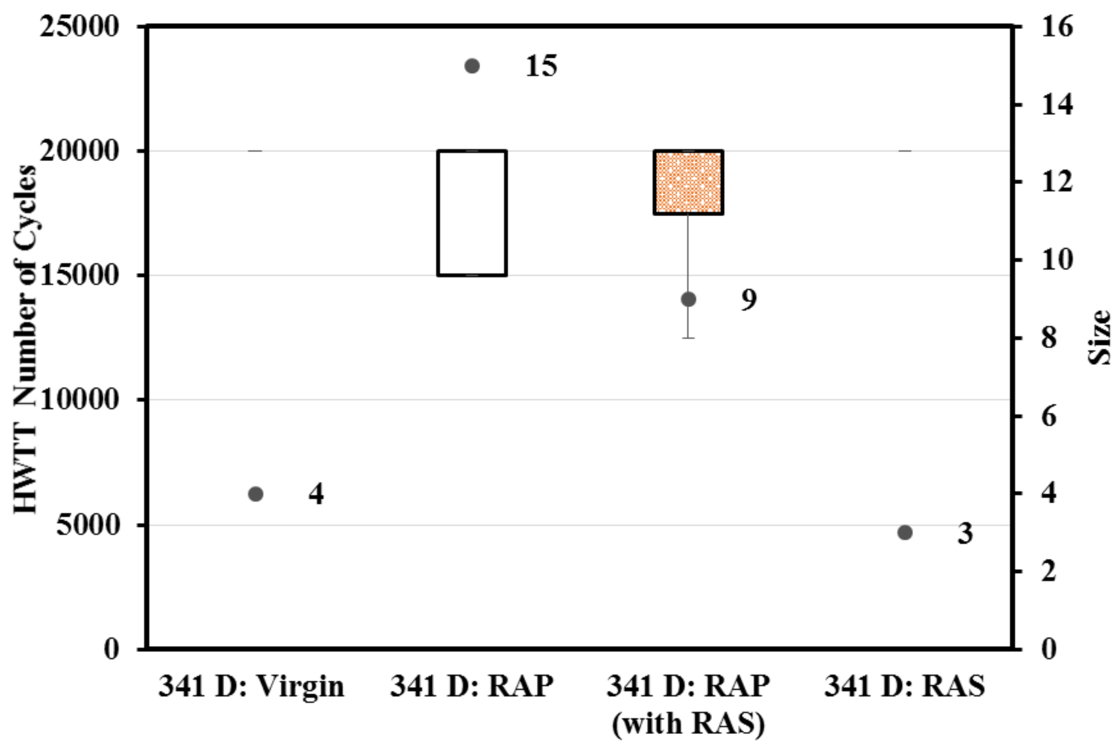

Figure B.12 HWTT Number of Cycles Box Plot for Item 341: Type D

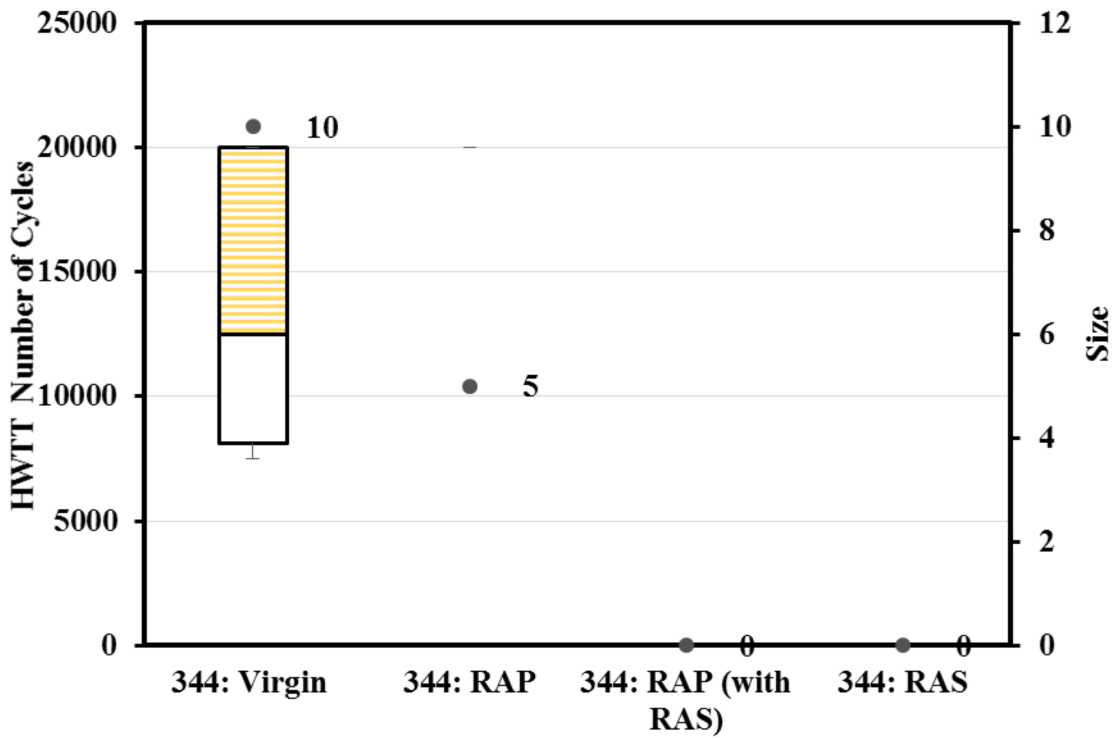

Figure B.13 HWTT Number of Cycles Box Plot for Item 344

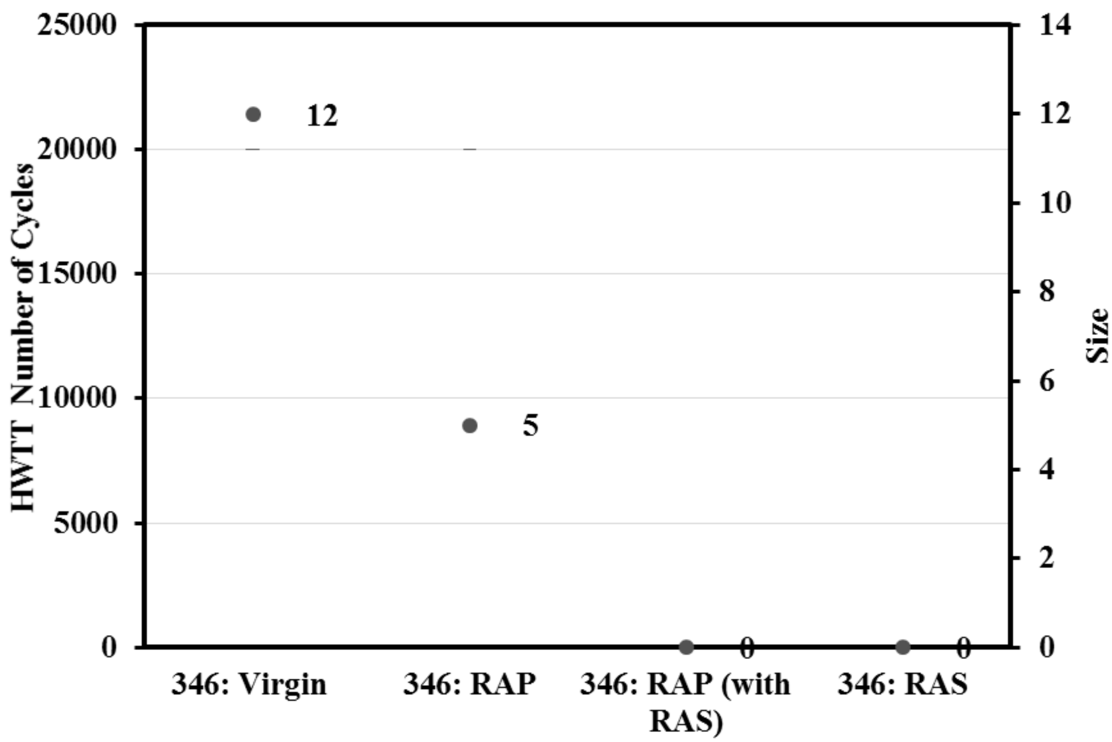

Figure B.14 HWTT Number of Cycles Box Plot for Item 346

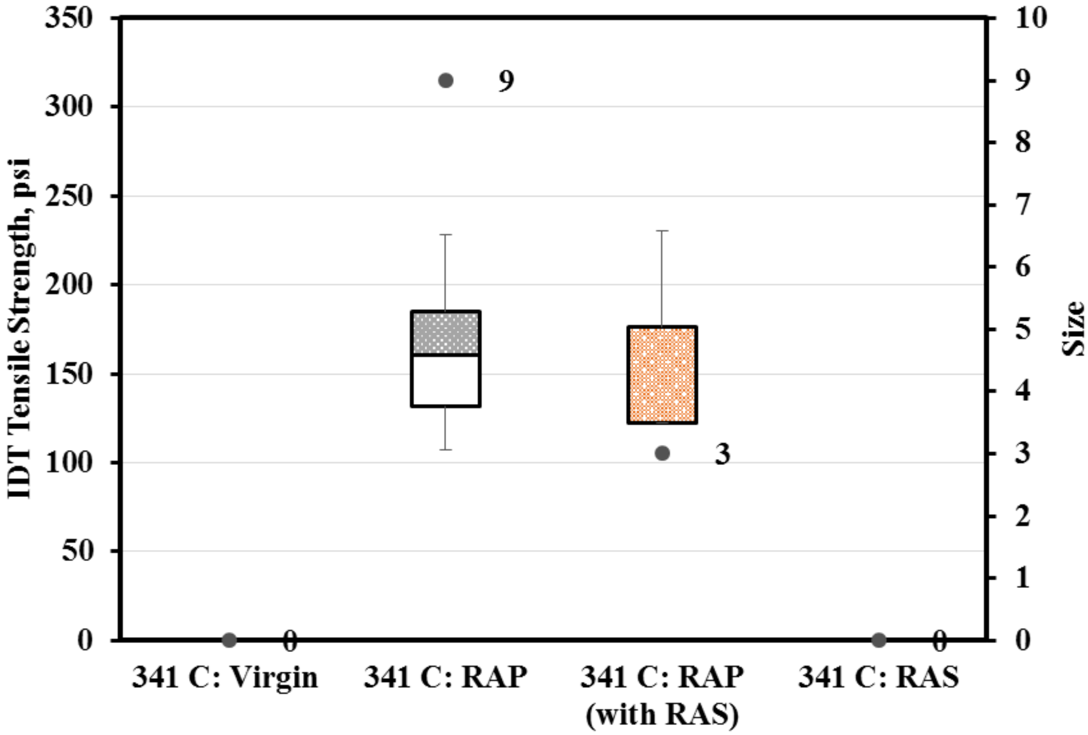

Figure B.15 IDT Tensile Strength Box Plot for Item 341: Type C

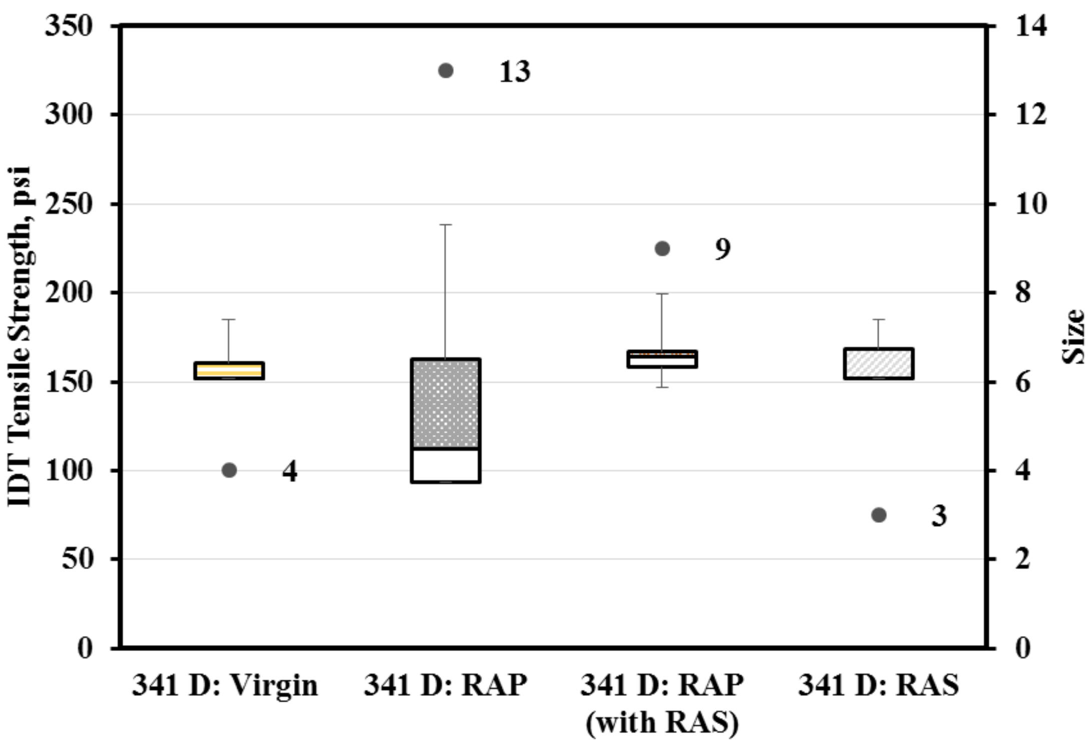

Figure B.16 IDT Tensile Strength Box Plot for Item 341: Type D

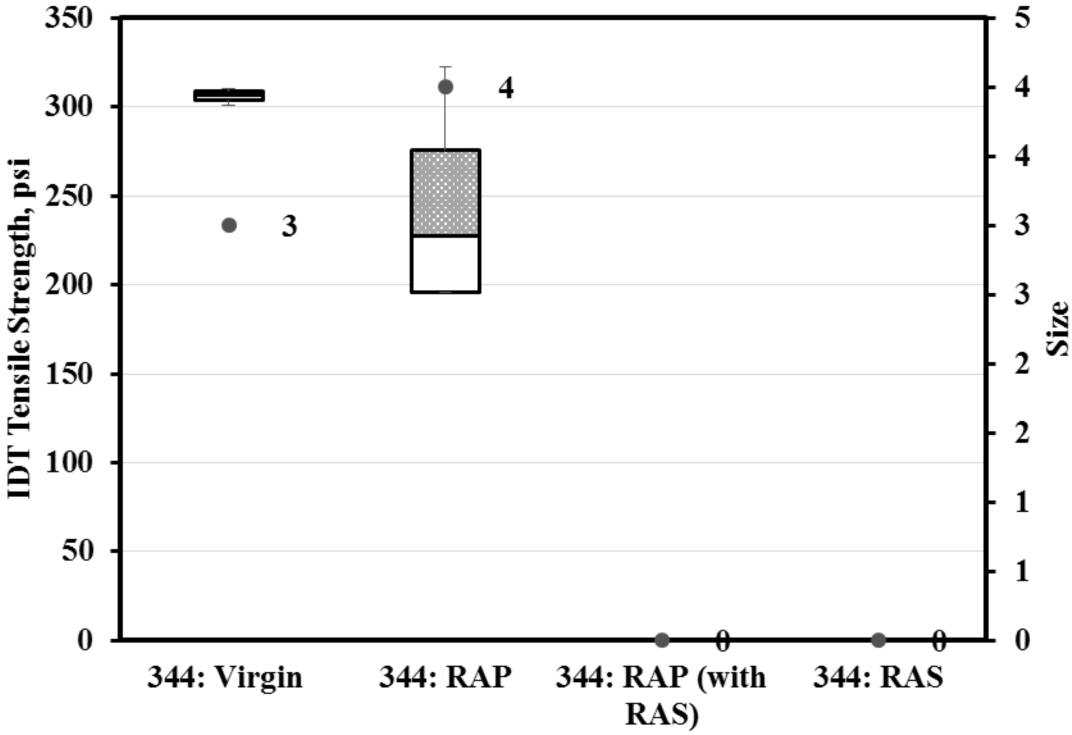

Figure B.17 IDT Tensile Strength Box Plot for Item 344

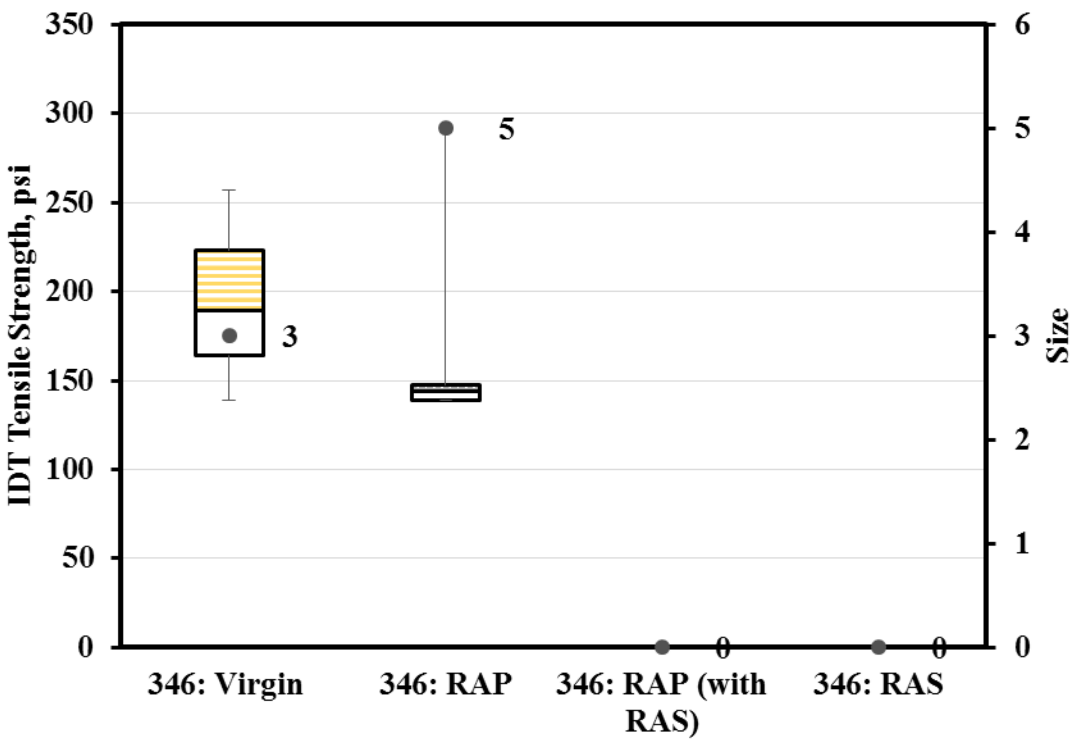

Figure B.18 IDT Tensile Strength Box Plot for Item 346

Vita

Berenice Salaices Gomez was born in Nuevo Casas Grandes, Chihuahua, Mexico and moved to El Paso, Texas to attend the University of Texas at El Paso to pursue a Bachelor's in Civil Engineering. During her junior year she started working at the Center for Transportation Infrastructure Systems (CTIS) where she got involved in multiple research projects working in the asphalt binder laboratory. She was also involved in the development of a research database for the Texas Department of Transportation (TxDOT). Right after graduation she decided to pursue a Master's of Science in Civil Engineering where she had the opportunity to conduct research in the area of asphalt pavement while working at CTIS. Throughout her graduate studies she also participated in an internship with Quantum Engineering Consultants in El Paso, Texas. For two consecutive years she received the Graduate Eisenhower Fellowship and had the opportunity to present her research at the Transportation Research Board in Washington D.C. She also received the International Road Federation Fellowship in 2017.

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This thesis was typed by Berenice Salaices Gomez.