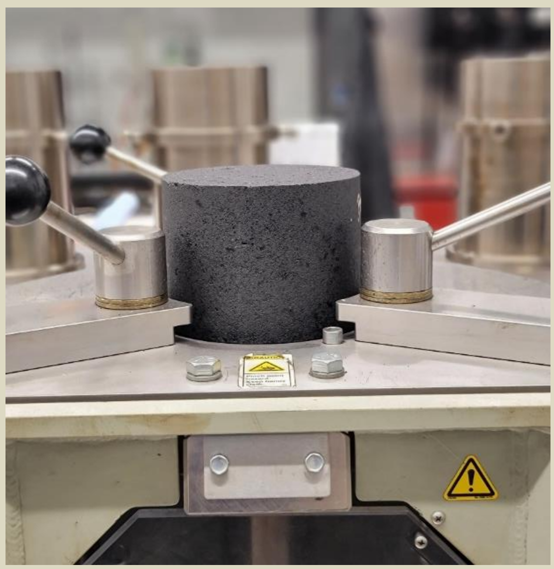
RESEARCH & DEVELOPMENT

Evaluation of New Asphalt Concrete Job Mix Formula Specifications



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The North Carolina Department of Transportation (NCDOT) modified the procedures for asphalt mixture design in 2018 in part, to increase the asphalt content and address observed cracking issues with asphalt mixtures. These changes have reduced the number of asphalt mixture types, changed compaction levels and the volumetric limits for some mixtures, and adjusted how recycled materials are considered. Given the complexity of the interactions between material parameters, the procedural changes do not guarantee that the resultant asphalt mixture designs have actually achieved the intended goal of improved durability.

This study investigates how these recent changes have affected asphalt mixture designs with respect to composition and performance. Direct statistical analysis of mixture volumetric properties (voids in mineral aggregates, voids filled with asphalt, recycled binder replacement, asphalt content, etc.) were first assessed to identify systematic changes in mixture composition resulting from the specification changes. Then, several performance prediction models identified from the literature were utilized to predict performance differences between mixtures before and after the changes based on compositional changes. Visual as well as statistical (Student's t-test) approaches were utilized to evaluate the differences in composition and performance. Some statistically significant differences in the composition and predicted performance of past and present asphalt mixtures were identified. However, the magnitudes of the differences and number of cases where statistically significant differences were identified versus not suggest no systematic differences of practically significance resulted from the mixture design specification changes.</td></tr>
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EXECUTIVE SUMMARY

The North Carolina Department of Transportation (NCDOT) has recently modified the asphalt mixture design procedures in part, to increase the asphalt content and address observed cracking issues with asphalt mixtures. These changes have reduced the number of asphalt mixture types, changed compaction levels and the volumetric limits for some mixtures, and adjusted how recycled materials are considered. Given the complexity of the interactions between material parameters, the procedural changes do not guarantee that the resultant asphalt mixture designs have actually achieved the intended goal of improved durability.

This study investigated how these recent changes have affected asphalt mixture designs with respect to composition and performance. Its significance is in the understanding of how procedural changes like the ones enacted by the NCDOT affect the performance of asphalt mixtures. The main study objectives were to: 1) compare and compile detailed comparisons of NCDOT approved asphalt concrete mixtures that were designed under the current and previous design procedures, i.e., before and after the 2018 change; and 2) evaluate the impact of these changes on the predicted mixture performance in terms of change in dynamic modulus and permanent deformation values.

Job Mix Formula (JMF) data were extracted from the Highway Construction and Materials System (HiCAMS) for 2014 to 2020. They were then classified into three main categories; 1) mixes designed and used before the 2018 change, 2) mixes designed before 2018 but reclassified within the 2018 naming system, and 3) mixes designed after 2018. In addition, JMFs were grouped according to region (Coastal, Piedmont, and Mountains) and NCDOT Division (1-14). Comparisons of the volumetric compositions were first carried out between each mixture type (RS9.5B, RS9.5C, etc.) within each category (pre-2018, reclassified, or post-2018), and across each region. More specific analysis involving comparisons within single mixture suppliers (so-called pair-wise analysis) were also carried out. Several performance prediction models were identified from the literature and utilized to predict performance differences between mixtures before and after the changes. Visual as well as statistical (Student's t-test) approaches were utilized to evaluate the differences in composition and performance.

For mixture volumetrics, the changes between pre-2018 and post-2018 mix designs for different regions were very small for all JMF categories. Statistical analysis does confirm some differences, but these differences are practically small (i.e., 0.18 mean change in voids in mineral aggregate (VMA) for the Piedmont region and RI19.0C mix). The same conclusion was reached when making pair-wise comparisons from single suppliers. Recycled binder replacement analysis showed that the majority of the designed and constructed mixes in the North Carolina contain recycled binder with RAP mixes being the most commonly used. No significant differences were found in the volumetric comparisons of the recycled mixtures. For the predicted performance-related properties (dynamic modulus and permanent deformation), and for all the conducted comparisons (including the supplier pair-wise comparisons), the average differences were small considering the potential prediction errors in the models; thus, no substantial statistically significant differences were found.

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1. INTRODUCTION

1.1. Overview

Identifying the appropriate proportions of aggregate, asphalt binder, reclaimed/recycled materials, and other additives and admixtures in asphalt mixtures is a crucial step to delivering long-lasting and durable asphalt pavements. In North Carolina, this process is carried out using volumetric design principles in combination with gyratory compaction and moisture sensitivity assessment. Within these basic elements, there are many potential ways for engineers to control the composition and therefore performance of asphalt mixtures. For example, the design compaction level can be adjusted, which would increase or decrease the final design asphalt content. However, these changes are not straightforward since many of the variables are interactive. For example, if the design compaction effort decreases, it will take more asphalt binder to achieve the design density; thus, it is possible that this change would lead to mixtures with greater asphalt contents. However, this increase is only guaranteed if all other factors remain the same. If a mixture designer elects to achieve the greater compactability requirement by adjusting gradation or asphalt source, it is also possible that changes in compaction effort could decrease the selected asphalt content.

In 2018, the NCDOT modified their mixture design procedures, in part to increase the asphalt content. These changes ultimately reduced the total number of asphalt mixture types from 12 to 6. In addition, the guidelines on asphalt binder grade selection for mixtures containing reclaimed asphalt pavements (RAP) and recycled asphalt shingles (RAS), compaction efforts, and volumetric limits were modified. However, it cannot be guaranteed that these changes have had the intended result due to the many interactive factors involved in asphalt mixture design. This research assessed how these changes have affected asphalt mixture compositions and used predictive models to assess how changes in composition have affected engineering properties. The specific objectives of this research are to;

1) Compare and compile detailed comparisons of NCDOT approved asphalt concrete mixtures that were designed under the current and previous design procedures; and
2) Evaluate the impact of these changes on asphalt mixture designs with respect to composition and performance.

This study has been performed so that the NCDOT can understand the effect of their changes and adjust these procedures (if necessary) to better align the resultant mixture designs with the results that were intended when the new procedures were created. In addition, no research currently exists that shows how changes in mixture design procedures affect the composition and mechanical properties of asphalt concrete mixtures. Also, mixture designs in North Carolina are performed by contractors and submitted to the NCDOT for approval. As such, the NCDOT itself has little control over how contractors interpret and use the mixture design procedures or how mixture designers may be able to use their local materials to meet the requirements of the mixture design process.

1.2. Status of the Literature

A substantial amount of research has been performed to best identify the methods to combine asphalt binder with aggregate to create a durable asphalt mixture. To understand and know the mixture design factors that need to be examined most closely after mixture design changes are made requires an understanding of the following;

- how volumetric factors affect the durability of asphalt mixtures,
- how asphalt mixtures are currently designed,
- efforts to adjust these designs using balanced mixture design approaches, and
- the changes in design process that the NCDOT has recently implemented.

1.2.1. Volumetric effects and mixture design

Engineers have recognized the importance of volumetric composition (e.g., the relative volumes of aggregate, asphalt, and air) on asphalt mixture performance for more than a century (*1*). Because of these links, asphalt mix designs have been closely linked to indices that include voids in mineral aggregate (VMA), voids filled with asphalt (VFA), dust-to-binder ratio (now called dust proportion or DP), and others since the 1940's (*2*). Much of the groundwork for the current implementation of these assessments was established in seminal works on effective specific gravity (*3*), maximum specific gravity (*4*), and voids analysis (*5*, *6*) from the 1950's.

The methods to best achieve desirable mixture volumetrics through specifications vary. The Marshall method of mixture design attempted to control these volumetrics by first establishing compaction controls, setting total voids limits at those compaction levels, fixing thresholds and limits for strength and ductility, and finally checking that sufficient void space was filled with asphalt (*2*). Other mix design methods (Hveem and Hubbard) used essentially the same process, but varied the precise methods to calculate voids, the means of controlling void content, and compaction (*7*). Superpave mixture design also followed this model except in final implementation it eliminated verification of the mechanical properties and elected to rely solely on volumetrics (*7*). Note, a final verification of resistance to moisture damage is done using indirect tensile strength in the Superpave mix design method, but this parameter is not used directly to determine the composition of the mixture. Rather, it serves as a final check of the compatibility of the constituent materials. Since the initial implementation of Superpave, two major approaches to controlling composition and ensuring that asphalt mixture design produces a durable material have emerged; 1) tweaking mixture design variables and 2) incorporating mechanical testing into the design process (also known as balanced mixture design methods).

The first method involves adjusting the compaction efforts, target air void contents, allowable volumetric thresholds, etc. in ways that increase the amount of asphalt binder in the mixture. NCHRP Projects 9-25 and 9-31 focused heavily on the design air void content level as a potential pathway to achieve this goal. This research found that increasing the allowable range of air voids content from a fixed value of 4% to a range between 3% and 5% could produce mixtures that are more durable because it permits mixture designers to best meet other important volumetric and compositional factors (sufficient asphalt binder and strong aggregate skeleton) given the characteristics of their specific materials. However, this work also highlighted the importance of adjusting VMA requirements when such changes are made in order to ensure sufficient VFA. Essentially, the study highlighted the difficulty in making changes to a single volumetric index to achieve desirable change to mixture composition. This research also surveyed states and found that some states had established maximum limits to VMA and/or made slight adjustments to the minimum VMA limits of the national Superpave standards (*8*, *9*). The research did not present any studies where agency mixture volumetrics were compared before and after changes to Superpave specifications were enacted. Instead, the researchers conducted a meta-analysis comparing the properties of mixtures that were designed with various approaches across multiple agencies. One thing to note on the volumetric mix designs is that the asphalt pavement community has been trying to find ways to implement performance testing during the mixture design process, but often faces practical constraints. For example, the original Superpave mix design procedure included a Level 1 approach wherein performance testing via the Superpave shear tester was to be part of the design process. However, in the end the final design procedure adopted only volumetric procedures because of 1990s limitations in the modeling and testing technologies. This timing is important because the efficacy of using only volumetrics was proven at a time when mix designers typically used only virgin aggregates and binder in their mix designs. The limitations of the conventional volumetric tests has become more apparent with the growth in new materials and technologies (i.e., \recycled materials, binder modifiers, warm mix asphalt, etc.) within the paving industry (*10*).

The second method of achieving desirable mixture characteristics involves characterizing the mechanical properties of asphalt mixtures during the design process, e.g., Balanced or Performance Engineered Mix Design (BMD or PEMD) methods. Multiple approaches within this broad method exist. At the simplest level, Superpave mixture design is supplemented with tests, which verify that the rutting and cracking resistance of the volumetric based design are sufficiently high. At the most complex level, volumetrics are practically abandoned and the design is only based on rutting and cracking resistance.

1.2.2. Comparison of Previous and Current NCDOT Mixture Design Requirements
Table 1 and

Table 2 show the current and previous NCDOT asphalt mixture design tables, respectively. Key changes include the elimination of the SF9.5A, S12.5C, S12.5D, I19.0B, I19.0D, and B25.0B mixtures. Other changes are highlighted in bold in Table 1 and include; changes to compaction levels, minimum VMA, the VFA range in S9.5B, the use of PG 64-22 instead of PG 70-22 for S9.5C, and the specification of I19.0C and B25.0C for all intermediate layer mixtures and all asphalt base mixtures, respectively. Though not shown here, no changes were made to the aggregate consensus property requirements and the recycled content guidance was modified to reflect the RBR% (recycled binder replacement) instead of RAP (reclaimed asphalt pavement) and RAS (recycled asphalt shingles) content. It is important to notice that the new surface “C” mixtures have the same specification as the pre-2018 “B” mixtures, but owing to the new traffic classification are now allowed on roadways with higher cumulative ESALs. Also, the same applies to the new surface “B” mixtures that have the same specification as the pre-2018 “A” mixtures. In addition, the pre-2018 surface 65-gyration design (S9.5B/RS9.5B) mixture required Asphalt Pavement Analyzer (APA) rutting less than 9.5 mm while the post-2018 surface 65-gyration design (S9.5C/RS9.5C) mixture required APA rutting less than 6.5 mm.

Table 1. Summary of NCDOT Mixture Designs and Volumetric Factors from 2018 Updated Procedures.

Mix Type	20-Year ESALs, millions	Binder PG Grade	Compaction G_{mm} @ N_{ini}	Compaction G_{mm} @ N_{des}	Volumetric Properties VMA % Min.	VTM %	VFA Min.-Max.	$\%G_{mm}$ @ N_{ini}	Max. Rut Depth (mm)
S4.75A	< 1	64-22	6	50	16.0	4.0-6.0	65-80	≤ 91.5	11.5
S9.5B	**0 - 3**	64-22	**6**	**50**	**16.0**	3.0-5.0	**70-80**	**≤ 91.5**	9.5
S9.5C	3 - 30	**64-22**	7	65	15.5	3.0-5.0	65-78	≤ 90.5	6.5
S9.5D	> 30	76-22	8	100	15.5	3.0-5.0	65-78	≤ 90.0	4.5
I19.0C	**ALL**	64-22	7	75	13.5	3.0-5.0	65-78	**≤ 90.5**	**-**
B25.0C	**ALL**	64-22	7	75	12.5	3.0-5.0	65-78	**≤ 90.5**	**-**
All Mix Types	Dust to Binder Ratio ($P0.075/P_{be}$)		0.6 - 1.4 (1.0 – 2.0 for SF9.5A)						
	Tensile Strength Ratio (TSR)		85% Min. (80% Min. for S4.75A and B25.0)						

Table 2. Summary of the NCDOT Mixture Designs and Volumetric Factors from the pre-2018 Procedures.

Mix Type	20-Year ESALs, millions	Binder PG Grade	Compaction G_{mm} @ N_{ini}	Compaction G_{mm} @ N_{des}	Volumetric Properties VMA % Min.	VTM %	VFA Min.-Max.	$\%G_{mm}$ @ N_{ini}	Max. Rut Depth (mm)
S4.75A	< 1	64-22	6	50	16.0	4.0-6.0	65-80	≤ 91.5	11.5
SF9.5A	< 0.3	64-22	6	50	16.0	3.0-5.0	70-80	≤ 91.5	11.5
S9.5B	0.3 - 3	64-22	7	65	15.5	3.0-5.0	65-80	≤ 90.5	9.5
S9.5C	3 - 30	70-22	7	75	15.5	3.0-5.0	65-78	≤ 90.5	6.5
S9.5D	> 30	76-22	8	100	15.5	3.0-5.0	65-78	≤ 90.0	4.5
S12.5C	3 - 30	70-22	7	75	14.5	3.0-5.0	65-78	≤ 90.5	6.5
S12.5D	> 30	76-22	8	100	14.5	3.0-5.0	65-78	≤ 90.0	4.5
I19.0B	< 3	64-22	7	65	13.5	3.0-5.0	65-78	≤ 90.5	-
- I19.0C	3 - 30	64-22	7	75	13.5	3.0-5.0	65-78	≤ 90.0	-
I19.0D	> 30	70-22	8	100	13.5	3.0-5.0	65-78	≤ 90.0	-
25.0B	< 3	64-22	7	65	12.5	3.0-5.0	65-78	≤ 90.5	-
B25.0C	> 3	64-22	7	75	12.5	3.0-5.0	65-78	≤ 90.0	-
All Mix Types	Dust to Binder Ratio ($P0.075/P_{be}$)		0.6 - 1.4 (1.0 – 2.0 for SF9.5A)						
	Tensile Strength Ratio (TSR)		85% Min. (80% Min. for S4.75A and B25.0)						

1.2.3. Knowledge Gaps and Applications

The literature clearly shows that volumetric composition of asphalt concrete mixtures has a substantial effect on the resultant durability of these mixtures and therefore asphalt pavements. It also shows that while these effects are understood in a general sense, means of completely controlling the volumetrics through mixture design specifications are lacking. Engineers have adopted two methods to overcome this limitation; 1) mixture design tweaking and 2) balanced mix design (BMD). Of the two, BMD approaches have the benefit that the properties of the mixture are directly evaluated and if using the simplest approach still retain the engineering experience that is embedded in the limits to VMA, VFA, and air void content. The benefits of the first approach are that additional testing and the associated burdens of laboratory verification, proficiency, sampling, etc. do not exist. The challenge in approach one is ensuring that expected changes in volumetric properties actually occur and that the desired compositional changes and requisite increases in material durability are achieved. This challenge represents a substantial knowledge gap and although research like that in NCHRP Projects 9-25 and 9-31 have identified general guidelines, the review was unable to identify published literature that examines how volumetric changes manifest after an agency implements design procedure changes.

1.3. Report Organization

This report is organized into six primary sections and four appendices. Section 1 (this section) describes the overall project, need, and report organization. Section 2 provides an overview of the basic methodology followed in this project to achieve the above stated objectives. Section 3 presents the findings from the analysis conducted. Section 4 summarizes the conclusions of this project along with some specific recommendations. Section 5 provides an overview of the implementation and technology transfer plan for the project results. Finally, Section 6 lists the references cited in this report. Appendices A-D provide the detailed analysis results related to Sections 2 and 3 for those who are interested.

2. METHODOLOGY

2.1. Overview

The overall approach taken for this research is outlined in Figure 1.

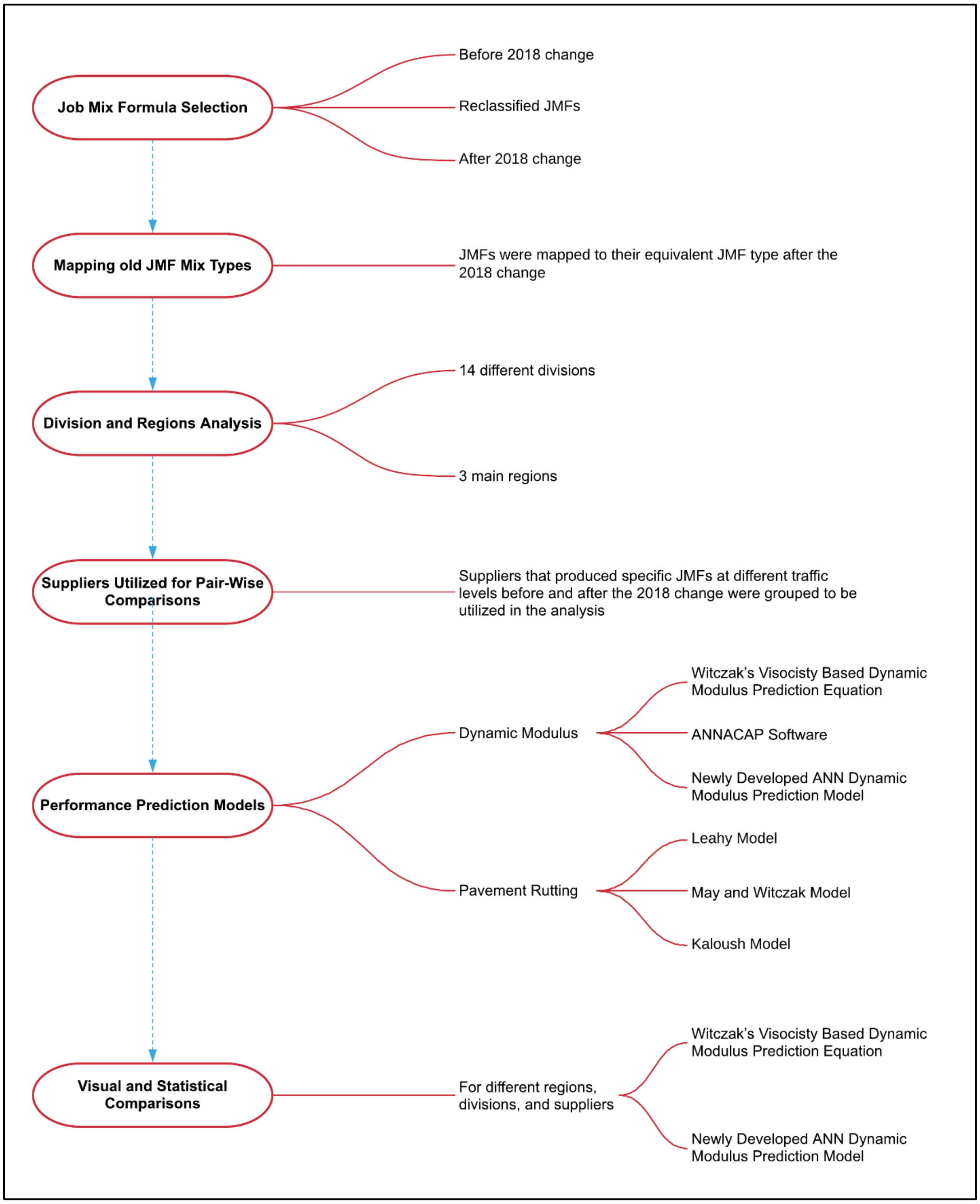

Figure 1. Research methodology outline.

The research started by extracting Job Mix Formula (JMF) data form the Highway Construction and Materials System (HiCAMS). Extracted JMFs were first classified under three main categories; mixes designed and used before the 2018 change, mixes designed before 2018 but reclassified within the 2018 naming system, and mixes designed after 2018. Mixes designed prior to 2018 were then mapped against their equivalent mixes from the 2018 mix design change. Next, the JMFs were grouped according to region (Coastal, Piedmont, and Mountains) and NCDOT Division (1-14). Comparisons of the volumetric compositions were first carried between each mixture type (RS9.5B, RS9.5C, etc.) within each category (pre-2018, reclassified, or post-2018), and across each region. More specific analysis involving comparisons within single mixture suppliers (so-called pair-wise analysis) were also carried out. The JMFs were then used to predict material properties (dynamic modulus and rutting resistance) and similar comparisons were made between the categories. In all cases, visual as well as statistical comparisons for mixture composition and performance were performed and summarized to draw the conclusions for this research. Figure 1. Research methodology outline.

2.2. Job Mix Formula Selection and Data Filtering

The data used for this study included all of the job mix formulas (JMFs) related to years 2014 to 2020 as extracted from HiCAMS. The data was limited to those years in an effort to keep a balanced and representative statistical sample. In total, this data included 4670 JMFs from 23 different JMF types as shown in Table 3. The extracted data was categorized under one of three categories as follows:

1) <u>Before 2018 change</u>: this category included all the JMFs that were present in years 2014 through 2017 and were never reclassified to a 2018 JMF. It represented 34.4% of the study data.
2) <u>Reclassified</u>: included all the reclassified JMFs from the years 2018 through 2020. These mixture designs were based on JMFs from years 2002 to 2017. This category represented 45.4% of the study data.
3) <u>After 2018 change</u>: this category included the new and never reclassified JMFs as present in years 2018 through 2020. It represented 20.2% of the study data.

Table 3. Job mix formula categories and year distribution.

JMF Year	Number of JMF by Category (Percent of JMF by Category)			
	Before 2018 Change	**Reclassified**	**After 2018 Change**	**Total**
14	547 (11.7)	0 (0.00)	0 (0.00)	547 (11.7)
15	395 (8.5)	0 (0.00)	0 (0.00)	395 (8.5)
16	312 (6.7)	0 (0.00)	0 (0.00)	312 (6.7)
17	352 (7.5)	0 (0.00)	0 (0.00)	352 (7.5)
18	0 (0.00)	2113 (45.3)	513 (11.0)	2626 (56.2)
19	0 (0.00)	7 (0.1)	314 (6.7)	321 (6.9)
20	0 (0.00)	0 (0.00)	117 (2.5)	117 (2.5)
Total	1606 (34.4)	2120 (45.4)	944 (20.2)	4670 (100.0)

It is important to note that the numbers shown in Table 3 were determined after conducting a filtering and cleaning process. The reclassified mixes in 2018 data were identified using the comment field. Then, the data was filtered based on the asphalt mix design (AMD) numbers. If the JMFs from the same AMD number were similar, one of them was kept and the other discarded. If they were different, then both were kept in the dataset. This approach helped reduce the bias from having the same compositional values under different JMF numbers. An example of this case is shown in Table 4. AMD number 14-0004 was utilized for JMF 14-0004-151 and 14-0004-251 and both of them were identical. In this case, only one was kept in the database. As for AMD number 14-0002, it was utilized to produce 14-0002-131 and 14-0002-132 JMFs, which have different asphalt content in the RAP stockpile. As a result, both of these JMF were retained in the database.

Table 4. Asphalt mix design and job mix formula numbers.

JMF	AC from RAP %	AC in RAP %	Addl. Binder %	AMD Number	RAP %	Total AC %
14-0002-131	1.2	5.5	4.6	14-0002	21	5.8
14-0002-132	0.9	4.5	4.9	14-0002	21	5.8
14-0004-151	1.1	4.5	3.2	14-0004	25	4.3
14-0004-251	1.1	4.5	3.2	14-0004	25	4.3

2.3. Mapping old JMF Mix Types

In the 2018 NCDOT QMS manual, base and intermediate layers mix types were consolidated into two designations, I19.0C/RI19.0C and B25.0C/RB25.0C. Mix types SF9.5A/RSF9.5A and all 12.5 mm nominal maximum aggregate size mixes were eliminated. Mix S9.5B/RS9.5B had different compaction levels, traffic levels, minimum VMA, and VFA range in comparison to the S9.5B/RS9.5B mixes in previous years. As a result, and in order to conduct a successful comparison, there was a need to remap the old JMF types to their equivalent new types as introduced by the 2018 QMS manual. The mix type as defined under the 2018 reclassified JMF was compared to its previous type as presented in its equivalent year data. In other words, a 2018 reclassified S9.5B JMF was found to be equivalent to the SF9.5A 2014 JMF.

Table 5 presents the reclassification process for the 2014 through 2017 mixes that serve as 2018 mixes under the new specifications. As shown in the table, the base and intermediate layer "B mixes" were reclassified to a 2018 "C mix". All of the pre-2018 surface "A mixes" were reclassified to serve as new "B mixes" while all the pre-2018 surface "B mixes" were reclassified to new "C mixes". It is worth mentioning that the new B mixtures have the same specification as the pre-2018 A mixtures, but are now allowed on roadways with higher cumulative ESALs. The pre-2018 "A mix" was considered for traffic levels less than 0.3 million ESALs while the new "B mix" is considered for traffic levels between 0 and 3 million ESALs.

Table 5. Old vs new mix types as presented under the reclassification process.

Pre-2018 Mix Type	Mix Type-2018								
	B25.0C	I19.0C	RB25.0C	RI19.0C	S9.5B (2018)	RS9.5B (2018)	S9.5C	RS9.5C	Total
B25.0B	6	0	0	0	0	0	0	0	6
RB25.0B	0	0	166	1	0	0	0	1	168
I19.0B	0	12	0	0	0	0	0	0	12
RI19.0B	0	0	0	204	0	0	0	0	204
SF9.5A	0	0	0	0	10	0	0	0	10
RSF9.5A	0	0	0	0	1	205	0	0	206
S9.5B	0	0	0	0	0	0	9	0	9
RS9.5B	0	0	0	0	0	0	0	247	247
Total	6	12	166	205	11	205	9	248	862

The final counts per mix type for the research data is shown in Table 6. This table shows 15 different mix types. It is interesting to note that the removed RI19.0D, RS12.5C, and RS12.5D from the 2018 specifications only formed 72 JMFs out of 1606 extracted JMFs (representing less than 5% of all mix designs).

Table 6. Final research study considered mix types and JMF categories.

	Number of JMF by Category (Percent of JMF by Category)			
Mix Type	**Before 2018 Change**	**Reclassified**	**After 2018 Change**	**Total**
B25.0C	8 (0.2)	41 (0.9)	4 (0.1)	53 (1.1)
RB25.0C	296 (6.3)	395 (8.5)	192 (4.1)	883 (18.9)
I19.0C	15 (0.3)	60 (1.3)	15 (0.3)	90 (1.9)
RI19.0C	367 (7.9)	458 (9.8)	175 (3.8)	1000 (21.4)
RI19.0D	49 (1.1)	0 (0.00)	0 (0.00)	49 (1.1)
RS12.5C	15 (0.3)	0 (0.00)	0 (0.00)	15 (0.3)
RS12.5D	8 (0.2)	0 (0.00)	0 (0.00)	8 (0.2)
S9.5B(2018)	9 (0.2)	55 (1.2)	12 (0.3)	76 (1.6)
RS9.5B(2018)	181 (3.9)	479 (10.3)	178 (3.8)	838 (17.9)
S9.5C	30 (0.6)	60 (1.3)	12 (0.3)	102 (2.2)
RS9.5C	482 (10.3)	569 (12.2)	210 (4.5)	1261 (27.0)
S9.5D	2 (0.0)	3 (0.1)	8 (0.2)	13 (0.3)
RS9.5D	41 (0.9)	0 (0.0)	47 (1.0)	88 (1.9)
S4.75A	10 (0.2)	0 (0.0)	16 (0.3)	26 (0.6)
RS4.75A	93 (2.0)	0 (0.00)	75 (1.6)	168 (3.6)

2.4. Division and Regions Considered in Analysis

The mix design supplier was identified according to the county where they were located. Then, where possible, the JMFs were clustered according to both NCDOT divisions and statewide regions for statistical analysis process. The counties considered under each division were as follows:

1) **Division 1**: Camden, Gates, Martin, Hyde, Dare, Tyrrell, Washington, Bertie, Chowan, Perquimans, Currituck, Pasquotank, Northampton, and Hertford.
2) **Division 2**: Beaufort, Pitt, Greene, Lenoir, Carteret, Jones, Craven, and Pamlico.
3) **Division 3**: Pender, New, Hanover, Brunswick, Onslow, Sampson, and Duplin.
4) **Division 4**: Wilson, Wayne, Johnston, Edgecombe, Nash, and Halifax.
5) **Division 5**: Wake, Franklin, Durham, Granville, Vance, Warren, and Person.
6) **Division 6**: Harnett, Robeson, Columbus, Bladen, and Cumberland.
7) **Division 7**: Orange, Alamance, Guilford, Caswell, and Rockingham.
8) **Division 8**: Chatham, Moore, Hoke, Scotland, Richmond, Montgomery, Lee, and Randolph.
9) **Division 9**: Rowan, Davidson, Davie, Forsyth, and Stokes.
10) **Division 10**: Union, Cabarrus, Anson, Mecklenburg, and Stanly.
11) **Division 11**: Wilkes, Caldwell, Avery, Yadkin, Watauga, Surry, Ashe, and Alleghany.
12) **Division 12**: Iredell, Gaston, Cleveland, Lincoln, Catawba, and Alexander.
13) **Division 13**: Rutherford, Buncombe, McDowell, Burke, Madison, Yancey, and Mitchell.

14) **Division 14**: Jackson, Transylvania, Macon, Cherokee, Clay, Henderson, Polk, Graham, Haywood, and Swain.

While the considered counties under each region were as follows:

1) **Mountains**: Alleghany, Ashe, Wilkes, Watauga, Avery, Caldwell, Burke, Mitchell, Yancey, McDowell, Madison, Buncombe, Rutherford, Polk, Henderson, Haywood, Transylvania, Jackson, Swain, Macon, Graham, Clay, and Cherokee.
2) **Piedmont**: Surry, Stokes, Yadkin, Alexander, Iredell, Catawba, Lincoln, Gaston, Cleveland, Davie, Forsyth, Davidson, Rowan, Cabarrus, Mecklenburg, Union, Stanly, Rockingham, Guilford, Randolph, Montgomery, Anson, Moore, Richmond, Lee, Chatham, Alamance, Orange, Durham, Caswell, Person, Granville, Vance, Wake, Warren, and Franklin.
3) **Coastal Plains**: Johnston, Beaufort, Bertie, Bladen, Brunswick, Camden, Carteret, Chowan, Columbus, Craven, Cumberland, Currituck, Dare, Duplin, Edgecombe, Edgecombe, Gates, Greene, Halifax, Harnett, Hertford, Hoke, Hyde, Jones, Lenoir, Martin, Nash, New Hanover, Northampton, Onslow, Pamlico, Pasquotank, Pender, Perquimans, Pitt, Robeson, Sampson, Scotland, Tyrrell, Washington, Wayne, and Wilson.

2.5. Suppliers Utilized for Pair-Wise Comparisons

Mix groupings by supplier were utilized to evaluate the differences in mix designs composition and performance. For performance comparisons, all the suppliers that produced specific JMFs at different traffic levels before and after the 2018 change were grouped and considered in the analysis. However, since mix composition for the same JMF type is not traffic level dependent, limited selected suppliers were utilized in the analysis. The suppliers were selected in a way to ensure that they produced the evaluated JMF type in statistically representative quantities in terms of numbers of mix designs before and after the change. Figure 2 shows the selected JMF types for the comparison along with the number of suppliers producing those JMFs. For example, JMF type RB25.0C was produced by 43 different suppliers out of which only five produced it before and after the change in comparable quantities; thus, only these five suppliers were used for detailed analysis. The same rule applies to the different JMF types shown in the figure. It is important to note that supplier names were kept anonymous even during the research project meetings and are not specified within this report or its appendices.

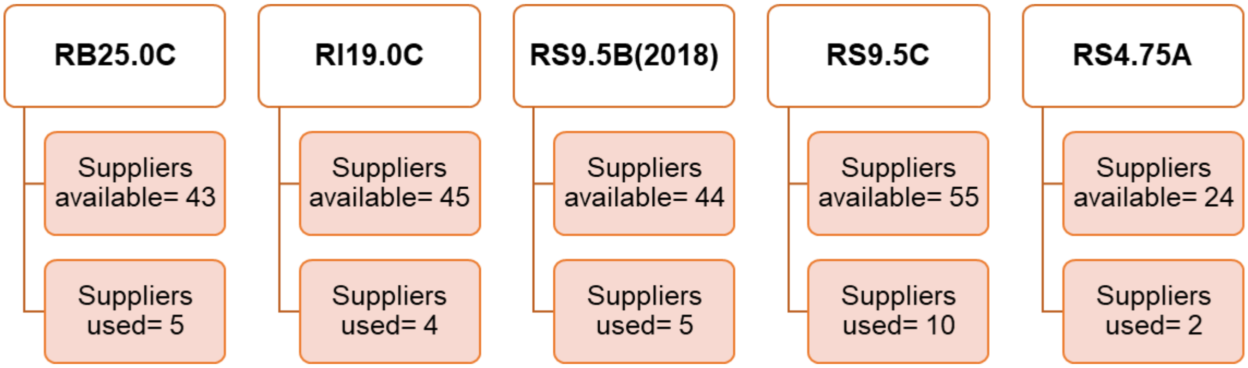

Figure 2. Supplier numbers utilized for the selected JMFs composition comparisons.

2.6. Performance Prediction Models for Dynamic Modulus

Dynamic modulus (|*E**|) represents the stiffness of the asphalt material when it is tested in a relatively low strain magnitude under sinusoidal compression. It is considered a key parameter to evaluate the rutting and fatigue cracking susceptibility of asphalt pavements. It also forms the primary material input for AASHTO Pavement ME design. In this research, it was not possible to measure the |*E**| values for mixtures prepared according to all of the JMFs. However, multiple |*E**| prediction models from the literature are available and were utilized to predict performance differences between mixtures before and after the mix design changes. Also, a newly developed artificial neural network model was developed using data available from past research projects in North Carolina (60% of data) and elsewhere (40% of data) for the use in |*E**| predictions and comparisons. The predicted |*E**| values were utilized to conduct group-wise and then, supplier based pair-wise comparisons.

2.6.1. Witczak's Viscosity Based Dynamic Modulus Prediction Equation

The Witczak viscosity based equation was initially developed by Witczak and his colleagues through the modification of Shook and Kallas (*11*) model and utilized a large database that contained hundreds of dynamic modulus measurements. The full research effort to establish the predictive model conducted prior to 1989 were summarized by Witczak and Fonseca (*12*). Between 1995 and 1996, Witczak-Fonseca further refined the model using 1429 test data points from either unaged or short-term oven aged lab-mixed asphalt mixtures utilizing conventional binders only (*13*). Further revision to that model was conducted by Witczak utilizing an expanded database encompassing 2750 test data points resulting from 205 unaged or short-term oven aged lab mixed asphalt mixtures, 34 of which included polymer modified binder. This database was known as UMD |*E**| database and the revision resulted in the original version of the |*E**| prediction model that was included in the earlier versions of the AASHTO Pavement ME Design and is given in Equation (1) (*14*).

The statistical summary of the equation as provided by the Guide for Mechanistic-Empirical Design (NCHRP 1-37A) as follows:

R^2= 0.96
Se/Sy= 0.24
Number of Data Points= 2750
Temperature Range=0 to 130°F
Loading Rates= 0.1 to 25 Hz
Number of Mixtures= 205 total, 171 utilizing unmodified and 34 utilizing modified binders

$$\log|E^*| = 3.750063 + 0.02932\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\rho_4 - 0.058097V_a - 0.802208\left(\frac{V_{beff}}{V_{beff} - V_a}\right) + \frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017(\rho_{38})^2 + 0.005470\rho_{34}}{1 + e^{(-0.603313 - 0.313351\log(f) - 0.393532\log(\eta))}}$$

(1)

where;

|*E**| = dynamic modulus in psi,
η = bitumen viscosity in 10^6 Poise,
f = loading frequency in Hz,

V_a = percent air void content,
V_{beff} = percent effective bitumen content,
ρ_{34} = cumulative percent retained on the ¾ in sieve,
ρ_{38} = cumulative percent retained on the 3/8 in sieve,
ρ_4 = cumulative percent retained on the No. 4 sieve, and
ρ_{200} = percent passing the No. 200 sieve.

The Witczak prediction equation requires the binder viscosity as an input variable. However, binder viscosity data is not available within the HiCAMS database. To utilize Witczak prediction equation herein, the viscosity of the binder at the analysis temperature was determined utilizing the ASTM viscosity temperature relationship shown in Equation (2). The *A* and *VTS* values were determined based on the recommendation of the AASHTO Pavement ME Design for each binder grade.

$$\log\log\eta = A + VTS\log T_R \tag{2}$$

where;
η = viscosity in cP,
A = regression intercept,
VTS = regression slope representing viscosity-temperature susceptibility, and
T_R = temperature in Rankine.

2.6.2. ANNACAP Software

ANNACAP is an artificial neural network (ANN)-based software that can be utilized to predict the dynamic modulus of asphalt mixtures based on the mixture composition. It was initially developed by the research team at North Carolina State University (NCSU) for computing the dynamic modulus parameter in the Long Term Pavement Performance (LTPP) database (*15*). For the model development, seven datasets coming from five different databases were utilized. The databases were Witczak, FHWA Mobile Trailer I (FHWA I), FHWA Mobile Trailer II (FHWA II), North Carolina Department of Transportation (NCDOT) I, NCDOT II, Western Research Institute (WRI), and Citgo. Of these mixtures, the vast majority contained no RAP, and those that did were all below 20%. For the NCDOT I and NCDOT II databases, the RAP contents were between 0% and 15%. The model had an average R^2 of approximately 0.91 and Se/Sy of approximately 0.31. A screenshot of the software main screen is shown in Figure 3 (*15*).

ANN models have an advantage over regression methods, like Witczak's model, because in that they do not require prior knowledge of the predictive functional form. In addition, the ANN technique has the ability to capture complicated nonlinear relationships between the many factors affecting dynamic modulus values. The disadvantage is that when the combination of input factors exceeds the ranges used in calibration, the model may yield large errors in the predicted modulus.

The viscosity-based ANN model within the ANNCAP software was utilized to predict $|E^*|$ for the HiCAMS extracted JMFs. This model predicts $|E^*|$ based on viscosity, VMA, and VFA inputs. The viscosity was calculated by the software internally for each given binder grade utilizing Equation (3) and the same default *A* and *VTS* values included in AASHTO Pavement ME Design.

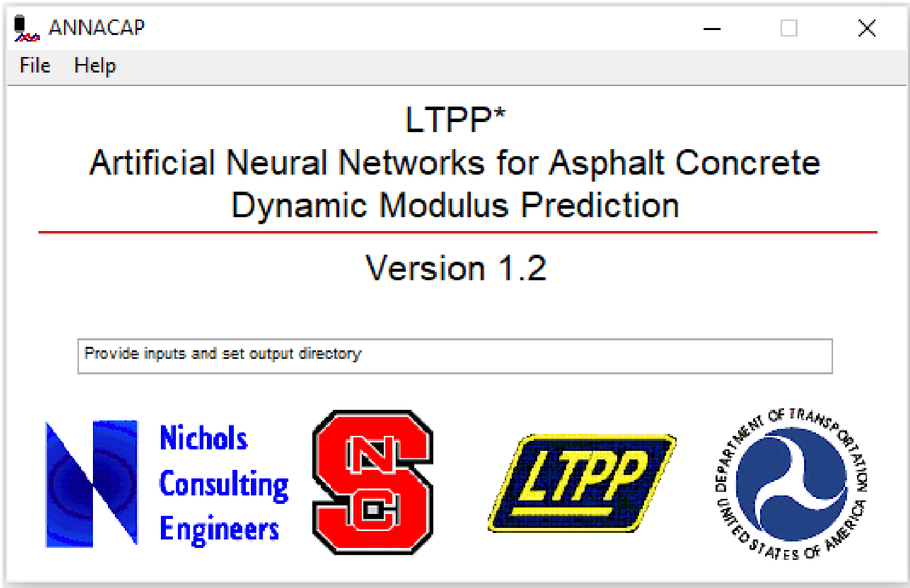

Figure 3. Screenshot of ANNACAP main screen.

2.6.3. Newly Developed ANN Dynamic Modulus Prediction Model

The project research team utilized the database collected for the research project to develop a new ANN model. The main difference between the newly developed model and the preexisting models is in the use of the RBR percent as one of the modeling variables (other variables remain the same as in the previously described prediction models). Also, almost 60% of the data utilized for model development, training, and validation were collected from NCDOT mixtures. All the details related to the newly developed ANN model under this research are available in Appendix A.

By the addition of this model, three different values of predicted $|E^*|$ were evaluated and compared using the JMFs from HiCAMs in order to draw practical conclusions about any differences introduced by 2018 mix design specification changes.

2.7. Performance Prediction Models for Rutting

Four different traffic levels (load repetitions) were considered for the rutting analysis: 0.3, 3, 30, and 60 million ESALs. At each traffic load level, the JMFs designed according to the pre-2018 specification were identified and compared to those designed under the 2018 specifications. For example, at the traffic level of 3 million ESALs, the selected JMFs before the change were RS9.5B, RI19B, and RB25C, while after the change and at the same traffic load level, the selected JMFs will be RS9.5C, RI19C, and RB25C. The JMFs used for comparison at different traffic levels and for different pavement layers are summarized in Figure 4. For the purposes of the comparisons here, a critical rutting testing temperature analysis was defined according to AASHTO TP 134-19 (SSR testing), yielding 48.5°C (119.3°F) as the average critical temperature.

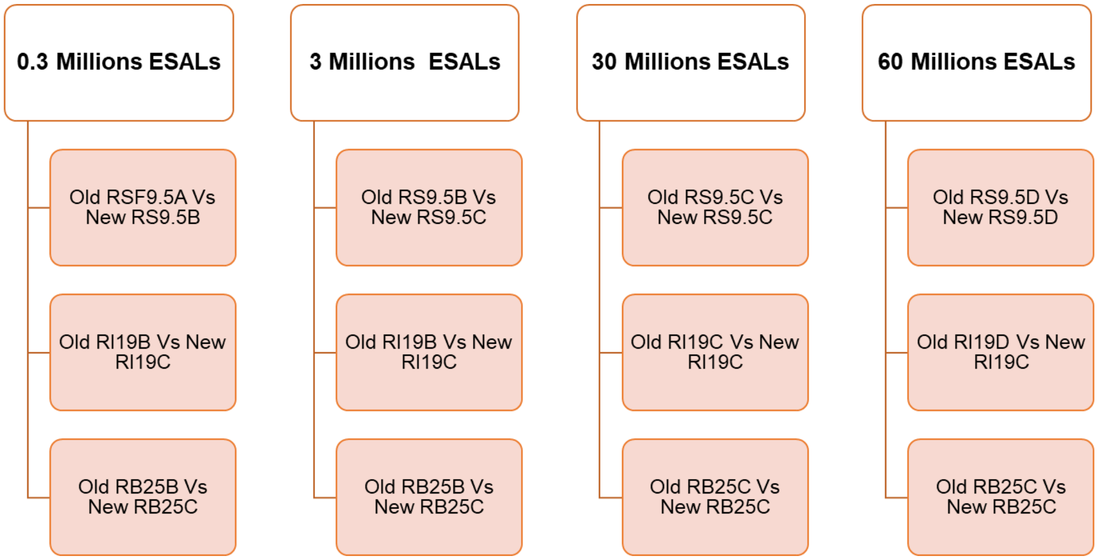

Figure 4. Selected JMFs for evaluation at each traffic load level.

Given the limited nature of the available data within the HiCAMS database (which includes primarily mixture volumetrics), it was challenging to find a recently developed rutting performance prediction model that could be used. However, three different models from the more distant literature that have reportedly good prediction abilities were identified and utilized to predict the rutting performance for the mixtures extracted from the HiCAMS database.

2.7.1. Leahy Model

Leahy (*16*) developed a model to predict the ratio of the cumulative permanent strain to the resilient strain based on the testing results of 251 specimens under dynamic repeated haversine pulse load. The experimental factorial had three asphalt content levels, three stress levels, two binder types, and two aggregate types. Testing was performed on 4-inch diameter specimens, which were evaluated using unconfined repeated load permeant deformation tests. The developed model was as shown in Equation (3) and had a coefficient of determination value (R^2) of 0.76.

$$\log\left(\frac{\varepsilon_p}{\varepsilon_r}\right) = -6.631 + 0.435\log(N) + 2.767\log(T) + 0.110\log(S) + 0.118\log(\eta) + 0.930\log(V_{beff}) + 0.501\log(V_a) \quad (4)$$

where;

ε_p = cumulative permanent strain (in./in.),
ε_r = resilient strain (in./in.),
N = number of load cycles,
T = pavement test temperature (°F),
S = deviator stress (psi),
η = viscosity at 70°F (10^6 poise),
V_{beff} = effective asphalt content (percent by volume), and
V_a = percent air voids.

2.7.2. May and Witczak Model

May and Witczak (*17*) developed an automated asphalt concrete mix analysis system called CAMAS. Leahy's developed improved rutting prediction models were utilized as the default rut depth prediction models in this program. The utilized model had a coefficient of determination value (R^2) of 0.842 and a standard error of estimate (Se) of 0.262 on log scale. The model was as shown in Equation (4). The variables in this model are the same as those defined with the Leahy model.

$$\log\left(\varepsilon_p\right) = -14.97 + 0.408\log(N) + 6.865\log(T) + 1.107\log(S) - 0.117\log(\eta) + 1.908\log(V_{beff}) + 0.971\log(V_a) \quad (5)$$

2.7.3. Kaloush Model

Kaloush (*18*) developed a flow number prediction model in 2001. Modified and conventional binders as well as testing temperatures between 100°F and 130°F were utilized in the model development. The model had a standard error ratio (Se/Sy) of 0.534 with a coefficient of determination value (R^2) of 0.72. The model is shown in Equation (5) and the applicable range of values specified for use in the model were as follows:

1) Test temperatures: 100°F to 130°F.
2) Unconfined Stress levels: 20 psi.
3) η: 0.92 to 26.7 million poise at 70°F.
4) V_{beff}: 7.4 to 14 percent by volume.
5) V_a: 2.5 to 12 percent.
6) Nominal aggregate sizes: 12.5 to 37.5mm.

$$FN = (432367000)T^{-2.215}\eta^{0.312}Vb_{eff}^{\ -2.6604}V_a^{\ -0.1525} \quad (6)$$

where; *FN* = flow number and all other variables are defined the same as in the previous two models.

3. Findings

3.1. Overview

The findings of the research project were mainly based on detailed comparisons. Comparisons relied on visual judgments (comparing the mean values visually from figures) as well as statistical testing. Figure 5 shows the comparison structure followed to draw the research conclusions. The two aspects used for evaluation were mixture composition and predicted mixture performance based on the composition. Under mixture compositions, the change in typical volumetric properties, i.e., VMA, VFA, and AC content, as well as the change in the RBR were evaluated in terms of mean and distribution. The evaluation was conducted by looking at different mix types, regions, and suppliers. For mixture performance, dynamic modulus and rutting predictions were compared. The comparisons were concluded by looking at different mix types and suppliers for different traffic levels, i.e., ESALs.

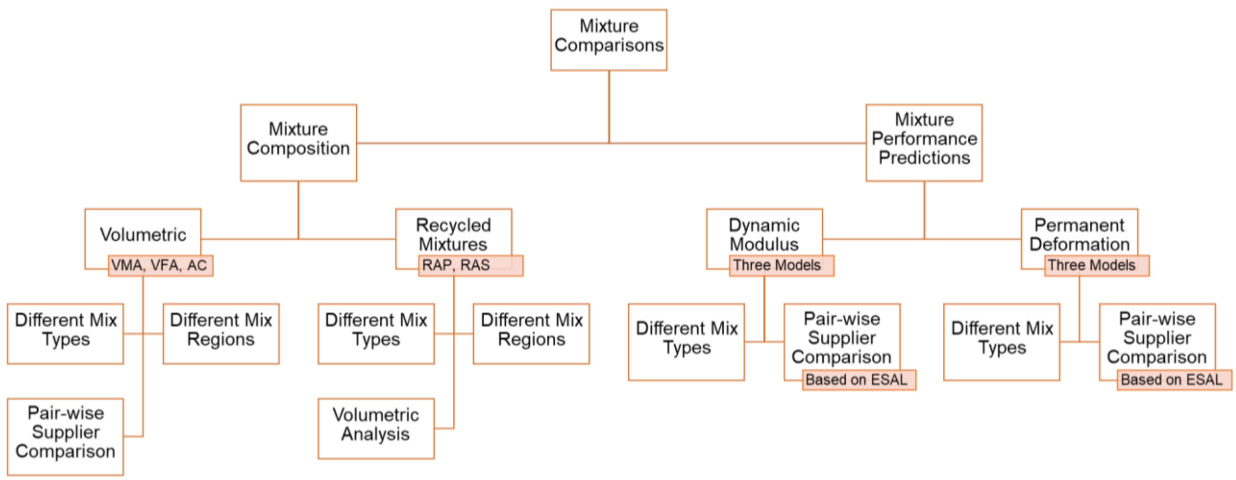

Figure 5. Utilized comparison structure.

3.2. Mixture Composition

3.2.1. Comparisons between Different Mix Types and Regions

The volumetric parameters of VMA, VFA, and total asphalt content (AC) were compared across regions and mix types before and after the 2018 change. Changes were evaluated by first starting to look at the JMF within different regions, and then each JMF type alone was examined, and finally each JMF was examined within each region (when sufficient data were available). The Student's t-test was utilized as the statistical test for this analysis. When conducting the Student's t-tests, only two different levels were considered, before and after the 2018 change. The folded form of the *F* statistic was computed to test for equality of the two group's variances. In the case of unequal variances, the degrees of freedom, as well as the probability level, were calculated based on Satterthwaite's approximation. A significance level of 95% was utilized for the comparisons.

Figure 6 shows the change of VMA between different regions for each JMF category. VMA is considered one of the most important asphalt volumetric properties and is affected by aggregate gradation, binder content, and compaction level. The data in this figure shows that before the 2018 change, the average VMA was consistent across all three regions of the state. However, after the change, the average VMA was higher in the Mountain region compared to the Piedmont and Coastal regions. This regional difference as well as the differences before and after the 2018 change is relatively small, especially considering the variation across the mixture types in the region. Figure 7 through Figure 9 show the changes in VMA for each mix type.

When interpreting the data shown in Figure 7 through Figure 9, it is important to keep in mind the remapping embedded within the JMF designations. Section 3.2.2 provides detailed comparisons with respect to the volumetrics of mixtures used under equivalent traffic conditions before and after the 2018 change. To better understand the "1.Before 2018 Change" series shown in Figure 7 through Figure 9, tables showing the number of JMFs according to old naming (pre-2018 change) that are included within the new naming shown in the figures (after 2018 change) were developed. Tables 7 and 8 show the distribution of before 2018 change mix types considered in the analysis for surface mixtures and the combination of base and intermediate mixtures, respectively. For example, Table 7 shows that the pre-2018 change series for RS9.5B(2018) (Figure 9) contains 181 different RSF9.5A mixtures that were designed pre-2018 change. Also, it shows that the pre-2018 change series for RS9.5C (Figure 9) is a combination of 213 RS9.5B and 269 RS9.5C mixtures that were designed pre-2018 change. This approach to grouping the mixture's was taken for the analysis results shown in this section because the new surface "C" mixtures have essentially the same specification as the pre-2018 "B" mixtures, but are now allowed on roadways with higher cumulative ESALs. Also, the same applies to the new surface "B" mixtures that have the same specification as the pre-2018 A mixtures. The pre-2018 "A mix" was applicable to traffic levels less than 0.3 million ESALs while the new "B mix" is applicable to traffic levels between 0 and 3 million ESALs. In the next section, direct comparisons of surface mixture volumetrics based on the applicable traffic levels is presented.

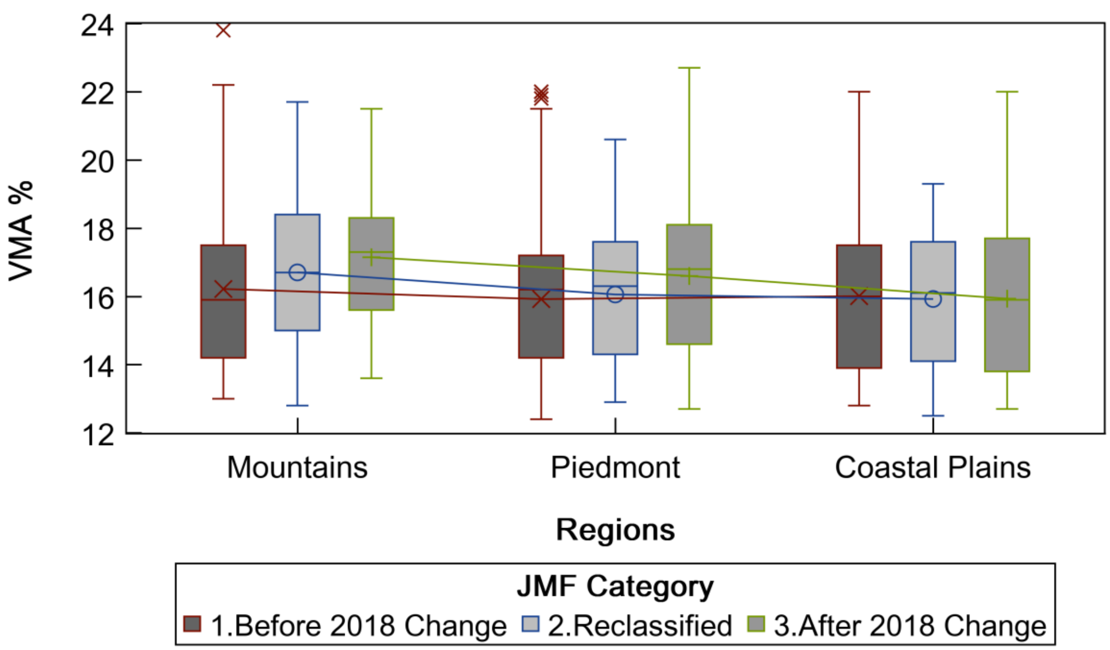

Figure 6. Change of VMA between different regions for each JMF category.

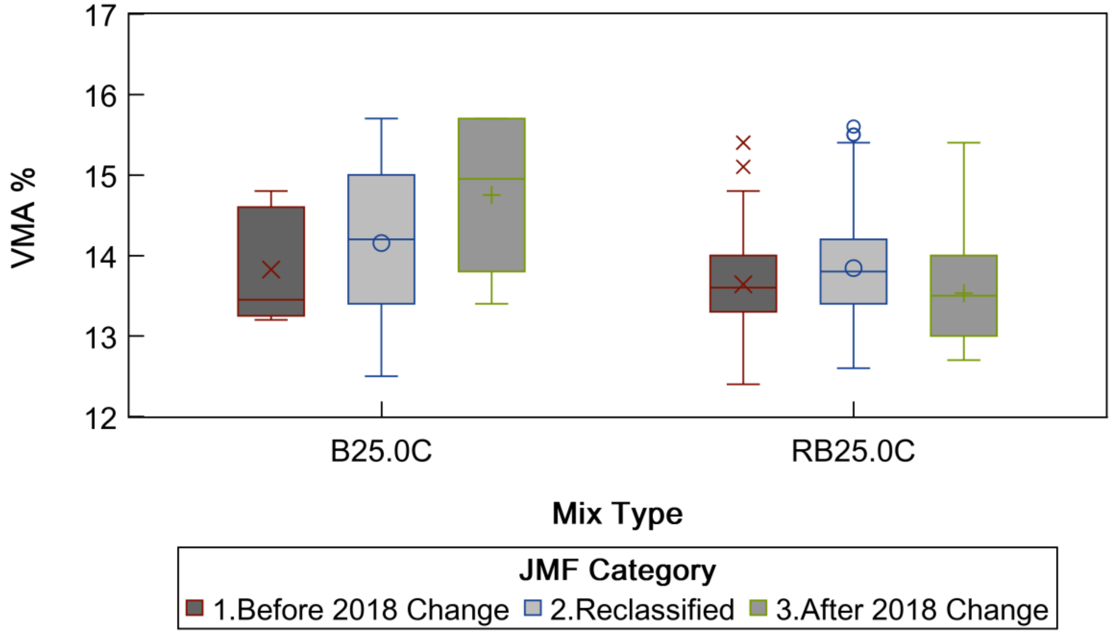

Figure 7. Change of VMA in base mixes for each JMF category (*Refer to Table 8 for counts details).

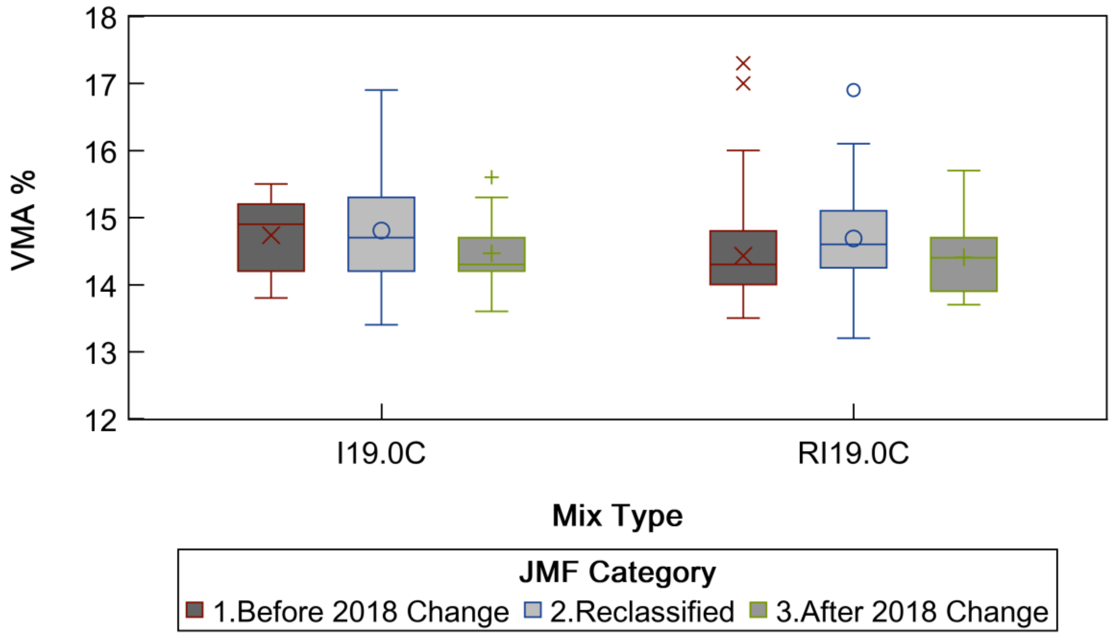

Figure 8. Change of VMA in intermediate mixes for each JMF category (*Refer to Table 8 for counts details).

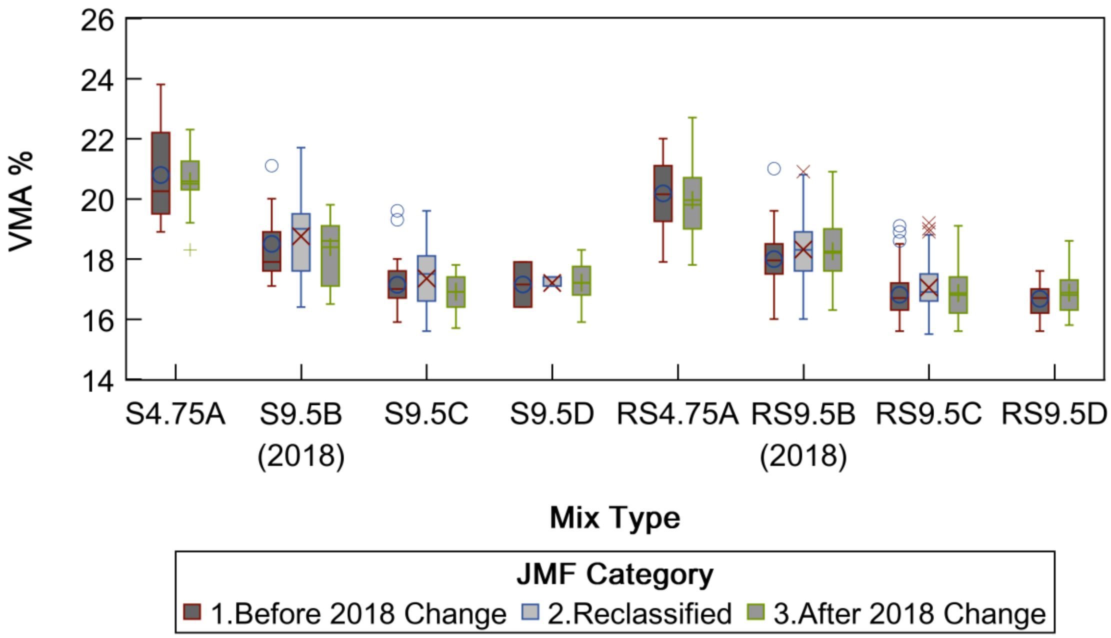

Figure 9. Change of VMA in surface mixtures for each JMF category (*Refer to Table 7 for count details).

Table 7. Distribution of Before 2018 Change mix types considered in the analysis for surface mixtures.

Mix Type-2018 (Used in Figures)	Pre-2018 Mix Type (Counts)									
	SF9.5A	S9.5			S4.75A	RSF9.5A	RS9.5			RS4.75A
		B	C	D			B	C	D	
S9.5B(2018)	9	0	0	0	0	0	0	0	0	0
S9.5C	0	10	20	0	0	0	0	0	0	0
S9.5D	0	0	0	2	0	0	0	0	0	0
S4.75A	0	0	0	0	10	0	0	0	0	0
RS9.5B(2018)	0	0	0	0	0	181	0	0	0	0
RS9.5C	0	0	0	0	0	0	213	269	0	0
RS9.5D	0	0	0	0	0	0	0	0	41	0
RS4.75A	0	0	0	0	0	0	0	0	0	93
Total	9	10	20	2	10	181	213	269	41	93

Table 8. Distribution of Before 2018 Change mix types considered in the analysis for base and intermediate mixtures.

Mix Type-2018 (Used in Figures)	Pre-2018 Mix Type (Counts)							
	B25		I19.0		RB25		RI19.0	
	B	C	B	C	B	C	B	C
B25.0C	3	5	0	0	0	0	0	0
I19.0C	0	0	8	7	0	0	0	0
RB25.0C	0	0	0	0	124	172	0	0
RI19.0C	0	0	0	0	0	0	152	215
Total	3	5	8	7	124	172	152	215

Further analysis and statistical testing were conducted on the basis of mix designation and the results are shown in Table 9. Most of the average mean differences in the VMA were less than 0.5 percent with the highest being around 0.9 percent. Even though some of those differences were statistically significant, all differences were less than one percent, which make those differences unsubstantial from an engineering point of view, i.e., a mean difference of 0.26 percent for the RS9.5B (2018) mix is expected to yield no notable change in performance even if it is statistically significant. Since some of the evaluated mean differences were statistically significant but not practically significant, the different mix types within each region were evaluated before and after the 2018 change. This was done to further evaluate the practical and statistical significant of differences imposed by the specification changes. As shown in Table 10, all the evaluated differences are regarded as unsubstantial from a practical engineering perspective since the VMA NCDOT control limit for mix production is 1%.

Table 9. VMA variable student t-test results for each mix type.

	Mean Difference		Mean Variance Test	t-test Results			
Mix Type	**Difference**	**JMF with Higher Value**	**Pr > |F|**	**t-test Method**	**DF**	**Pr > |t|**	**Sig.?**
B25.0C	-0.9250	After 2018 Change	0.2802	Pooled	10	0.1127	No
RB25.0C	**0.1102**	**Before 2018 Change**	**0.0118**	**Satterthwaite**	**340**	**0.0318**	**Yes**
I19.0C	0.2690	Before 2018 Change	0.4924	Pooled	27	0.2044	No
RI19.0C	0.0229	Before 2018 Change	0.0029	Satterthwaite	397	0.6309	No
S9.5B(2018)	0.1091	Before 2018 Change	0.6449	Pooled	18	0.8437	No
RS9.5B(2018)	**-0.2571**	**After 2018 Change**	**0.9943**	**Pooled**	**347**	**0.0035**	**Yes**
S9.5C	0.2309	Before 2018 Change	0.3740	Pooled	39	0.4286	No
RS9.5C	-0.0570	After 2018 Change	0.0016	Satterthwaite	318	0.3648	No
S9.5D	-0.0625	After 2018 Change	0.4331	Pooled	8	0.9257	No
RS9.5D	-0.2061	After 2018 Change	0.0718	Pooled	83	0.1342	
S4.75A	0.2087	Before 2018 Change	0.0539	Pooled	24	0.6822	No
RS4.75A	0.2232	Before 2018 Change	0.3695	Pooled	163	0.2130	No

A similar analysis was conducted for both VFA and asphalt content (AC). Like the analysis for VMA, the results suggested that mixes among different regions had an almost similar average value of VFA and AC before the change while after the change the Mountains had slightly higher average values of both. This result was in line with what was found for VMA analysis. The figures and tables related to these volumetric properties are presented in Appendix B.

Table 10. VMA variable student t-test results for each mix type within each region.

Mix Type*	Region	Mean Difference+	Mean Variance Test		t-test Results		
			Pr > |F|	t-test Method	DF	Pr > |t|	Sig.?
B25.0C	**Mountains**	**-1.6667**	**<.0001**	**Satterthwaite**	**5**	**0.0023**	**Yes**
RB25.0C	**Coastal**	**0.2609**	**0.0599**	**Pooled**	**204**	**0.0002**	**Yes**
	Mountains	-0.5694	0.6213	Pooled	35	0.0610	No
	Piedmont	-0.2093	0.5430	Pooled	228	0.0022	Yes
I19.0C	Coastal	0.2067	0.0855	Pooled	12	0.3901	No
	Mountains	-0.3700	0.5753	Pooled	5	0.4068	No
	Piedmont	0.1750	0.3817	Pooled	6	0.6515	No
RI19.0C	Coastal	-0.0145	0.0424	Satterthwaite	204	0.8192	No
	Mountains	0.0725	0.0109	Satterthwaite	38	0.7238	No
	Piedmont	**-0.1795**	**0.2120**	**Pooled**	**277**	**0.0100**	**Yes**
S9.5B(2018)	Coastal	-0.0700	0.5969	Pooled	5	0.9192	No
	Piedmont	-0.6200	0.3110	Pooled	8	0.2256	No
RS9.5B(2018)	**Coastal**	**-0.5414**	**0.2464**	**Pooled**	**149**	**<.0001**	**Yes**
	Mountains	0.2133	0.7653	Pooled	22	0.6094	No
	Piedmont	**-0.3055**	**0.3371**	**Pooled**	**172**	**0.0123**	**Yes**
S9.5C	Coastal	0.4400	0.4806	Pooled	8	0.3828	No
	Mountains	-0.0333	0.1557	Pooled	3	0.9495	No
	Piedmont	-0.0217	0.5710	Pooled	24	0.9677	No
RS9.5C	Coastal	0.0638	0.1662	Pooled	234	0.5316	No
	Mountains	-0.1857	0.7164	Pooled	58	0.3044	No
	Piedmont	**-0.2478**	**0.3774**	**Pooled**	**376**	**0.0009**	**Yes**
S9.5D	Piedmont	0.2667	0.2480	Pooled	6	0.6480	No
RS9.5D	Coastal	-0.0470	0.4854	Pooled	20	0.8724	No
	Mountains	-0.6889	0.9706	Pooled	9	0.3019	No
	Piedmont	-0.1536	0.3754	Pooled	50	0.3432	No
S4.75A	**Mountains**	**2.3905**	**0.8547**	**Pooled**	**8**	**0.0149**	**Yes**
	Piedmont	-0.2625	0.4661	Pooled	10	0.6266	No
RS4.75A	Coastal	0.3284	0.1410	Pooled	105	0.1695	No
	Piedmont	-0.1580	0.9802	Pooled	48	0.5684	No

+Negative if JMFs after 2018 change had higher average mean value.

*Comparisons were only performed by mix type and region when at least three different mixes for the mix type in the region were available before and after the change.

3.2.2. Comparisons of Surface Mixtures at Different Equivalent Single Axle Load (ESAL)

The previous comparisons were conducted considering the mixture remapping introduced by the 2018 change, i.e., the specification of pre-2018 change RS9.5B mixture is the same as the specification of post-2018 change RS9.5C mixture. However, RS9.5B and RS9.5C were specified to serve under two different traffic levels, i.e., the new surface "C" mixtures have the same specification as the pre-2018 "B" mixtures, but are now allowed on roadways with higher cumulative ESALs. To further assess the differences invoked by the specification changes, if any, additional comparisons at three different traffic levels were conducted by comparing pre-2018 to post-2018 mixture types at specific traffic levels as follows:

1) Less than 0.3 million ESAL: Pre-2018 SF9.5A vs post-2018 S9.5B(2018)
2) From 0.3 to 3 million ESAL: Pre-2018 S9.5B vs post-2018 S9.5B(2018)
3) From 3 to 30 million ESAL: Pre-2018 S9.5C vs post-2018 S9.5C

Figures 10, 11, and 12 show the comparison results for traffic levels less the 0.3 million ESAL, between 0.3 and 3 million ESAL, and between 3 and 30 million ESAL respectively. In addition, Table 11 shows the Student's t-test results for the same comparisons. Figure 10 shows that there is almost no difference in the mean value of VMA for surface mixtures placed on roadways with less than 0.3 million ESALs. From Table 11, the mean difference in VMA observed is 0.17, which is statistically significant, but its magnitude is not practically significant. Figure 11 shows that the mean VMA value for surface mixes placed on roadways with between 0.3 and 3 million ESALs was higher after the 2018 change (RS9.5B(2018) versus RS9.5B pre-2018 change. This mean VMA difference of 1.37 was found to be statistically significant as shown in Table 11. Since the VMA change was statistically significant, it is also worth noting that on average the mean asphalt content has increased by 0.70% for the 0.3-3 million ESALs roadways (see detailed analysis in Appendix B). There was almost no difference in the mean VMA value for the surface mixes to be placed on roadways with traffic volumes between 3 and 30 million ESALs as shown in Figure 12. From Table 11, the difference was found to be statistically insignificant. A similar analysis was conducted for both VFA and AC. The results were in line with what was found for VMA analysis. The figures and tables related to these volumetric properties are presented in Appendix B.

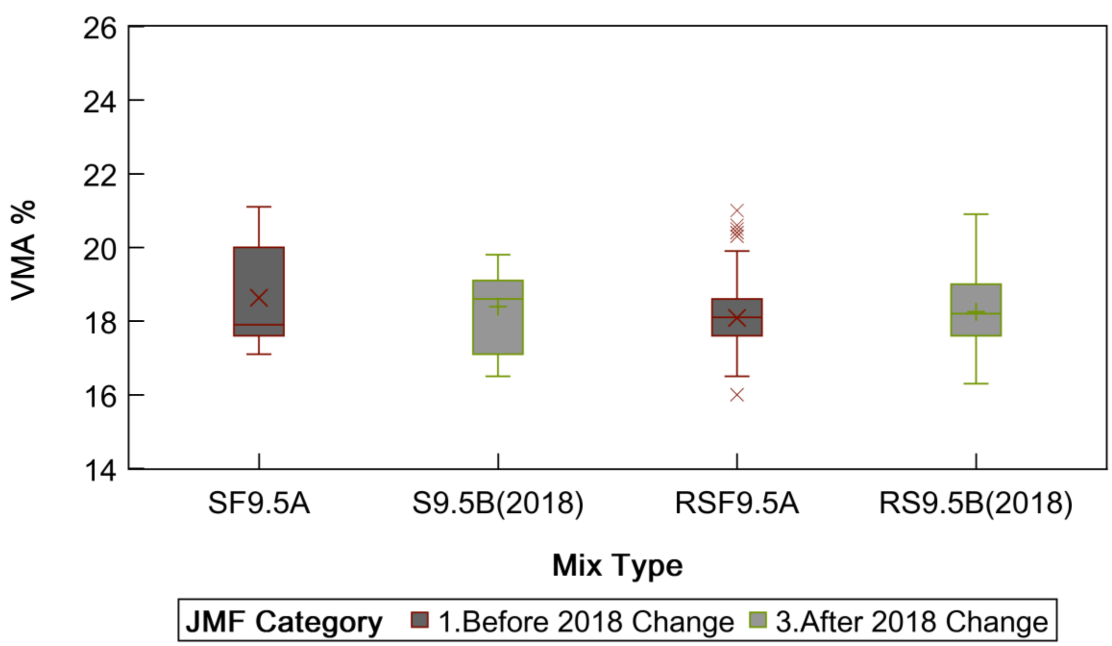

Figure 10. Change of VMA in surface mixtures for less than 0.3 million ESAL.

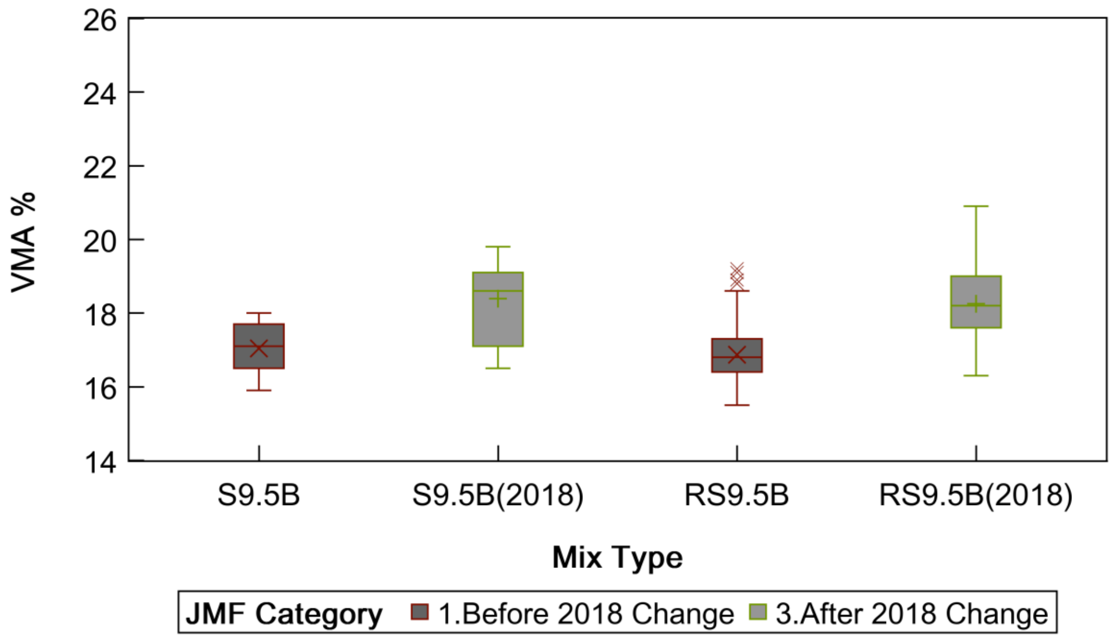

Figure 11. Change of VMA in surface mixtures from 0.3 to 3 million ESAL.

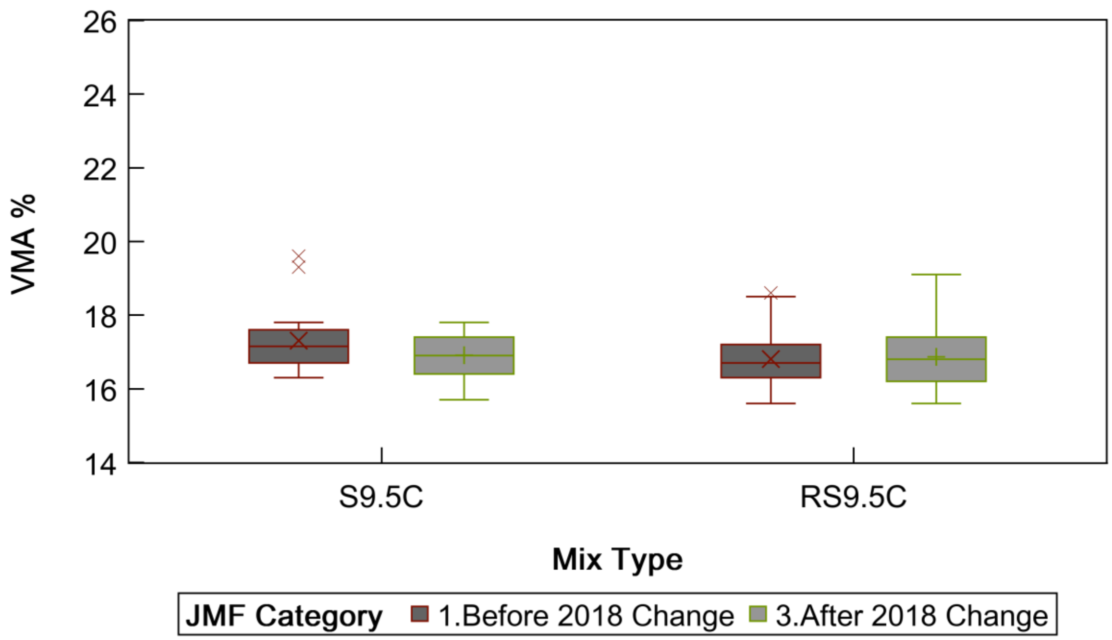

Figure 12. Change of VMA in surface mixtures from 3 to 30 million ESAL.

Table 11. VMA t-test results for surface mixtures at different ESAL levels.

Traffic Category	JMF Type	Difference+	Pr > |F|	DF	Pr > |t|	Sig.?
< 0.3 Million ESALs	**RSF9.5A vs RS9.5B(2018)**	**0.17**	**0.9521**	**562.0000**	**0.0270**	**Yes**
	SF9.5A vs S9.5B(2018)	-0.20	0.5094	29.0000	0.6676	No
0.3 – 3 Million ESALs	**RS9.5B vs RS9.5B(2018)**	**1.37**	**0.0010**	**271.5067**	**<.0001**	**Yes**
	S9.5B vs S9.5B(2018)	**1.35**	**0.1161**	**29.0000**	**0.0002**	**Yes**
3 – 30 Million ESALs	RS9.5C vs RS9.5C(2018)	0.04	0.0112	409.0958	0.5141	No
	S9.5C vs S9.5C(2018)	-0.35	0.3162	30.0000	0.2470	No

+Negative if JMFs before 2018 change had higher average mean value.

3.2.3. Pair-wise Supplier Comparisons Student t-test

Mix groupings by supplier were conducted as discussed under the methodology section. Supplier names were kept anonymous even during the research project meetings and presentations. VMA, VFA, and total AC content for RB25C, RI19C, RS4.75A, RS9.5B(2018), and RS9.5C were evaluated for the selected number of suppliers JMFs before and after the change. As shown in Table 12 almost all of the average mean differences for the pre and post-2018 mix design changes in terms of VMA were less than 0.2 percent with the highest being 1.0 percent. Even though some of those differences were statistically significant, all differences were less than one percent, which make those differences practically insignificant. The analysis tables for the VMA, VFA and total AC contents led to similar conclusions and are presented in Appendix B.

Table 12. Selected suppliers VMA t-test results for RS9.5C JMF type.

Supplier Code	JMF Type	Difference+	Pr > |F|	Variances	t Value	DF	Pr > |t|	Sig.?
AS-15	RS9.5C	-0.1333	0.7647	Equal	-0.6860	4	0.5304	No
AS-21	RS9.5C	0.1167	1.0000	Equal	0.3531	7	0.7344	No
AS-40	RS9.5C	-0.1000	<.0001	Unequal	-0.1176	2	0.9171	No
AS-45	RS9.5C	-0.1611	0.7964	Equal	-1.0955	11	0.2967	No
AS-60	RS9.5C	0.4222	0.2310	Equal	1.7307	12	0.1091	No
AS-92	**RS9.5C**	**-1.0000**	**0.3491**	**Equal**	**-3.3845**	**9**	**0.0081**	**Yes**
AS-130	RS9.5C	-0.7533	0.3265	Equal	-1.8073	6	0.1207	No
AS-135	RS9.5C	0.0534	0.8447	Equal	0.7499	25	0.4603	No
AS-141	RS9.5C	-0.1714	0.5300	Equal	-1.2932	18	0.2123	No
AS-153	RS9.5C	0.1667	0.9143	Equal	0.8452	4	0.4456	No

+Negative if JMFs after 2018 change had higher average mean value.

3.3. Recycled Binder Replacement

3.3.1. Classification and Distribution among Mix Types and Regions

In the 2018 QMS manual, the recycled content guidance was modified to RBR% instead of RAP and RAS contents. While examining the extracted data, the research team noticed inconsistent naming of the mixes containing recycled binder. Some of the RAP mixes that contained fractionated RAP included entries in both the RAP and RAS asphalt content fields. The AC from RAS and in some cases from fine or coarse RAP was placed in the other AC field in the HiCAMS database. To overcome these inconsistencies, the research team applied a classification algorithm and added a new recycled material classification field to the research database as follows:

1) Fractionated RAP Mix (fine RAP was identified in the "RAS" field whenever the AC content indicated was less than 8%)
2) RAP Mix
3) RAP/RAS Mix
4) RAS Mix
5) Virgin Mix

The distribution of the recycled material classification among surface, intermediate, and base mixes for the study data are shown in Table 13. From this table, it may be concluded that the majority of the mixes contained RAP (61.4%), the highest proportion of these are surface mixes, and that the RAP/RAS mixes are used more than fractionated RAP mixes (18.5% vs 11.0%). Finally, only 7.7% of the mixes in the database had neither RAP nor RAS. In other words, the majority of the designed and constructed mixes (92.3%) in the State of North Carolina contained recycled binder.

Table 13. Distribution of recycled material classification among different mix types.

Recycled Material Classification	Number of JMF by Category (Percent of JMF by Category)			
	Base Mix	Intermediate Mix	Surface Mix	Total
Fractionated RAP Mix	93 (2.0)	154 (3.3)	267 (5.7)	514 (11.0)
RAP Mix	608 (13.0)	672 (14.7)	1589 (34.0)	2869 (61.4)
RAP/ RAS Mix	173 (3.7)	216 (4.6)	474 (10.2)	863 (18.5)
RAS Mix	9 (0.2)	7 (0.2)	48 (1.0)	64 (1.4)
Virgin Mix	53 (1.1)	90 (1.9)	217 (4.7)	360 (7.7)
Total	936 (20.0)	1139 (24.4)	2595 (55.6)	4670 (100.0)

Figure 13 shows the distribution of recycled material mixes among the main three regions within North Carolina. Non-fractionated RAP only mixtures are most prevalent in all regions. In the Coastal Plains and Mountains region, the RAP/RAS mix type second most common and in the Piedmont it was the fractionated RAP mix type. It can also be seen that mixtures containing only RAS were confined to the Coastal Plains region.

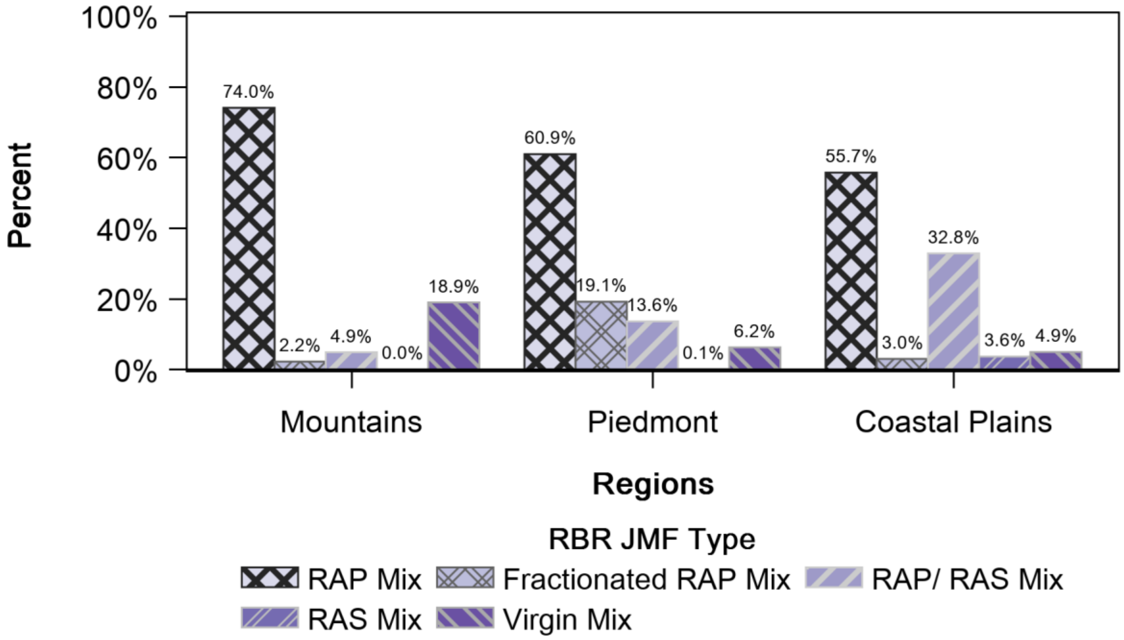

Figure 13. Distribution of recycled material classification among different regions.

3.3.2. Distribution among Different Divisions

The geographical distribution of the RBR in JMFs is shown in Table 14. Mixtures are separated according to whether they are a RAP mix (containing only a single RAP stockpile in the mixture), fractionated RAP mix (including a fine and coarse RAP stockpile), RAP/RAS mix (containing both RAP and RAS), RAS mix (containing RAS only), or virgin mix (having no recycled content). Division 5 (Wake, Franklin, Durham, Granville, Vance, Warren, and Person counties) had the highest presence of the RAP modified mixes at 6.9% rate while Division 10 (Union, Cabarrus, Anson, Mecklenburg, and Stanly counties) ranked the highest in the presence of fractionated RAP mixes at a rate of 4.1%. The highest presence of RAP/RAS and RAS mixes was in Division 1 (Camden, Gates, Martin, Hyde, Dare, Tyrrell, Washington, Bertie, Chowan, Perquimans, Currituck, Pasquotank, Northampton, and Hertford counties) at rates of 3.5% and 0.8%, respectively.

The effect of the introduced changes in year 2018 on the distribution of the RBR modified JMFs was evaluated for each type of RBR modification separately as shown in Table 15 through Table 18 for RAP, fractionated RAP, RAP/ RAS, and RAS modified mixes respectively. It is interesting to note that Division 1 is one of the divisions that showed substantial changes in the RBR distributions pre- versus post-2018. For instance, RAP mixes have the highest presence after the 2018 change in Division 1. Also, RAP/RAS and RAS mixes jumped from 2.3% and 6.3% to 11.4% and 34.4%, respectively after the 2018 change. Finally, before the 2018 change, Division 1 did not have any fractionated RAP mixes while after the change, four new JMFs were utilized. It is worth mentioning that within the 14 Divisions, only Divisions 1, 2, 4, and 8 had RAS mixes.

Table 14. RBR Job mix formulas distribution by divisions.

Divisions	Number of JMF by Division (Percent of JMF by Division)				
	RAP Mix	Fractionated RAP Mix	RAP/ RAS Mix	RAS Mix	Unmodified Mix
Division 1	231 (5.0%)	4 (0.1%)	161 (3.5%)	36 (0.8%)	14 (0.3%)
Division 2	204 (4.4%)	1 (0.0%)	145 (3.1%)	2 (0.0%)	25 (0.5%)
Division 3	122 (2.6%)	15 (0.3%)	66 (1.4%)	0 (0.0%)	3 (0.1%)
Division 4	166 (3.6%)	26 (0.6%)	95 (2.0%)	19 (0.4%)	4 (0.1%)
Division 5	321 (6.9%)	131 (2.8%)	58 (1.2%)	0 (0.0%)	28 (0.6%)
Division 6	143 (3.1%)	0 (0.0%)	42 (0.9%)	0 (0.0%)	30 (0.6%)
Division 7	217 (4.7%)	16 (0.3%)	109 (2.3%)	0 (0.0%)	11 (0.2%)
Division 8	154 (3.3%)	81 (1.7%)	83 (1.8%)	3 (0.1%)	27 (0.6%)
Division 9	224 (4.8%)	3 (0.1%)	42 (0.9%)	0 (0.0%)	1 (0.0%)
Division 10	239 (5.1%)	191 (4.1%)	19 (0.4%)	0 (0.0%)	39 (0.8%)
Division 11	234 (5.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	44 (0.9%)
Division 12	181 (3.9%)	19 (0.4%)	0 (0.0%)	0 (0.0%)	15 (0.3%)
Division 13	184 (3.9%)	0 (0.0%)	30 (0.6%)	0 (0.0%)	20 (0.4%)
Division 14	130 (2.8%)	15 (0.3%)	3 (0.1%)	0 (0.0%)	82 (1.8%)
Out of State	119 (2.6%)	12 (0.3%)	10 (0.2%)	4 (0.1%)	17 (0.4%)
Total	**2869 (61.4%)**	**514 (11.0%)**	**863 (18.5%)**	**64 (1.4%)**	**360 (7.7%)**

Table 15. RAP job mix formulas distribution by divisions before and after 2018 change.

Divisions	Number of JMF by Division (Percent of JMF by Division)		
	RAP Mix Before 2018 Change	RAP Mix Reclassified	RAP Mix After 2018 Change
Division 1	32 (1.1%)	100 (3.5%)	99 (3.5%)
Division 2	79 (2.8%)	72 (2.5%)	53 (1.9%)
Division 3	50 (1.7%)	48 (1.7%)	24 (0.8%)
Division 4	62 (2.2%)	59 (2.1%)	45 (1.6%)
Division 5	115 (4.0%)	152 (5.3%)	54 (1.9%)
Division 6	38 (1.3%)	66 (2.3%)	39 (1.4%)
Division 7	81 (2.8%)	93 (3.2%)	43 (1.5%)
Division 8	46 (1.6%)	90 (3.1%)	18 (0.6%)
Division 9	96 (3.4%)	97 (3.4%)	31 (1.1%)
Division 10	108 (3.8%)	96 (3.4%)	35 (1.2%)
Division 11	50 (1.7%)	170 (5.9%)	14 (0.5%)
Division 12	26 (0.9%)	123 (4.3%)	32 (1.1%)
Division 13	55 (1.9%)	99 (3.5%)	30 (1.1%)
Division 14	19 (0.7%)	98 (3.4%)	13 (0.5%)
Out of State	23 (0.8%)	75 (2.6%)	21 (0.7%)
Total	**880 (30.7%)**	**1438 (50.1%)**	**551 (19.2%)**

Table 16. Fractionated RAP job mix formulas distribution by divisions before and after 2018 change.

Divisions	Number of JMF by Division (Percent of JMF by Division)		
	Fractionated RAP Mix Before 2018 Change	**Fractionated RAP Mix Reclassified**	**Fractionated RAP Mix After 2018 Change**
Division 1	0 (0.0%)	0 (0.0%)	4 (0.8%)
Division 2	0 (0.0%)	0 (0.0%)	1 (0.2%)
Division 3	6 (1.1%)	7 (1.4%)	2 (0.4%)
Division 4	12 (2.3%)	14 (2.7%)	0 (0.0%)
Division 5	83 (16.1%)	34 (6.6%)	14 (2.7%)
Division 6	0 (0.0%)	0 (0.0%)	0 (0.0%)
Division 7	0 (0.0%)	8 (1.6%)	8 (1.6%)
Division 8	25 (4.9%)	50 (9.7%)	6 (1.2%)
Division 9	0 (0.0%)	0 (0.0%)	3 (0.6%)
Division 10	129 (25.1%)	44 (8.6%)	18 (3.5%)
Division 11	0 (0.0%)	0 (0.0%)	0 (0.0%)
Division 12	8 (1.6%)	3 (0.6%)	8 (1.6%)
Division 13	0 (0.0%)	0 (0.0%)	0 (0.0%)
Division 14	8 (1.6%)	6 (1.2%)	1 (0.2%)
Out of State	4 (0.8%)	5 (1.0%)	3 (0.6%)
Total	**275 (53.5%)**	**171 (33.3%)**	**68 (13.2%)**

Table 17. RAP/ RAS job mix formulas distribution by divisions before and after 2018 change.

Divisions	Number of JMF by Division (Percent of JMF by Division)		
	RAP/ RAS Mix Before 2018 Change	**RAP/ RAS Mix Reclassified**	**RAP/ RAS Mix After 2018 Change**
Division 1	20 (2.3%)	43 (5.0%)	98 (11.4%)
Division 2	69 (8.0%)	39 (4.5%)	37 (4.3%)
Division 3	31 (3.6%)	25 (2.9%)	10 (1.2%)
Division 4	46 (5.3%)	34 (3.9%)	15 (1.7%)
Division 5	34 (3.9%)	11 (1.3%)	13 (1.5%)
Division 6	12 (1.4%)	17 (2.0%)	13 (1.5%)
Division 7	63 (7.3%)	31 (3.6%)	15 (1.7%)
Division 8	31 (3.6%)	39 (4.5%)	13 (1.5%)
Division 9	30 (3.5%)	12 (1.4%)	0 (0.0%)
Division 10	12 (1.4%)	4 (0.5%)	3 (0.4%)
Division 11	0 (0.0%)	0 (0.0%)	0 (0.0%)
Division 12	0 (0.0%)	0 (0.0%)	0 (0.0%)
Division 13	17 (2.0%)	12 (1.4%)	1 (0.1%)
Division 14	0 (0.0%)	3 (0.4%)	0 (0.0%)
Out of State	3 (0.4%)	1 (0.1%)	6 (0.7%)
Total	**368 (42.6%)**	**271 (31.4%)**	**224 (26.0%)**

Table 18. RAS Job mix formulas distribution by divisions before and after 2018 change.

Divisions	Number of JMF by Division (Percent of JMF by Division)		
	RAS Mix Before 2018 Change	**RAS Mix Reclassified**	**RAS Mix After 2018 Change**
Division 1	4 (6.3%)	10 (15.6%)	22 (34.4%)
Division 2	2 (3.1%)	0 (0.0%)	0 (0.0%)
Division 3	0 (0.0%)	0 (0.0%)	0 (0.0%)
Division 4	3 (4.7%)	8 (12.5%)	8 (12.5%)
Division 5	0 (0.0%)	0 (0.0%)	0 (0.0%)
Division 6	0 (0.0%)	0 (0.0%)	0 (0.0%)
Division 7	0 (0.0%)	0 (0.0%)	0 (0.0%)
Division 8	0 (0.0%)	3 (4.7%)	0 (0.0%)
Division 9	0 (0.0%)	0 (0.0%)	0 (0.0%)
Division 10	0 (0.0%)	0 (0.0%)	0 (0.0%)
Division 11	0 (0.0%)	0 (0.0%)	0 (0.0%)
Division 12	0 (0.0%)	0 (0.0%)	0 (0.0%)
Division 13	0 (0.0%)	0 (0.0%)	0 (0.0%)
Division 14	0 (0.0%)	0 (0.0%)	0 (0.0%)
Out of State	0 (0.0%)	0 (0.0%)	4 (6.3%)
Total	**9 (14.1%)**	**21 (32.8%)**	**34 (53.1%)**

3.3.3. Volumetric Analysis

More than 90% of mixes designed in the State of North Carolina contain recycled binder. In order to evaluate the changes in the breakdown of different RBR categories produced and the corresponding properties, the RBR mixes were analyzed under the five main categories discussed earlier. Analysis was completed along a few different factors.

- RAP Mix % - refers to the average amount of RAP in the mixture as a percentage of total mass (RAP and RAP/RAS categories).
- Fine RAP Mix % - refers to the average amount of fine RAP in the mixture as a percentage of total mass (Fractionated RAP category only).
- Coarse RAP Mix % - refers to the average amount of coarse RAP in the mixture as a percentage of total mass (Fractionated RAP category only).
- RAS Mix % - refers to the average amount of RAS in the mixture as a percentage of total mass (RAS and RAP/RAS categories).
- Virgin Mix %- refers to the average amount of virgin mix in the mixture as a percentage of total mass (determined for the RAP, Fractionated RAP and RAP/RAS categories).
- AC in RAP %- refers to the average asphalt content of RAP mix as a percentage of total RAP mix mass (RAP and RAP/RAS categories).
- AC in Fine RAP % - refers to the average asphalt content of fine RAP in the mixture as a percentage of total fine RAP mix mass (Fractionated RAP category only).
- AC in Coarse RAP % - refers to the average asphalt content of coarse RAP in the mixture as a percentage of total coarse RAP mix mass (determined for the Fractionated RAP category only).

- AC in RAS % - refers to the average asphalt content of RAS in the mixture as a percentage of total RAS mix mass (RAS and RAP/RAS categories).
- AC from RAP % - refers to the average percent contribution made to the total asphalt content of the mix from RAP mix (RAP and RAP/RAS categories).
- AC from Fine RAP% - refers to the average percent contribution made to the total asphalt content of the mix from fine RAP mix (Fractionated RAP category only).
- AC from Coarse RAP % - refers to the average percent contribution made to the total asphalt content of the mix from coarse RAP mix (Fractionated RAP category only).
- AC from RAS % - refers to the average percent contribution made to the total asphalt content of the mix from RAS mix (RAS and RAP/RAS categories).
- Virgin AC % - refers to the average percent contribution made to the total asphalt content of the mix from Virgin mix (RAP, Fractionated RAP, RAS, and RAP/RAS categories).
- Total AC % - refers to the average asphalt content the mixture as a percentage of total mix mass (all the categories).

As shown in Table 19, for RAP modified mixture, the mean RAP mix % was lower after the 2018 change while the Virgin Mix % was higher after the change. These differences also mean that the Virgin AC% was higher after the change (on average) than it was before. Having higher virgin AC and lower RAP AC may introduce an improvement to the mix performance. In the fractionated RAP mixes, mean coarse RAP mix % decreased while means fine RAP mix % and Virgin mix % increased after the 2018 change as shown in Table 20.

Table 19. RAP mix statistics for each JMF category.

JMF Category	Property	N	Mean	Std Dev
Before 2018 Change	RAP Mix %	822	24.55	6.81
	Virgin Mix %	822	75.45	6.81
	AC in RAP %	822	4.93	0.47
	AC from RAP %	822	1.21	0.36
	Virgin AC %	822	4.14	1.02
	Total AC %	822	5.36	0.93
After 2018 Change	RAP Mix %	530	22.57	6.70
	Virgin Mix %	530	77.37	6.72
	AC in RAP %	530	4.98	0.47
	AC from RAP %	530	1.12	0.33
	Virgin AC %	530	4.43	0.99
	Total AC %	530	5.55	0.95

Table 21, for RAP/RAS modified mixtures, shows an increase in the mean proportion of RAS mix % and a decrease in the mean proportion RAP mix % after the 2018 change. As for the RAS modified only mix, Table 23 shows a decrease in the mean proportion of RAS mix % after the 2018 change. Finally, for the virgin mixes, the mean virgin AC % was increased after the 2018 change as shown in Table 22.

Table 20. Fractionated RAP mix statistics for each JMF category.

JMF Category	Property	N	Mean	Std Dev
Before 2018 Change	Fine RAP Mix %	254	20.23	6.88
	Coarse RAP Mix %	254	14.45	5.89
	Virgin %	254	65.32	4.94
	AC in Fine RAP %	254	5.41	0.43
	AC in Coarse RAP %	254	3.35	0.66
	AC from Fine RAP %	254	1.09	0.40
	AC from Coarse RAP %	254	0.50	0.27
	Virgin AC %	254	3.49	0.69
	Total AC %	254	5.08	0.75
After 2018 Change	Fine RAP Mix %	65	21.32	5.50
	Coarse RAP Mix %	65	12.14	4.21
	Virgin Mix %	65	66.54	7.36
	AC in Fine RAP %	65	5.18	0.98
	AC in Coarse RAP %	65	3.14	0.88
	AC from Fine RAP %	65	1.15	0.35
	AC from Coarse RAP %	65	0.42	0.15
	Virgin AC %	65	3.91	0.86
	Total AC %	65	5.48	0.82

Table 21. RAP/RAS mix statistics for each JMF category.

JMF Category	Property	N	Mean	Std Dev
Before 2018 Change	RAP Mix %	354	18.39	5.88
	RAS Mix %	354	4.25	0.95
	Virgin Mix %	354	77.36	5.77
	AC in RAP %	354	5.02	1.04
	AC in RAS %	354	20.45	2.29
	AC from RAP %	354	0.91	0.30
	AC from RAS %	354	0.85	0.19
	Virgin AC %	354	3.76	0.77
	Total AC %	354	5.51	0.91
After 2018 Change	RAP Mix %	218	16.24	6.61
	RAS Mix %	218	4.32	0.95
	Virgin Mix %	218	79.43	6.47
	AC in RAP %	218	4.84	0.55
	AC in RAS %	218	20.23	0.99
	AC from RAP %	218	0.80	0.35
	AC from RAS %	218	0.86	0.19
	Virgin AC %	218	3.83	0.75
	Total AC %	218	5.49	0.97

Table 22. Virgin mix AC% statistics for each JMF category.

JMF Category	N	Mean	Std Dev
Before 2018 Change	73	5.85	1.03
After 2018 Change	65	6.02	1.09

Table 23. RAS mix statistics for each JMF category.

JMF Category	Property	N	Mean	Std Dev
Before 2018 Change	RAS Mix %	8	5.13	0.35
	AC in RAS %	8	21.74	2.99
	AC from RAS %	8	1.09	0.14
	Addl. Binder %	8	5.64	0.41
After 2018 Change	RAS Mix %	30	4.67	0.96
	AC in RAS %	30	22.27	2.96
	AC from RAS %	30	1.02	0.19
	Addl. Binder %	30	5.20	1.03

3.4. Dynamic Modulus

The dynamic modulus values were predicted at a single temperature and a single frequency (10 Hz and 20°C) using the mixture information extracted from the HiCAMS database. These predicted values were then utilized to conduct group-wise and pair-wise comparisons analogous to those conducted on the basis of volumetric properties. Prior to conducting the comparisons, a sensitivity analysis was performed to verify the prediction models' behavior under different temperatures and frequencies matched expectations. For this sensitivity analysis, predictions were made at the combination of five temperatures (-10°C, 4.4°C, 21.1°C, 37.8°C, and 54.4°C) and six frequencies (25 Hz, 10 Hz, 5 Hz, 1 Hz, 0.5 Hz, and 0.1 Hz). Other input variables needed to carry out the predictions were obtained by averaging the value of that variable for the extracted HiCAMS mixtures.

Figure 14 and Figure 15 show that by increasing the temperature at constant frequency of 10Hz, the predicted $|E^*|$ values reduced and by increasing the frequency at constant temperature of 21.1°C, the $|E^*|$ increased for all the study models. Since the prediction behavior of the models matches the anticipated $|E^*|$ behavior with changing temperature and frequency, the use of single temperature and single frequency to evaluate the extracted HiCAMS mixtures in terms of $|E^*|$ was deemed appropriate.

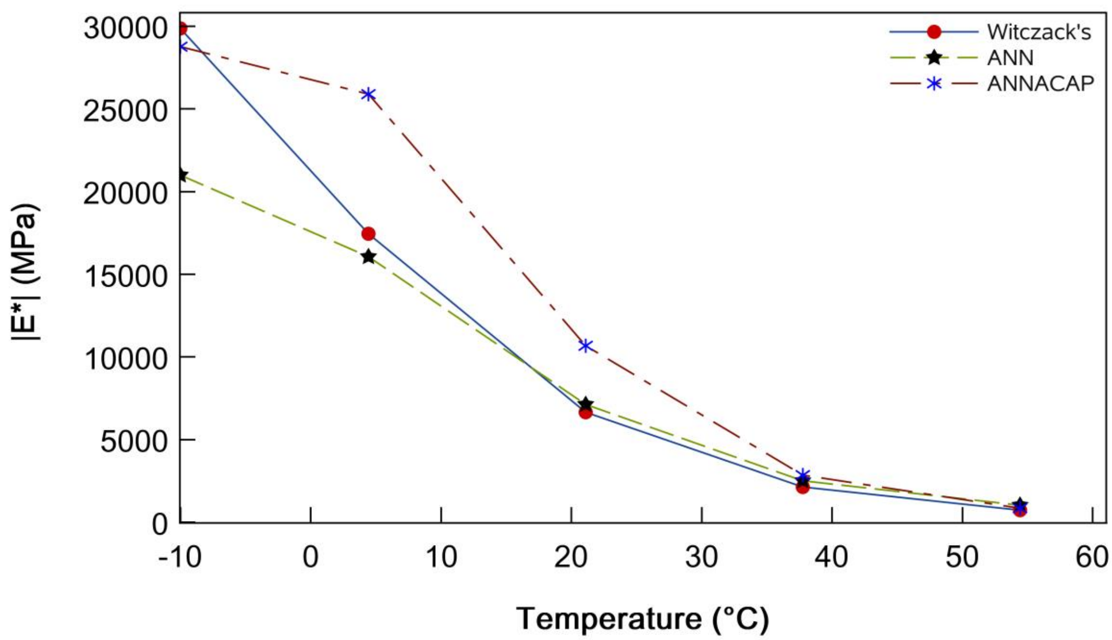

Figure 14. |E*| temperature sensitivity analysis at constant frequency of 10Hz.

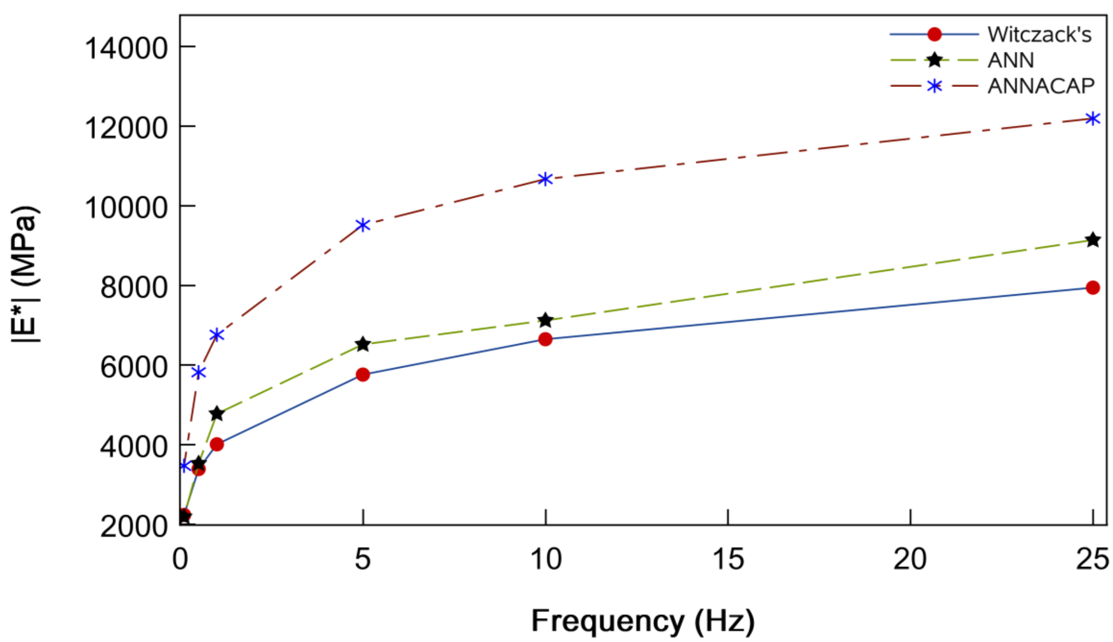

Figure 15. |E*| frequency sensitivity analysis at constant temperature of 21.1°C.

3.4.1. Comparisons between Different Mix Types

The predicted dynamic modulus values were compared between different mix types before and after the 2018 specification change. For the base and intermediate mixes, RB25.0B and RI19.0B mixtures designed before the change were compared to RB25.0C and RI19.0C designed after the change because the changes made by the NCDOT completely eliminated the B category in the base and intermediate mixtures. Following the same reasoning, surface mixes RSF9.5A and

RS9.5B designed before the 2018 change were compared to RS9.5B(2018) and RS9.5C designed after the change. The results of the analysis for the RSF9.5A versus RS9.5B(2018) and RS9.5B versus RS9.5C comparisons are shown in Figure 16 and Figure 17, respectively. From both figures, the mean predicted |*E**| values from the three models at constant temperature of 21.1°C and constant frequency of 10 Hz were slightly higher for the mixtures designed after the 2018 specification change when comparted to comparative values of mixtures designed before the change. A similar analysis was conducted for all mixes and led to the same conclusions. The detailed results are shown in Appendix C.

Considering the prediction error in the different models, the differences between the predicted |*E**| values before and after 2018 change are considered negligible for all the mix types. In addition, and because of the prediction errors embedded in the models, no further statistical testing for the DM predictions were conducted.

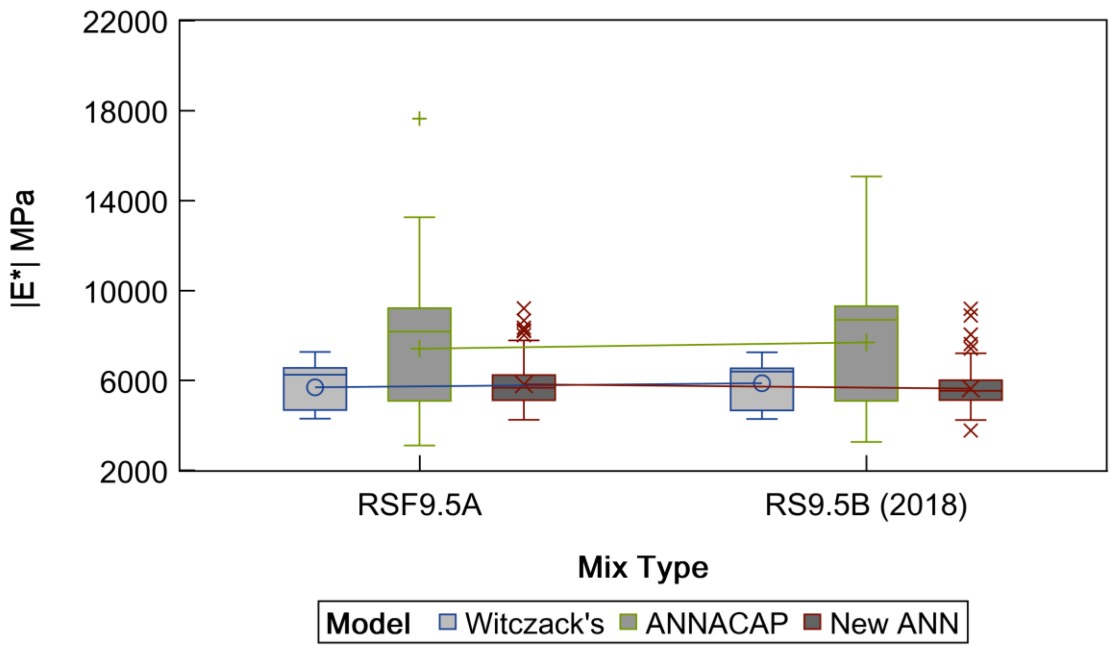

Figure 16. Comparison of |E*|predicted values for surface mixes RSF9.5A and RS9.5B (2018) before and after 2018 change.

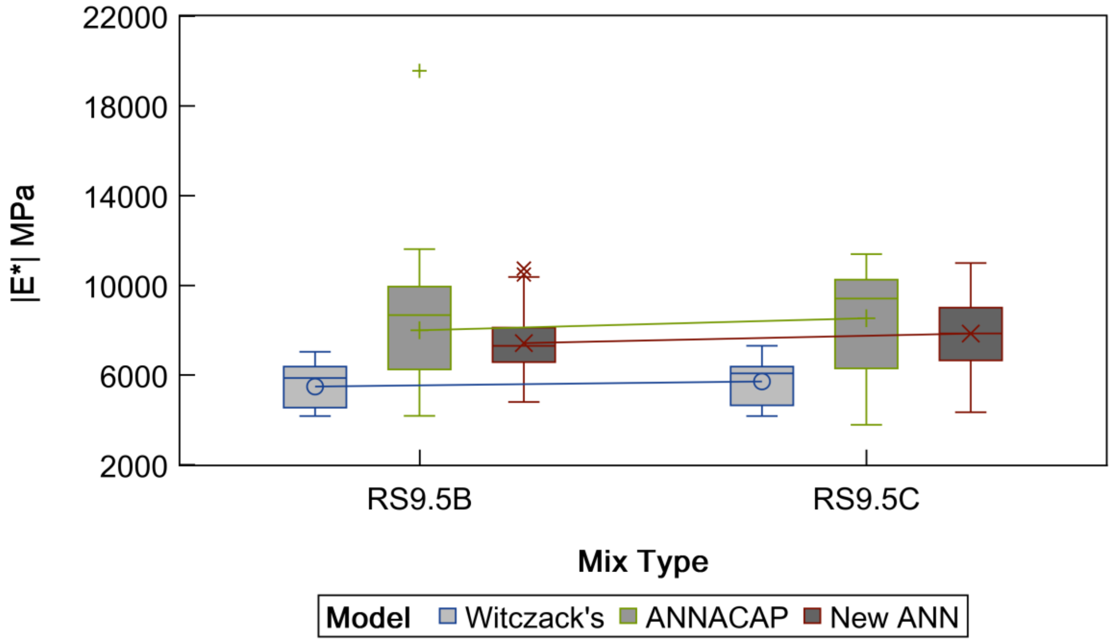

Figure 17. Comparison of |E*|predicted values for surface mixes RS9.5B and RS9.5C (2018) before and after 2018 change.

3.4.2. *Comparisons Based on Different Equivalent Single Axle Load (ESAL) and Suppliers*
To investigate the expected performance differences invoked by the 2018 mix design specification changes further, mixes were grouped and compared within individual suppliers. Supplier names were kept anonymous even during the research project meetings and presentations. Three different levels of ESALs were considered: less than 0.3 million, between 0.3 to 3 million, and greater than 3 million ESALs. For base and intermediate mixes at a design load that is less than 3 million ESALs, RB25.0B and RI19.0B JMF types were chosen to represent the conditions before the 2018 change while at the same ESAL level, RB25.0C and RI19.0C were chosen to represent the mixes used the change.

Table 24 and Table 25 shows the summary of the comparison results for base and intermediate mixes, respectively. These tables show that there were 30 and 33 suppliers that produced the base and intermediate mixes before and after the 2018 change, respectively. For the base mixtures, ANNACAP predictions suggest that 17 suppliers had mixes with higher |*E**| values before the change while 13 suppliers produced base mixes with higher predicted |*E**| after the change. All the predicted |*E**| values were at 10 Hz and 20°C. The average percent difference column demonstrates how much higher or lower the predicted |E*| values are between the JMFs produced before and after the 2018 specification change. Tables that present similar comparisons for the surface mixes at ESAL levels less the 0.3 and from 0.3 to 3 are provided in Appendix C.

As clearly shown within the tables, the average differences in predicted |*E**| values invoked by the specification changes are small considering the potential prediction errors in the models. Thus, it may be concluded that there were negligible differences found between the predicted |*E**| values before and after the 2018 change for the different mix types.

Table 24. Supplier based comparison before and after 2018 change for base mixes at less than 3 million ESAL.

Prediction Model	Mix Type	Count	Percent with Higher Moduli	|E*| Average Percent Difference
ANNACAP Software	RB25.0B	17	56.7%	19%
	RB25.0C	13	43.3%	26%
ANN Model	RB25.0B	15	50.0%	17%
	RB25.0C	15	50.0%	20%
Witczack's Model	RB25.0B	17	56.7%	11%
	RB25.0C	13	43.3%	9%

Table 25. Supplier based comparison before and after 2018 change for intermediate mixes at less than 3 million ESALs.

Prediction Model	Mix Type	Counts	Percent with Higher Moduli	|E*| Average Percent Difference
ANNACAP Software	RI19.0B	15	45.5%	16%
	RI19.0C	18	54.5%	22%
ANN Model	RI19.0B	12	36.4%	26%
	RI19.0C	21	63.6%	16%
Witczack's Model	RI19.0B	14	42.4%	14%
	RI19.0C	19	57.6%	11%

3.5. Permanent Deformation

3.5.1. Comparisons between Different Mix Types

The predicted cumulative permanent strain to the resilient strain ratio was compared between different mix types before and after the 2018 change at each traffic level. The comparison results for the Leahy model at 0.3, 3, 30, and 60 million ESALs are presented in Figure 18 to Figure 21, respectively. A similar approach was followed for the May and Witczak model to predict the cumulative permanent strain values. The flow numbers predicted utilizing Kaloush model were also compared. The full figures for the rutting prediction comparisons are available in Appendix D.

As shown in the figures below and in Appendix D, in general all models suggest a slight improvement or no change in rutting performance due to the mix design changes. However, considering the prediction error in the different models, the differences between the predicted rutting performance measures before and after 2018 change are considered negligible for all the mix types at the four evaluated traffic levels. Due to the prediction errors embedded in the models, no further statistical testing for the rutting performance predictions were conducted.

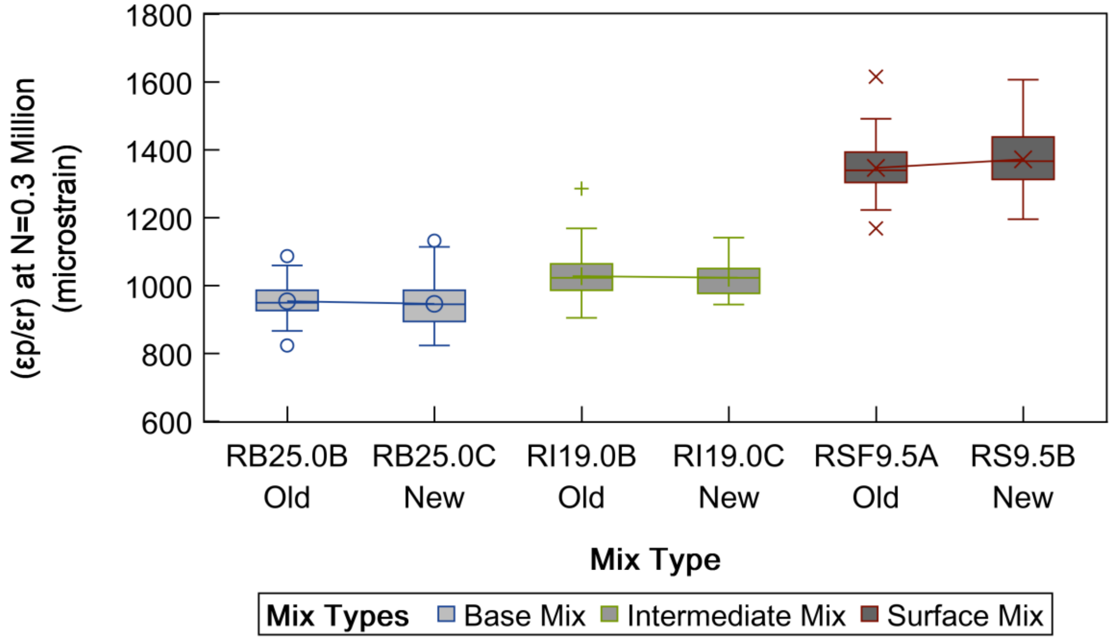

Figure 18. Comparison of predicted (εp/εr) values at 0.3 million ESALs utilizing Leahy's model.

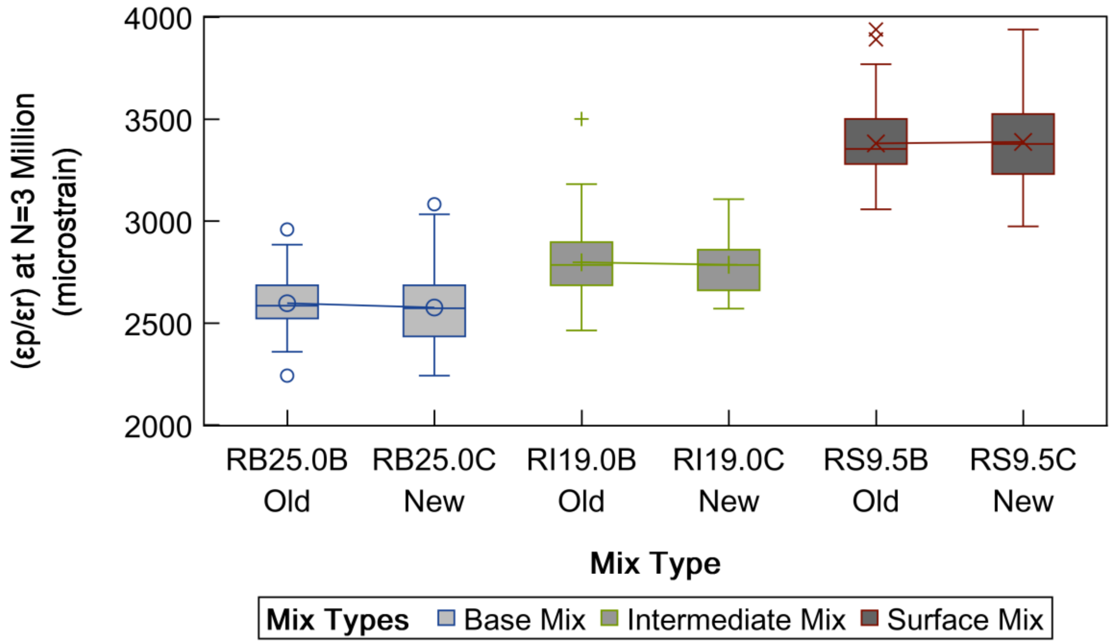

Figure 19. Comparison of predicted (εp/εr) values at 3 million ESALs utilizing Leahy's model.

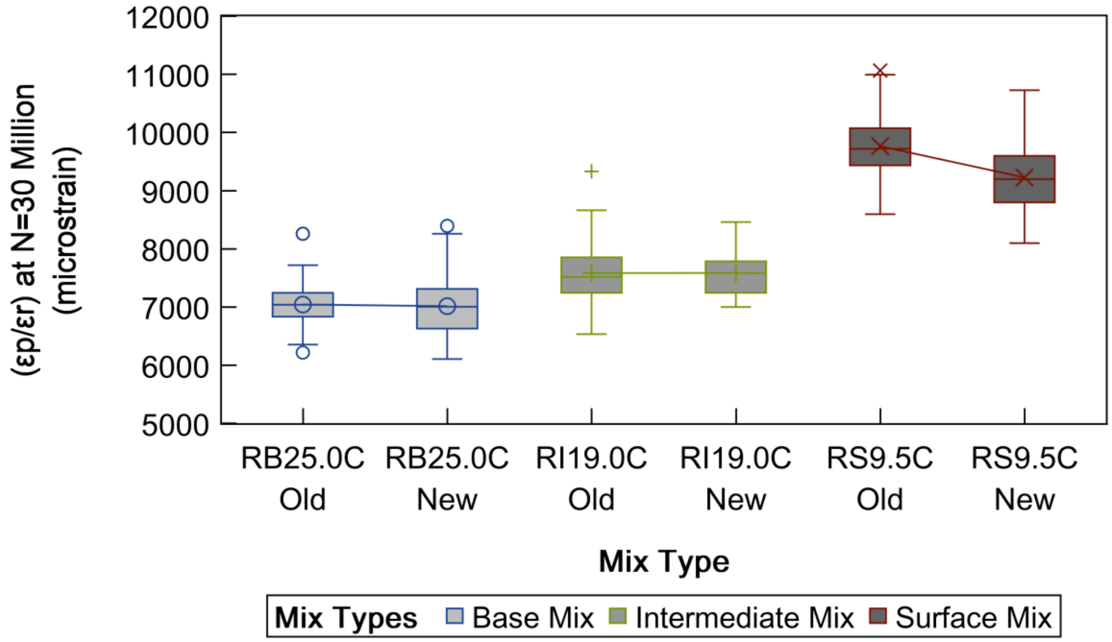

Figure 20. Comparison of predicted (εp/εr) values at 30 million ESALs utilizing Leahy's model.

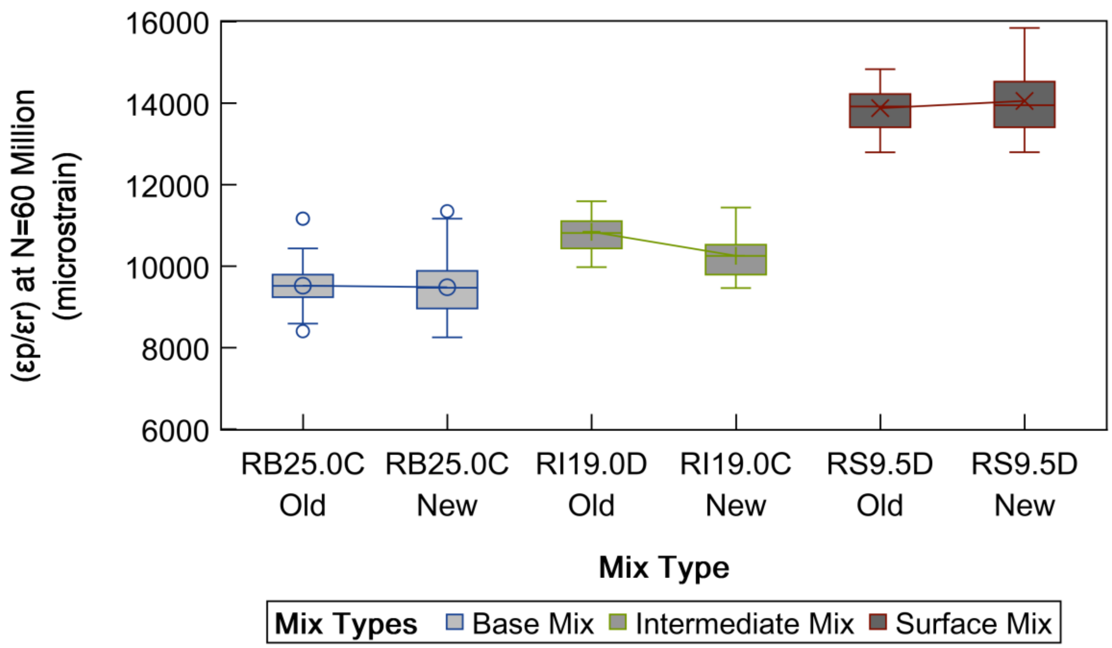

Figure 21. Comparison of predicted (εp/εr) values at 60 million ESALs utilizing Leahy model.

3.5.2. Pair-wise Supplier Comparisons

Mix groupings and comparisons by supplier were conducted to further investigate the differences in rutting performance between mixtures designed before versus after the 2018 specification change. Supplier names were kept anonymous even during the research project meetings and presentations. The specified JMFs for the selected ESAL levels were compared before and after the 2018 change by comparing the predicted rutting performance of the produced JMFs before and after the 2018 change. Table 26 shows the summary of the comparison results using the Kaloush model while Table 27 show the summary of the comparison results using the Leahy and the May and Witczak models at 0.3 million ESALs. Similar comparison was conducted at the remaining three evaluated traffic load levels and the tables are presented in Appendix D.

The supplier-based comparison is investigated in more detail using the base mixes at the 0.3 million ESAL level in Table 27. From this table, there were 30 suppliers that produced the base mixes, RB25.0B and RB25.0C, before and after the 2018 change, respectively. Out of the 30 suppliers, 15 (50%) had their pre-2018 RB25.0B outperform their new RB25.0C in terms of rutting while 11 (36.7%) had the opposite trend (their new RB25.0C outperforming their pre-2018 RB25.0B). Finally, four suppliers (13.3%) produced base mixes with similar performance before and after the change. Table 27 also shows the average difference, which was calculated by averaging the percent performance difference for the 30 suppliers.

As clearly shown within the tables, the proportion of suppliers with better performance predicted for the mixtures after the 2018 mix design changes is approximately the same as the proportion of suppliers with better performance predicted before the 2018 mix design changes. Also, the average differences were small considering the potential prediction errors in the models. Thus, it may be concluded that there were no noticeable differences found between the predicted rutting performance before and after the 2018 change for the different mix types.

Table 26. Supplier based comparison before and after 2018 change utilizing Kaloush model.

Prediction Model	Mix Type	JMF	Counts	Percent in Category	Average Difference (FN)
Kaloush Model	Base Mix	Pre-2018 RB25.0B is Better	13	43.3%	8.8%
		New RB25.0C is Better	13	43.3%	7.8%
		Both are Similar	4	13.3%	0.0%
	Intermediate Mix	Pre-2018 RI19.0B is Better	14	41.2%	8.1%
		New RI19.0C is Better	18	52.9%	7.1%
		Both are Similar	2	5.9%	0.0%
	Surface Mix	Pre-2018 RSF9.5A is Better	19	43.2%	11.0%
		New RS9.5B is Better	21	47.7%	7.9%
		Both are Similar	4	9.1%	0.0%

Table 27. Supplier based comparison before and after 2018 change utilizing Leahy and May and Witczak models at 0.3 million ESALs.

Prediction Model	Mix Type	JMF	Counts	Percent in Category	Average Difference (εp/εr or εp)
Leahy Model	Base Mix	Pre-2018 RB25.0B is Better	15	50.0%	2.6%
		New RB25.0C is Better	11	36.7%	3.0%
		Both are Similar	4	13.3%	0.0%
	Intermediate Mix	Pre-2018 RI19.0B is Better	14	41.2%	2.7%
		New RI19.0C is Better	18	52.9%	3.5%
		Both are Similar	2	5.9%	0.0%
	Surface Mix	Pre-2018 RSF9.5A is Better	19	43.2%	3.5%
		New RS9.5B is Better	21	47.7%	3.1%
		Both are Similar	4	9.1%	0.0%
May & Witczak Model	Base Mix	Pre-2018 RB25.0B is Better	14	46.7%	5.3%
		New RB25.0C is Better	12	40.0%	6.4%
		Both are Similar	4	13.3%	0.0%
	Intermediate Mix	Pre-2018 RI19.0B is Better	15	44.1%	4.6%
		New RI19.0C is Better	17	50.0%	7.4%
		Both are Similar	2	5.9%	0.0%
	Surface Mix	Pre-2018 RSF9.5A is Better	19	43.2%	6.9%
		New RS9.5B is Better	21	47.7%	6.6%
		Both are Similar	4	9.1%	0.0%

4. Conclusions and Recommendations

4.1. Summary

The NCDOT has modified the asphalt mixture design procedures in part, to increase the asphalt content and address observed cracking issues with asphalt mixtures in 2018. This research study investigated how these recent changes have affected asphalt mixture designs with respect to composition and performance.

The asphalt mix design procedures from before and after the most recent changes were identified and job mix formulas (JMFs) for mixture designed before and after the 2018 procedure update were extracted from HiCAMS for the use in analysis. The extracted job mix formulas were compared based on their volumetric and constituent composition, e.g., asphalt content, voids in mineral aggregate (VMA) at the design compaction level, and voids filled with asphalt (VFA) at the design compaction level. Comparisons were clustered by material type, supplier, division, traffic designation, and region to identify any non-uniform trends that may exist. The predicted performance in terms of dynamic modulus and rut resistance of the mixtures designed before and after the 2018 procedure changes were compared and clustered by material type, supplier, and design traffic level. Visual as well as statistical comparisons were utilized for assessing the impacts of the 2018 specification changes.

4.2. Conclusions Based on Mixture Composition

The conclusions drawn based on comparisons of mixture composition (Sections 3.2 and 3.3) are summarized below.

- For mixture volumetrics statistical testing and comparisons and results showed that:
    - The changes in mixture volumetric properties between different regions for each JMF category (Before 2018 change, Reclassified, and After 2018 change) visually look very small.
    - Surface mixtures used for the 0.3 to 3 million ESAL traffic category after the 2018 change have had an increase in asphalt content by 0.7% (on average) when compared with the mixtures used pre-2018.
    - Statistical testing of these changes showed that the majority of the average mean difference in VMA, VFA, and AC% before and after the change were less than 0.5, which make them unsubstantial from an engineering point of view since the NCDOT control limits of VMA and AC% for mix production are 1% and 0.7%, respectively.
    - There is no practically significant difference among mixture volumetrics before versus after the 2018 change.
- Recycled binder replacement analysis showed that:
    - The majority of the study mixtures contained RAP (61.4%) and most of these were surface mixes.
    - RAP/RAS mixtures are used more frequently than fractionated RAP mixes (18.5% vs 11.0%).
    - Only 7.7% of the evaluated JMFs did not include any recycled binder replacement.
    - RAS mixtures were mainly used in the Coastal Plains region.

- The geographical distribution assessment of RBR mixtures showed that Division 5 had the largest number of RAP mixes, Division 10 had the highest number of fractionated RAP mixes, and Division 1 had the largest number of RAP/ RAS and RAS mixes.
    - The evaluation of the effect of the specification changes introduced in 2018 on the distribution of JMFs containing recycled materials showed that Division 1 had noticeable changes. For instance, RAP mixes have the highest presence after the 2018 change in Division 1 and RAP/RAS and RAS mixes jumped from 2.3% and 6.3% to 11.4% and 34.4% pre- versus post-2018, respectively.
    - Within the 14 evaluated divisions, only Divisions 1, 2, 4, and 8 had JMFs that included RAS.
- The volumetric analysis of the recycled mixtures showed that:
    - The mean RAP content for the RAP mix was lower after 2018 while the mean virgin binder content was higher after the change.
    - For the fractionated RAP mixes, mean coarse RAP content decreased while means fine RAP and virgin binder contents increased after 2018.
    - For the RAS mixtures, a decrease in the mean RAS content after 2018 change was found.
    - All the changes (increment or decrement) were unsubstantial in terms of mean values.

4.3. Conclusions Based on Predicted Performance Related Properties

The conclusions drawn based on comparisons of mixture performance related properties (Sections 3.4 and 3.5) are summarized below.

- The predicted dynamic modulus values at 10 HZ and 20°C conducted and evaluated comparisons showed that:
    - The differences between the predicted $|E^*|$ values of JMFs before and after 2018 are negligible for all the mix types.
    - Dynamic modulus comparisons for mix groupings by supplier at three different traffic levels showed that the average differences were small and unsubstantial considering the potential prediction errors in the models.
- The predicted cumulative permanent strain to the resilient strain ratio were compared between different mix types before and after 2018 change at four different levels of ESALs and results showed that:
    - All the utilized models suggest a slight improvement to no change in rutting performance post 2018.
    - The conducted mix groupings and comparisons by supplier at different ESALs levels showed that the proportion of suppliers with better performance predicted for the mixtures after the 2018 mix design changes is approximately the same as the proportion of suppliers with better performance predicted before the 2018 mix design changes.
    - The average differences were small considering the potential prediction errors in the models.

In total, the analysis presented in this research shows that there were no systematic changes to the asphalt mixtures at equivalent gyration levels after the specification changes. Some suppliers do show higher asphalt contents for moderate traffic levels for surface mixtures. However, this result is not universal and is just as likely to be the result of random chance and normal variations in mix design results. The net result of the changes in mix design designations has been an increase in asphalt content and other volumetric properties on surface mixtures in the 0.3 to 3 million 20-year ESAL category. Prior to the 2018 change surface mixtures were designed using a 65 gyration mix design procedure and now these mixtures are designed using a 50 gyration procedure. Based on the analysis here, the net effect of this change is an increase in asphalt content by 0.7% (on average) for mixtures placed on roads with 20-year cumulative ESALs between 0.3 and 3 million.

4.4. Recommendations

The specific recommendations from this study are as follows;

1. The NCDOT should closely monitor pavements that have been recently constructed in the 20-year, 0.3 to 3 million ESAL traffic category for any improvements in durability performance, declines in rutting performance, and changes in functional performance. Mixtures used for this traffic category after the 2018 change have had an increase in asphalt content by 0.7% (on average) when compared with the mixtures used pre-2018.
2. The NCDOT should also monitor pavements that have been recently constructed in the 20-year, 3-30 million ESAL traffic category for any improvements in performance. While this project did not detect any volumetric changes in these mixtures, the required binder grade changed from a PG 70-22 to a PG 64-22, which could impart long-term performance variations in the mixtures.
3. The NCDOT should consider integrating a durability related performance test into the mixture design process. The pre-2018 surface 65-gyration design (S9.5B/RS9.5B) mixture required Asphalt Pavement Analyzer (APA) rutting less than 9.5 mm while the post-2018 surface 65-gyration design (S9.5C/RS9.5C) mixture required APA rutting less than 6.5 mm. Despite these changes, no systematic differences were detected in volumetric composition of the two mix designs. Thus, it is believed that in the aggregate, these mixtures were already performing very well in rutting and may be (overall) ‘unbalanced’ with respect to durability and rutting performance. Additional results from RP2019-20 support this recommendation by showing highly varying performance indicators across mixtures of the same type.

5. Implementation and Technology Transfer Plan

The Materials and Tests Unit of the NCDOT is the primary user of this product. The statistical analysis that this research produced can be used by the NCDOT to explain how durability is expected to improve for the 0.3 – 3 million ESAL traffic category after the 2018 procedure revisions. The findings of the research will be communicated to the NCDOT in the form of this report, the appendices and supplementary information, and a closeout meeting with the project panel.

For follow-up activities, the research team believes that the NCDOT could consider the following activities:

1. allocating resources to identifying and tracking the performance of pavements constructed with the new mixtures to see if any systemic changes in field performance have occurred;
2. evaluating the effect of changes more systematically by constructing multiple sections of pavement along the same segment of roadway using the current S/RS9.5B and S/RS9.5C mixtures as well as a pre-2018 S/RS9.5C mixture; and
3. investigating the inclusion of durability testing (IDEAL-CT, I-FIT, IDT, cyclic fatigue, etc.) as part of the mix design process in order to better ensure long-term durability of its asphalt concrete mixtures.

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APPENDIX A: ANN DYNAMIC MODULUS PREDICTION MODEL

Developed Model Architecture

The model developed for this effort involved a three-layer feed-forward neural network, utilizing a backpropagation-error calculation algorithm, and nine neurons within the hidden layer. The three-layer feed-forward backpropagation neural network with a sigmoid activation function and one hidden layer is considered as one of the commonly used ANN architecture for regression (*19*). The developed model architecture is shown in Figure A.1 and its main components are as follows:

1. Input layer (*i*) with nine different input neurons, one neuron for each independent variable utilized in modeling.
2. Weight factors (*Wih*) between the input layer (*i*) and the hidden layer (*h*). The weight matrix contained 81 different values, one value from each input to each hidden neuron.
3. Hidden layer (*h*) with nine hidden neurons having a tan-sigmoid activation function and nine biases values, one for each hidden neuron (*bh*1 to *bh*9).
4. Weight factors (*W′ho*) between the hidden layer and the output layer. The weight matrix contained nine values, one value from each hidden neuron to the single output neuron.
5. Output layer (*o*) having single output neuron for the dependent variable with a linear transfer function and one bias value (*Bo*).

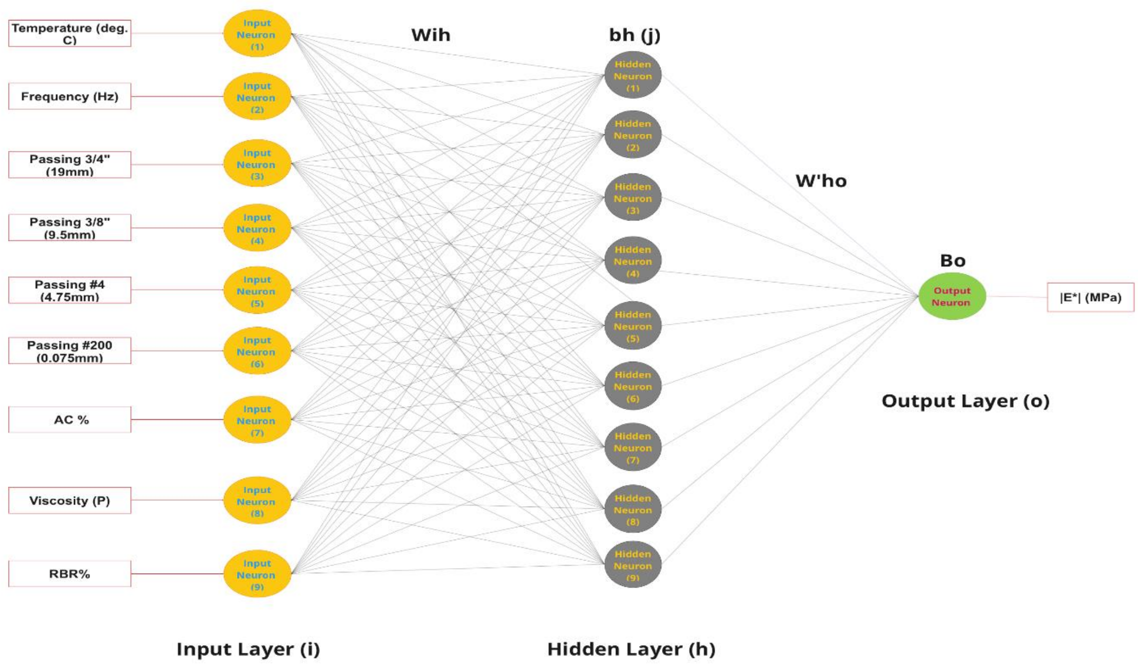

Figure A.1. Developed ANN model architecture.

Developed Model Training

The available research group mixture database was utilized in the model training. This database had testing data points for 345 different mixes. Those mixes were divided into two groups, 15% of the mixes were used for independent model validation and the other 85% were used for ANN training. The data ranges for the training mixes is shown in Table A.1 and the data distribution among different research projects is shown in Table A.2. The ANN model was trained to predict |*E**| as shown in Equation (6).

$$|E^*| = f(T_c, Fr, \rho_{3/4}, \rho_{3/8}, \rho_{\#4}, \rho_{\#200}, AC, \eta, RBR) \quad (7)$$

where;

- $|E^*|$ = dynamic modulus in MPa,
- T_c = temperature in degrees Celsius,
- F_r = loading frequency in Hz,
- ρ_{34} = cumulative passing the ¾ in sieve,
- ρ_{38} = cumulative passing the 3/8 in sieve,
- ρ_4 = cumulative passing the No. 4 sieve, and
- ρ_{200} = percent passing the No. 200 sieve.
- AC = percent binder content,
- η = bitumen viscosity in Poise, and
- RBR = percent recycled binder replacement content.

Table A.1. ANN modeling data ranges.

Modeling Variable	Minimum	Maximum	Mean
RBR %	0.00	48.80	4.69
Temperature (°C)	-11.30	55.15	19.60
Frequency (Hz)	0.01	25.00	5.82
Percent Passing 3/4" (19mm)	71.03	100.00	97.65
Percent Passing 3/8" (9.5mm)	44.10	100.00	86.25
Percent Passing #4 (4.75mm)	31.24	86.00	60.79
Percent Passing #200 (0.075mm)	2.05	7.21	5.10
AC %	4.00	7.40	5.40
Viscosity (P)	4738.15	746081382716	90631644356

Table A.2. ANN modeling data distribution among different research projects.

Project	Dynamic Modulus Tests	
	Counts	Percentage
Chemical Lime Study	12	3.5
FHWA-HRT-08-073	50	14.5
Korea Expressway Corp.	15	4.3
Kumho	12	3.5
HWY-2002-07	10	2.9
HWY-2003-09	123	35.7
HWY-2007-07	36	10.4
NCDOT 2011-04	4	1.2
NCDOT 2012-04	12	3.5
NCDOT 2013-05	9	2.6
NCDOT 2013-06	21	6.1
NCHRP 9-19 Task F	5	1.4
NCHRP 1-42A	30	8.7
FHWA PRS	6	1.7
Total	345	100.0

The developed model was trained utilizing Levenberg-Marquardt backpropagation algorithm in MATLAB (MATLAB R2020a, The Math Works Inc.) with the 293 mixes testing data points. The data were divided by the training algorithm into three different sets. From the training dataset, 70% of the data was utilized in the model development and training while the remaining 30% of the data were utilized for trained model validation and divided into 15% testing data and 15% validation data. The training was stopped when the validation data set error had stopped decreasing for six consecutive iterations, as an effort to avoid overfitting and maintain network generalization as shown in Figure A.2. After concluding the training, the trained developed ANN model had weight and bias values as shown in the below matrices.

$$Wih = \begin{bmatrix} 0.1868 & -0.5936 & 0.0766 & -2.7410 & 2.0387 & 1.5817 & 0.3092 & -1.8815 & -0.2889 \\ 2.2264 & -0.0518 & -0.0461 & 5.3159 & 1.1425 & 2.8358 & 1.0621 & -0.0937 & -0.3045 \\ -1.8792 & -0.9627 & 0.1038 & -2.1578 & -7.8720 & 12.0273 & 7.7582 & -8.5808 & -0.4202 \\ 2.6869 & -0.1791 & -0.0423 & 7.6406 & 1.3453 & 3.4841 & 1.2128 & -0.3019 & -0.2913 \\ -5.2104 & -3.2559 & 0.0091 & -1.9125 & -7.7496 & 2.8917 & 6.0908 & 1.7202 & 5.2759 \\ 0.1432 & 7.2736 & 0.1980 & -1.0333 & -5.4557 & 4.9253 & 0.7366 & 0.2282 & -2.5455 \\ 1.3908 & -0.3390 & -0.0534 & 4.4111 & -8.8862 & -1.8659 & -1.3753 & 7.2335 & -0.0632 \\ 0.0188 & 0.7865 & -0.0764 & -0.4164 & -0.2063 & 0.5627 & 0.1953 & -0.1230 & 0.1176 \\ -0.0618 & 0.5074 & -10.0048 & 0.0271 & 0.0254 & -0.0928 & 0.0173 & -0.0068 & 0.0875 \end{bmatrix}$$

$$W'ho = \begin{bmatrix} 0.596 \\ 1.5404 \\ 0.202 \\ -1.5854 \\ 0.1306 \\ -0.2045 \\ 0.2648 \\ -1.5816 \\ -5.4706 \end{bmatrix} \qquad bh(j) = \begin{bmatrix} 1.2611 \\ -5.3059 \\ -5.4591 \\ -7.4382 \\ -6.3937 \\ 9.9237 \\ 0.3059 \\ 0.2046 \\ -11.3154 \end{bmatrix} \qquad Bo = [\text{-}6.1663]$$

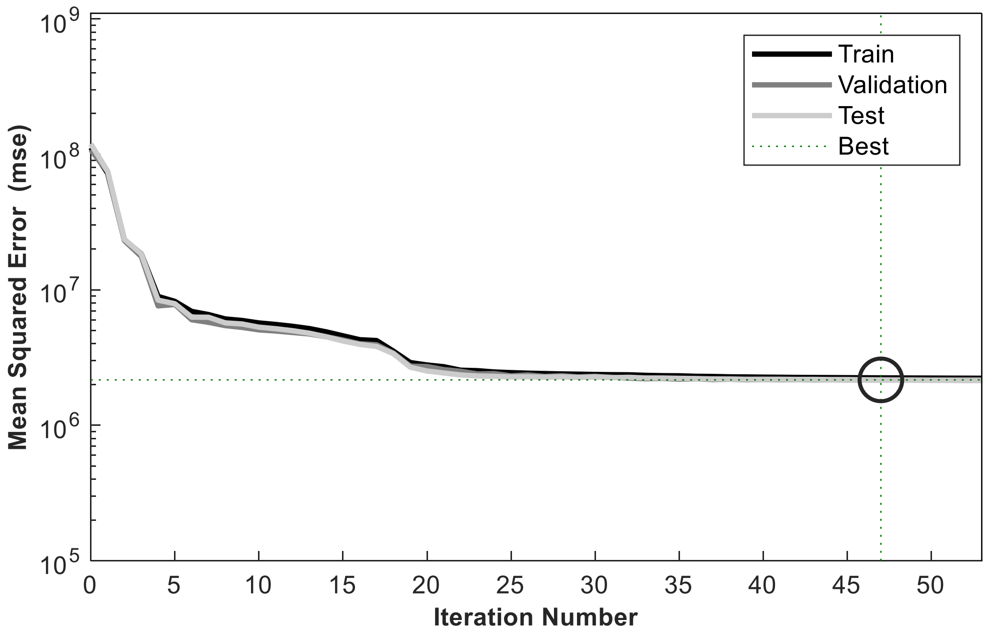

Figure A.2. Number of iterations/ epochs required for model training.

Developed Model Evaluation

The developed ANN model was evaluated internally by MATLAB training algorithm and externally utilizing the 15% of the mix data that were not used in ANN modeling. The model was statistically validated by having a high overall coefficient of correlation value of 0.99 and high coefficient of determination (R^2) value of 0.96 for the independent validation as shown in Figure A.3 through Figure A.5.

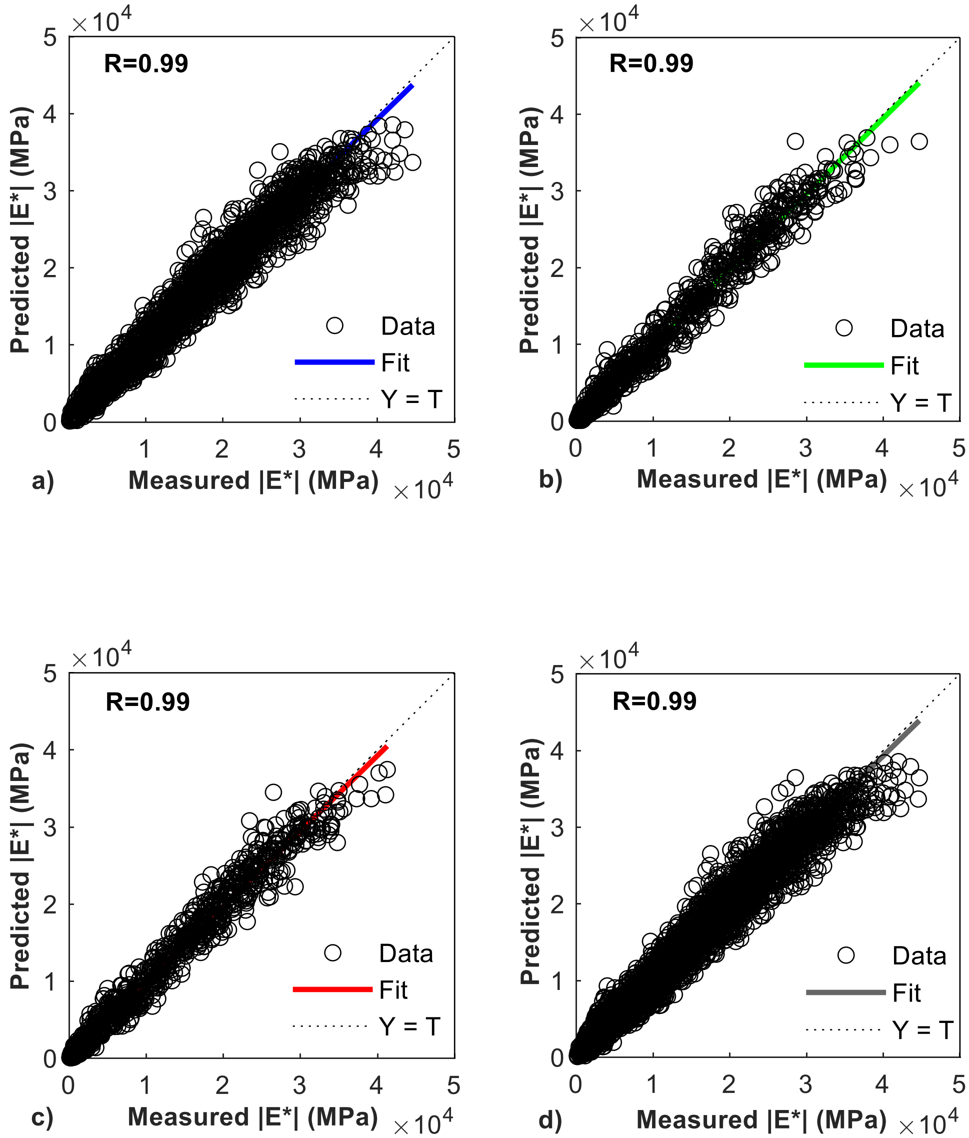

Figure A.3. Correlation plots on arithmetic scale for: a) training, b) validation, c) testing, and d) overall data.

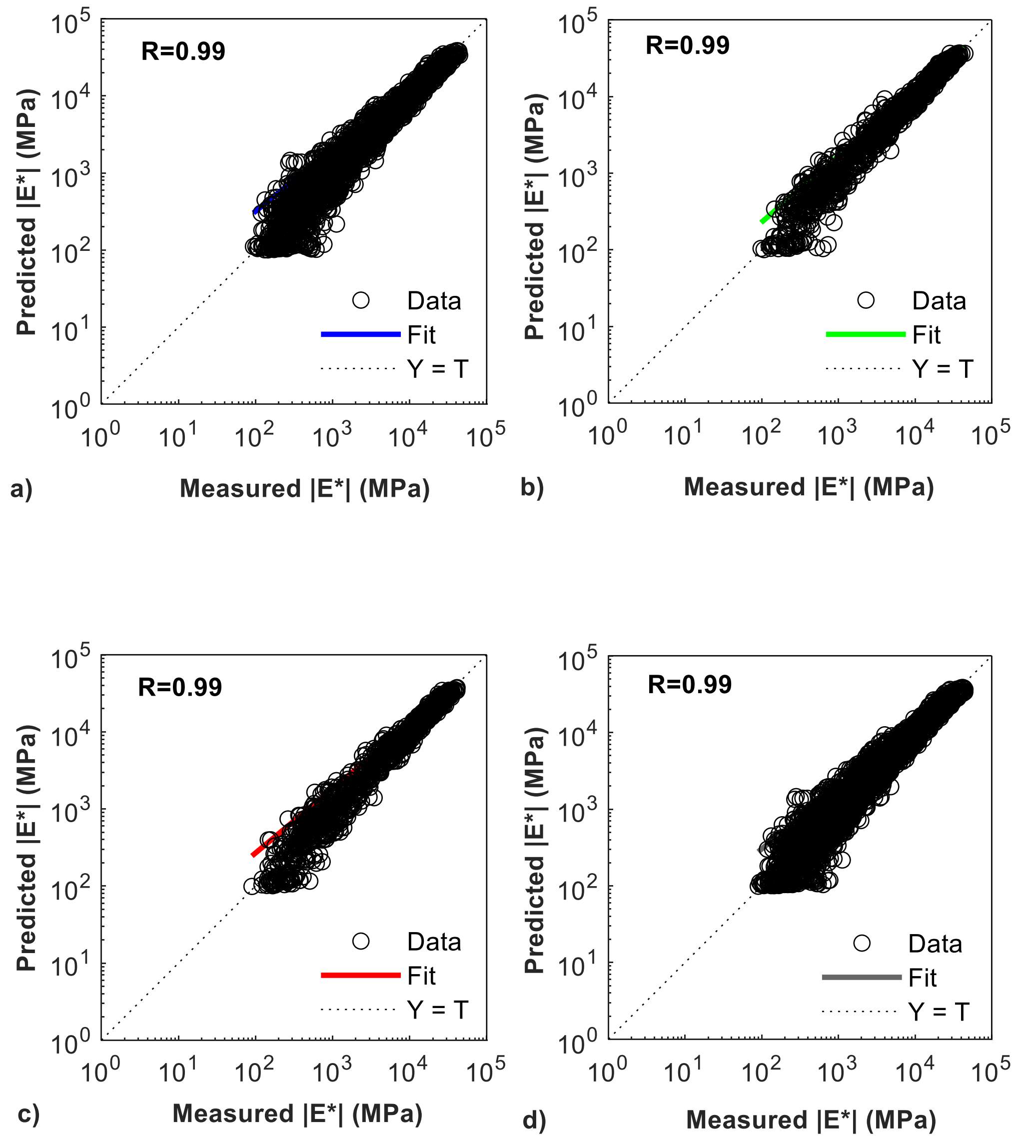

Figure A.4. Correlation plots on log-log scale for: a) training, b) validation, c) testing, and d) overall data.

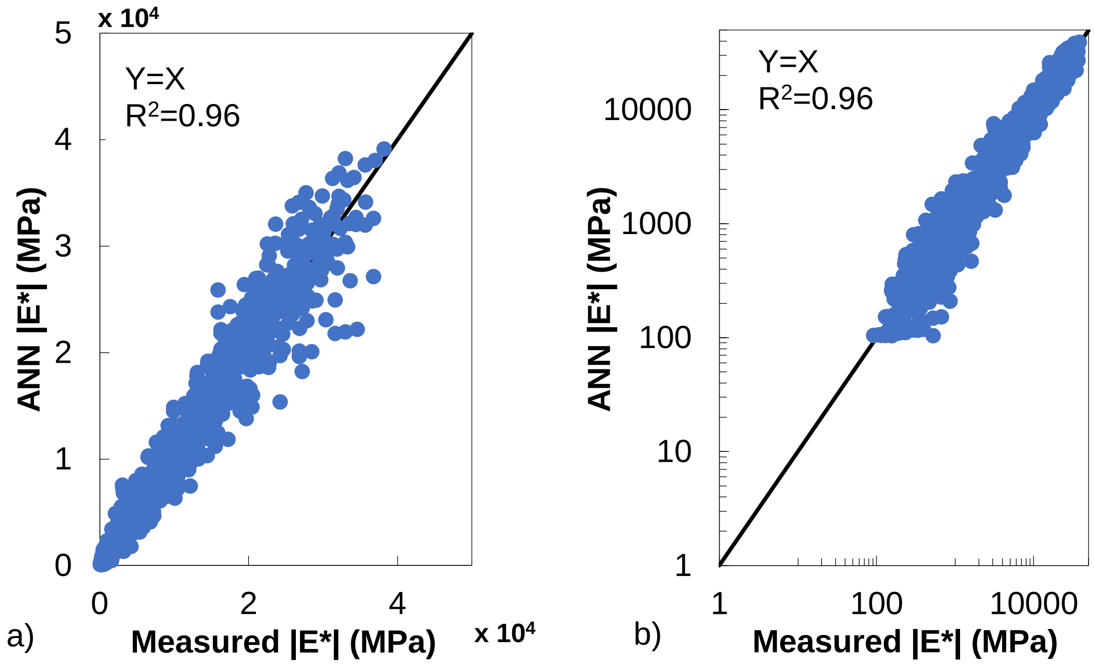

Figure A.5. Predicted vs measured |E*| values for the independent validation dataset: a) arithmetic scale, and b) log-log scale.

APPENDIX B: SUPPLEMENTARY COMPARISON TABLES AND FIGURES FOR MIXTURE COMPOSITIONS

VFA Analysis

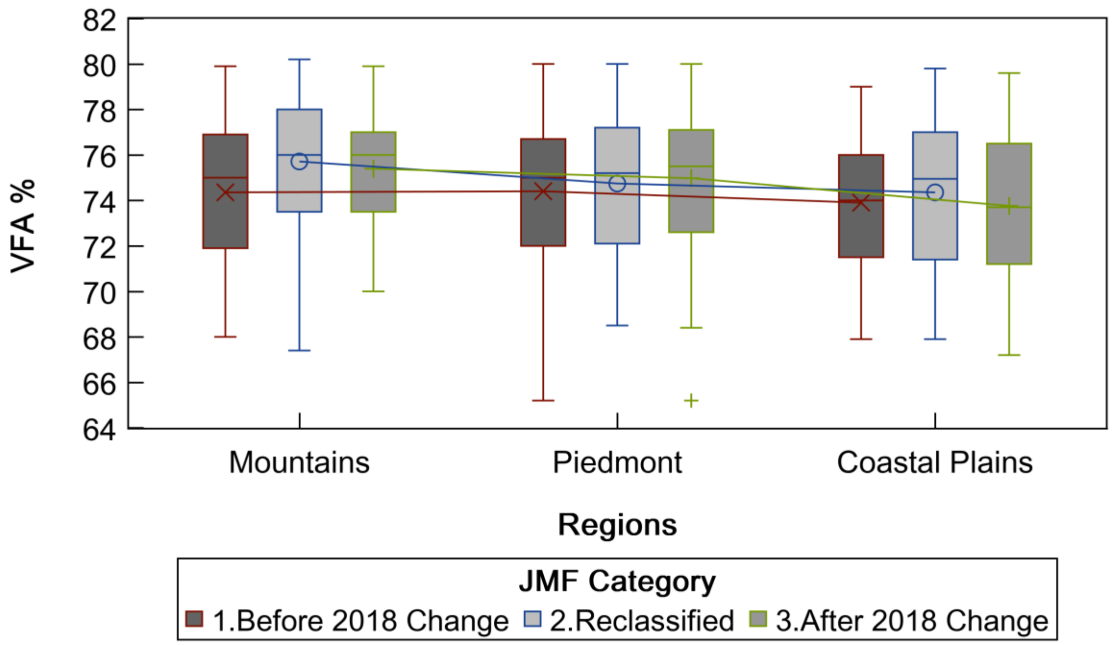

Figure B.1. Change of VFA between different regions for each JMF category.

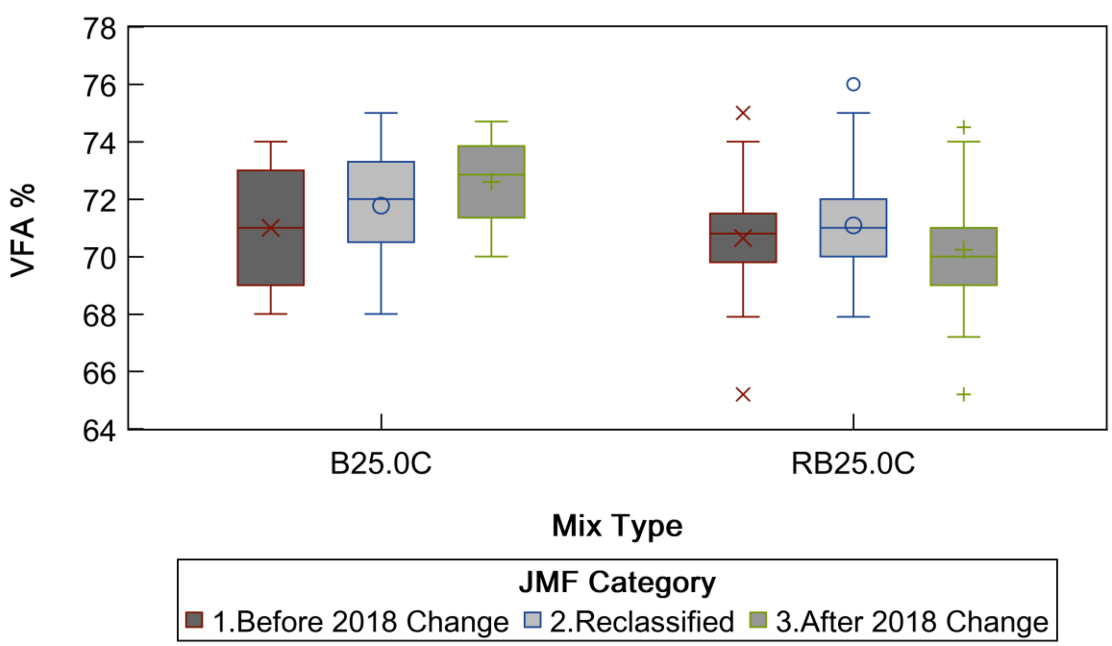

Figure B.2. Change of VFA in base mixes for each JMF category (*Refer to Table 8 for counts details).

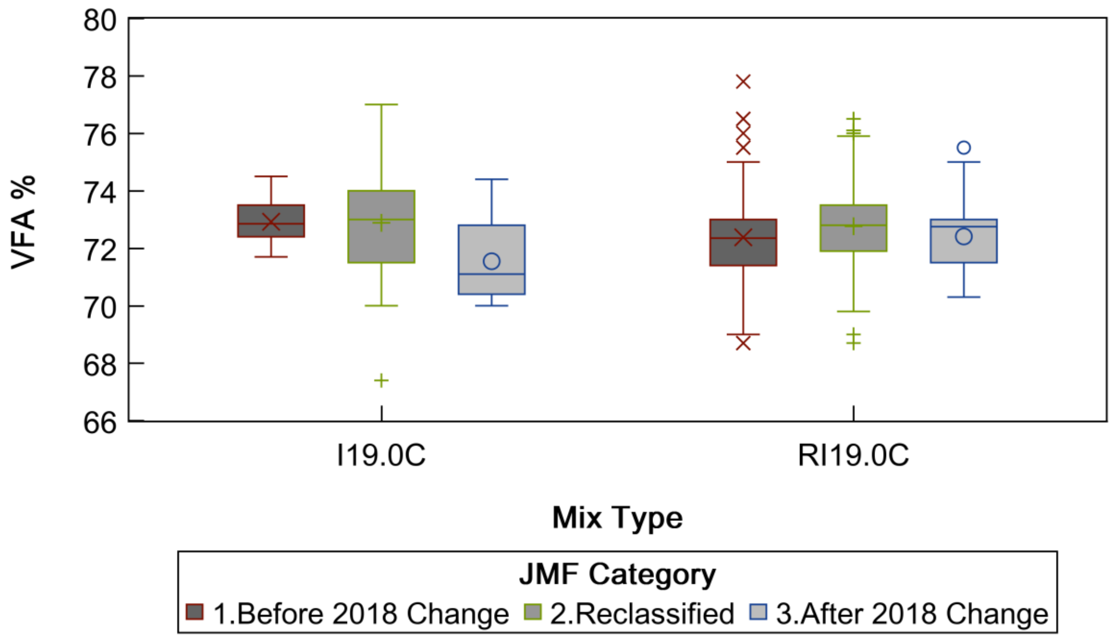

Figure B.3. Change of VFA in intermediate mixes for each JMF category (*Refer to Table 8 for counts details).

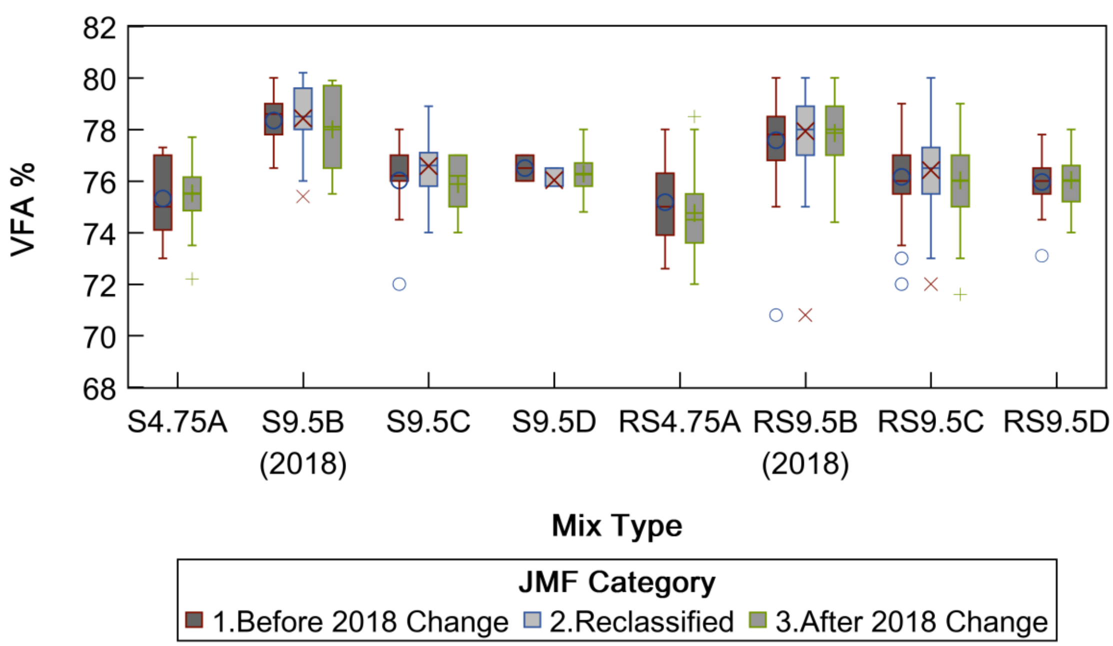

Figure B.4. Change of VFA in surface mixes for each JMF category (*Refer to Table 7 for counts details).

Table B.1. VFA variable student t-test results for each mix type.

	Mean Difference		Mean Variance Test		T-test Results		
Mix Type	**Difference**	**JMF with Higher Value**	**Pr > |F|**	**t-test Method**	**DF**	**Pr > |t|**	**Sig.?**
B25.0C	-1.6000	After 2018 Change	0.8337	Pooled	10	0.2667	No
RB25.0C	**0.4052**	**Before 2018 Change**	**0.2552**	**Pooled**	**471**	**0.0018**	**Yes**
I19.0C	**1.3748**	**Before 2018 Change**	**0.1197**	**Pooled**	**27**	**0.0038**	**Yes**
R19.0C	-0.0298	After 2018 Change	<.0001	Satterthwaite	425	0.7765	No
S9.5B(2018)	0.3444	Before 2018 Change	0.3366	Pooled	18	0.6017	No
RS9.5B(2018)	**-0.2822**	**After 2018 Change**	**0.0434**	**Satterthwaite**	**342**	**0.0330**	**Yes**
S9.5C	0.1382	Before 2018 Change	0.3400	Pooled	39	0.7631	No
RS9.5C	0.1315	Before 2018 Change	0.0118	Satterthwaite	327	0.2315	No
S9.5D	0.2125	Before 2018 Change	1.0000	Pooled	8	0.7759	No
RS9.5D	-0.0732	After 2018 Change	0.2122	Pooled	83	0.7415	No
S4.75A	-0.2050	After 2018 Change	0.7973	Pooled	24	0.7201	No
RS4.75A	0.4183	Before 2018 Change	0.7700	Pooled	163	0.0689	No

Table B.2. VFA variable student t-test results for each mix type within each region.

Mix Type	Region	Mean Difference	Mean Variance Test		t-test Results		
			Pr > |F|	t-test Method	DF	Pr > |t|	Sig.?
B25.0C	Mountains	-1.7000	1.0000	Pooled	6	0.2495	No
RB25.0C	**Coastal Plains**	**0.4765**	**0.3734**	**Pooled**	**204**	**0.0074**	**Yes**
	Mountains	-1.2683	0.8522	Pooled	35	0.1122	No
	Piedmont	0.0114	0.5005	Pooled	228	0.9534	No
I19.0C	**Coastal Plains**	**1.7422**	**0.6574**	**Pooled**	**12**	**0.0016**	**Yes**
	Mountains	-0.7600	1.0000	Pooled	5	0.3614	No
	Piedmont	1.1500	0.5514	Pooled	6	0.2374	No
RI19.0C	Coastal Plains	-0.2535	0.0045	Satterthwaite	200	0.0899	No
	Mountains	0.5033	0.0446	Satterthwaite	31	0.3070	No
	Piedmont	-0.2192	0.3840	Pooled	277	0.1951	No
S 9.5B(2018)	Coastal Plains	0.7900	0.5373	Pooled	5	0.3315	No
	Piedmont	-0.8600	0.0647	Pooled	8	0.1440	No
RS9.5B(2018)	**Coastal Plains**	**-0.5263**	**0.3317**	**Pooled**	**149**	**0.0042**	**Yes**
	Mountains	0.4867	0.3761	Pooled	22	0.3678	No
	Piedmont	**-0.4560**	**0.0071**	**Satterthwaite**	**168**	**0.0157**	**Yes**
S9.5C	Coastal Plains	0.6400	0.6436	Pooled	8	0.3337	No
	Mountains	0.3667	<.0001	Satterthwaite	2	0.4226	No
	Piedmont	-0.5246	0.1462	Pooled	24	0.5492	No
RS9.5C	Coastal Plains	0.2727	0.9345	Pooled	234	0.1513	No
	Mountains	-0.1484	0.7597	Pooled	58	0.6387	No
	Piedmont	-0.1960	0.1765	Pooled	376	0.1186	No
S9.5D	Piedmont	0.4500	1.0000	Pooled	6	0.4864	No
RS9.5D	Coastal Plains	0.2991	0.4870	Pooled	20	0.5252	No
	Mountains	-0.2444	0.1531	Pooled	9	0.8215	No
	Piedmont	-0.1720	0.8255	Pooled	50	0.5206	No
S4.75A	Mountains	1.1381	0.6745	Pooled	8	0.3798	No
	Piedmont	0.0375	0.3894	Pooled	10	0.9454	No
RS4.75A	Coastal Plains	0.4999	0.6642	Pooled	105	0.0938	No
	Piedmont	0.0555	0.9250	Pooled	48	0.8869	No

[+]Negative if JMFs after 2018 change had higher average mean value.

Asphalt Content Analysis

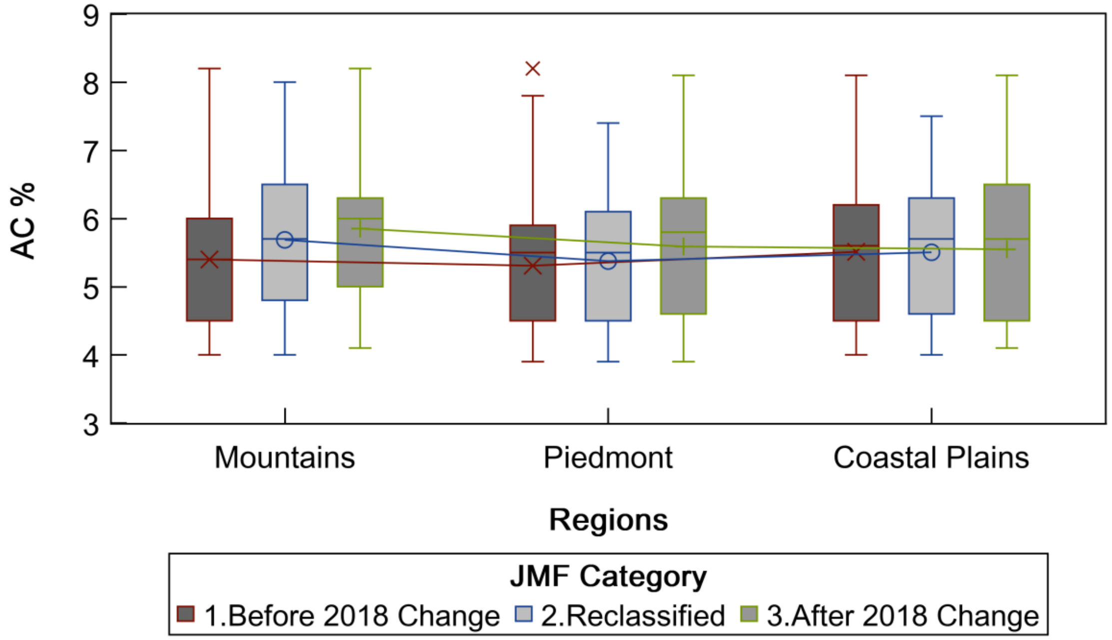

Figure B.5. Change of total asphalt content between different regions for each JMF category.

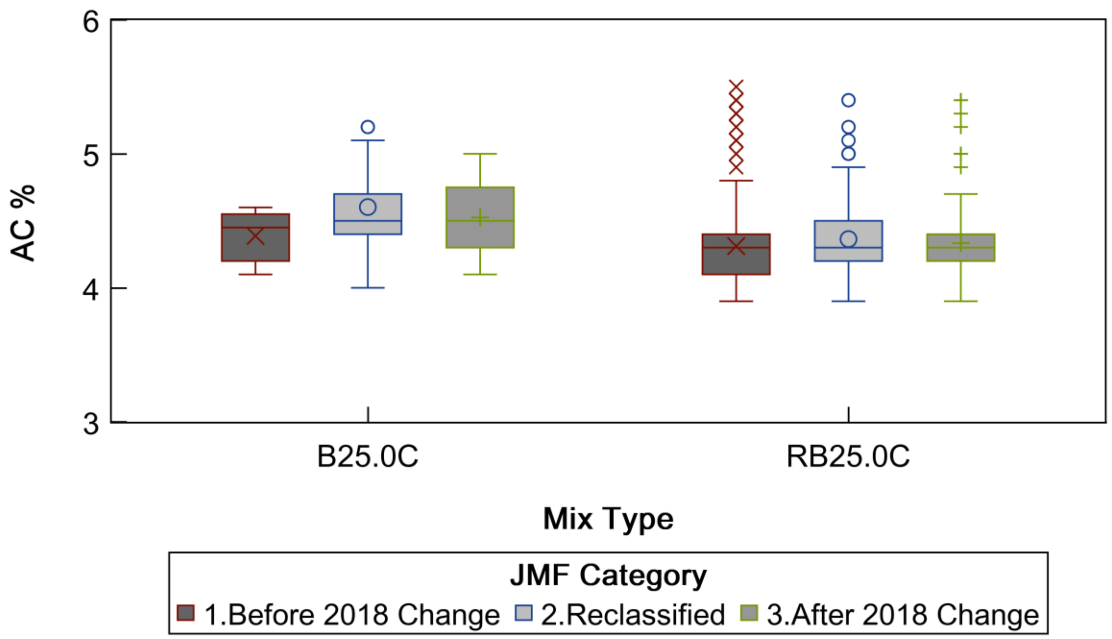

Figure B.6. Change of total asphalt content in base mixes for each JMF category (*Refer to Table 8 for counts details).

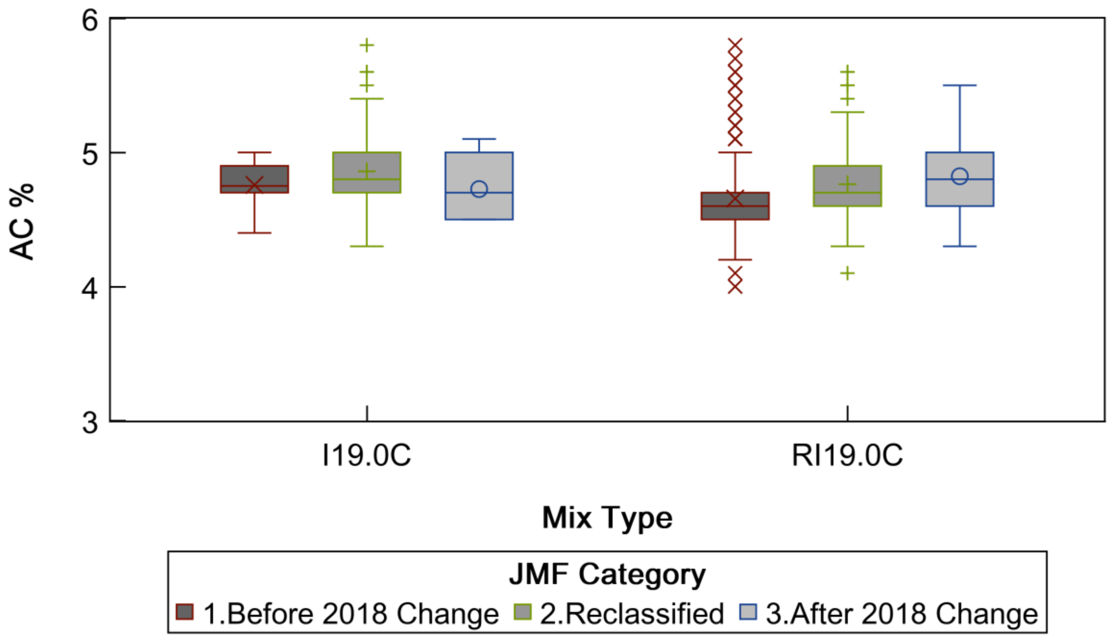

Figure B.7. Change of total asphalt content in intermediate mixes for each JMF category (*Refer to Table 8 for counts details).

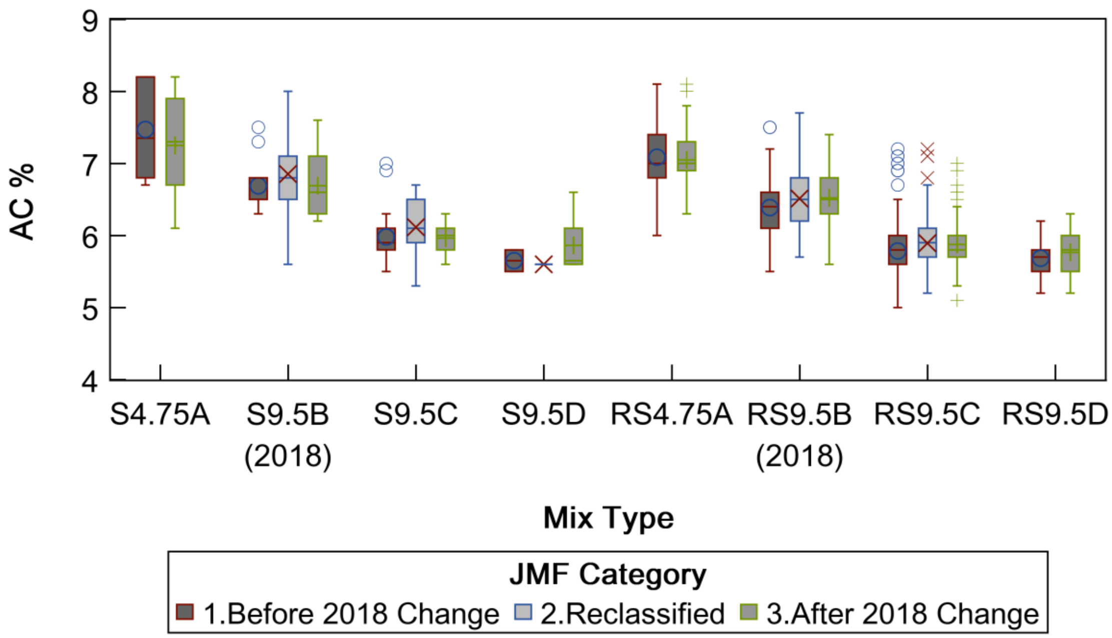

Figure B.8. Change of total asphalt content in surface mixes for each JMF category (*Refer to Table 7 for counts details).

Table B.3. Total asphalt content variable student t-test results for each mix type.

	Mean Difference		Mean Variance Test		t-test Results		
Mix Type	**Difference**	**JMF with Higher Value**	**Pr > |F|**	**t-test Method**	**DF**	**Pr > |t|**	**Sig.?**
B25.0C	-0.1375	After 2018 Change	0.1758	Pooled	10	0.4147	No
RB25.0C	-0.0228	After 2018 Change	0.0001	Satterthwaite	452	0.3476	No
I19.0C	0.0305	Before 2018 Change	0.2946	Pooled	27	0.6799	No
RI19.0C	**-0.1660**	**After 2018 Change**	**0.0365**	**Satterthwaite**	**376**	**<.0001**	**Yes**
S9.5B(2018)	-0.0020	After 2018 Change	0.9724	Pooled	18	0.9918	No
RS9.5B(2018)	**-0.1340**	**After 2018 Change**	**0.1194**	**Pooled**	**347**	**0.0002**	**Yes**
S9.5C	0.0164	Before 2018 Change	0.0488	Satterthwaite	32	0.8460	No
RS9.5C	**-0.0918**	**After 2018 Change**	**0.1504**	**Pooled**	**672**	**0.0004**	**Yes**
S9.5D	-0.2125	After 2018 Change	0.8020	Pooled	8	0.4860	No
RS9.5D	-0.0806	After 2018 Change	0.0158	Satterthwaite	79	0.1800	No
S4.75A	0.2200	Before 2018 Change	0.7042	Pooled	24	0.4354	No
RS4.75A	0.0379	Before 2018 Change	0.0342	Satterthwaite	163	0.5637	No

Table B.4. Total asphalt content variable student t-test results for each mix type within each region.

Mix Type	Region	Mean Difference[+]	Mean Variance Test Pr > |F|	t-test Method	t-test Results DF	Pr > |t|	Sig.?
B25.0C	Mountains	-0.2667	0.0585	Pooled	6	0.1187	No
RB25.0C	**Coastal Plains**	**0.1002**	**<.0001**	**Satterthwaite**	**133**	**0.0398**	**Yes**
	Mountains	**-0.3011**	**0.6590**	**Pooled**	**35**	**0.0410**	**Yes**
	Piedmont	**-0.0820**	**0.9585**	**Pooled**	**228**	**0.0038**	**Yes**
I19.0C	Coastal Plains	0.1156	0.0158	Satterthwaite	9	0.1738	No
	Mountains	-0.2300	1.0000	Pooled	5	0.2924	No
	Piedmont	0.0000	0.6850	Pooled	6	1.0000	No
RI19.0C	**Coastal Plains**	**-0.2181**	**0.0034**	**Satterthwaite**	**200**	**<.0001**	**Yes**
	Mountains	-0.0447	0.0112	Satterthwaite	38	0.5939	No
	Piedmont	**-0.0752**	**0.2184**	**Pooled**	**277**	**0.0161**	**Yes**
S9.5B(2018)	Coastal Plains	-0.0800	<.0001	Satterthwaite	4	0.5965	No
	Piedmont	-0.2200	0.6832	Pooled	8	0.4519	No
RS9.5B(2018)	**Coastal Plains**	**-0.2365**	**0.0329**	**Satterthwaite**	**97**	**<.0001**	**Yes**
	Mountains	-0.0067	0.7827	Pooled	22	0.9675	No
	Piedmont	-0.0585	0.9508	Pooled	172	0.2397	No
S9.5C	Coastal Plains	0.2800	0.4556	Pooled	8	0.0792	No
	Piedmont	-0.0696	0.3999	Pooled	24	0.7509	No
RS9.5C	Coastal Plains	-0.0056	0.0018	Satterthwaite	233	0.9024	No
	Mountains	-0.0937	0.0328	Satterthwaite	23	0.3802	No
	Piedmont	**-0.1321**	**0.4640**	**Pooled**	**376**	**<.0001**	**Yes**
S9.5D	Piedmont	-0.0167	0.2805	Pooled	6	0.8892	No
RS9.5D	Coastal Plains	-0.0752	0.6683	Pooled	20	0.6123	No
	Mountains	0.0000	1.0000	Pooled	9	1.0000	No
	Piedmont	-0.0327	0.0142	Satterthwaite	37	0.6349	No
S4.75A	**Mountains**	**0.9048**	**0.0363**	**Satterthwaite**	**6**	**0.0307**	**Yes**
	Piedmont	0.3250	0.7446	Pooled	10	0.3943	No
RS4.75A	Coastal Plains	0.0779	0.1687	Pooled	105	0.3548	No
	Piedmont	-0.0637	0.0756	Pooled	48	0.6074	No

[+]Negative if JMFs after 2018 change had higher average mean value.

Supplier Analysis

Table B.5. Selected suppliers VMA t-test results for RB25.0C JMF type.

Supplier Code	JMF Type	Difference+	Pr > |F|	t-test Method	Variances	t Value	DF	Pr > |t|	Sig.?
AS-14	**RB25.0C**	**-0.6667**	**0.1847**	**Pooled**	**Equal**	**-6.5622**	**9.0000**	**0.0001**	**Yes**
AS-21	RB25.0C	-0.1167	0.7583	Pooled	Equal	-0.4575	8.0000	0.6595	No
AS-38	RB25.0C	-0.4571	0.0005	Satterthwaite	Unequal	-2.2065	6.3722	0.0669	No
AS-140	RB25.0C	0.1235	<.0001	Satterthwaite	Unequal	1.0414	6.2268	0.3364	No
AS-141	RB25.0C	0.0304	0.1097	Pooled	Equal	0.3705	13.0000	0.7170	No

+Negative if JMFs after 2018 change had higher average mean value.

Table B.6. Selected suppliers VFA t-test results for RB25.0C JMF type.

Supplier Code	JMF Type	Difference+	Pr > |F|	t-test Method	Variances	t Value	DF	Pr > |t|	Sig.?
AS-14	RB25.0C	0.3200	0.1106	Pooled	Equal	0.5163	9.0000	0.6181	No
AS-21	RB25.0C	0.3417	1.0000	Pooled	Equal	0.7041	8.0000	0.5013	No
AS-38	RB25.0C	-0.3714	0.0026	Satterthwaite	Unequal	-0.7090	6.6537	0.5024	No
AS-140	RB25.0C	0.2151	0.0272	Satterthwaite	Unequal	0.5702	7.3023	0.5857	No
AS-141	RB25.0C	0.1821	0.4129	Pooled	Equal	0.6448	13.0000	0.5302	No

+Negative if JMFs after 2018 change had higher average mean value.

Table B.7. Selected suppliers Total AC t-test results for RB25.0C JMF type.

Supplier Code	JMF Type	Difference+	Pr > |F|	t-test Method	Variances	t Value	DF	Pr > |t|	Sig.?
AS-14	**RB25.0C**	**-0.2000**	**<.0001**	**Satterthwaite**	**Unequal**	**-4.4721**	**5.0000**	**0.0066**	**Yes**
AS-21	RB25.0C	-0.0083	0.0841	Pooled	Equal	-0.1480	8.0000	0.8860	No
AS-38	RB25.0C	0.3571	0.0042	Satterthwaite	Unequal	2.0643	6.7812	0.0792	No
AS-140	RB25.0C	0.0143	<.0001	Satterthwaite	Unequal	1.0000	6.0000	0.3559	No
AS-141	RB25.0C	-0.0464	0.0861	Pooled	Equal	-1.0825	13.0000	0.2987	No

+Negative if JMFs after 2018 change had higher average mean value.

Table B.8. Selected suppliers VMA t-test results for RI19.0C JMF type.

Supplier Code	JMF Type	Difference+	Pr > |F|	tT-test Method	Variances	t Value	DF	Pr > |t|	Sig.?
AS-14	RI19.0C	-0.4500	0.6040	Pooled	Equal	-1.9723	10.0000	0.0768	No
AS-15	RI19.0C	0.1667	0.7742	Pooled	Equal	0.8980	4.0000	0.4199	No
AS-38	**RI19.0C**	**0.3833**	**0.1613**	**Pooled**	**Equal**	**2.7373**	**10.0000**	**0.0209**	**Yes**
AS-153	RI19.0C	-0.2000	0.1429	Pooled	Equal	-0.8018	4.0000	0.4676	No

+Negative if JMFs after 2018 change had higher average mean value.

Table B.9. Selected suppliers VFA t-test results for RI19.0C JMF type.

Supplier Code	JMF Type	Difference+	Pr > |F|	t-test Method	Variances	t Value	DF	Pr > |t|	Sig.?
AS-14	RI19.0C	-0.4833	0.3755	Pooled	Equal	-0.7833	10.0000	0.4516	No
AS-15	RI19.0C	-0.7667	0.1878	Pooled	Equal	-0.6516	4.0000	0.5502	No
AS-38	**RI19.0C**	**1.3333**	**0.0685**	**Pooled**	**Equal**	**5.2342**	**10.0000**	**0.0004**	**Yes**
AS-153	RI19.0C	-0.3000	0.4375	Pooled	Equal	-0.9186	4.0000	0.4103	No

+Negative if JMFs after 2018 change had higher average mean value.

Table B.10. Selected suppliers Total AC t-test results for RI19.0C JMF type.

Supplier Code	JMF Type	Difference+	Pr > |F|	t-test Method	Variances	t Value	DF	Pr > |t|	Sig.?
AS-14	RI19.0C	-0.1833	0.0657	Pooled	Equal	-2.0426	10.0000	0.0683	No
AS-15	RI19.0C	-0.0333	0.5000	Pooled	Equal	-0.5000	4.0000	0.6433	No
AS-38	RI19.0C	0.2667	0.4821	Pooled	Equal	1.6903	10.0000	0.1218	No
AS-153	RI19.0C	0.0000	<.0001	Satterthwaite	Unequal	0.0000	2.0000	1.0000	No

+Negative if JMFs after 2018 change had higher average mean value.

Table B.11. Selected suppliers VMA t-test results for RS4.75A JMF type.

Supplier Code	JMF Type	Difference+	Pr > |F|	t-test Method	Variances	t Value	DF	Pr > |t|	Sig.?
AS-131	RS4.75A	0.0625	1.0000	Pooled	Equal	0.5717	10.0000	0.5802	No
AS-135	RS4.75A	-0.1911	0.1077	Pooled	Equal	-1.0189	12.0000	0.3283	No

+Negative if JMFs after 2018 change had higher average mean value.

Table B.12. Selected suppliers VFA t-test results for RS4.75A JMF type.

Supplier Code	JMF Type	Difference+	Pr > |F|	T-test Method	Variances	t Value	DF	Pr > |t|	Sig.?
AS-131	RS4.75A	-0.4875	0.0008	Satterthwaite	Unequal	-1.5193	7.1136	0.1718	No
AS-135	**RS4.75A**	**-0.7400**	**0.0001**	**Satterthwaite**	**Unequal**	**-2.7266**	**8.1308**	**0.0256**	**Yes**

+Negative if JMFs after 2018 change had higher average mean value.

Table B.13. Selected suppliers TotalAC t-test results for RS4.75A JMF type.

Supplier Code	JMF Type	Difference+	Pr > |F|	t-test Method	Variances	t Value	DF	Pr > |t|	Sig.?
AS-131	RS4.75A	-0.0500	<.0001	Satterthwaite	Unequal	-1.5275	7.0000	0.1705	No
AS-135	**RS4.75A**	**-0.1111**	**<.0001**	**Satterthwaite**	**Unequal**	**-3.1623**	**8.0000**	**0.0133**	**Yes**

+Negative if JMFs after 2018 change had higher average mean value.

Table B.14. Selected suppliers VMA t-test results for RS9.5B (2018) JMF type.

Supplier Code	JMF Type	Difference+	Pr > |F|	t-test Method	Variances	t Value	DF	Pr > |t|	Sig.?
AS-45	RS9.5B(2018)	0.2000	0.8244	Pooled	Equal	0.8660	6.0000	0.4198	No
AS-130	**RS9.5B(2018)**	**-1.5133**	**0.3512**	**Pooled**	**Equal**	**-3.4108**	**6.0000**	**0.0143**	**Yes**
AS-135	RS9.5B(2018)	0.0286	<.0001	Satterthwaite	Unequal	0.2654	13.0000	0.7948	No
AS-141	RS9.5B(2018)	-0.4000	0.4539	Pooled	Equal	-1.8592	7.0000	0.1053	No
AS-147	RS9.5B(2018)	-0.0048	0.6031	Pooled	Equal	-0.0686	8.0000	0.9470	No

+Negative if JMFs after 2018 change had higher average mean value.

Table B.15. Selected suppliers VFA t-test results for RS9.5B (2018) JMF type.

Supplier Code	JMF Type	Difference+	Pr > |F|	t-test Method	Variances	t Value	DF	Pr > |t|	Sig.?
AS-45	RS9.5B(2018)	0.2267	0.1412	Pooled	Equal	0.6671	6.0000	0.5295	No
AS-130	**RS9.5B(2018)**	**-1.8267**	**0.7667**	**Pooled**	**Equal**	**-3.1435**	**6.0000**	**0.0200**	**Yes**
AS-135	RS9.5B(2018)	-0.2179	0.0532	Pooled	Equal	-0.5443	20.0000	0.5922	No
AS-141	**RS9.5B(2018)**	**-0.5800**	**0.7772**	**Pooled**	**Equal**	**-2.6811**	**7.0000**	**0.0315**	**Yes**
AS-147	RS9.5B(2018)	-0.1048	1.0000	Pooled	Equal	-0.3254	8.0000	0.7532	No

+Negative if JMFs after 2018 change had higher average mean value.

Table B.16. Selected suppliers Total AC t-test results for RS9.5B (2018) JMF type.

Supplier Code	JMF Type	Difference+	Pr > |F|	t-test Method	Variances	t Value	DF	Pr > |t|	Sig.?
AS-45	RS9.5B(2018)	0.1667	0.7200	Pooled	Equal	2.1651	6.0000	0.0736	No
AS-130	**RS9.5B(2018)**	**-0.6200**	**0.9096**	**Pooled**	**Equal**	**-2.5071**	**6.0000**	**0.0461**	**Yes**
AS-135	RS9.5B(2018)	-0.0250	0.2606	Pooled	Equal	-0.3532	20.0000	0.7276	No
AS-141	RS9.5B(2018)	-0.0600	0.6197	Pooled	Equal	-0.8819	7.0000	0.4071	No
AS-147	RS9.5B(2018)	0.0714	0.7465	Pooled	Equal	0.6325	8.0000	0.5447	No

+Negative if JMFs after 2018 change had higher average mean value.

Table B.17. Selected suppliers VFA t-test results for RS9.5C JMF type.

Supplier Code	JMF Type	Difference[+]	Pr > |F|	t-test Method	Variances	t Value	DF	Pr > |t|	Sig.?
AS-15	RS9.5C	-0.1667	0.6000	Pooled	Equal	-0.3162	4.0000	0.7676	No
AS-21	RS9.5C	0.0333	0.3955	Pooled	Equal	0.0509	7.0000	0.9608	No
AS-40	RS9.5C	1.5333	<.0001	Satterthwaite	Unequal	2.4838	2.0000	0.1310	No
AS-45	RS9.5C	-0.2694	0.7799	Pooled	Equal	-0.7893	11.0000	0.4466	No
AS-60	RS9.5C	0.2778	0.0242	Satterthwaite	Unequal	0.3286	4.6889	0.7567	No
AS-92	RS9.5C	-0.7786	1.0000	Pooled	Equal	-1.4842	9.0000	0.1719	No
AS-130	RS9.5C	-0.6400	0.5589	Pooled	Equal	-0.8517	6.0000	0.4270	No
AS-135	RS9.5C	-0.0170	0.5612	Pooled	Equal	-0.0607	25.0000	0.9521	No
AS-141	RS9.5C	0.2619	0.3037	Pooled	Equal	0.7109	18.0000	0.4863	No
AS-153	RS9.5C	-0.7000	0.3345	Pooled	Equal	-1.2268	4.0000	0.2872	No

[+]Negative if JMFs after 2018 change had higher average mean value.

Table B.18. Selected suppliers TotalAC t-test results for RS9.5C JMF type.

Supplier Code	JMF Type	Difference[+]	Pr > |F|	t-test Method	Variances	t Value	DF	Pr > |t|	Sig.?
AS-15	RS9.5C	-0.0667	0.5000	Pooled	Equal	-1.0000	4.0000	0.3739	No
AS-21	RS9.5C	0.0833	0.4096	Pooled	Equal	0.6525	7.0000	0.5349	No
AS-40	RS9.5C	-0.1400	0.0021	Satterthwaite	Unequal	-0.3483	2.0401	0.7603	No
AS-45	RS9.5C	-0.0472	0.4967	Pooled	Equal	-0.7430	11.0000	0.4731	No
AS-60	RS9.5C	-0.0511	0.2182	Pooled	Equal	-0.4781	12.0000	0.6412	No
AS-92	**RS9.5C**	**-0.4679**	**0.1200**	**Pooled**	**Equal**	**-6.3428**	**9.0000**	**0.0001**	**Yes**
AS-130	RS9.5C	-0.3600	0.5931	Pooled	Equal	-1.9797	6.0000	0.0951	No
AS-135	RS9.5C	-0.0205	0.8742	Pooled	Equal	-0.5148	25.0000	0.6112	No
AS-141	RS9.5C	-0.0643	<.0001	Satterthwaite	Unequal	-2.5898	13.0000	0.0224	Yes

[+]Negative if JMFs after 2018 change had higher average mean value.

Surface Mixtures Comparisons at Different Equivalent Single Axle Load (ESAL)

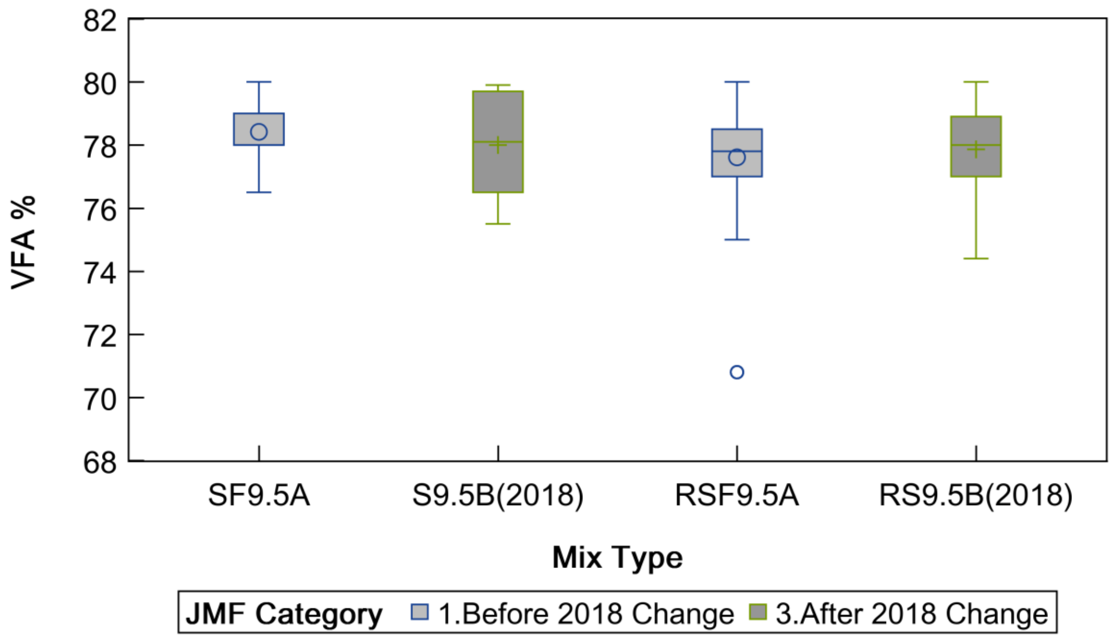

Figure B.9. Change of VFA in surface mixtures for less than 0.3 million ESAL.

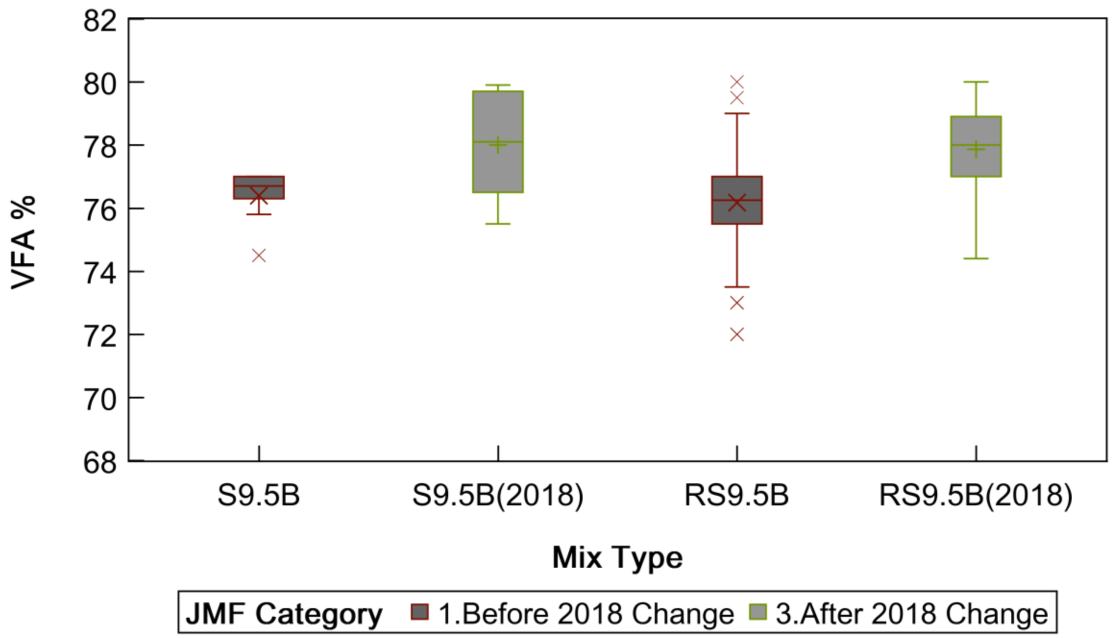

Figure B.10. Change of VFA in surface mixtures from 0.3 to 3 million ESAL.

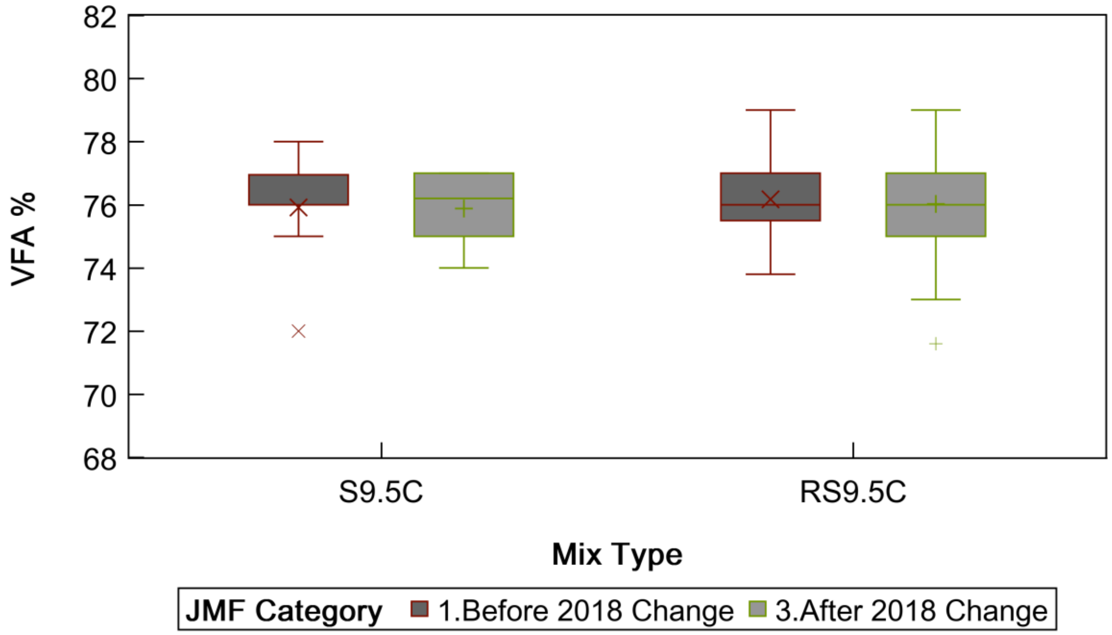

Figure B.11. Change of VMA in surface mixtures from 3 to 30 million ESAL.

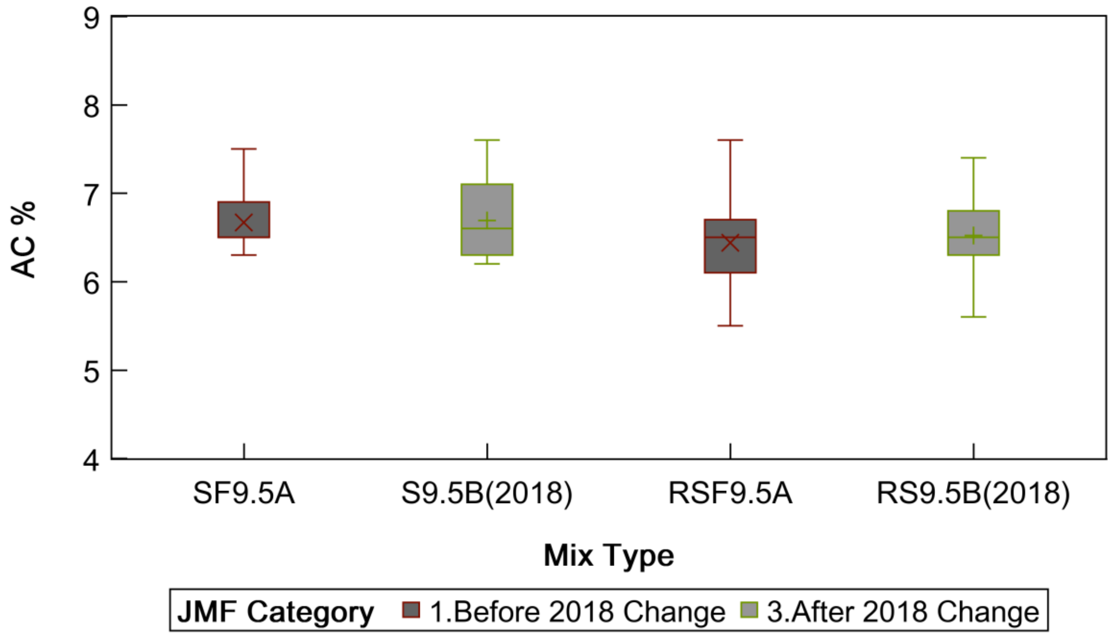

Figure B.12. Change of AC in surface mixtures for less than 0.3 million ESAL.

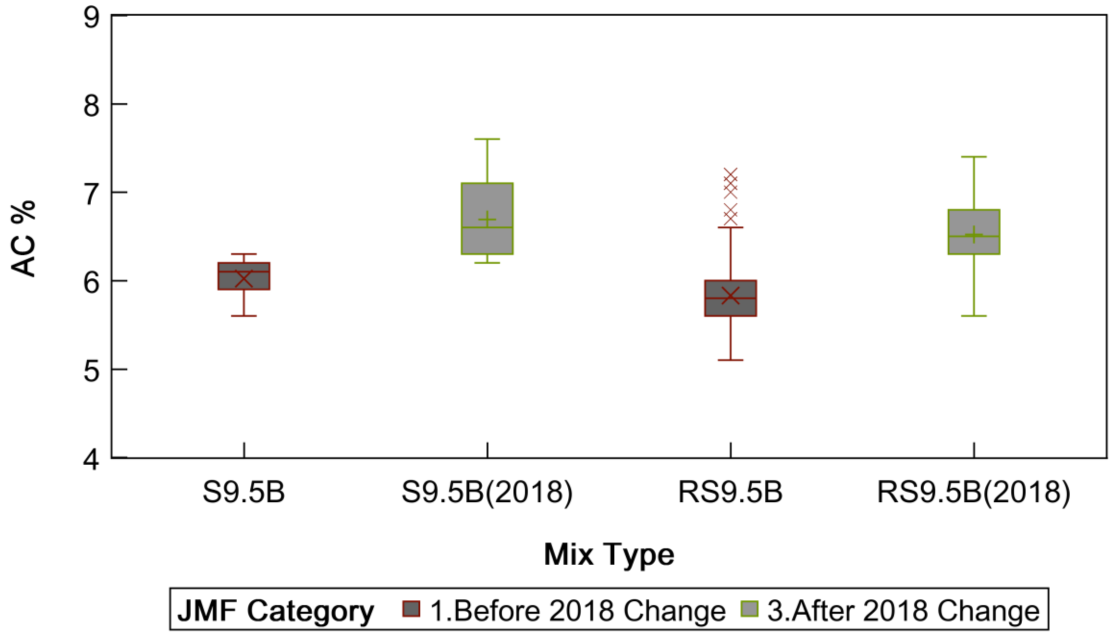

Figure B.13. Change of AC in surface mixtures from 0.3 to 3 million ESAL.

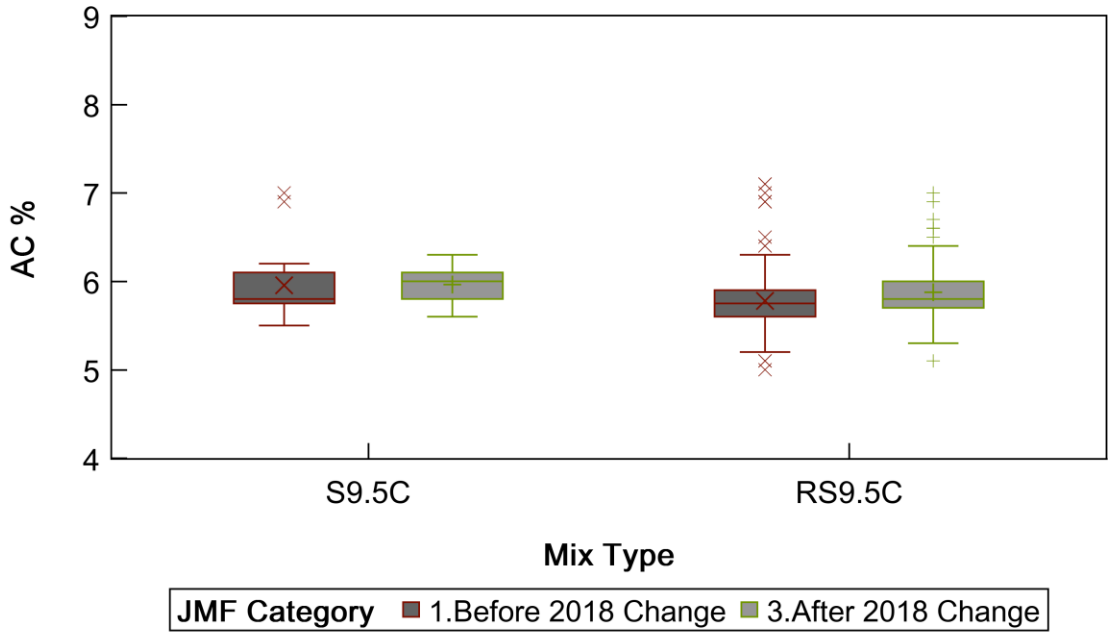

Figure B.14. Change of AC in surface mixtures from 3 to 30 million ESAL.

Table B.19. VFA t-test results for surface mixtures at different ESAL levels.

Traffic Category	JMF Type	Difference+	Pr > |F|	t-Test Method	Variances	DF	Pr > |t|	Sig.?
< 0.3 Million ESALs	**RSF9.5A vs RS9.5B(2018)**	**0.27**	**0.0012**	**Satterthwaite**	**Unequal**	**416.8**	**0.0154**	**Yes**
	SF9.5A vs S9.5B(2018)	-0.42	0.0564	Pooled	Equal	29.0	0.3608	No
0.3 – 3 Million ESALs	**RS9.5B vs RS9.5B(2018)**	**1.69**	**0.0102**	**Satterthwaite**	**Unequal**	**374.4**	**<.0001**	**Yes**
	S9.5B vs S9.5B(2018)	**1.57**	**0.0089**	**Satterthwaite**	**Unequal**	**14.5**	**0.0056**	**Yes**
3 – 30 Million ESALs	RS9.5C vs RS9.5C(2018)	-0.16	<.0001	Satterthwaite	Unequal	382.6	0.1714	No
	S9.5C vs S9.5C(2018)	0.06	0.1760	Pooled	Equal	30.0	0.9057	No

+Negative if JMFs before 2018 change had higher average mean value.

Table B.20. AC content t-test results for surface mixtures at different ESAL levels.

Traffic Category	JMF Type	Difference+	Pr > |F|	t-Test Method	Variances	DF	Pr > |t|	Sig.?
< 0.3 Million ESALs	**RSF9.5A vs RS9.5B(2018)**	**0.09**	**0.0643**	**Pooled**	**Equal**	**562.0**	**0.0074**	**Yes**
	SF9.5A vs S9.5B(2018)	0.04	0.3676	Pooled	Equal	29.0	0.7680	No
0.3 – 3 Million ESALs	**RS9.5B vs RS9.5B(2018)**	**0.70**	**0.5720**	**Pooled**	**Equal**	**635.0**	**<.0001**	**Yes**
	S9.5B vs S9.5B(2018)	**0.69**	**0.0261**	**Satterthwaite**	**Unequal**	**15.3**	**<.0001**	**Yes**
3 – 30 Million ESALs	**RS9.5C vs RS9.5C(2018)**	**0.10**	**0.0330**	**Satterthwaite**	**Unequal**	**471.5**	**0.0005**	**Yes**
	S9.5C vs S9.5C(2018)	0.05	0.1058	Pooled	Equal	30.0	0.6656	No

+Negative if JMFs before 2018 change had higher average mean value.

APPENDIX C: SUPPLEMENTARY COMPARISON TABLES AND FIGURES FOR DYNAMIC MODULUS PREDICTIONS

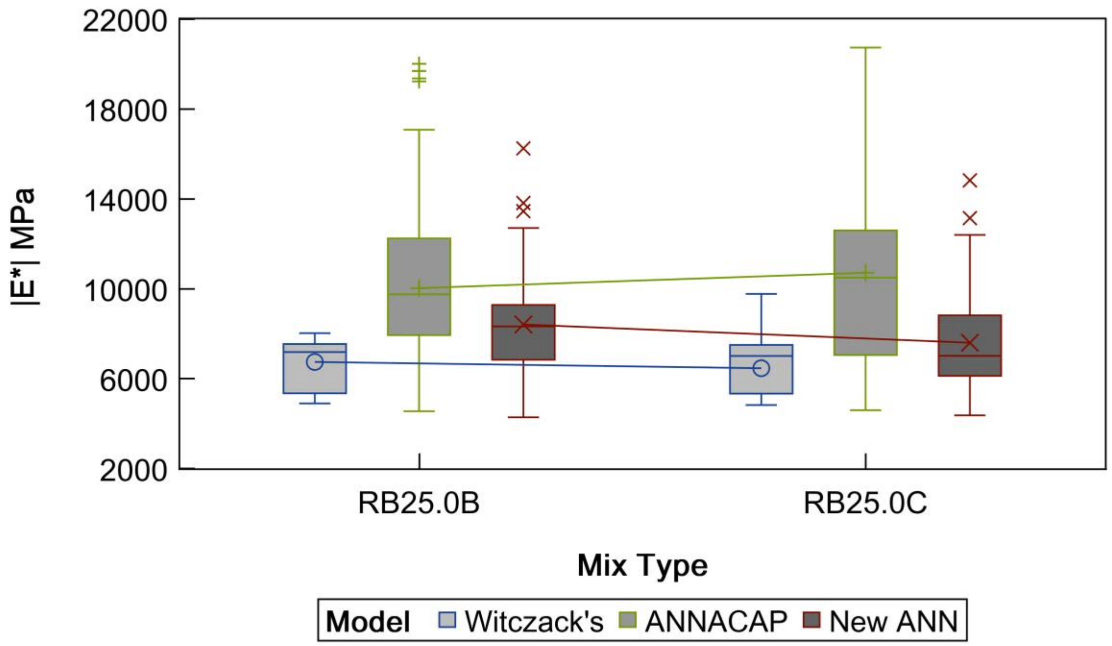

Figure C.1. Comparison of |E*|predicted values for base mixes before and after 2018 change.

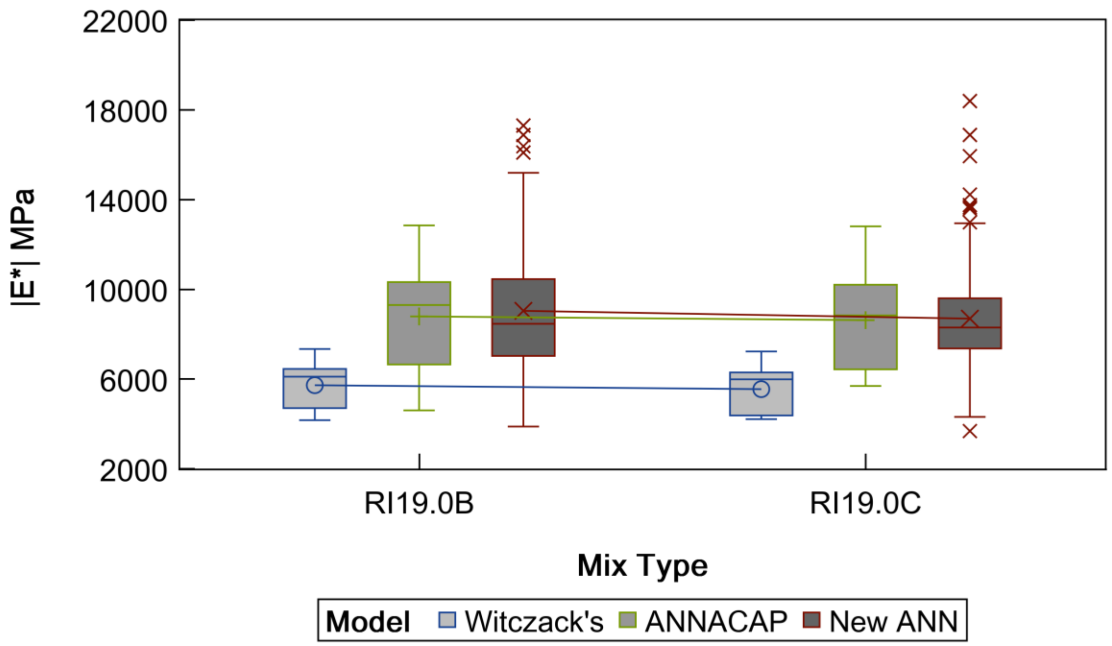

Figure C.2. Comparison of |E*|predicted values for intermediate mixes before and after 2018 change.

Table C.1. Supplier based comparison before and after 2018 change for surface mixes at less than 0.3 million ESALs.

Prediction Model	Mix Type	Counts	Percent with Higher Moduli	|E*| Average Percent Difference
ANNACAP Software	RSF9.5A	20	46.5%	40%
	RS9.5B(2018)	23	53.5%	25%
ANN Model	RSF9.5A	26	60.5%	12%
	RS9.5B(2018)	17	39.5%	7%
Witczack's Model	RSF9.5A	13	30.2%	18%
	RS9.5B(2018)	30	69.8%	11%

Table C.2. Supplier based comparison before and after 2018 change for surface mixes from 0.3 to 3 million ESALs.

Prediction Model	Mix Type	Counts	Percent with Higher Moduli	|E*| Average Percent Difference
ANNACAP Software	RS9.5B	19	41.3%	17%
	RS9.5C	27	58.7%	31%
ANN Model	RS9.5B	22	47.8%	7%
	RS9.5C	24	52.2%	11%
Witczack's Model	RS9.5B	14	30.4%	13%
	RS9.5C	32	69.6%	15%

APPENDIX D: SUPPLEMENTARY TABLES AND FIGURES FOR RUTTING PERFORMANCE PREDICTIONS

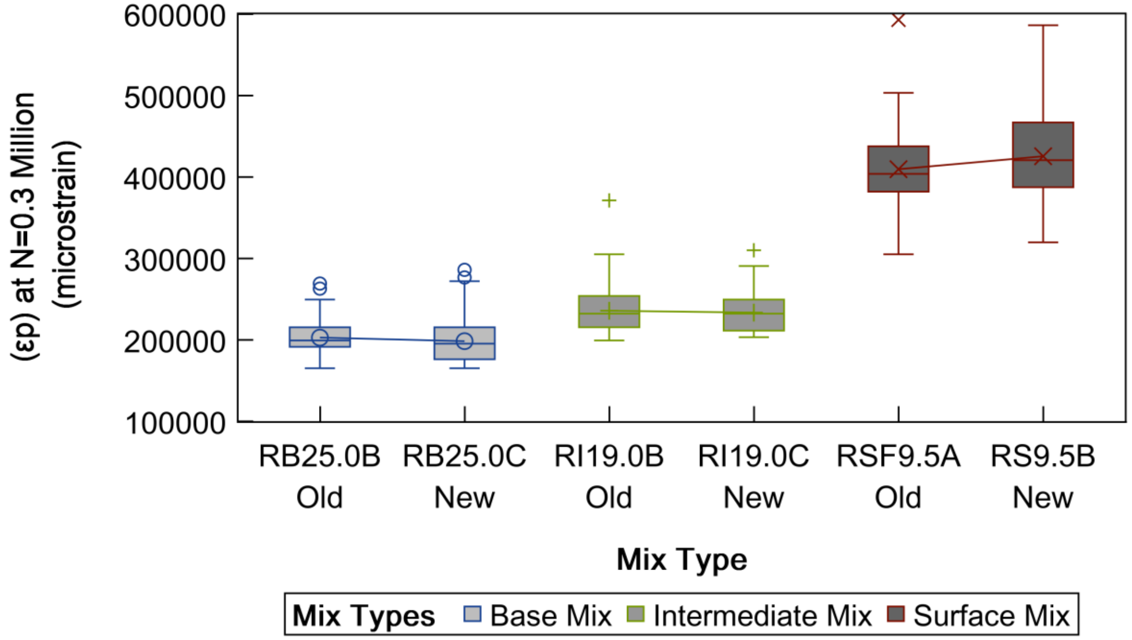

Figure D.1. Comparison of predicted (εp) values at 0.3 million ESALs utilizing May and Witczak model.

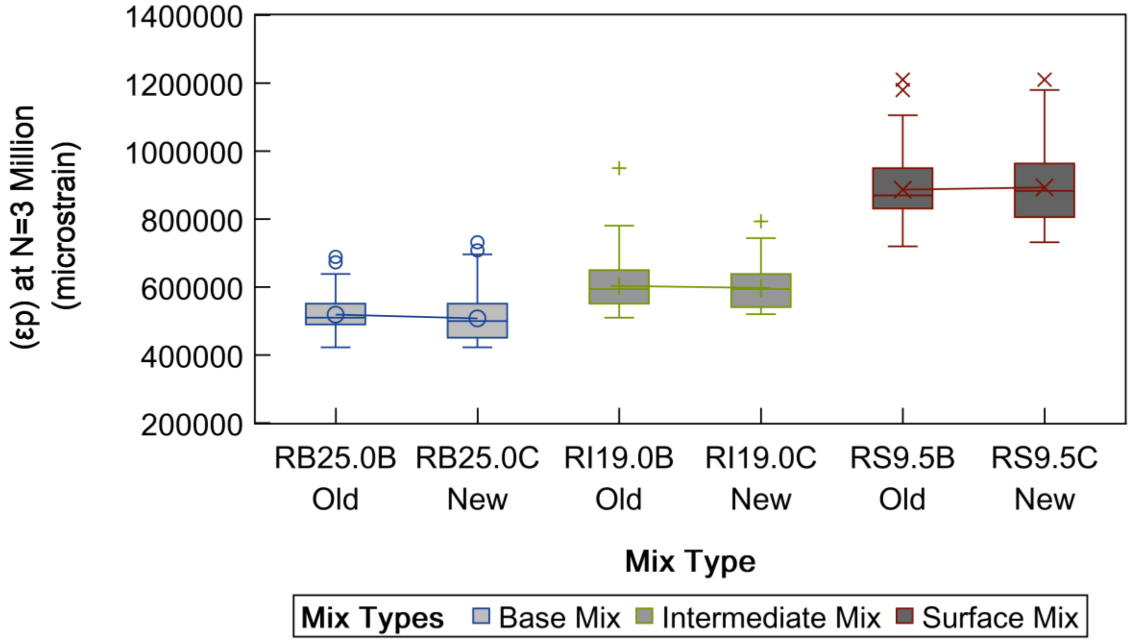

Figure D.2. Comparison of predicted (εp) values at 3 million ESALs utilizing May and Witczak model.

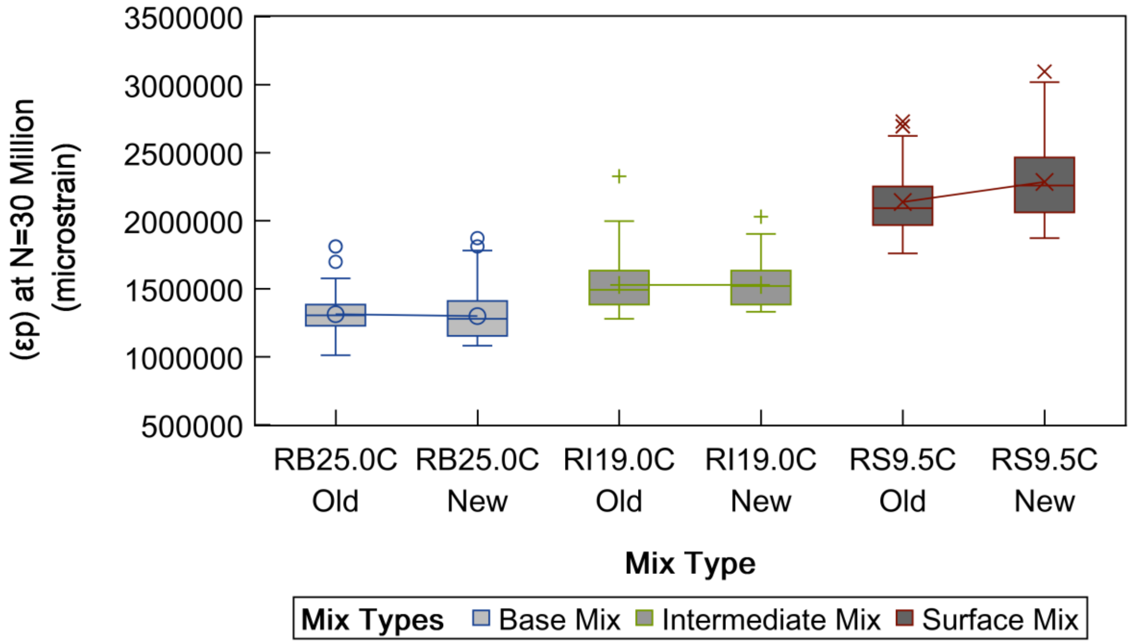

Figure D.3. Comparison of predicted (εp) values at 30 million ESALs utilizing May and Witczak model.

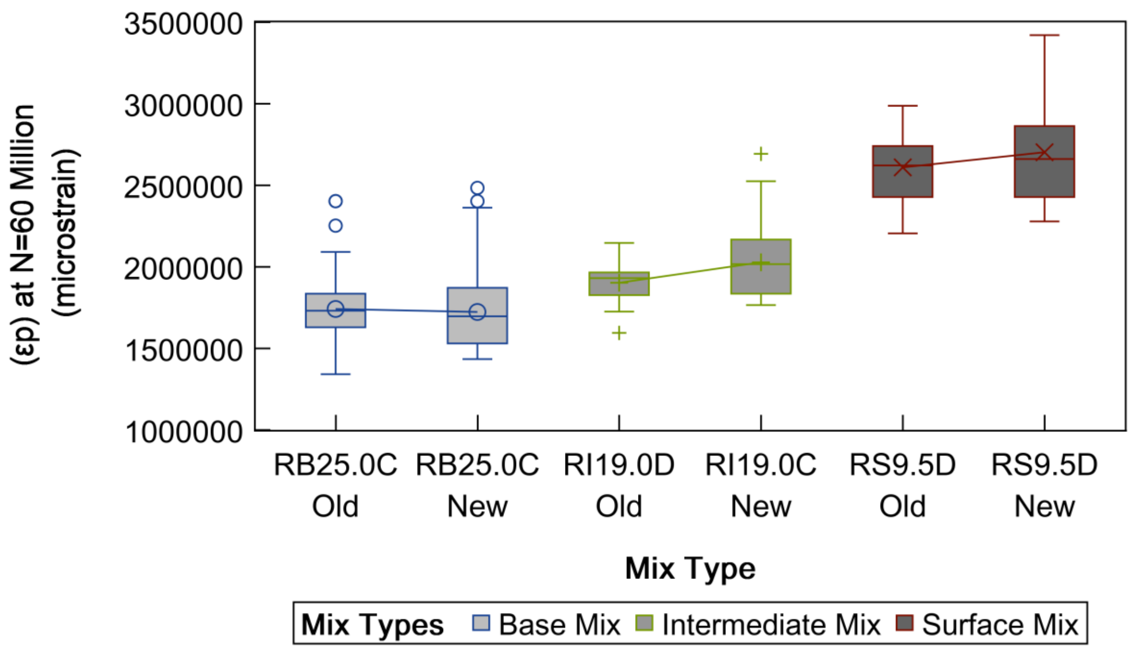

Figure D.4. Comparison of predicted (εp) values at 60 million ESALs utilizing May and Witczak model.

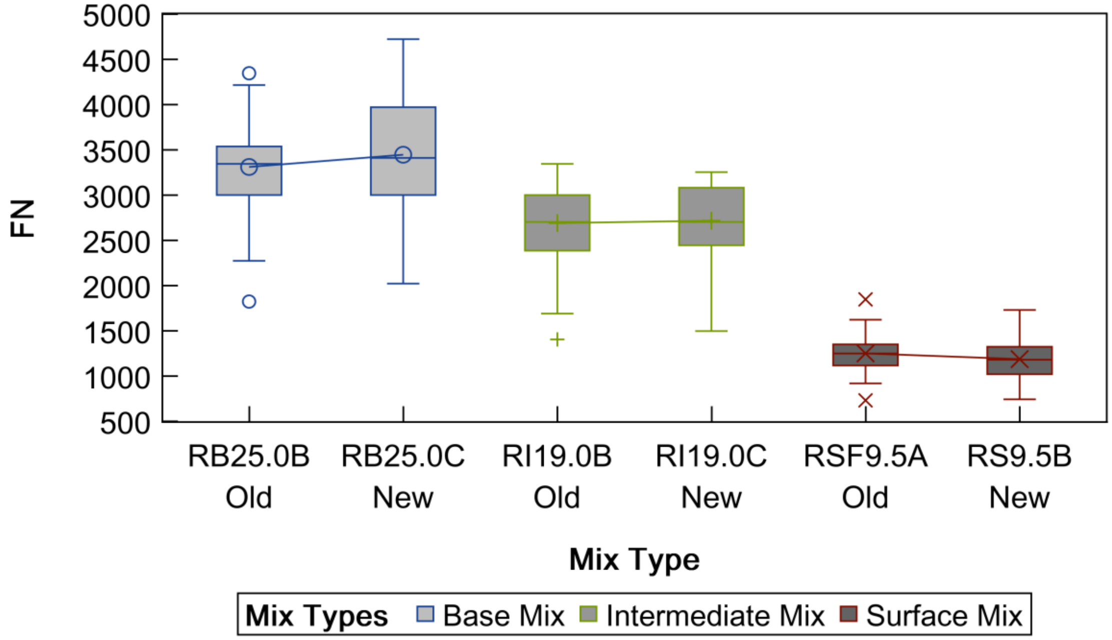

Figure D.5. Comparison of predicted FN values utilizing Kaloush model.

Table D.1. Supplier based comparison before and after 2018 change utilizing Leahy and May and Witczak models at 3 million ESALs.

Prediction Model	Mix Type	JMF	Counts with Better Performance	Percent with Better Performance	Average Difference (εp/εr or εp)
Leahy Model	Base Mix	Old RB25.0B is Better	15	50.0%	2.6%
		New RB25.0C is Better	11	36.7%	3.0%
		Both are Similar	4	13.3%	0.0%
	Intermediate Mix	Old RI19.0B is Better	14	41.2%	2.7%
		New RI19.0C is Better	18	52.9%	3.5%
		Both are Similar	2	5.9%	0.0%
	Surface Mix	Old RS9.5B is Better	27	56.3%	2.7%
		New RS9.5C is Better	20	41.7%	4.2%
		Both are Similar	1	2.1%	0.0%
May & Witczak Model	Base Mix	Old RB25.0B is Better	14	46.7%	5.3%
		New RB25.0C is Better	12	40.0%	6.4%
		Both are Similar	4	13.3%	0.0%
	Intermediate Mix	Old RI19.0B is Better	14	41.2%	2.7%
		New RI19.0C is Better	18	52.9%	3.5%
		Both are Similar	2	5.9%	0.0%
	Surface Mix	Old RS9.5B is Better	27	56.3%	5.4%
		New RS9.5C is Better	20	41.7%	8.5%
		Both are Similar	1	2.1%	0.0%

Table D.2. Supplier based comparison before and after 2018 change utilizing Leahy and May and Witczak models at 30 million ESALs.

Prediction Model	Mix Type	JMF	Counts with Better Performance	Percent with Better Performance	Average Difference (εp/εr or εp)
Leahy Model	Base Mix	Old RB25.0C is Better	28	70.0%	4.3%
		New RB25.0C is Better	12	30.0%	3.4%
	Intermediate Mix	Old RI19.0C is Better	27	64.3%	3.2%
		New RI19.0C is Better	14	33.3%	6.1%
		Both are Similar	1	2.4%	0.0%
	Surface Mix	Old RS9.5C is Better	9	18.4%	2.3%
		New RS9.5C is Better	40	81.6%	6.9%
May & Witczak Model	Base Mix	Old RB25.0C is Better	27	67.5%	7.8%
		New RB25.0C is Better	13	32.5%	7.8%
	Intermediate Mix	Old RI19.0C is Better	28	66.7%	6.1%
		New RI19.0C is Better	13	31.0%	13.2%
		Both are Similar	1	2.4%	0.0%
	Surface Mix	Old RS9.5C is Better	39	79.6%	9.9%
		New RS9.5C is Better	10	20.4%	5.0%

Table D.3. Supplier based comparison before and after 2018 change utilizing Leahy and May and Witczak models at 60 million ESALs.

Prediction Model	Mix Type	JMF	Counts with Better Performance	Percent with Better Performance	Average Difference (εp/εr or εp)
Leahy Model	Base Mix	Old RB25.0C is Better	28	70.0%	4.3%
		New RB25.0C is Better	12	30.0%	3.4%
	Intermediate Mix	Old RI19.0D is Better	5	29.4%	3.8%
		New RI19.0C is Better	12	70.6%	4.3%
	Surface Mix	Old RS9.5D is Better	3	37.5%	3.4%
		New RS9.5D is Better	1	12.5%	4.6%
		Both are Similar	4	50.0%	0.0%
May & Witczak Model	Base Mix	Old RB25.0C is Better	27	67.5%	7.8%
		New RB25.0C is Better	13	32.5%	7.8%
	Intermediate Mix	Old RI19.0D is Better	16	94.1%	14.0%
		New RI19.0C is Better	1	5.9%	2.1%
	Surface Mix	Old RS9.5D is Better	4	50.0%	7.3%
		Both are Similar	4	50.0%	0.0%