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Final Report

VALIDATION OF SUPERPAVE FINE AGGREGATE ANGULARITY VALUES

MINNESOTA DEPARTMENT OF TRANSPORTATION

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16. Abstract (Limit: 200 words)

This report presents the results of laboratory testing to validate the use of Fine Aggregate Angularity (FAA) measurements with the Superpave method of Hot Mix Asphalt (HMA) design. A search of literature and Minnesota FAA data was conducted in preparation for FAA testing of aggregates and HMA design.

Laboratory tests of aggregates included sieve analysis, specific gravity and FAA. Additional work was also performed by acquiring digital imaging data for the aggregates.

Testing of asphalt mixtures included dynamic modulus tests and asphalt pavement analyzer tests. Testing was performed on four asphalt mixtures representing a range of Minnesota FAA values. Dynamic modulus testing was performed at three temperatures and five frequencies. Data from the dynamic modulus tests were processed using nonlinear regression. The resulting master curves of dynamic modulus vs. frequency were referenced to test temperature 54C. Asphalt pavement analyzer data at 54C was analyzed with respect to rutting curve. Laboratory test results for aggregates and mixtures were analyzed together using statistical methods to develop correlation coefficients and linear trends.

It was found that dynamic modulus and rut resistance values are strongly related to aggregate blend FAA. Some additional parameters from digital imaging also predicted modulus and rut resistance very well and should be included in future reference.

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VALIDATION OF SUPERPAVE FINE AGGREGATE ANGULARITY VALUES

Final Report

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Table of Contents

List of Figures

List of Tables

EXECUTIVE SUMMARY

The State of Minnesota includes Fine Aggregate Angularity (FAA) as an important factor in Superpave mixture design because it can enhance rut resistance. The FAA requirement is one of the aggregate consensus properties recommended by the Strategic Highway Research Program (SHRP). A standard test method (AASHTO T304, ASTM C1252 Method A, also called AASHTO TP 33 Method A) is used to indirectly measure angularity. This method determines the void content in a standard, uncompacted aggregate sample. The uncompacted void content of an aggregate is used as an indicator of FAA since aggregates with greater angularity should likewise have greater uncompacted void content values.

Recent concerns about pavement performance and aggregate shape have caused transportation agencies to reinvestigate whether standard FAA testing provides information indicative of performance.

This report presents the results from new digital imaging and standard test methods for determining angularity to validate the use of Fine Aggregate Angularity measurements with the Superpave method of Hot Mix Asphalt design. In preparation for testing of aggregates and Superpave asphalt mixture design, a search of literature was conducted and Minnesota Fine Aggregate Angularity data was collected.

Mixture testing included both dynamic modulus tests and asphalt pavement analyzer tests evaluated at test temperature 54C. Dynamic modulus testing was performed at three temperatures and five frequencies on four asphalt mixtures representing a range of Minnesota FAA values. Data from the dynamic modulus tests were processed using nonlinear regression. Asphalt pavement analyzer data was analyzed with respect to the rutting curve and rate of rutting. Laboratory test results for aggregates and mixtures were analyzed together using statistical methods to develop correlation coefficients and linear trends.

It was found that dynamic modulus and rut resistance values are strongly related to aggregate blend FAA. Some additional parameters from digital imaging also predicted modulus and rut resistance very well and should be included in future research

CHAPTER 1: INTRODUCTION

1.1 Introduction

Aggregate angularity is recognized as an important part of asphalt mixtures, along with other mixture properties, including aggregate gradation, air voids, Voids in the Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA). Angularity is often mentioned as having the potential to influence aggregate and mixture performance through interaction with other properties, as indicated in the following research papers. Results of post-Superpave research have increased concerns about pavement performance and aggregate shape. This concern has caused transportation agencies to reinvestigate whether standard Fine Aggregate Angularity (FAA) testing provides information indicative of performance (3).

1.2 Objectives

The main objective of this project was to evaluate angularity and performance separately and then analyze the results to determine how performance is influenced by angularity. Additional work was performed with respect to digital imaging analysis and is included with the results. Four asphalt mixtures were designed to differ chiefly by angularity and contain aggregate materials representative of several Minnesota regions. Mixtures were similar in binder, air voids, coarse aggregate, gradation, VMA, and VFA. Complex modulus tests and asphalt pavement analyzer tests were performed on the four Minnesota asphalt mixtures. Master curves and rutting curves were generated from the test data. Model master curves were to be compared against rutting, FAA, and digital imaging angularity data.

1.3 Scope

Four different asphalt mixtures were evaluated in this study. In order to emphasize rutting, the dynamic modulus was measured at test temperatures 20, 40, and 54ºC, and frequencies of 25, 10, 1, 0.1, and 0.01 Hz. Asphalt pavement analyzer rut testing was also performed at 54ºC.

1.4 Report Organization

This report is arranged into nine chapters: Introduction, Literature Review, Review of Existing Minnesota FAA Data, Analysis of Measured FAA Data, Development of Laboratory Testing Program, Mixture Design, Fabrication and Testing of HMA Specimens, Analysis of Laboratory Results and Conclusions.

The Literature Review in Chapter 2 describes FAA from a historical viewpoint, touching on the inclusion of angularity in Superpave mixture design methodology. Post-Superpave research is cited with respect to the ability of FAA to predict rutting resistance, and new angularity testing methods are described. The Review of Existing Minnesota FAA Data in Chapter 3 includes results from Minnesota Department of Transportation databases. Analysis of Measured FAA Data in Chapter 4 reports on the properties of 11 Minnesota aggregates. Digital imaging angularity results are also presented. Development of a Laboratory Testing Program in Chapter 5 outlines reasons for including specific materials for dynamic modulus and asphalt pavement analyzer testing. Mixture Design in Chapter 6 reports the methodology used in obtaining four asphalt mixtures. A discussion is presented regarding the interaction of various aggregates in trial mixtures, and final designs are presented. Fabrication and Testing of HMA Specimens in Chapter 7 describes specimen production from proportioning aggregate and gyratory compaction to final cutting and coring. Preliminary analysis of dynamic modulus data is presented. Analysis of Laboratory Results in Chapter 8 discusses the results from statistical analysis of imaging, FAA, dynamic modulus, and rut testing. Chapter 9 includes a report summary and presents conclusions.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The Superpave method of hot mix asphalt (HMA) concrete design identifies aggregate angularity as an important factor in obtaining rut resistance. The Superpave Fine Aggregate Angularity (FAA) requirement is one of the aggregate consensus properties recommended by the Strategic Highway Research Program (SHRP), and is outlined in the Asphalt Institute publication; *Superpave Mix Design, Superpave Series No. 2 (SP-2)* (1). The uncompacted void content of an aggregate is used as an indicator of FAA because aggregates with greater angularity should likewise have greater uncompacted void content values. A standard test method (AASHTO T304, ASTM C1252 Method A, also called AASHTO TP 33 Method A) is used to determine the void content. The State of Minnesota includes FAA as part of Standard Specification for Construction 2360, Superpave Mixture Design (2).

Recent concerns about pavement performance and aggregate shape have caused transportation agencies to reinvestigate whether standard FAA testing provides information indicative of performance (3). Chapter 2 offers background on pavement design concerns, FAA testing, new methods of aggregate characterization, and the approach of other states regarding FAA testing.

2.2 Historical Perspective

Aggregate angularity is recognized as an important part of asphalt mixtures, along with other mixture properties, including aggregate gradation, Voids in the Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA). Angularity is often mentioned as having the potential to influence aggregate and mixture performance through interaction with other properties, as indicated in the following research papers.

2.2.1 Review: "The Difficult Nature of VMA: A Historical Perspective" (4)

The authors present information regarding aggregate angularity in a subsection entitled **The Shift Towards a Minimum VMA Requirement (1955-62)**. In 1957, Lefebvre studied VMA (voids in mineral aggregate). He mentioned the influence of fine aggregate on VMA and says that fine aggregate should be "angular, with rough texture, and suitably graded." The authors note that Lefebvre included neither references nor data to support his findings.

In the section entitled **VMA: 1962 – Superpave,** the authors list Hudson and Davis (1965) and McLeod (1971), who emphasize that higher VMA values can be attained by using angular aggregate particles.

The section entitled **VMA In The Era of Superpave** cites the work of Aschenbrenner and MacKean (1994), where results showed Fine Aggregate Angularity (FAA) was "more influential for coarse mixes or mixes following the Maximum Density Line (MDL) than for mixes on the fine side of the MDL."

2.2.2 Review: "Hot Mix Asphalt Materials, Mixture Design, and Construction" (5)

Chapter 4 of *Hot Mix Asphalt Materials, Mixture Design, and Construction* (5) introduces the NAA Flow Test (AASHTO TP 33 Method A "Test Method for Uncompacted Void Content of Fine Aggregate as Influenced by Particle Shape, Surface Texture, and Grading". The test is currently used as one of the methods of evaluating aggregate in the Superpave asphalt mixture design method. The authors state that fine and coarse aggregate angularity influence the performance of asphalt mixtures and that particle angularity is greater for aggregate materials possessing greater amounts of uncompacted voids. The equation used to determine the "percent of uncompacted voids" by NAA Flow Test (AASHTO TP 33 Method A) is as follows:

$$\text{Percent Uncompacted Voids} = \frac{V - \left(\dfrac{M}{\rho_{\text{WATER}} \cdot \text{Gsb}} \right)}{V} \times 100 \, .$$

Where V = volume of cylinder (ml), M = mass of loose fine aggregate to fill cylinder (g), ρ water = $1 \text{g}/\text{ml}$, and Gsb = bulk specific gravity of fine aggregate.

The authors also refer to an equation developed by Brown and Cross that describes the relationship between uncompacted void content and rut resistance, called the NCAT Rutting Equation.

$$Y = (0.08 - 0.000089\,(CF) - 0.00152\,(NAA)) \times \sqrt{ESALs}$$

Where Y = rut depth (mm), CF = % of coarse aggregate particles with 2 or more fractured faces, and NAA = NAA (AASHTO TP 33 Method A) test results for fine aggregates.

2.2.3 Review: “Superpave Mix Design” (1)

In 1996 the Asphalt Institute published *Superpave Mix Design* (1). Chapter 2 of this reference covers Superpave mixture design procedures and notes that no new test procedures were developed for evaluating Superpave aggregates but two types of aggregate properties are specified in the Superpave system. The first type, called SHRP Consensus Properties, depends on traffic and the position within pavement and includes:

- Coarse Aggregate Angularity (CAA)
- Fine Aggregate Angularity (FAA)
- Flat and elongated particles, and
- Clay content.

The second type, called source properties, is used by agencies to qualify local aggregate materials and includes:

- Toughness (LA abrasion),
- Soundness (Na or Mg sulfate test), and
- Deleterious materials (clay lumps & friable particles test).

Chapter 3 covers materials selection, including fine aggregate angularity and designates AASHTO TP 33, “Test Method for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, & Grading, Method A)”, as the recommended method. AASHTO TP 33 is determined using the NAA Flow procedure. The calculation procedure requires a cylinder with known volume, aggregate bulk specific gravity, unit weight of water, and mass of fine aggregate (0.150 - 2.36mm) retained in the cylinder.

2.3 Post-Superpave Research

Work has been done with respect to evaluating the performance of various types of asphalt mixtures. This work includes evaluation of the major contributors considered when evaluating asphalt rutting so FAA, Voids in Mineral Aggregate (VMA), and the Superpave Restricted Zone are often linked in laboratory studies.

2.3.1 Review: "Effects of Fine Aggregate Angularity on Rutting Performance" (6)

In 1999 the Federal Highway Administration (FHWA) published a study entitled *Effects of Fine Aggregate Angularity on Rutting Performance* (6). This two-part study used 18 asphalt mixtures and Superpave design criteria. All of the mixtures used the same partially crushed 9.5-mm coarse aggregate surface mix and PG 64-22 binder. Mixture evaluation included the analysis of test results from:

- PURWheel Laboratory Wheel Tracking Device
- Simple Shear Test
- Compacted Aggregate Resistance (CAR) Test, and
- Florida Bearing Value.

Phase one of the study included 9 mixtures. This portion used single sands (natural FAA = 39, crushed FAA = 49) and blends (FAA targeted to 43, 45, 46). The second phase (9 mixtures) included redesigns of 2 poor performers from phase 1 using slag and an S-shaped gradation as well as the addition of mineral filler, replacing part of original sand with natural sand, and changing the gradation of the aggregate blend.

It was found that mixtures exhibited good PURWheel performance when FAA values were 43–48 and there was high VMA and high asphalt content. The addition of slag material increased PURWheel and RSCH shear test performance. Gradations modified to an S-shape also exhibited increased performance.

Adding dust and changing the gradation of the aggregate blend caused no change in FAA. Therefore, mixtures with FAA 47 or 44 could perform well or poorly. Compacted Aggregate Resistance (CAR) test and Florida Bearing Value of the fine aggregate both had good correlation with FAA but did not predict performance. The best performing mix had a film thickness of 8.2 microns. (Range was 8 to 10).

The study recommendations included developing guidelines for an upper limit of VMA or for a range of asphalt film thickness.

2.3.2 Review: "Aggregate Tests Related To Asphalt Concrete Performance in Pavements" (7)

In Chapter 4 of their report, *Aggregate Tests Related To Asphalt Concrete Performance in Pavements* (7), Kandhal and Parker describe the findings of a study regarding fine aggregate particle shape, angularity, and surface texture. Materials for this study included nine fine aggregate materials that were evaluated with the following three aggregate tests:

1. ASTM D 3398 Index of Aggregate Particle Shape and Texture (Index)
2. AASHTO T 304 or ASTM C1252 Uncompacted Voids, Method A (FAA)
3. Particle shape from Image Analysis (University of Arkansas Method).

Mixture gradations were designed above the restricted zone to maximize the effect of fine aggregate in the dense-graded HMA. The coarse aggregate material was a round, uncrushed gravel. A single PG 64-22 binder was used and mixtures were produced at 4 % air voids.

Correlation statistics were developed for all of the aggregate and mix validation tests using the SAS program to determine if aggregate characterization test methods give comparable results or correlate well with mix validation properties. It was found that traditional FAA has an excellent correlation with Index, and imaging analysis.

Index is the fine aggregate parameter that is best related to performance of HMA in terms of permanent deformation. However, FAA is recommended over Index because of the following reasons:

1. FAA has an excellent correlation with Index
2. FAA has the second best correlation with rut depth (-0.776) but this is only slightly less than Index.
3. FAA is more practical than Index because it is significantly less time consuming. FAA testing takes only 1 hour where Index testing takes about 8 hours (bulk specific gravity must be known for either test).

2.4 New Methods for Evaluating Fine Aggregate

New methods of characterizing aggregate particles according to shape, angularity, and texture have recently received considerable attention at the national level.

2.4.1 Review: “Effects of Fine Aggregate Properties on Rutting Resistance” (8)

The paper *Effects of Fine Aggregate Properties on Rutting Resistance* (8) reports on comparisons of rutting resistance for six different fine aggregates that have FAA values ranging from 39 to 48. The aggregate angularity, shear strength, and shape were tested using FAA, direct shear, compacted aggregate resistance (CAR), and image analysis. Analysis results showed that FAA is not sensitive to mixture rut resistance and that the friction angle from CAR and image analysis correlates well with rut depth. This reference cites Kallas and Griffith (1958), who concluded that fines having greater angularity would increase stability values and void content in bituminous mixtures produced at optimum asphalt content.

Tests of fine aggregate angularity included:

- FAA (ASTM C1252, Method A)
- Direct shear test (ASTM D3080). Friction angle is an indirect indicator of particle shape, angularity.
- CAR test (a stability test on unbound, compacted aggregates using a Marshall testing machine). The test method includes compacting the sample to 50 blows then using a 38.1-mm (1.5-in) cylinder at a rate of 50-mm/minute (2-inches/minute) to test resistance.
- Digital image analysis used the Washington State University method, in which an optical microscope views aggregate. The binary images were analyzed for:

1. Surface Parameter, where image pixels are examined for a series of erosions and dilations. Results are reported using:

$$\text{Surface Parameter} = \text{percent decrease in area} = \left(\frac{\text{A1 - A2}}{\text{A1}}\right)\times 100\,.$$

2. Fractal Length = slope of the log-log plot of Effective Width vs. Erosion/Dilation Cycles. Where the effective width value is the difference between the eroded and dilated particle radius.
3. Form Factor = $\left(\frac{4\pi \times \text{Area}}{\text{Perimiter}^2}\right)$. Form factor is 1 for a circle and decreases with increasing surface irregularity.
4. Slenderness Ratio. Image analysis was conducted in Virginia using theVDG-40. This test is of French design and uses a hopper, conveyor, light source, and camera.

Experimental design included: one gradation falling below the restricted zone, one traffic level of 3-10 million ESAL's, one PG 64-22 binder, and dust proportion 0.6 – 1.2. Mixtures were designed to 4% air voids, $N_I = 8$ (≤ 89% Gmm), $N_D = 96$, $N_M = 152$ (≤ to 98% Gmm), with minimum VMA of 13 and VFA of 65 – 75.

The Asphalt Pavement Analyzer was used to find each specimen's relative rutting resistance. Results showed rut depth was poorly correlated to FAA (R squared = 0.68), CAR (R squared = 0.46), WSU surface parameter (R squared = 0.08), WSU fractal length (R squared = 0.54), WSU form factor (R squared = 0.13), and VDG-40 Slenderness (R squared = 0.42). Rut depth was well correlated to friction angle (R squared = 0.7).

Conclusions and recommendations stated that FAA is not acceptable as a criterion for aggregate acceptance, and that there is need for a study that relates shear strength and surface texture. It was also recommended that the use of visual methods for determining particle shape and surface texture should be employed to supplement traditional FAA angularity estimates.

2.4.2 Review: "Aggregate Imaging System (AIMS) for Characterizing the Shape of Fine and Coarse Aggregate" (9)

The paper *Aggregate Imaging System (AIMS) for Characterizing the Shape of Fine and Coarse Aggregates* (9) proposes a unified and automated computer system to be used for fine and coarse aggregate shape characterization. Analysis shows how the proposed system correlates to HMA deformation. When developing an automated system, the requirements include the ability to (1) analyze fine and coarse material, and quantify (2) texture, (3) angularity and, (4) three-dimensional form. The stated objectives were to develop an Aggregate Imaging System (AIMS) and then correlate aggregate shape properties with HMA performance.

Three Superpave consensus tests are cited, along with a discussion regarding their inability to identify aggregates of poor quality:

1. Fine Aggregate Angularity (FAA, Method A of AASHTO T304)
2. Coarse Aggregate Angularity (ASTM D5821)
3. Flat-Elongated Particles (ASTM D4791)

In addition to a presentation of reviews of imaging techniques, the authors note that “little attention has been given to the angularity and texture of aggregates and especially fine aggregates”.

AIMS evaluation includes placing aggregate on a tray and providing backlighting while video equipment collects images of aggregate. Servo actuators control the video collection equipment position in three dimensions. The z location depends on resolution criteria. Row and column scans are conducted in the x-y plane.

Angularity information is collected with black and white images, while grey images capture texture. Fine aggregate angularity only is measured. Angularity calculations use two methods:

1. Gradient Method uses the difference between gradient vectors:

$$\text{Gradient} = \frac{1}{\frac{N}{3}-1}\sum_{i=1}^{N-3}\left|\theta_i - \theta_{i=3}\right|.$$

Where N = number of edge points on particle, θ is the gradient vector, and *i* is the edge point. The drawing in Figure 2.1 represents gradient vectors located at such an edge point on a 2-dimensional projection of an aggregate particle.

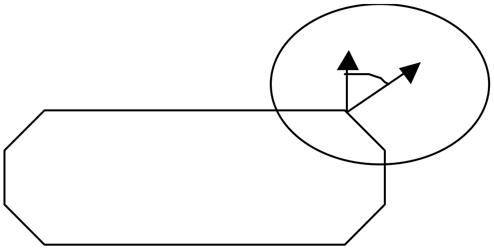

Figure 2.1 Gradient Vectors (circled) at Particle Edge Point

2. Masad’s Radius Method uses the equation: $AI = \sum_{0}^{355}\frac{\left|R_\theta - R_{EE\theta}\right|}{R_{EE\theta}}$.

Where R_{EE} is the radius of an equivalent ellipse and R_θ is the particle radius at angle θ. Figure 2.2 shows the projection of an elongated particle and equivalent ellipse. The dotted line with large arrowhead shows R_θ while the solid line and small arrowhead shows $R_{EE\theta}$.

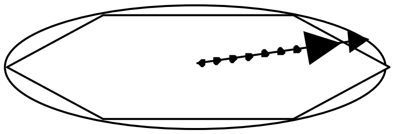

Figure 2.2 Radii on Partical and Equivalent Ellipse Projections (Radial Angularity)

Analysis and results were presented for two groups of fine aggregates, totaling 13 samples subjected to laboratory rutting tests. There was a good correlation between the Radius Method and performance. (R-squared = 0.95).

The study concluded by noting that an average FAA value might not be enough to predict performance and that more statistical work is needed for fine aggregate imaging.

2.4.3 Review: "Aggregate Shape Classification System Using AIMS" (10)

In the introduction to *Aggregate Shape Classification System Using AIMS* (10) the authors comment on the successful application of imaging technology to material science and state that the purpose of the study was to provide a framework for the developing a classification system for fine and coarse aggregates. It was important that 3-D form, angularity and texture are all quantifiable for all aggregate sizes. Additionally, a cumulative distribution function should represent aggregate shape characteristics, much like current gradation curves. This distribution function is preferred to average values because of the ability to represent the influence of blending component aggregates.

Several changes in equipment and method had been made prior to this study, including:

- Progressive scan camera is less affected by vibration
- Lighting table area was doubled to analyze larger samples
- Use of white LED's and variable backlighting.

Three-dimensional information is gained by measuring particle depth, with an auto focus microscope, and eigenvector analysis of the principal axes (from the 2-D projection). Angularity is analyzed using the gradient and radius methods while wavelet analysis is used to quantify texture. Discussions of the advantages of the selected methods are presented.

Comparisons are made with the existing geological 2-D methods of form and angularity classification developed by RittenHouse and Krumbein. High correlations were obtained between gradient angularity, radial angularity, the form index and geological methods. Statistical analysis using Tukey's method showed that the form index described RittenHouse well, while angularity methods described Krumbein well.

The study concludes by stating that gradient angularity is more sensitive to slight changes than is radial angularity. Results of an associated study show that crushing of gravel material did not improve texture, but increased angularity.

2.5 FAA Specifications

This section describes the acceptance of FAA specifications, chiefly among state DOT's.

2.5.1 Review: "Aggregate Tests For Hot-Mix Asphalt: State of the Practice " (11)

Angularity Tests are used in asphalt mix design to ensure particle interlock and adequate void content. *Aggregate Tests For Hot-Mix Asphalt: State of the Practice* (11) lists types of tests and their inclusion in state DOT specification at the beginning of the Superpave era.

The authors state that current tests have often been developed to empirically characterize aggregate properties but may not relate well to the performance of HMA. Since some types of performance related tests were needed for Superpave, NCHRP began Project 4-19 "Aggregate Tests Related to Asphalt Concrete Performance in Pavements". Particle Shape and Surface Texture (Fine Aggregate) are found by the two tests:

1. ASTM D3398 Index of Aggregate Particle Shape and Texture. (Similar to coarse aggregate).
2. AASHTO TP 33 (ASTM C1252) Uncompacted Void content of Fine Aggregate.

The authors note that both natural and manufactured sand products may vary from smooth, rounded to rough, subangular and that, "There is a need to quantify the shape and texture of the fine aggregate in order to write the specifications on a more rational basis." AASHTO TP 33 was adopted by ASTM in 1993 and is recommended by the Strategic Highway Research Program (SHRP) in the SUPERPAVE mix design system. At the time of this survey (1997) some state highway agencies were using this test for research and some were including it in specifications.

Results state that at the time there were no nationally acceptable standards available and there was a need to identify performance related aggregate tests for HMA that could be adopted by all highway agencies.

2.5.2 Survey of State Agencies Using “NCAT Asphalt Forum”

In order to determine trends prevalent among state agencies, the project staff placed a notice in the Fall 2003 edition of *Asphalt Technology News* (12), published by the National Center for Asphalt Technology (NCAT). The following question appeared in the “Asphalt Forum” section.

> *What are the experiences of other states with the fine aggregate angularity (FAA) requirement in Superpave mixture design? We are interested in finding out if ASTM C1252 Method A has been preferred or if alternate methods/technologies have been used for evaluating the fine aggregates. Have some agencies discontinued the FAA evaluation?*

Responses were unavailable at the writing of this report but will be published in the spring 2004 edition of “NCAT Asphalt Forum”.

CHAPTER 3: MINNESOTA DEPARTMENT OF TRANSPROTATION FINE AGGREGATE ANGULARITY (FAA) HISTORY

3.1 Introduction

Minnesota Department of Transportation Fine Aggregate Angularity (FAA) values were gathered for the purpose of later comparing FAA Validation materials and mixtures with in-place designs. FAA values were obtained from:

- Production records from the Metro District (279 Superpave mixture records available from 2000 – 2002).
- LIMS statewide database. Values were obtained from a search of all available mixture records in the LIMS database. Many of these values come from annual quality or certification tests.

3.2 LIMS and Production Record Average FAA Data

Due to the relatively recent implementation of the LIMS database, historic asphalt mixture data was limited to a three-year period (2000–2002). Even though this was true it was possible to obtain mixture design information for 3,976 data points. LIMS database combined with Metro District information yielded FAA values from 1,268 Superpave (Standard Specification for Construction 2360) mixture designs. Table 3.1 and Figure 3.1 include a breakdown of all available FAA statistics.

The following pie chart is a breakdown of the useable portion of the above data. The term “useable” data will include mean FAA values from project bit-records. Minimum requirements for useable data are that data points have both a bit-record number and a project number description. This requirement is set to facilitate future research regarding the referencing of location, material proportions, and field performance evaluation. A table of “useable” data is provided in an appendix at the end of this report and includes averages for 980 of the original 3,976 LIMS data points.

Table 3.1 Minnesota FAA Records (2000 – 2002)

FAA	# Records
32.1	1
< 40	372
40–41	956
41–42	875
42–43	499
43–44	311
44–45	291
45–46	340
> 46	330
51.4	1

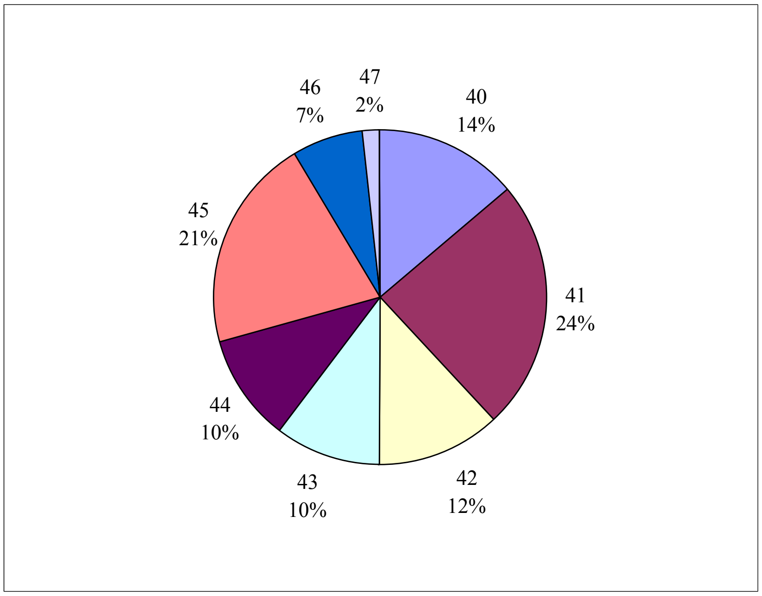

Figure 3.1 Average FAA Values (Minnesota 2000–2002)

Average FAA values were obtained by calculating mean FAA values from project bit-records. Sorting the remaining useable portion using Mixture Type, Project Number, Mean FAA, Bit-record, and an arbitrarily chosen minimum bit-record sample size of 10 as breakdown criteria yields the following:

N	Min	Q1	Q3	Max
59	40.0	41.3	45.3	47.3

The spread in average FAA values, depending on asphalt mixture type, is shown using a box-and-whiskers plot in Figure 3.2. Moving from top to bottom; box-and-whiskers plots show the location of Maximum, 3rd Quartile, Median, 1st Quartile, and Minimum values. Potential outliers are plotted as individual points.

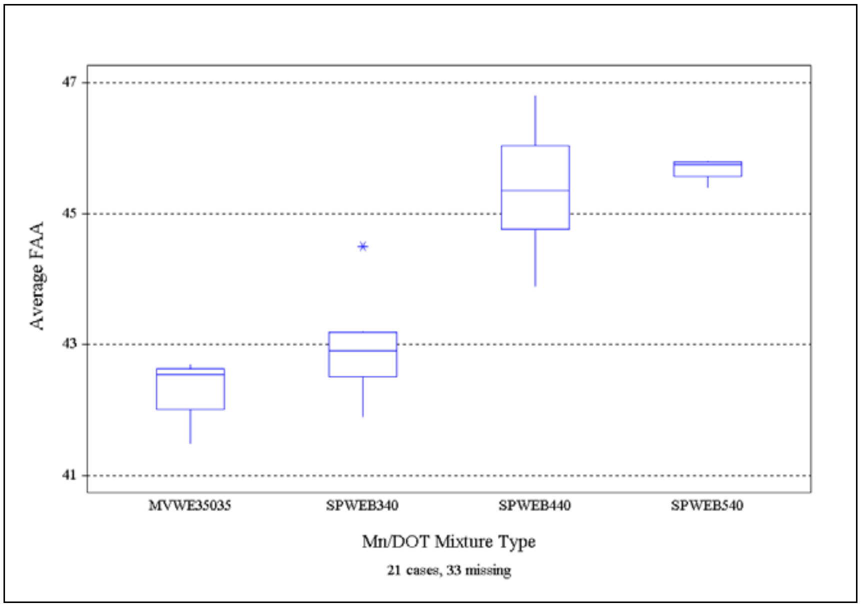

Figure 3.2 Average FAA vs. Mn/DOT Mixture Type

Figure 3.2 includes Mn/DOT 2360 Superpave mixtures SPWEB340, SPWEB440, and SPWEB540. Mixture MVWE35035 is described in Mn/DOT 2350.2 (2). Note a gap in average FAA data between SPWEB340 and 440.

A plot of FAA frequency is shown in Figure 3.3. This plot includes mixtures SPWEB340, 440, 540 and MVWE35035. The plot shows a frequency increase for FAA values ranging from 40–41 and 44.4–45. Additionally, the plot shows a trend in decreasing frequency of FAA values between 41 and 44.4.

The set of useable data is presented as an appendix (Table A.1). “Useable” data information like as bit-record and project number can be taken from the results of Table 3.1 and used to cross reference mixture proportion data available in LIMS. Mixture proportion data is similar to that presented in the example in Table 3.2.

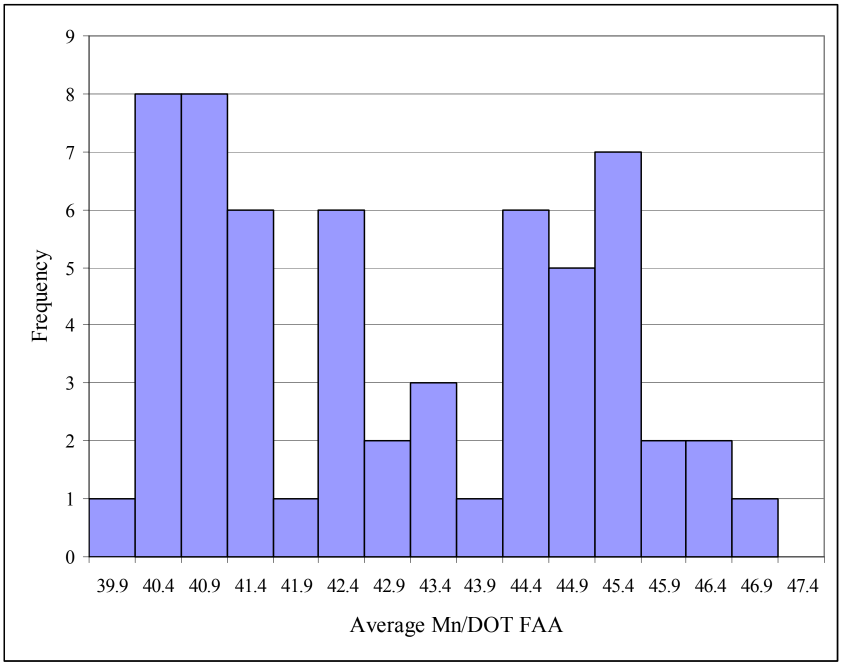

Figure 3.3 Histogram: Frequency of Average Mn/DOT FAA Values

Table 3.2 Typical Project Mixture Proportion Data (LIMS)

P_BITREC	Product	Source, (Material Type) Mn/DOT Product ID	Specific Gravity	Proportion
0-2001-XXX	1	Pit A, FA-3 (GRANITE) #7312402818390	2.711	19
	2	Pit A, CA-50 (GRANITE) #7312402818390	2.729	23
	3	Pit A, WASHED SAND (GRANITE) #7312402818390	2.682	26
	4	Pit B, MILLINGS #2711902223133	2.6	15
	5	Pit C, WASHED SAND (LIMESTONE) #1902702433230	2.71	12
	6	Pit D, WASHED SAND #7103302621118	2.648	5

Mixture Information

OLDREC	WTDSPG	VNEW AC	% VOIDS	% VMA	% AC
0-2001-YYY	2.687	4.5	4	14	5.3

CHAPTER 4: ANALYSIS OF MEASURED FAA DATA

4.1 Introduction

The Superpave Fine Aggregate Angularity (FAA) requirement is one of the aggregate consensus properties recommended by the Strategic Highway Research Program (SHRP), and is outlined in the Asphalt Institute publication; *Superpave Series No. 2 (SP-2)* (1). The uncompacted void content of an aggregate is used as an indicator of FAA because aggregates with greater angularity should likewise have greater uncompacted void content values. A standard test method (AASHTO T304, ASTM C1252) is used to determine the void content.

The Uncompacted Void Content for FAA is determined by sieving and then proportioning a washed sample of aggregate into the 190-g gradation indicated in Table 4.1.

Table 4.1 FAA test gradation requirements (13)

Sieve	Mass (g) retained for AASHTO T 304
# 8 (2.36 mm)	None, but material must pass this sieve.
# 16 (1.16 mm)	44 ± 0.2
# 30 (0.6 mm)	57 ± 0.2
# 50 (0.3 mm)	72 ± 0.2
# 100 (0.15 mm)	17 ± 0.2

The test method includes running the 190-g sample through a funnel-to-cylinder apparatus as pictured in Figure 4.1. Calculating FAA requires knowledge of the aggregate bulk specific gravity (Gsb), the measured aggregate mass in the cylinder after striking off ($M_{aggregate}$), ρ_{water} (1g/ml), and the volume of the cylinder ($V_{cylinder}$ = 100 ml recommended).

FAA = % Uncompacted Voids =

$$\frac{V_{cylinder} - V_{stone}}{V_{cylinder}} \times 100 = \frac{V_{cylinder} - {M_{aggregate}}/{(\rho_{water} \times Gsb)}}{V_{cylinder}} \times 100 \qquad (1).$$

Figure 4.1 Standard testing apparatus for AASHTO T304, ASTM C1252 Method A

SP-2 recommends FAA values that correspond to design traffic and position within the pavement structure. Table 4.2 reproduces that recommendation.

Table 4.2 Fine Aggregate Angularity Criteria (1)

Traffic, million ESALs	FAA Requirements Depending on Depth from Surface	
	< 100 mm	> 100 mm
< 0.3	-	-
< 1	40	-
< 3	40	40
< 10	45	40
< 30	45	40
< 100	45	45
≥ 100	45	45

The State of Minnesota uses Standard Specification for Construction 2360 for Superpave mixture design (2). Section 2360.2D2 corresponds to the SP-2 FAA requirements in stating that ASTM C1252 Method A shall be used to evaluate the composite blend according to Table 4.3. Traffic levels 2–7 are also defined.

Table 4.3 Minnesota FAA Specification 2360.2D2 for Traffic and Layer Depth (2)

Mn/DOT Traffic Level (million ESALs)	**Depth of Pavement from Surface**	
	≤ 100 mm (4 inch)	> 100 mm (4 inch) & Shoulders
	Minimum FAA (%)	Minimum FAA (%)
Level 2 (0.3 ≤ 1) - Level 3 (1 ≤ 3)	40	40
Level 4 (3 ≤ 10) - Level 5 (10 ≤ 30)	45	40
Level 6 (30 ≤ 100) - Level 7 (> 100)	45	45

4.2 Aggregate Materials

Aggregate materials were obtained from Minnesota Department of Transportation (Mn/DOT) offices and donated from various private sources. Several districts and contractors were able to supply aggregate samples appropriate for the study. Not all aggregates were used during the mixture design phase. Omission was not a reflection on the aggregate quality, but appropriateness for mixture comparison with respect to regional origin, quantity available, and FAA. Material sources and descriptions are presented in Table 4.4.

Table 4.4 Aggregate materials included in Mn/DOT FAA validation study

Aggregate	**Source**	**Size**	**Type**	**Supplier**
D1	Glacier Pit	½-in. minus	Pit gravel	Mn/DOT D1
D2	J & S Pit	No. 4 minus	Pit gravel	Mn/DOT D2
SP	Spilman	3/8-in. minus	Pit gravel	Mn/DOT D3
RI	Ringo Pit	3/8-in. minus	Pit gravel	Mn/DOT D6
BA ½	Barton	½-in. minus	Pit gravel	Commercial Asphalt
DCF	Danner	No. 4 minus	Danner Crushed Fines	MnROAD stockpile
OP	Otto Ped Sand	No. 4 minus	Natural sand	MnROAD stockpile
SL	Unknown	No. 4 minus	Natural sand	U of M stockpile
NU	New Ulm Quarries	No. 4 minus	Manufactured quartzite sand	NUQQ stockpile
NE	Aggregate Industries – Nelson	No. 4 minus	Manufactured sand	U of M lab stockpile
KLS	Kraemer	No. 4 minus	Manufactured lime sand	Contractor stockpile
K 9/16	Kraemer	9/16-in.	Limestone chips	Contractor stockpile

4.2.1 Sieve Analysis Results

Gradation analyses were conducted using a nest of square sieves, sized: 37.5, 25, 19, 12.5, 9.5, 4.75, 2.36, 1.18, 0.6, 0.3, 0.15, and 0.075-mm.

Table 4.5 and Figure 4.2 show measured, washed gradations for the aggregate materials. Included are 1 coarse and 11 fine aggregates. On the figure, a maximum density line is shown for a 12.5-mm Nominal Maximum Aggregate Size (NMAS).

Table 4.5 Source Aggregate Sieve Analysis Results (% Passing)

Size [mm] (Standard)	19 (3/4 in.)	12.5 (1/2 in.)	9.5 (3/8 in.)	4.75 (#4)	2.36 (#8)	1.18 (#16)	0.6 (#30)	0.3 (#50)	0.15 (#100)	0.075 (#200)
D1	100	99.4	96.9	86.6	76.4	61.5	41.8	21.3	6.5	3
D2	-	-	100	93.7	76.7	58.2	37.7	16.2	4.6	1.8
SP		100	99.7	88.7	70.4	46.7	18.4	2.6	0.6	0.4
RI	100	99.6	97.1	84.7	72.2	58.4	41.2	19.2	5.1	1.7
BA1/2	100	99.9	96.5	80.9	69.4	57.9	42.2	17.2	7.5	5
DCF	-	-	100	94.8	69	48.3	31.8	17.8	8.9	4.2
OP	-	-	100	93.9	83.5	68.3	39.8	10.4	2.4	1.5
SL	-	-	100	98.8	94.6	81.3	37.1	8.4	1.2	0.3
NU	-	-	100	94.5	77	60.9	37.2	12.8	2.2	0.6
NE	-	-	100	96.6	59.4	32.7	19.4	12	4.7	1.9
KLS	-	-	100	96.2	63.1	43.7	33.7	24.5	13	4.5
K 9/16	100	94.2	45.2	3.8	2.4	-	-	-	-	1

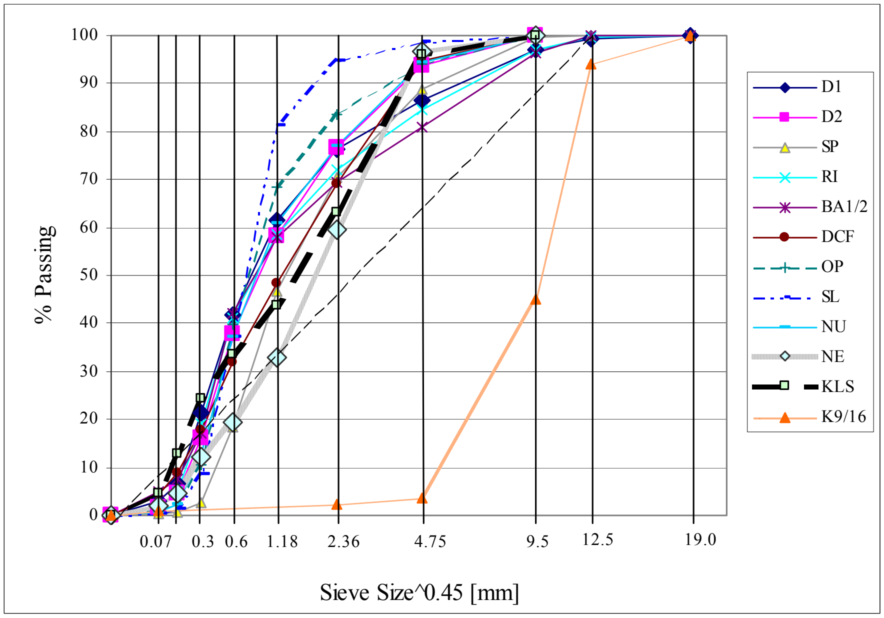

Figure 4.2 Fine and Coarse Aggregates Sieve Analysis Results

4.2.2 Properties of Aggregates and FAA Analysis Results

Aggregate Bulk (dry) Specific Gravity (Gsb), Apparent Specific Gravity (Gsa), and absorption values are used in asphalt mixture analysis and design, and for determining the FAA of a particular material. Recall the general definition of specific gravity:

$$Gs = \frac{M_{\text{material}}}{M_{\text{equal volume of water}}} = \frac{\gamma_{\text{material}}}{\gamma_{\text{water}}} \qquad (16).$$

Where γ is unit weight (weight/volume)

Apparent specific gravity differs from the bulk (dry) specific gravity according to how γ_{material} is defined. Roberts, et al. (5), provides the following definitions:

$$\gamma \text{ Apparent} = W_s/V_{s+ip}$$

and

$$\gamma \text{ Bulk} = W_s/(V_{s+ip} + V_{pp}).$$

Where W_s is the oven-dry sample weight, V_{s+ip} is volume of solids plus impermeable voids, and V_{pp} is volume of water-permeable voids.

Roberts also defines percent absorption as Absorbed Water Weight/Ws.

Specific gravity measurements were performed on fine and coarse materials in accordance with Mn/DOT Modified AASHTO T84 and T 85 (14, 15), respectively. Coarse and fine materials are defined by the Mn/DOT Lab Manual, sections 1204.1 and 1205.1. The definitions state that material passing 4.75-mm shall be called fine and material retained on the 4.75-mm [#4] sieve shall be called coarse. Results are presented in Table 4.6.

As seen previously, Minnesota Superpave 2360 FAA (% Uncompacted Voids) specifications range from 40 to 45. FAA measurements of these 11 source materials ranged from 38.8 to 47.9. Materials having measured values outside the specification may be useable as components of composite aggregate blends.

Table 4.6 Aggregate Specific Gravity, Absorption, and % Uncompacted Voids (FAA)

Aggregate	Gsb	Gsa	% Absorption	% Uncompacted Void Content
D1	2.667	2.799	1.626	41.1
D2	2.670	2.705	0.482	39.9
D3 (SP)	2.600	2.655	0.786	38.7
D6 (RI)	2.520	2.654	1.999	38.9
BA ½	2.622	2.683	0.867	40.8
DCF	2.637	NA	NA	47.8
OPS	2.622	NA	NA	38.8
SL	2.620	2.691	1.010	39.7
NU	2.599	2.635	0.523	46.5
NE	2.667	2.783	1.564	46.9
KLS	2.710	2.782	0.951	47.9
K 9/16	2.645	2.820	2.340	NA – coarse aggregate

4.3 FAA Sensitivity to Physical Conditions

The “angularity” of a particular aggregate grain may be regarded as fixed as long as no action is taken to change the grain shape. However, since the testing process includes interaction between the sample and testing apparatus, the possibility of measuring misrepresentative FAA values exists. This interaction is partially represented in the Figure 4.3. The diagram of the aggregate sample shows the external forces present during FAA testing. In addition to the external gravitational and friction forces there are internal forces. Internal forces may vary with aggregate material. The significance of these interactions is beyond the scope of this study.

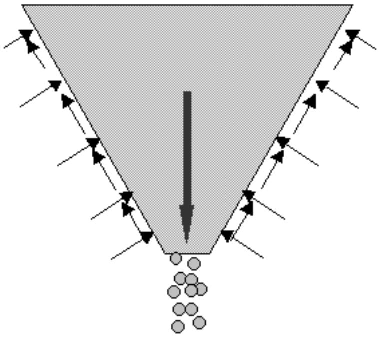

Figure 4.3 External forces acting on FAA sample

Aggregate material slides through a metal funnel having a fixed opening, drops a short distance then finally lands in a metal cylinder. Two nonstandard experiments were performed to evaluate the influence of the drop height on FAA and to measure the duration of the test.

4.3.1 Drop Height Experiment

The first experiment was conducted to estimate how FAA is sensitive to the testing configuration. Measurements of the standard FAA testing configuration showed that the standard drop distance is approximately 197-mm. In this experiment the drop distance from funnel tip to the cylinder bottom was varied from this standard distance. Several things were evident:

- for all drop heights; materials maintained an angularity order,
- angularity values decreased as the drop height distance increased, and
- high FAA (manufactured) materials tended to remain above 45.

FAA values were measured for distances from 100–444-mm. This interval is near the practical limit since funnel-cylinder crowding occurs <100-mm and all of the aggregate may not fall directly into the cylinder at distances >444-mm. Results of the test are observed in Figure 4.4. The best-fit lines on Figure 4.4 show that FAA changes slowly with respect to drop height.

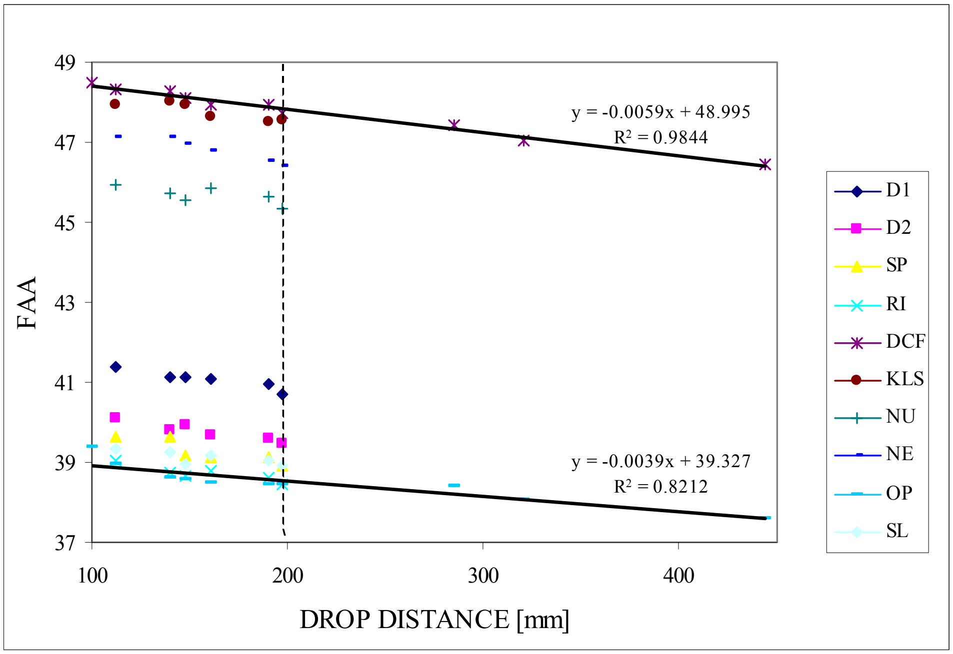

Figure 4.4 FAA vs. Aggregate Drop Distance for modified AASHTO T304.

4.3.2 Timing Experiment

A second nonstandard experiment was conducted to find out if the flow time of a 190-g FAA sample is related to the sample FAA.

FAA is used to estimate the ability of an asphalt mixture to resist rutting deformation in the field. In addition to high angularity, rut resistant aggregates may have form and surface texture qualities that promote high internal friction.

The standard FAA test occurs in a controlled manner, with three basic external forces as shown in Figure 4.5. Internal forces are also present but they may vary from material to material because of angularity, form, or texture. The timing test is used here as an indirect indicator of these properties; much as the Uncompacted Void Content indirectly indicates angularity.

Flow timing was measured using a stopwatch, standard 190-g FAA samples, and standard FAA testing apparatus. Five time measurements per sample were obtained for averaging. For the purpose of this experiment, flow time duration is defined as beginning with funnel opening and ending when the last aggregate particle exits the funnel.

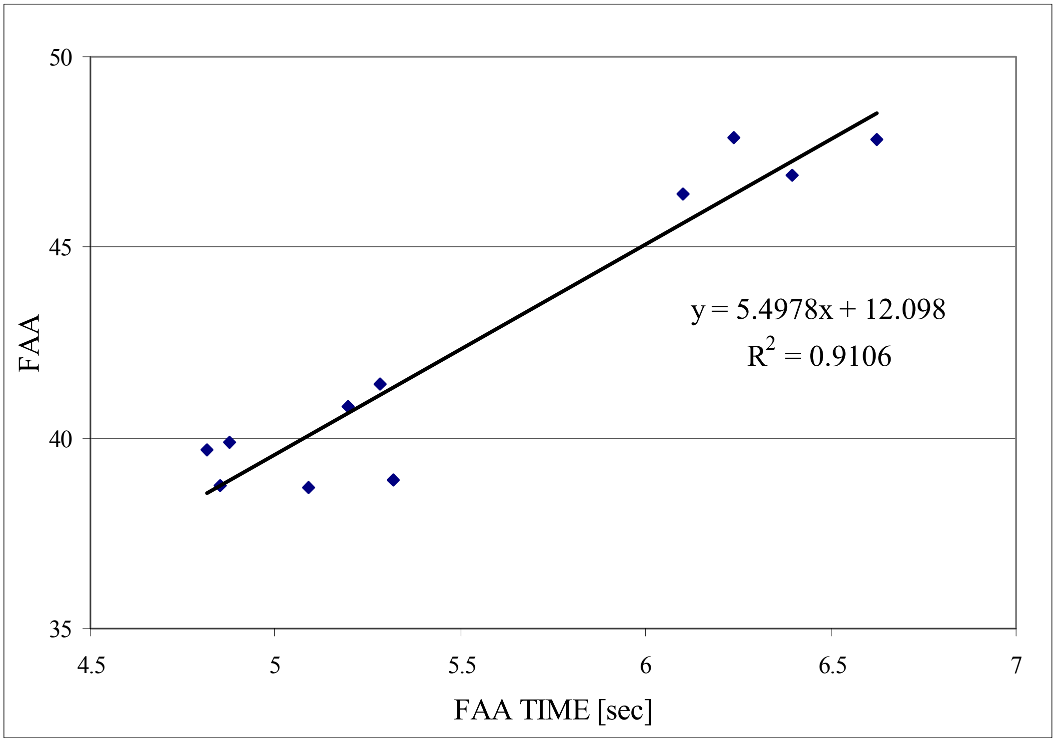

Figure 4.5 FAA vs. FAA Flow Time

The graphical results presented in Figure 4.5 show that flow time correlates well to FAA for these 11 Minnesota aggregate materials. Flow times ranged from 4.8 to 6.6 seconds, with higher flow time corresponding to higher FAA material. This trend gives confidence to the standard FAA measurements and may be useful in the analysis of mixture performance.

4.4 Aggregate Imaging Systems (AIMS)

The characterization of aggregates by digital imaging techniques was not part of the project work plan. However, this additional work was later included because the research team thought this analysis would be beneficial for the project; taking into consideration the fact that AIMS has received considerable attention at the national level.

Samples of eight of the Minnesota aggregates were sent to the Civil Engineering Department at Texas A&M University (TAMU), where digital imaging was performed.

4.4.1 AIMS Description and Definitions

An Aggregate Imaging System (AIMS) is described in the work of Fletcher (9) and Al–Rousan (10) as a digital imaging system that includes digital cameras, microscopes, top and back lighting systems, and 3-dimensional motion actuators for analysis of coarse and fine aggregates. Black and white images capture angularity and grey images capture texture. The testing procedure includes:

- Aggregate placed on tray. Backlighting is used.
- A video microscope or video camera collects images of aggregate. Servo actuators control the camera position relative to the x, y, or z-axis. The z-location depends on resolution criteria. Resolution is based on the number of pixels available to image a particle.
- A row and column type scan is conducted in the x-y plane. Images of particles are included in subsequent analyses based on resolution criterion.

Fine aggregate data is analyzed for angularity and form.

Angularity – Uses two methods:

1. Gradient Method uses an average of the difference between gradient vectors.

$$\text{Gradient} = \frac{1}{\frac{N}{3}-1}\sum_{i=1}^{N-3}\left|\theta_i - \theta_{i=3}\right| \qquad (10).$$

Where N = number of edge points on particle, θ is the gradient vector, and *i* is the edge point. The drawing in Figure 4.6 represents gradient vectors located at such an edge point on a 2-dimensional projection of an aggregate particle.

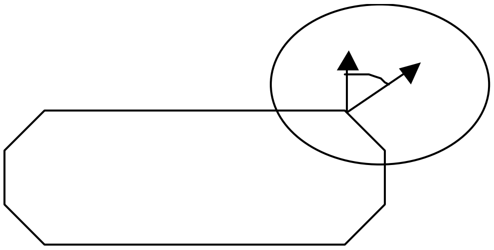

Figure 4.6 Gradient Vectors (circled) at Particle Edge Point

2. Masad's Radius Method uses the equation: $AI = \sum_{0}^{355} \frac{\left| R_{\theta} - R_{EE\theta} \right|}{R_{EE\theta}}$ (9,10).

Where $R_{EE\theta}$ is the radius of an equivalent ellipse and R_{θ} is the particle radius at angle θ. Figure 4.7 shows the projection of an elongated particle and equivalent ellipse. The dotted line with large arrowhead shows R_{θ} while the solid line and small arrowhead shows $R_{EE\theta}$.

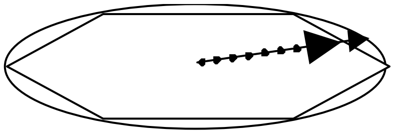

Figure 4.7 Radii on Partical and Equivalent Ellipse Projections (Radial Angularity)

Form

The Form Index for fine aggregates is based on a 2-dimensional projection of the aggregate image. $2-\mathrm{D\ Form} = \sum_{\theta=0}^{\theta=360-\Delta\theta} \frac{\lfloor \mathrm{R}_{\theta=\Delta\theta} - \mathrm{R}_{\theta} \rfloor}{\mathrm{R}_{\theta}}$ (10).

Where R_{θ} is the radius in a given direction and directional angle is given as angle θ.

2-D Form Index will equal 0 for a perfect circle. The drawing Figure 4.8 shows one set of radii that contribute to the Form Index.

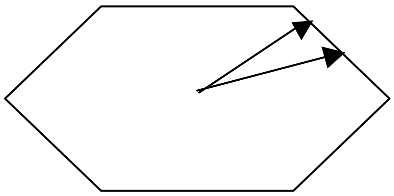

Figure 4.8 Radii Used for Calculating 2-D Form

4.4.2 Sample Preparation

Aggregates were washed on the #200 sieve and separated by sieve analysis using a nest of sieves having square opening sizes: 9.5, 4.75, 2.36, 1.18, 0.6, 0.3, 0.15, and 0.075-mm.

50-g of material retained on each sieve from 0.075–4.75-mm was individually packaged, marked, and sent to Texas A&M for AIMS testing.

4.4.3 AIMS Results

Figures 4.9–4.11 show AIMS results for eight of the Minnesota aggregates described in section 4.2. These figures include angularity and form measurements on 50-g samples of material retained on the 2.36 (#8) and 1.18-mm (#16) sieves.

Figure 4.9 (Gradient Angularity) shows how angularity varies for each sample. Lower-angularity materials plotted on the left side of the group. At 100% of particles measured, gradient angularity values vary from approximately 5000 to a maximum of 10000.

Figure 4.10 (Radial Angularity) shows how angularity varies for each sample. Lower-angularity materials plotted on the left side of the group. Minimum values for all material are near 3 or 4. At 100% of particles measured, radial angularity measurements are spread from approximately 10 to 20.

Figure 4.11 (2-D Form) shows how shape varies for each sample. Materials having a more rounded shape are plotted on the left side of the group. Minimum values for all materials are near 3, indicating that a few particles in each sample project a nearly circular area. At 100% of particles measured, 2-D form measurements are spread from approximately 10 to 18.

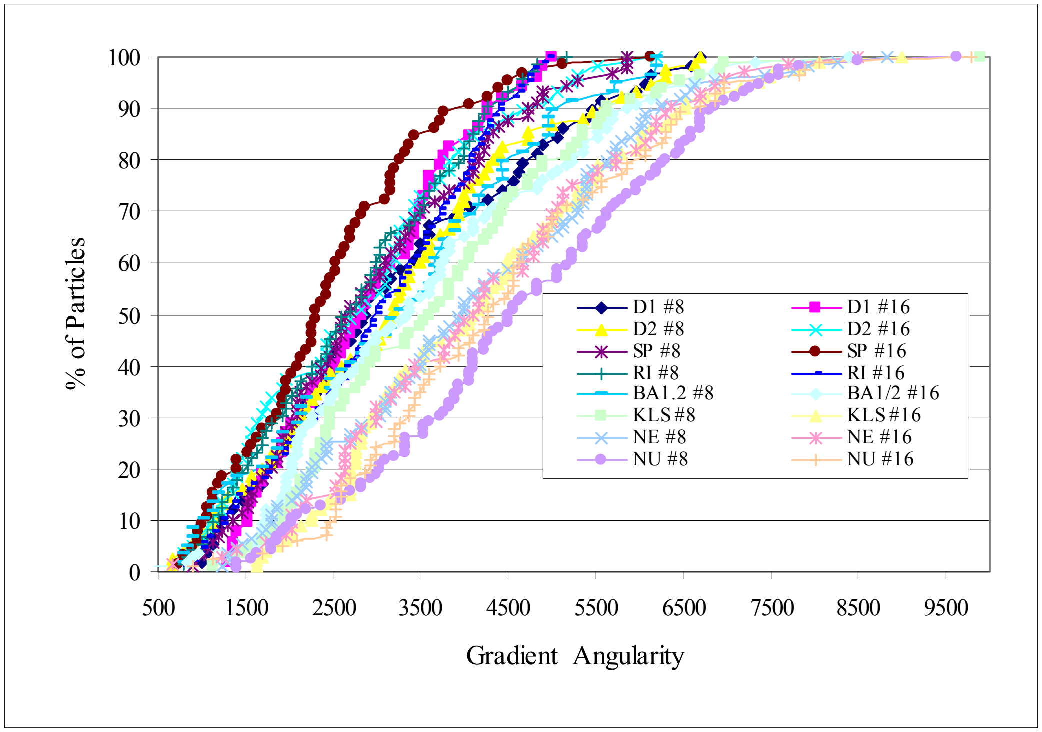

Figure 4.9 AIMS Gradient Angularity for 8 Minnesota Aggregates

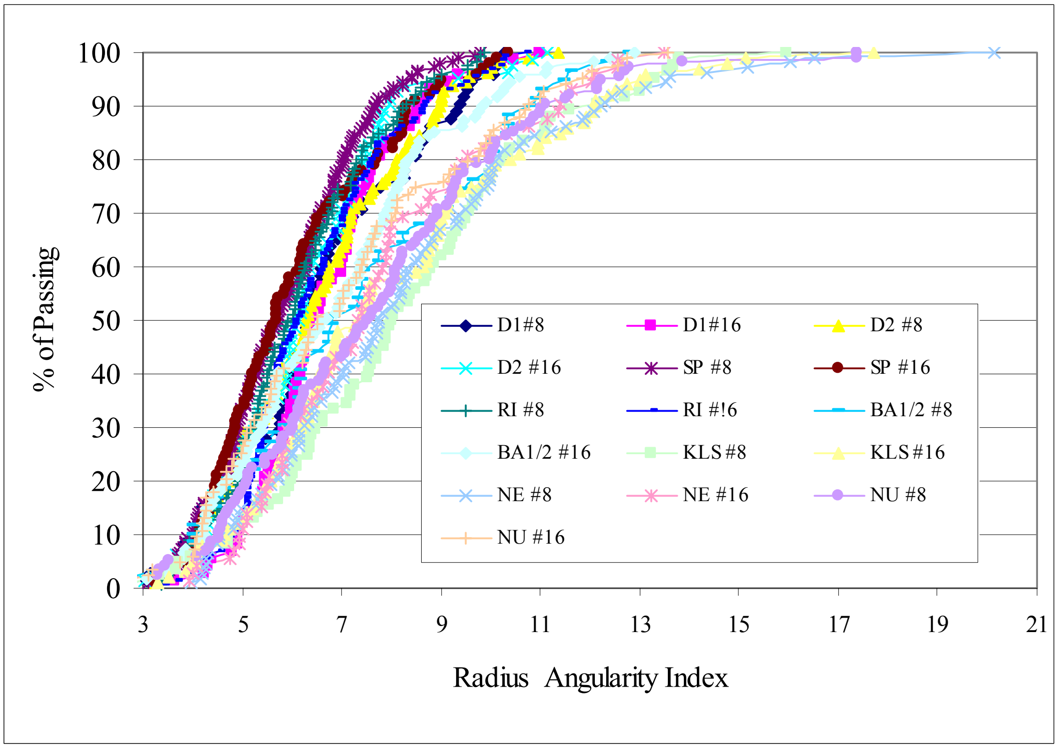

Figure 4.10 AIMS Radial Angularity for 8 Minnesota Aggregates

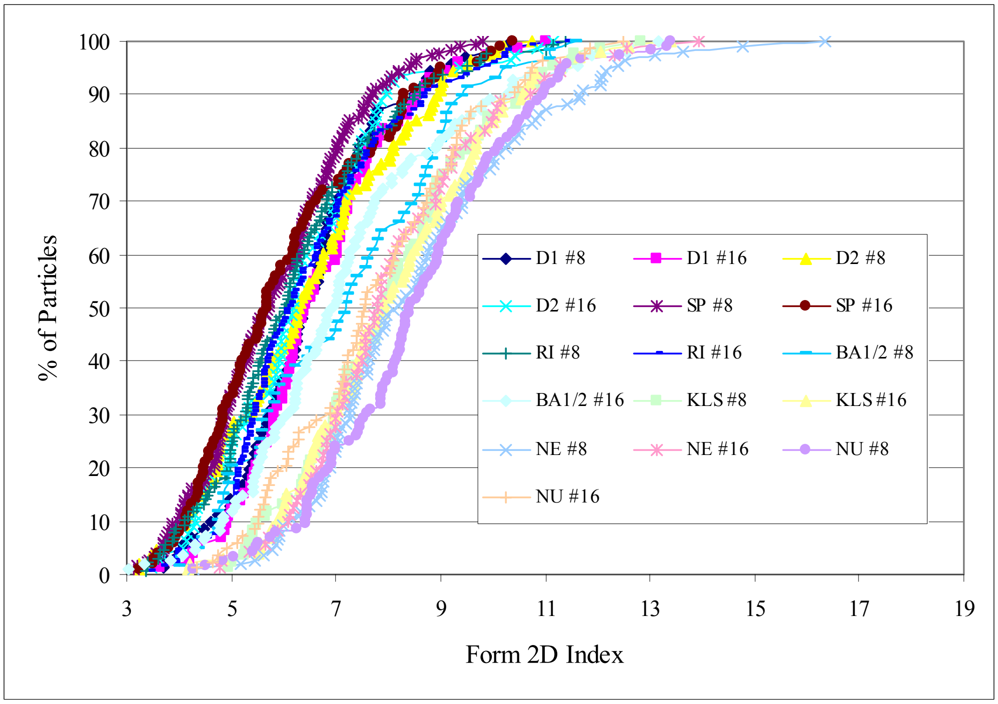

Figure 4.11 AIMS 2-D Form for 8 Minnesota Aggregates

Figures 4.12–4.16 show typical black and white imaging data for several unblended aggregates. This type of data is used in the process of evaluating angularity and 2-dimensional form.

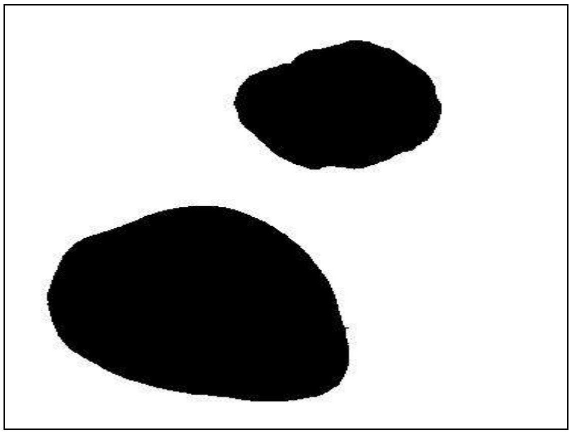

Figure 4.12 Image of SP (FAA 37.8)

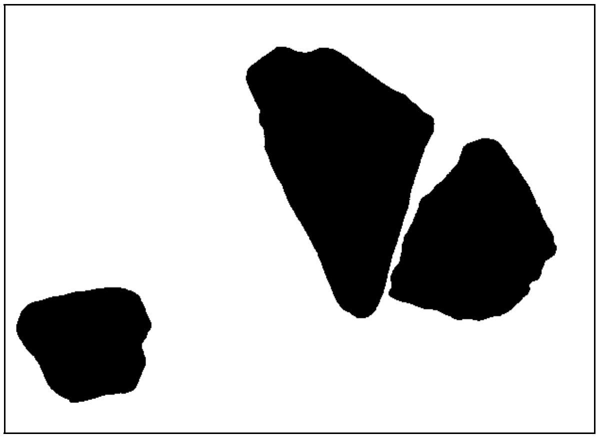

Figure 4.13 Image of RI (FAA 38.9)

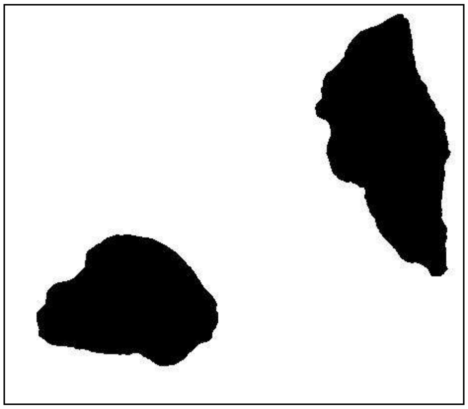

Figure 4.14 Image of BA1/2 (FAA 40.8)

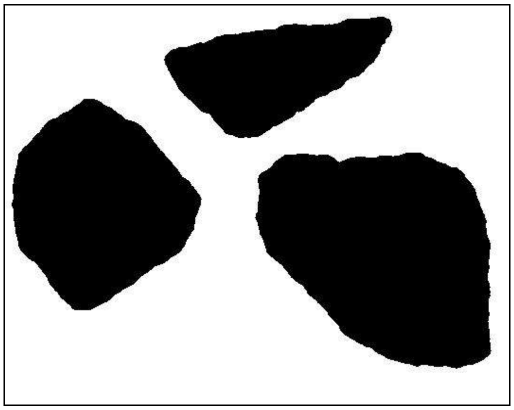

Figure 4.15 Image of NE (FAA 46.9)

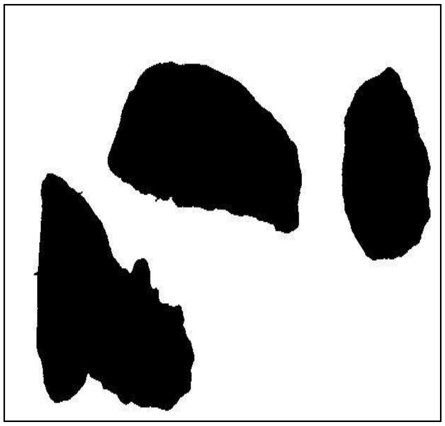

Figure 4.17 Image of KLS (FAA 47.9)

CHAPTER 5: DEVELOPMENT OF A LABORATORY TESTING PROGRAM

5.1 Introduction

A laboratory testing program was developed for Fine Aggregate Angularity (FAA) validation based upon the following criteria.

In order to reduce the number of factors that affect mixture properties and emphasizing the role of FAA:

1. With the exception of FAA, mixtures shall be designed to Mn/DOT 2360 Superpave specifications (2). If possible, the range of composite blend FAA values in the testing program shall be designed both above and below the Mn/DOT 2360 Superpave specifications.
2. The number of variables shall be minimized in order to see the effect of FAA. Mixtures shall have similar gradations and void content. A single performance-graded asphalt binder shall be used. Voids Filled with Asphalt (VFA) and Voids in Mineral Aggregate (VMA) shall meet Mn/DOT 2360 requirements.
3. The testing regimen shall include aggregate and mixture evaluation. Aggregate evaluation includes sieve analysis, specific gravity, and FAA for component aggregates and the composite blends. Mixture evaluation includes dynamic modulus (|E*|) testing at appropriate conditions and rutting performance testing. |E*| data corresponding to high temperatures shall be useful since mixtures are more sensitive to rutting at high temperatures. The principle of time-temperature superposition can be used to show how high temperature relates to low frequency modulus values.

5.2 Range of FAA values

With reference to Chapter 2: it was possible to break down Mn/DOT reported FAA values and average them so they correspond with State Project Number, mixture type, and record number. Table 5.1 shows 34 such averaged values.

Table 5.1 Year 2001 - 02 Mn/DOT Average FAA Values (LIMS database)

Record	# Data Points	Mix Type	State Project #	Record Average FAA
0-2001-275	11	SPNWC430	0208-102	45.5
0-2001-477	18	SPWEB440	2758-60	46.4
0-2002-026	12	SPWEB540	6284-131	45.7
0-2002-042	10	SPWEB440	1913-56	44.8
0-2002-165	10	SPWEB440	6221-40	45.7
0-2002-224	14	SPNWC430	1004-24	44.7
0-2002-246	13	SPWEB440	1004-24	43.9
06-2002-148	10	SPNWB430	7408-29	45.2
07-2002-012	13	SPWEB440	7205-21	46.8
07-2002-022	16	SPWEB440	5380-112	45.4
07-2002-048	15	SPWEB340	1703-64	42.9
07-2002-072	11	SPWEB340	5905-21	42.5
3A-2002-079	10	SPWEB440	1115-18	44.7
3A-2002-096	13	SPWEB340	8604-30	43.2
3A-2002-142	14	SPWEB340	7319-34	44.5
3A-2002-150	10	SPWEB440	1115-18	45.3
0-2001-133	17		2785-316	45.1
0-2001-170	10		1901-137	44.8
0-2001-210	32		7007-24	45.8
04-2001-033	24		5606-40	43.2
04-2002-018	22	MVWE35035	1414-02	42.7
04-2002-052	14	MVWE35035	7805-31	42.6
07-2001-010	13		6704-16	41.8
07-2001-017	18		3206-17	41.2
07-2001-044	12		0804-72	41.3
07-2001-076	30		2280-119	46.2
07-2001-077	24		0704-78	41.1
07-2001-102	18		4001-45	41.2
07-2002-055	12	MVWE35035	165-999-01	42.5
3A-2001-049	28		8606-50	40.7
3A-2001-064	10		1814-01	40.6
3A-2001-122	27		3302-12	40
3A-2002-146	11	MVWE35035	1809-58	41.5
8A-2001-011	20		3411-63	40.7
	542 Total			

Minnesota Department of Transportation Fine Aggregate Angularity (FAA) values ranged from less than 40 to greater than 46, with an overall reported minimum and maximum values of 32.1 and 51.4 respectively.

The project committee recommended that FAA composite-blend values should be designed both above and below the Mn/DOT 2360 Superpave FAA specifications, if possible. All other aspects of the mixtures should conform to 2360 criteria.

Table 5.2 shows that recent Mn/DOT project reports do not indicate construction having FAA values below 40. The aggregate gathered for study is similar in range to Mn/DOT records, with a somewhat smaller median. This comparison also shows that in order to measure below the FAA minimum, a mixture would likely include high proportions of the aggregates that fall into the first quartile.

Table 5.2 FAA Comparison: Mn/DOT Mixtures (Table 5.1) and Available Aggregate

	Min.	**Quartile 1**	**Median**	**Quartile 3**	**Max.**
2001-02 Mn/DOT Records (34 mixture)	40	41.6	43.6	45.3	46.8
Available FAA –Aggregate (11 fine components)	38.7	39.3	40.8	46.7	47.9
Mn/DOT FAA Specification 2360	40	-	-	-	45

Committee and project staff agreed to develop a total of four asphalt mixtures. Of the four mixtures, two should have high FAA and two should have low FAA measurements. The minimum material required to design four mixtures was one coarse aggregate and four fine aggregates, as long as 2360 requirements were satisfied. The Chapter 5 report will present aggregates the blend design process.

5.3 Mixture Design

Mixture design must meet the Mn/DOT 2360 Superpave criteria. Since all aggregate materials were obtained from reputable known sources and are normally approved for mixture design, they were assumed to possess adequate toughness and soundness. The design process could then focus mainly on FAA, gradation, and optimum asphalt content.

To expedite design, gyratory compaction levels were recommended by the Mn/DOT Bituminous Office. The high-FAA mixtures would follow traffic level 4 and the low-FAA mixtures would follow traffic level 3 as listed in Table 2360-7.

The mix design procedure is described below:

1. Gradation design. All gradations have:

  - A single PG58-28 asphalt binder
  - Nominal Maximum Aggregate Size of 12.5 mm
  - No more than three aggregate components; 1 coarse and 1–2 fine
  - A single coarse aggregate material was used for all blends, and in the same (approximate) proportion
  - Fine aggregate material consisted of the study aggregate (2 high, 2 low FAA) and, if needed, a second (low FAA) aggregate.
2. Mixture design specimens were two identical 4800-g specimens, having a diameter of 150-mm, per design iteration. Compaction was carried out on a Brovold Gyratory Compactor at 600-kPa and gyration angle of 1.25 degrees.
3. Optimum asphalt content determination using 4800-g specimens.
   - Vary asphalt content
   - 96% Gmm at N_{design}
   - 97% Gmm at $N_{maximum}$
4. Final designs satisfied Mn/DOT 2360 design criteria.

5.4 Dynamic Modulus Test

Dynamic modulus |E*| testing was used to determine the rut resistance of each mixture. This approach is based on previous research performed by T. Pellinen and M. Witczak that showed that |E*| correlates to mixture rutting. The testing regimen required four 100-mm (diameter) by 150-mm (height) cylindrical cored specimens per mixture design. Each specimen was cut and cored from a 150-mm by 170-mm cylinder. All specimens were produced at 95% Gmm in the Brovold Gyratory Compactor at 600-kPa and gyration angle of 1.25 degrees. Modulus testing was carried out using a MTS load frame.

Dynamic modulus testing included 3 temperature conditions with 5 frequencies per temperature condition. Temperatures of 20, 40, and 54C were chosen since the binder material used was PG58-28. Frequencies of 25, 10, 1, 0.1, and 0.01 Hz were used for 20 and 40C. At 54C the same set of frequencies was used; however 0.01 Hz was excluded because of difficulty in measuring high frequencies at high temperatures.

5.5 Rut Susceptibility Testing

Rut development analysis was done using the Asphalt Pavement Analyzer (APA). APA testing was included as a means of ranking mixtures according to performance. This testing setup required 150-mm (diameter) by 75-mm (height) cylindrical specimens. Two APA specimens were cut from a single gyratory-compacted cylindrical specimen (150-mm by 170-mm). APA specimens were produced at 95% Gmm in the Brovold Gyratory Compactor at 600-kPa and gyration angle of 1.25 degrees.

APA testing included two APA specimens per mixture design. The specimens were tested at a temperature of 54C for comparison with dynamic modulus results. Figure 5.1 shows the basic APA testing setup. Test components include an automated rolling wheel applying a 445-N (100-lb) load while moving along a hose pressurized to 700-kPa (100-psi).

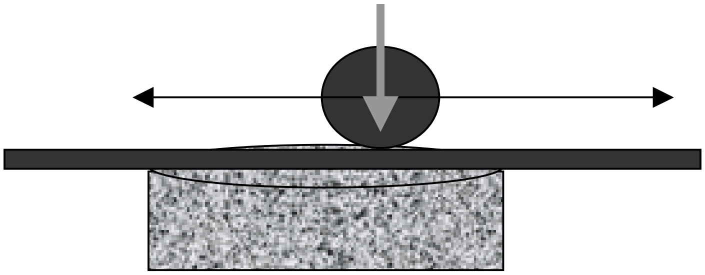

Figure 5.1 APA Testing Setup. Asphalt specimen below pressure hose and roller.

CHAPTER 6: LABORATORY MIXTURE DESIGN

6.1 Introduction

Chapter 5 (Development of Laboratory Testing Program) described points from which the FAA validation testing program was developed. Development of the mixture design portion of the FAA validation study was based upon several points:

1. With the exception of FAA criteria, asphalt mixtures should be designed to Mn/DOT 2360 specifications (2).
2. Mixtures should have similar gradations and void content. A single performance-graded asphalt binder should be used. Voids Filled with Asphalt (VFA) and Voids in Mineral Aggregate (VMA) should meet Mn/DOT 2360 requirements.
3. The testing regimen should include aggregate and mixture evaluation.
   With reference to Chapter 3: it was possible to break down Mn/DOT reported FAA values and average them so they correspond with State Project Number, mixture type, and record number. Since all aggregate materials were obtained from reputable known sources and are normally approved for mixture design they were assumed to possess adequate toughness and soundness. The design process could then focus mainly on FAA, gradation, and optimum asphalt content.

Final mixture designs (Chapter 6) for validating Fine Aggregate Angularity (FAA) were the culmination of several points:

1. Mixtures included aggregate materials representative of Minnesota. Some aggregate materials presented in Chapter 4 (Analysis of FAA Data) were obtained from several Mn/DOT district offices. Other aggregate materials were also obtained from the Metro area and greater Minnesota. A total of one (1) coarse and eleven (11) fine aggregate materials were available for use in this study.
2. Materials used should display low, medium, and high FAA in composite blends. Chapter 5 compared FAA values for available aggregates, past Mn/DOT mixture data, and Mn/DOT specifications. Table 4.1 showed that in order to measure below the FAA minimum, a mixture would probably include high proportions of the aggregates having FFA from the minimum to the first quartile. Five (5) fine aggregate materials measured below FFA 40.

3. Mixtures were designed with current Minnesota Superpave volumetrics (2). A 12.5-mm Nominal Maximum Aggregate Size (NMAS) was used. Mn/DOT Specifications, Table 2360-2 (2) contains gradation limits for Superpave mix designs. Percent mixture in the "FAA band" may be determined, and is noted below in Table 6.1. "FAA band" is defined as the material passing the 2.36-mm (#8) sieve and retained on 0.300 (#50).

Table 6.1 Percent of Mn/DOT 2360 Mixture Located in FAA Band (2)

Mixture NMAS	% of Mn/DOT Mix in FAA Band
9.5 mm	27.05 – 53.20
12.5 mm	23.44 – 45.08
19 mm	18.93 – 37.87

For purposes of comparison, FAA percentages for other Mn/DOT asphalt mixture designs are given in Table 6.2, taken from Mn/DOT Specifications, Table 3139-1 (2).

Table 6.2 Percent of Mixture Located in FAA Band (2)

Mn/DOT Mixture Type	% of Mix in FAA Band
31&32 A	23.32 – 47.25
31&32 B	23.32 – 47.25
31&32 C	23.32 – 47.25
41&42 A	23.32 – 47.25
41&42 B	23.32 – 47.25
47&48 A	23.32 – 47.25
47&48 B	23.32 - 41.11
61 CC, CS WEAR	20.70 – 47.86
61 CC, CS NONWEAR	20.70 – 47.86
61 TT WEAR	34.98 – 57.07
61 TT NONWEAR	34.98 – 57.07

Specification 2360 section F3 to F5 presents a set of volumetric Voids in Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA) criteria for mixture design.

- 2360 F3 states that mixture design air voids at N_{design} should equal 4% for those mixtures placed above a 100-mm final depth and 3% for mixtures placed below. For the purposes of this FAA study the 4% at N_{design} criterion was used.

- 2360 F4 specifies VMA criteria for 9.5, 12.5, and 19.0-mm Nominal Maximum Aggregate Size (NMAS). For the purposes of this FAA study the 12.5-mm NMAS criteria was used. Summarizing:
- Fine mixtures (>39% passing 2.36-mm (#8) sieve) having 12.5-mm NMAS require a minimum 14% VMA. Corresponding coarse mixtures require a minimum 13.5% VMA.

2360 F5 specifies VFA criteria for traffic levels. For this FAA study, the project committee suggested traffic levels 3 and 4. Summarizing;

- Traffic level 3 requires 65–78 % design VFA for mixtures placed below a 100-mm final depth. Traffic level 4 requires 65–75% design VFA for mixtures placed below a 100-mm final depth.

4. Performance graded asphalt binder, appropriate for Minnesota climate, shall be used. For the purposes of this project, and for comparison with other Mn/DOT-sponsored projects, a Koch PG58-28 unmodified asphalt binder was used.
5. No recycled material was included in this study.

6.2 Mixture Design Material

Aggregate materials included in trial mixtures were selected according to FAA measurement, ability to represent a Minnesota region, and quantity available. Available material is listed below in Table 6.3. As stated in Chapter 4, not all aggregates were used during the mixture design phase. However, omission is not a reflection on the aggregate quality or general usefulness in bituminous mixtures. Inclusion was based on appropriateness for mixture comparisons, variety of regional origin, quantity available, and FAA.

Table 6.3 Material Available for FAA Study

Material	Description	Quantity	Comments	Trial Mix
Asphalt Binder	Koch PG58-28	NA		Yes
Coarse Aggregate	Kraemer 9/16 Lime Chips	1000 kg		Yes
Fine Aggregate	D1 ½-in. minus (Glacier) FAA 41.1	50 kg	Low-FAA (NE MN) AIMS Data	No
	D2 No. 4 minus (J&S) FAA 39.9	75 kg	Low-FAA (NW MN) AIMS Data	No
	SP 3/8-in. minus (Spilman) FAA 38.7	75 kg	Low-FAA (NW MN) AIMS Data	Yes
	RI 3/8-in. minus (Ringo) FAA 40.8	100 kg	Low-FAA (S MN) AIMS Data	Yes
	BA½ ½-in. minus (Barton) FAA 40.8	500 kg	Low-FAA (Metro) contributes P_{200} AIMS Data	Yes
	DCF No. 4 minus (Danner) FAA 47.8	20 kg	High-FAA (Metro)	No
	OP No. 4 minus (Otto Ped) FAA 38.8	20 kg	Low-FAA (Metro)	No
	No. 4 minus (U of M Lab) FAA 39.7	500 kg	Low-FAA (no region) AIMS Data	No
	No. 4 minus (New Ulm) FAA 46.5	150 kg	High-FAA (S-Central MN) AIMS Data	Yes
	No. 4 minus (Agg. Ind. NE) FAA 46.9	500 kg	High-FAA (Metro) AIMS Data	Yes
	KLS No. 4 minus (Kraemer) FAA 47.9	1000 kg	High-FAA (Metro)	Yes

6.3 Trial Laboratory Mixtures

6.3.1 Mixture Production

Trial mixtures were produced using the following procedure:

- Select aggregate blend according to Mn/DOT Specification 2360 gradation bands in Figure 6.1. Calculate binder for several trial mixtures.

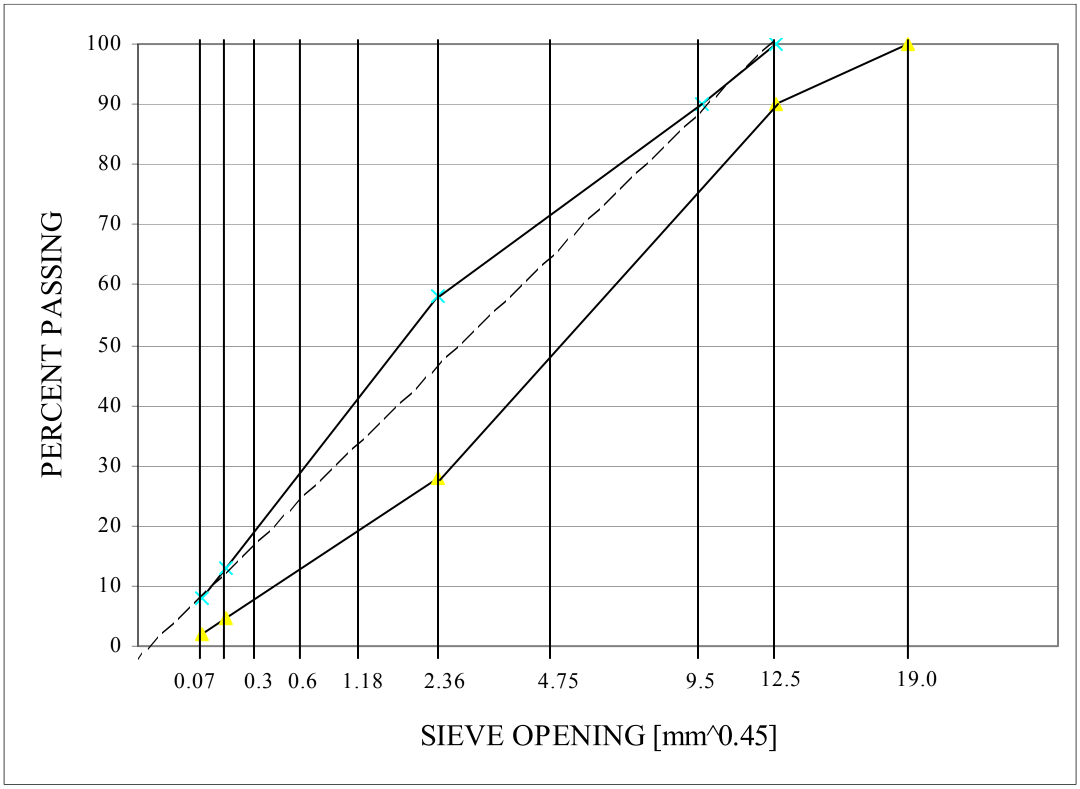

Figure 6.1 Mn/DOT 12.5-mm Mixture Design Gradation Band (2)

- Using ovens, heat enough aggregate and binder to produce two 4800-g gyratory specimens and one 2000-g maximum specific gravity specimen at 145C (4 hours). Also heat mixing tools.
- Combine coarse aggregate, fine aggregate and binder in bucket mixer, noting actual binder added to mixture.
- Return mixture to ovens for aging at 135C (3 hours, stirring every hour). Heat gyratory mold, plates, and tools. Lower temperature to 133C for compaction.
- Compact two specimens to N_{max} for volumetric analysis. Compactor software records specimen height and automatically generates an average densification curve using height and estimated volumetrics (Gmm, Gmb).
- Obtain trial mixture volumetrics using Theoretical Maximum Specific Gravity (ASTM D 2041) and Bulk Specific Gravity of Compacted Specimens (ASTM D 2726) calculations as follows:

Where $\text{Gmm} = \dfrac{\text{A}}{\text{A} + \text{B} - \text{C}}$

A = Oven dry mass of loose asphalt sample

B = Buoyant mass of pycnometer filled with water

C = Buoyant mass of pycnometer, mixture and water

Where $\text{Gmb} = \dfrac{\text{A}}{\text{B} - \text{C}}$

A = Oven dry mass of compacted specimen

B = Saturated surface dry mass of compacted specimen

C = Buoyant mass of compacted specimen

- Input volumetrics into the compaction curve estimate to obtain the corrected densification curve.
- Evaluate trial mixture with VMA, VFA, Binder content, and air voids (Va) for particular gyration levels $\text{N}_{\text{initial}}$, N_{design}, and $\text{N}_{\text{maximum}}$ as follows:

$$\text{Va} = 100\frac{\text{Gmm} - \text{Gmb}}{\text{Gmm}}$$

$$\text{VMA} = 100 - \frac{\text{Gmb} \times \text{Ps}}{\text{Gsb}}$$

$$\text{VFA} = 100\frac{\text{VMA} - \text{Va}}{\text{VMA}}$$

(1).

- Adjust mixture design by either altering the aggregate material, gradation blend, or binder content. Best results were obtained when reserving binder content changes for fine adjustments.

6.3.2 Mix Design Issues

Mix design requires an understanding of volumetrics and how different factors affect voids in the mixture. By far the most important issue in designing a good asphalt mixture is selecting the proper aggregate structure. A large portion of the initial mix design process included mixture blend improvement by process of trial and error.

High FAA Trial One:

The first trial mixture design used a blend of two high-angularity materials. The coarse aggregate was 9/16 limestone chips (K9/16), and the fine aggregate was a 100% crushed, manufactured sand (NE). Gradations for both materials are presented in Chapter 4. The limestone material was basically a single size aggregate, with approximately 3% passing the 4.75-mm sieve. The NE sand was well graded, with a fine aggregate angularity (FAA) value of 46.9. Initial proportions were 35% limestone and 65% sand. With 5.4% asphalt binder, the mixture had air voids of about 7.7% at N_{design}. 4.0% air voids were achieved at N_{design} by adding 7.4% asphalt binder. This drove the voids in mineral aggregate (VMA) to about 17% and the voids filled with asphalt (VFA) to 76%. These values are significantly higher than what is typically used in Minnesota.

Aggregate proportions were then changed in an attempt to improve mixture volumetrics. A mix of 26% limestone and 74% sand and was produced at 6.0% asphalt. The air voids and related parameters were still unreasonably high.

High FAA Trial Two:

A second aggregate combination was used to see if mixture volumetrics could be improved. Trial two included 30% K9/16 with 70% washed limestone sand (KLS). The trial two mixture yielded acceptable volumetric results. At 5.4% asphalt, the air voids were 4.0%, the VMA was 14.1%, and the VFA was 72.3%. These satisfied specification limits and were reasonable values for Minnesota mixtures. This mixture was the first selected for dynamic modulus testing. This high-FAA trial mix will be referred to hereafter as “Mix 1 (KR)”.

The KLS sand and NE sands had similar gradations and FAA values. However, vastly different mixture results were obtained.

High FAA Trial Three:

A high-angularity, quartzite sand with a FAA of 46.5 was evaluated. The gradation of this material differed from the previous high-FAA sands. A mixture of 30% K9/16, 70% quartzite sand and 5.0% asphalt yielded air voids of approximately 12% at N_{design}. These results showed it was necessary to use other aggregate blends in order to satisfy the project volumetric requirements.

High FAA Aggregate Blend Improvement:

The project technical support committee suggested including another aggregate product in the design gradations. BA½ was obtained aid in our mix design. This product is a natural gravel, and is well graded from the ½-inch (12.5-mm) to #200 (0.075-mm) sieve. The fine portion had a FAA value of 40.8.

High FAA Trial Four:

A mixture was produced with 15% K9/16, 46% BA ½ inch, 39% NU sand, and 5.5% asphalt binder. The mixture had approximately 76% passing the #4 sieve. Air voids were measured at 11% at N_{design}, requiring additional blend adjustment.

High FAA Trial Five:

A mixture was produced with 20% K9/16, 50% BA ½ inch, 30% NE, and 5.6% asphalt binder. Air voids measured 4% N_{design}. VMA and VFA values were within the specified range. This high-FAA trial mix will be referred to hereafter as “Mix 2 (NE)”.

Design of Low FAA Aggregate Blends

While all of the high-FAA mixture blends fell within the specified gradation limits, the mixtures often did not meet volumetric requirements. Plots of both acceptable high-FAA trial blends fell close to the line of maximum density for a 12.5-mm NMAS. Bailey mixture design coefficients were employed as a tool for further evaluating the high-FAA blends. These coefficients were then used as a reference point for designing the low-FAA blends for “Mix 3 (RI)” and “Mix 4 (SP)”.

Description of Bailey Coefficients:

The Bailey method of asphalt mixture gradation design (3) analyzes packing characteristics by dividing gradations into segments according to primary and secondary sieve sizes and then forming coefficients based upon the aggregate proportions retained within those particular segments. A range of values is recommended for each coefficient based upon design experience.

Nominal Maximum Aggregate Size (NMAS) = one sieve size larger than the first sieve that retains 10% or more of the material.

Table 6.4 Bailey Sieve Terminology (3)

SieveTerminology	Definition	Critical Sieve Sizes [mm] For 12.5 NMAS
Primary Control Sieve	PCS = NMAS(0.22)	2.36mm
Half Sieve	HS = NMAS(0.5)	4.75mm
Fine Agg. Initial Break Sieve	FAIB = PCS(0.22)	0.600mm
Fine Agg. Secondary Break Sieve	FASB = FAIB(0.22)	0.15mm

Bailey coefficients compare particular portions of gradations and are named: Coarse Aggregate Ratio (CA), Coarse Fraction of Fine Aggregate (FA c), and Fine Fraction of Fine Aggregate (FA f).

The four final FAA mixture design gradations are similar in that they fall within the Specification 2360 gradation bands, stay close to the line of maximum density, and have similar components. Low-FAA blends 3&4 were designed to stay near the line of maximum density and have similar Bailey coefficients. Blend Bailey coefficients are given in the following table. Some difference exists between high (1&2) and low angularity (3&4) blend CA coefficients.

Table 6.5 Composite Blend Coefficients for Four Asphalt Mixture Designs

Bailey Gradation Coefficient Definition	Suggested Range	Blend Coefficients			
		1 (KR)	2 (NE)	3 (RI)	4 (SP)
CA = (%HS-%PCS) ÷ (100 - %HS)	0.4 - 0.8	0.76	0.70	0.21	0.20
FA c = %FAIB ÷ %PCS	0.25 - 0.5	0.52	0.48	0.61	0.49
FA f = %FASB ÷ %FAIB	0.25 - 0.5	0.30	0.18	0.19	0.13

6.4 Final Mixture Designs

Table 6.6 presents the four final aggregate blends used for mixture design. Each blend contains 20–30% of K 9/16, a poorly graded coarse material. Refer to Chapter 4 for sieve analysis results covering individual aggregate products.

Table 6.6 Description and Proportions of Aggregates in Final Mixture Designs

Aggregate Material	Description	Mixture Aggregate Proportions			
		Blend 1 (KR)	Blend 2 (NE)	Blend 3 (RI)	Blend 4 (SP)
KLS	well graded manufactured sand	70%			
K 9/16	poorly graded crushed rock	30%	20%	30%	30%
NE	poorly graded manufactured sand		30%		
BA 1/2	well graded gravel		50%	40%	40%
RI	well graded gravel			30%	
SP	well graded gravel				30%

Composite gradations were calculated from mixture proportions and individual sieve analysis results. Results follow in Table 6.7 and are plotted in Figure 6.2.

Table 6.7 Mixture Design Composite Gradations

Sieve Size (mm)	Blend 1 (KR)	Blend 2 (NE)	Blend 3 (RI)	Blend 4 (SP)
19	100	100	100	100
12.5	98.3	98.8	98.1	98.2
9.5	83.6	85.3	81.3	82.1
4.75	68.5	69.2	58.9	60.1
2.36	44.5	47.7	50.3	52.1
1.18	30.2	33.8	41.2	41.1
0.6	23.0	23.1	30.5	25.5
0.3	16.3	9.4	14.4	8.3
0.15	6.9	4.1	5.6	3.4
0.075	2.2	2.9	3.5	2.6

6.4.1 Composite FAA Angularities by Measured and Calculated and Methods

The scope of this study includes comparison of measured and calculated FAA values. The Mn/DOT Lab Manual, section 1206, presents methods for proportioning individual aggregate products and performing FAA measurements and calculations (4). Figure 6.3 shows measured FAA values for the four mixture designs in relation to Superpave criterion (reference Chapter 4). Knowing individual product proportions, FAA, Gsb, and gradation, it is possible to calculate the FAA values of composite blends.

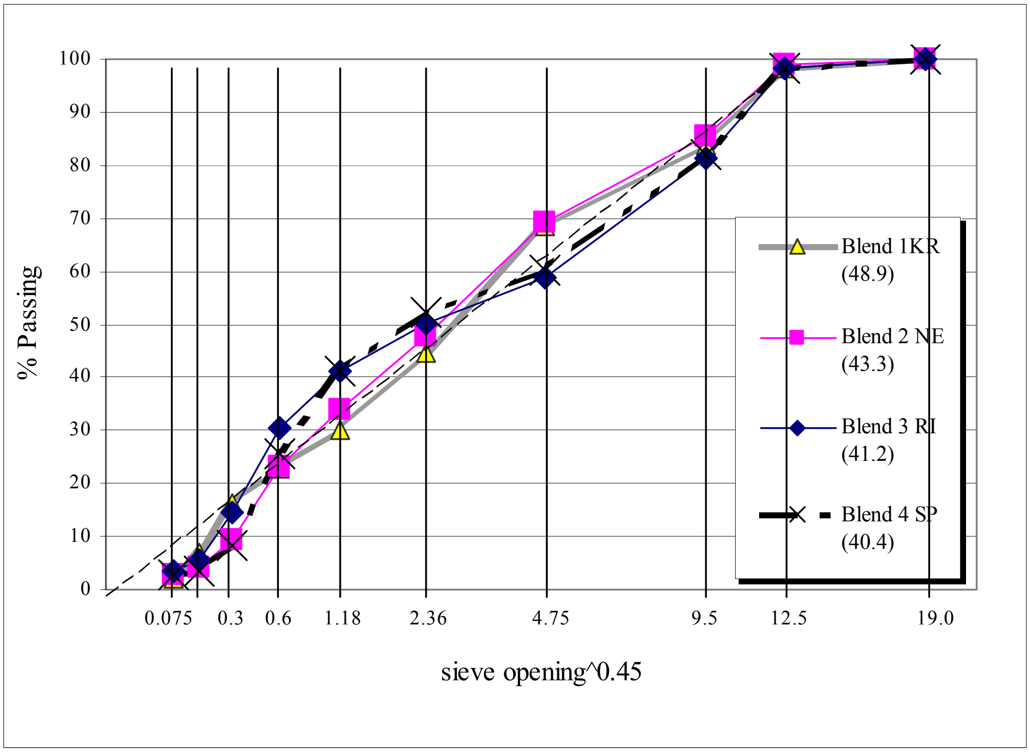

Figure 6.2 12.5-mm NMAS Mixture Design Gradations, Blend FAA Value in Parenthesis

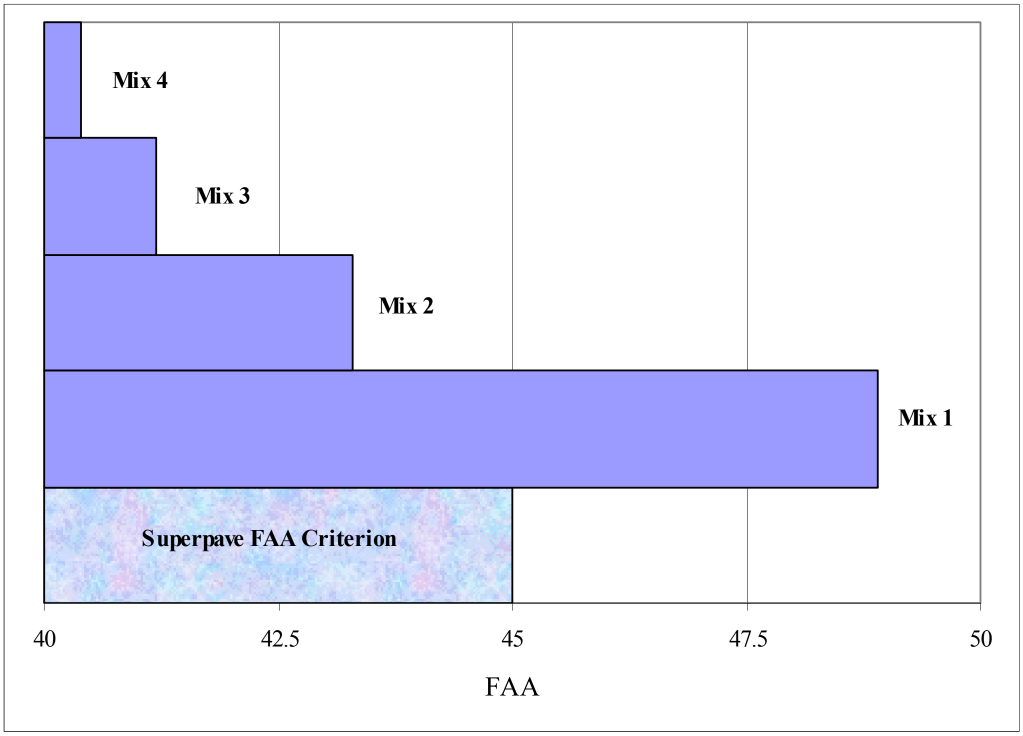

Figure 6.3 Measured FAA of Composite Gradations

It is possible to either calculate a proportion-weighted FAA value similar to an aggregate-blend specific gravity calculation or a gradation-weighted average, as shown below:

Proportion-Weighted Blend Calculation

$$\text{Blend FAA} = \frac{\sum P_i}{\sum {P_i}/{FAA_i}}$$

Gradation-Weighted Average Calculation

$$\text{Blend FAA} = \frac{\sum P_i \times \%Fines_i \times FAA_i}{\sum P_i \times \%Fines_i}$$

Where:

P_i = Percent of component aggregate in mixture blend

FAA_i = Component aggregate FAA

% $Fines_i$ = % of component aggregate passing the 4.75-mm (#4) sieve

Table 6.8 compares weighting methods by showing estimated and measured FAA values for aggregate blends. The estimates are conservative since they do not take into account the contribution of fines from crushed coarse aggregate K9/16. In this case only 3.8% of the high-angularity K 9/16 material passes the 4.75-mm sieve and 2.4% passes the 2.36-mm (#8) sieve, but nevertheless raises the composite blend angularity.

Table 6.8 Measured and Estimated FAA Values for Mixture Design Composite Blends (FAA Validation)

	Blend 1 (KR)	**Blend 2 (NE)**	**Blend 3 (RI)**	**Blend 4 (SP)**	**Average**
Measured FAA	48.9	43.3	41.2	40.4	-
Proportion-weighted Calculation (% Error)	47.9 (2.04)	42.9 (0.92)	40.0 (2.91)	39.9 (1.24)	- (1.78)
Gradation-weighted Calculation (% Error)	47.9 (2.04)	43.3 (0)	40.0 (2.91)	39.9 (1.24)	- (1.55)

6.4.2 Composite Aggregate Imaging System (AIMS) Angularities

The characterization of aggregates with digital imaging was not included as part of the initial project work plan. It was included subsequent to the start of research in an effort to compare conclusions about the effect of aggregate form and angularity on mixture performance. Refer to Chapter 4 for a description of aggregate imaging data.

It was possible to proportion aggregate imaging data using nearly the same method used for obtaining composite aggregate blends. Since no AIMS data existed for the coarse K9/16 material, it was necessary to modify the proportions of the remaining component materials accordingly. This was done assuming that the coarse material made an insignificant contribution to the amount retained on the 1.16-mm (#16) sieve. Recall that sieve analysis of the K9/16 reported 2.4% passing the 2.36-mm sieve, which would amount to less than 0.8% of the material in the total aggregate blend.

Digital imaging quartile and median values were chosen for description since they offer a robust means of evaluating data. The representative AIMS values are presented in Table 6.9.

Table 6.9 Blended AIMS Angularities

	Minimum	Quartile 1	Median	Quartile 3	Maximum
	#16 Radial Angularity				
Blend 1 (KR)	3.30	5.89	7.39	9.66	17.71
Blend 2 (NE)	3.25	5.68	7.68	10.13	13.11
Blend 3 (RI)	3.08	5.35	6.80	8.71	11.95
Blend 4 (SP)	3.01	4.98	6.33	8.08	11.80
	#16 Gradient Angularity				
Blend 1 (KR)	1631.45	2812.85	4135.01	5414.78	9001.35
Blend 2 (NE)	534.50	2587.82	4156.01	6209.48	8424.53
Blend 3 (RI)	594.75	2177.97	3423.64	4741.73	6911.58
Blend 4 (SP)	570.64	2129.73	3399.53	5392.71	7417.89
	#16 Fines Form				
Blend 1 (KR)	4.16	6.67	7.94	9.47	13.41
Blend 2 (NE)	3.70	6.43	7.79	10.39	13.44
Blend 3 (RI)	3.21	5.77	6.76	9.00	12.40
Blend 4 (SP)	3.14	5.39	6.47	8.17	11.96

CHAPTER 7: FABRICATION AND TESTING OF HMA SPECIMENS

7.1 Specimen Fabrication for Dynamic Modulus and Asphalt Pavement Analyzer Testing

Asphalt mixture rutting resistance is related to the internal friction provided by the aggregate component. A total of sixteen cylindrical dynamic modulus specimens were produced from four asphalt mixtures for the purpose of evaluating rutting resistance by dynamic modulus (|E*|) testing. Additionally, a total of eight cylindrical specimens were produced from the same four mixtures for evaluating rutting resistance with the Asphalt Pavement Analyzer (APA).

The four mixture designs were produced from one coarse material, four fine materials typical of several Minnesota regions, and a fifth fine material used to improve the laboratory mixture design. Source and manufacture method information is found in Chapter 4. Current Mn/DOT specifications require FAA from 40–45. The range of measured composite blend FAA values was 40.4 to 48.9.

7.1.1 Mixture Descriptions

Mixtures 1 and 2 were designed using high-FAA materials while mixtures 3 and 4 were designed with low-FAA materials.

- Mixture 1 included 2 aggregate materials, 30% crushed, coarse limestone and 70% manufactured limestone sand (FAA = 47.9). Optimum asphalt was determined to be 5.5%.
- Mixture 2 included 3 aggregate materials, 20% crushed, coarse limestone, 50% bituminous aggregate (FAA = 40.8), and 30% crushed granite (FAA = 46.9).
- Mixture 3 included 3 aggregate materials, 30% crushed, coarse limestone, 40% bituminous aggregate (FAA = 40.8), and 30% natural gravel (FAA = 38.9).
- Mixture 4 included 3 aggregate materials, 30% crushed, coarse limestone, 40% bituminous aggregate (FAA = 40.8), and 30% natural gravel (FAA = 38.7).

7.2 Dynamic Modulus Specimen Fabrication Steps

Specimens were fabricated using the results from the trial mixture phase as reported in Chapter 6. A total of four (4) 7200-g gyratory specimens were produced using NCHRP Project 9-29 procedures (18).

1. Measure two batches of aggregate proportioned for mixture blend. Each batch shall contain enough material to produce two (2) 7200-g gyratory specimens. Place in oven along with binder and mixing tools and heat at 145C for 4 hours.
2. Mix first batch of aggregate and binder in bucket mixer. Record binder measurement. Place mix in pan. Repeat for second batch of aggregate and binder.
3. Mix both batches together. Measure out mixture for 4 specimens.
4. Place mixture in oven and age at 135C for 4 hours. Stir hourly. Last 30 minutes lower temperature to 133C.
5. Compact cylindrical specimen (150 by 170-mm) to 5.5–6% air voids by trial and error using a gyratory compactor.
6. Core and cut specimen produced in (5) to 100 by 150-mm cylinder.
7. Measure Gmb. Calculate void content, VMA, VFA. Void content of cut, cored specimen should be 5%.

7.2.1 Dynamic Modulus Specimen Volumetric Documentation

In preparation for dynamic modulus testing, the 150 by 170-mm gyratory specimens were cored and cut to final dimensions of 100 by 150-mm. Tables 7.1 and 7.2 report averaged measurements for each asphalt mixture.

Table 7.1 N-design Asphalt Mixture Measurements

Spec. 2360 Requirements	Mix 1 (KR)	Mix 2 (NE)	Mix 3 (RI)	Mix 4 (SP)
	Mixture FAA (Measured)			
	48.9	43.3	41.2	40.4
	Mixture FAA (Calculated)			
	47.9	42.9	40.0	39.9
	Gsb			
	2.690	2.640	2.613	2.630
	Gmm			
	2.538	2.475	2.475	2.470
	% Asphalt Content			
	5.54%	5.93%	5.20%	5.50%
	Gyrations			
	Ndesign Gyrations			
	90	90	60	60
	% Design Air Voids			
	4.0%	4.0%	4.0%	4.0%
14% minimum	% VMA at Ndesign			
	15.7%	16.5%	14.4%	15.6%
65 - 78%	% VFA at Ndesign			
	74.5%	75.8%	72.2%	74.3%

Table 7.2 Asphalt Mixtures for |E*| Testing (Target void content of 5%)

Mix 1 (KR)	Mix 2 (NE)	Mix 3 (RI)	Mix 4 (SP)
Gmb			
2.401	2.342	2.360	2.350
N Gyrations			
40	35	35	30
%Air Voids			
5.4%	5.4%	4.6%	4.9%
% VMA			
15.7%	16.5%	14.4%	15.6%
% VFA			
65.6%	67.5%	67.7%	68.8%

7.3 Asphalt Pavement Analyzer Specimen Fabrication

APA specimens were fabricated using the same steps discussed for |E*| specimens with these exceptions:

1. A single gyratory specimen was produced for each mixture by compacting to 5–5.5% air voids by trial and error.
2. Two (2) 150 by 75-mm cylindrical specimens were cut from the same 150 by 170-mm cylindrical gyratory specimen for purposes of APA testing.
    - The gyratory specimen was halved and both ends removed.
3. Measure Gmb. Calculate void content, VMA, VFA. Void content of cut specimen should be 5%.

7.3.1 Asphalt Pavement Analyzer Specimen Volumetric Documentation

APA specimens were produced at asphalt contents identical to |E*| specimens. Compaction levels were altered by trial and error in an effort to also keep void content identical. Table 7.3 reports values for each 150 by 75-mm APA specimen. Note that cut specimens Mix 1-(1), Mix 2-(2), and Mix 3-(2) have air voids out of range.

Table 7.3 Mixture 1 APA Specimen Measurements

		Mix1 (KR)	**Mix 2 (NE)**	**Mix 3 (RI)**	**Mix 4 (SP)**
Gyrations		70	45	45	40
% Asphalt		5.6	5.95	5.16	5.74
Gmb	Uncut	2.395	2.313	2.362	2.342
	Cut (1)	2.419	2.341	2.352	2.347
	Cut (2)	2.389	2.305	2.387	2.35
Air Voids	Uncut	4.8	6.5	4.6	5.0
	Cut (1)	3.8	5.4	4.9	4.8
	Cut (2)	5.0	6.9	3.5	4.7
VMA	Uncut	16	17.6	14.3	16.1
	Cut (1)	15.1	16.6	14.6	15.9
	Cut (2)	16.2	17.9	13.3	15.8
VFA	Uncut	70.1	62.8	68.0	68.7
	Cut (1)	74.8	67.4	66.1	69.7
	Cut (2)	69	61.6	73.4	70.1
Height [mm]	Cut (1)	74.85	74.08	74.27	76.04
	Cut (2)	73.26	77.63	68.91	71.97

7.4 Testing of HMA Specimens

Testing was performed to gather both dynamic modulus data and rutting data. Dynamic modulus data was acquired from testing on a MTS load frame. Testing was performed at three temperatures (20, 40 and 54C) and five frequencies (0.01, 0.1, 1, 10, and 25-Hz). Modulus computations were performed using the spreadsheet program SINAAT (19). SINAAT inputs are the last 6 cycles of testing data. Some of the test phase angle results have improper notation; for example Mix 1, Specimen D5, Temperature 20, Freq 0.106 has a computed phase angle of – 324.5 degrees.

Phase angles have theoretical limits of 0 and 90 degrees, therefore these discrepancies should be reviewed if used for further analysis.

Rutting data was obtained using the APA testing machine.

Average values of all dynamic modulus results are plotted in Figure 7.1 – 7.4.

7.4.1 SINAAT |E*| Analysis Results

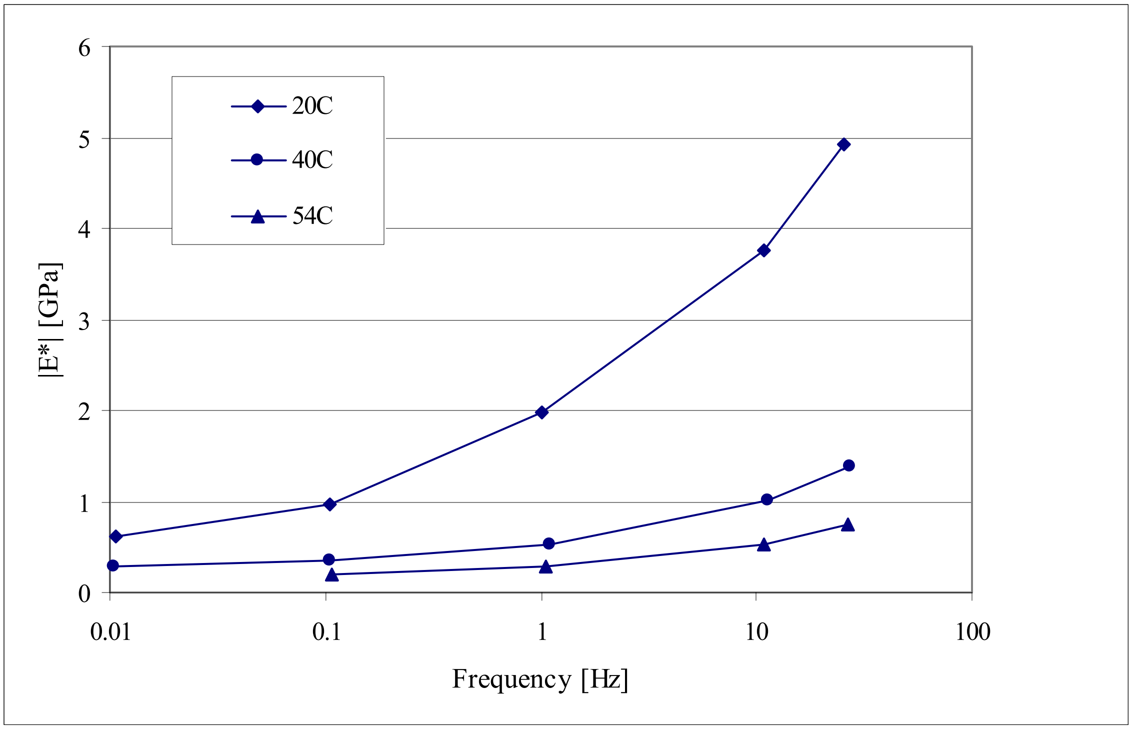

Figure 7.1 Averaged Dynamic Modulus Values for Mix 1 (KR), FAA = 48.9

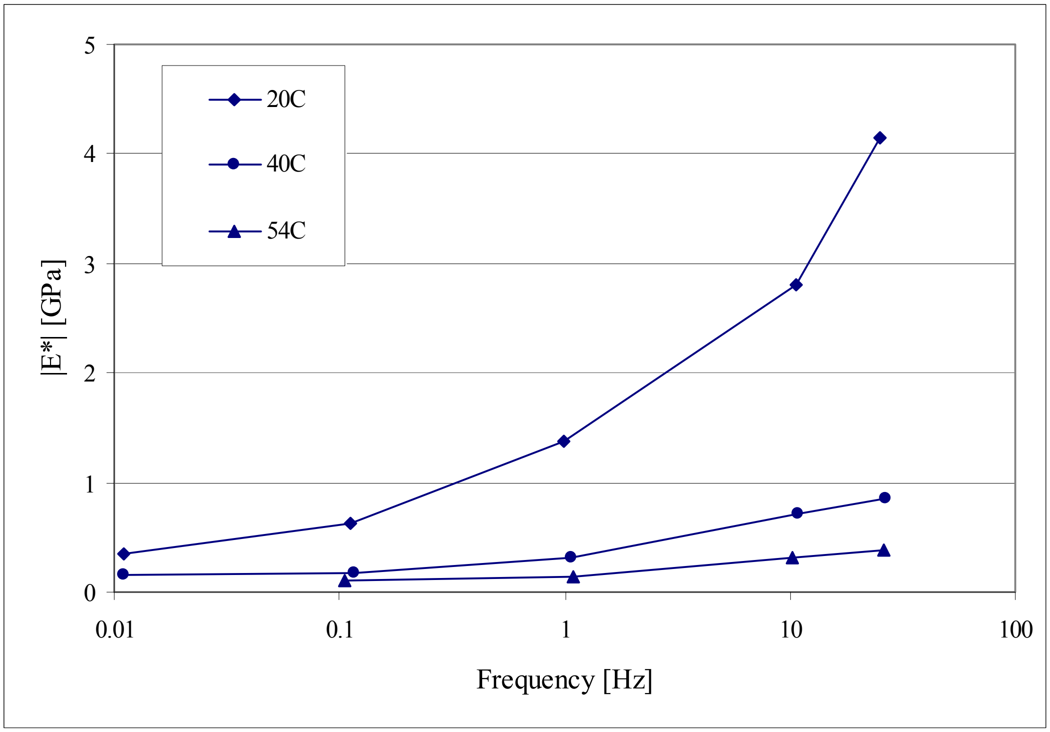

Figure 7.2 Averaged Dynamic Modulus Values for Mix 2 (NE), FAA = 43.3

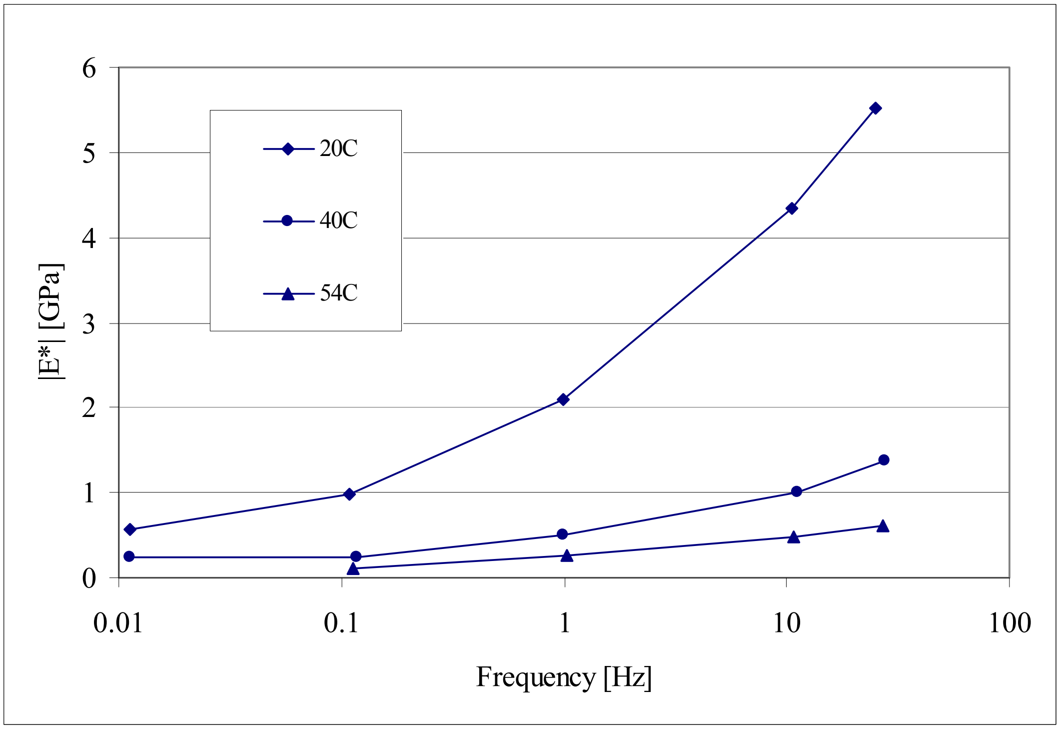

Figure 7.3 Averaged Dynamic Modulus Values for Mix 3 (RI), FAA = 41.2

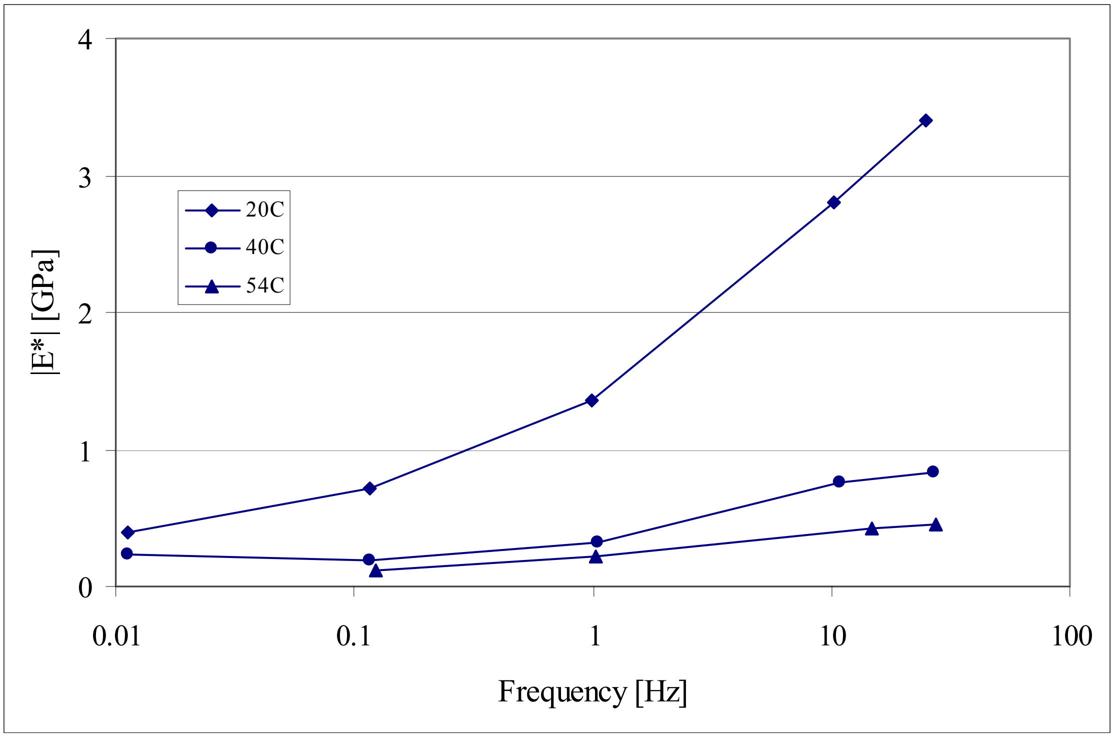

Figure 7.4 Averaged Dynamic Modulus Values for Mix 4 (SP), FAA = 40.4

The number of data points for each specimen is given by: 2 temperatures by 5 frequencies + 1 temperature by 4 frequencies = 14. Four specimens were produced for each of the asphalt mixtures, totaling 14 by 4 by 4 = 224 data points. Mean, median, standard deviation, and coefficient of variation (CV) values were found for the full set of |E*| data then plotted for analysis. It was observed that the some averaged data had CV values near 70%. The full set was then conditioned to CV <40% by removal of outlying data points. Possible outliers were identified for removal by using the inter-quartile method then checking graphical trends. Inter-quartile criterion identifies outliers as points located a distance greater than ±1.5 (3rd quartile – 1st quartile) from the median (20). The final data set contained 205 total data points.

Figures 7.5–7.7 are presented to show the effects of data conditioning. Figure 7.5 shows standard deviations for the full set of data, Figure 7.6 compares CV for both the full and conditioned data sets, and Figure 7.7 shows standard deviations based on the points remaining in the conditioned data set.

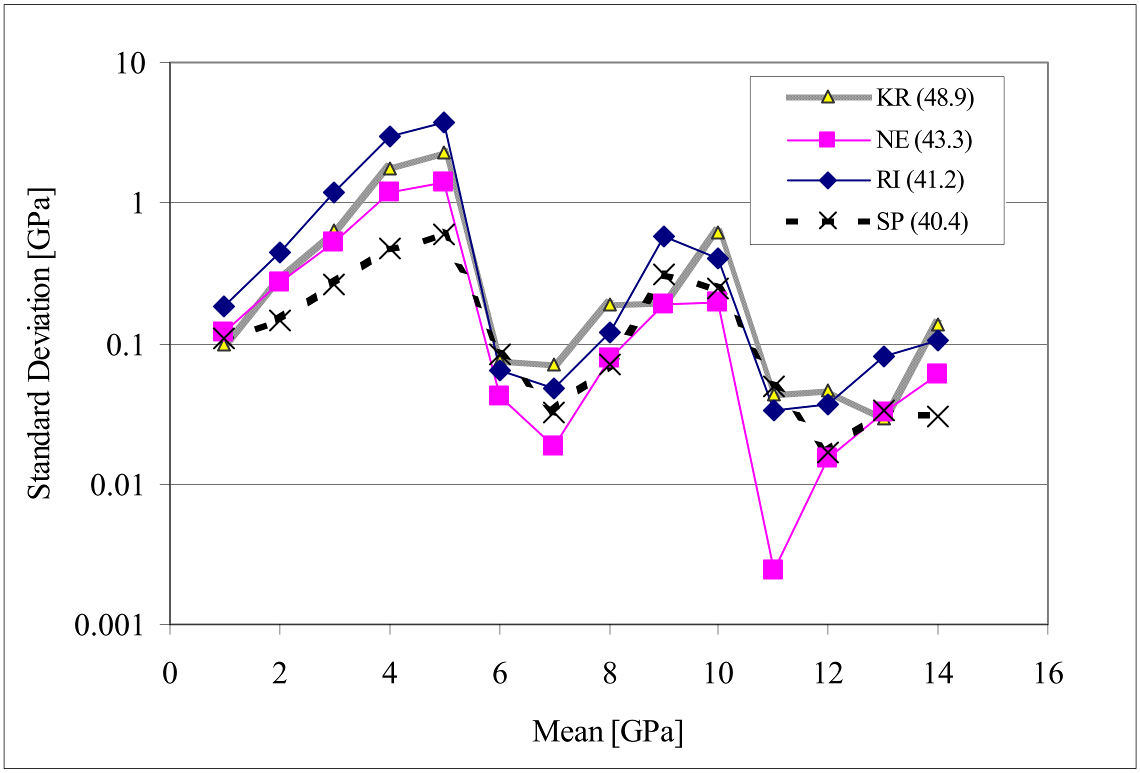

Figure 7.5 Full Set of |E*| Data Points; Std Deviation vs. Mean

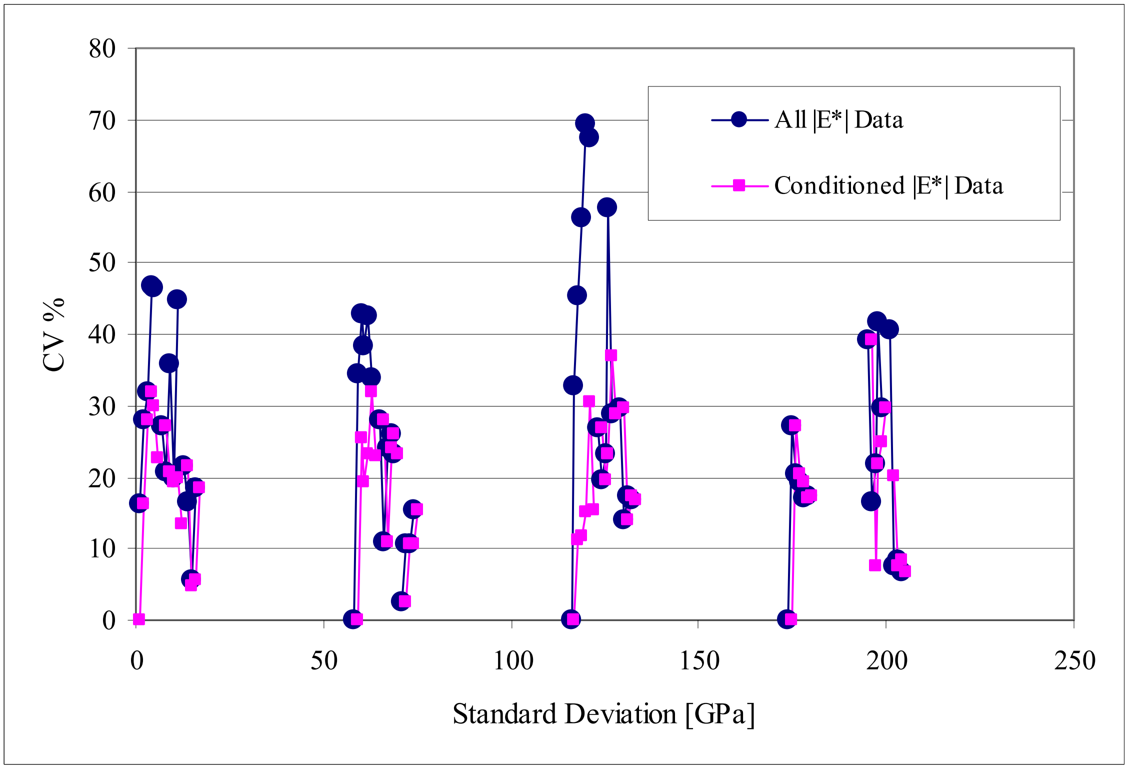

Figure 7.6 Coefficient of Variation Comparisons

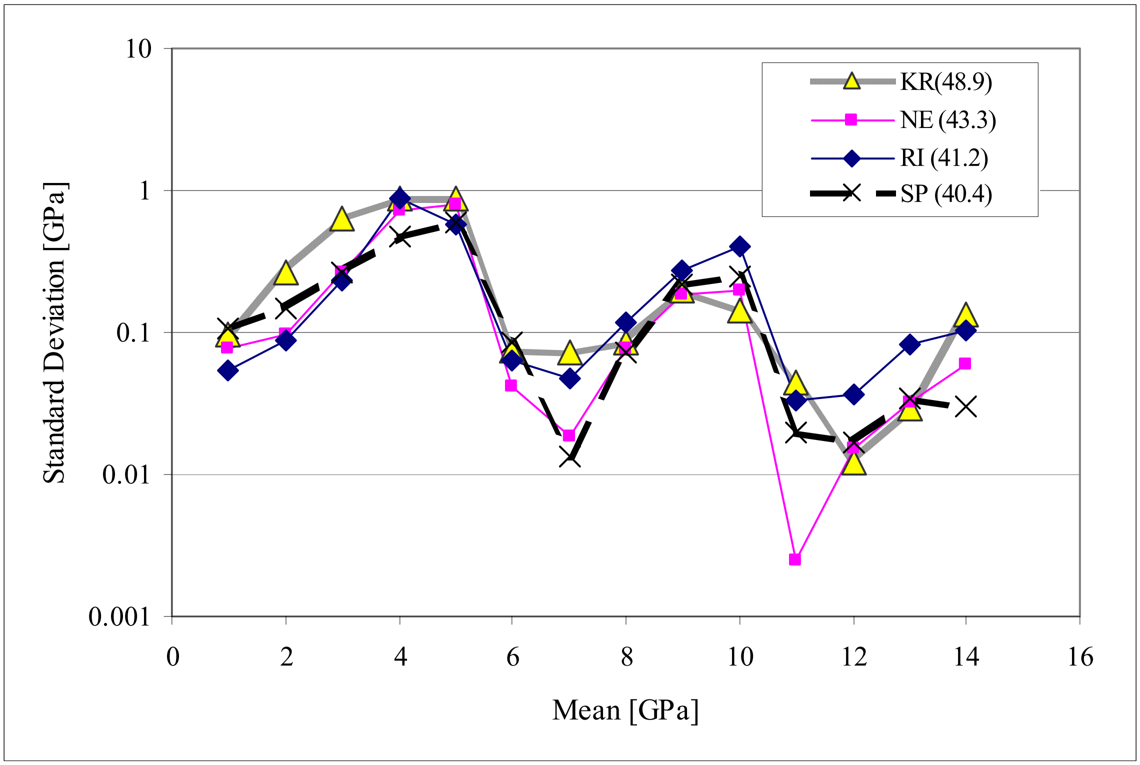

Figure 7.7 Final Conditioned Set of |E*| Data Points, Std Deviation vs. Mean

7.4.2 Asphalt Pavement Analyzer (APA) Testing Results

Refer to Chapter 5 for a description of APA testing. The APA testing machine collects rut depths automatically. Output is in Microsoft Excel format. The results are presented in Table 7.4 and plotted in Figure 7.8. Rut development is plotted in Figure 7.9.

Table 7.4 APA Averaged Test Results (rut depth in mm) at 54C.

Stroke Count	**Mix 1 (KR)**	**Mix 2 (NE)**	**Mix 3 (RI)**	**Mix 4 (SP)**
1	0.906965	-0.41532	-0.14741	0.36382
5000	4.513769	7.091806	7.11396	11.60078
8000	4.566852	8.373692	8.42322	--
Mixture FAA	48.9	43.3	41.2	40.4

APA rut depth results at stroke count 1 are used as a reference point for subsequent rutting. Rut depths at 8000 and 5000 strokes should subtract stroke count 1 to establish differential rutting. Notes regarding APA results:

- Some APA specimens were not cut to the specified 75-mm height. For these cases, testing personnel were able to minimize negative effects by matching specimens with similar heights or adding a shim-platform into the APA specimen testing-mold.
- After cutting the APA testing specimens it was observed that for specimen halves, air voids typically varied both above and below the target of 5%. Average values of rutting depth are plotted for each mixture in Figures 7.8 and 7.9.
- The Asphalt Pavement Analyzer test ran to 8000 cycles at test temperature 54C for all but one mixture (Mixture 4). Test technicians reported that this particular mixture had completely rutted at 5000 cycles.

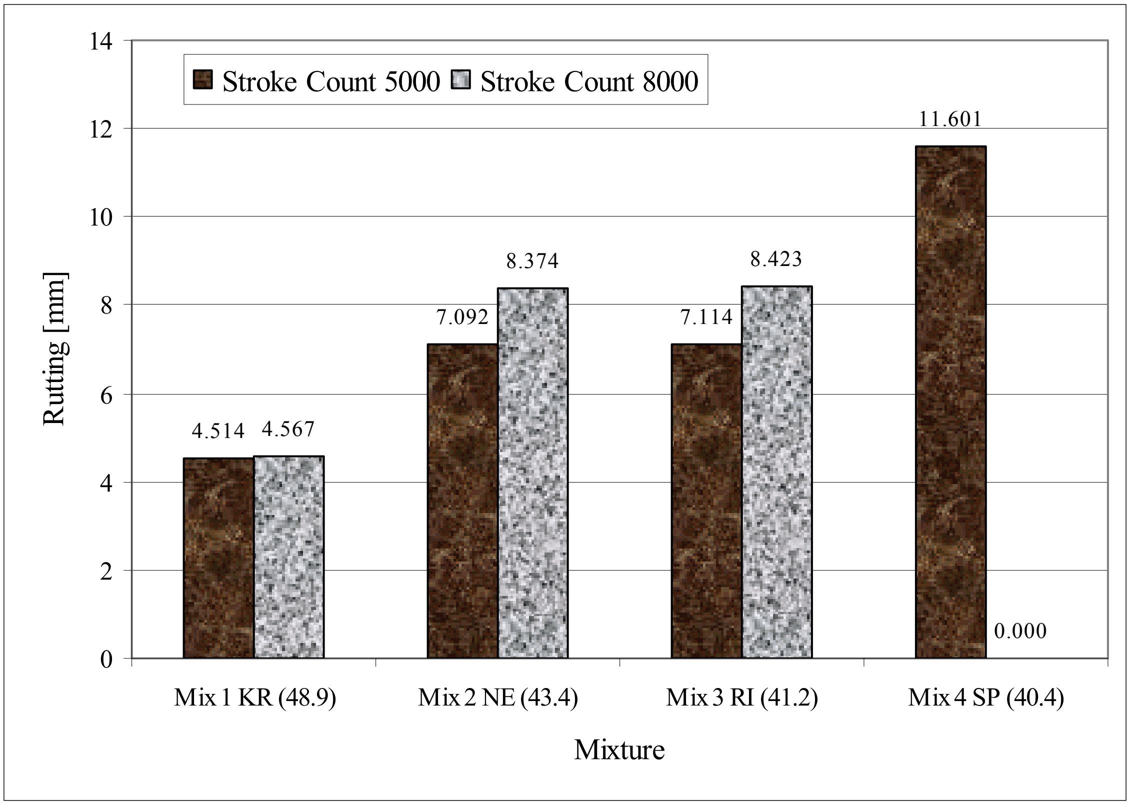

Figure 7.8 APA Rut Susceptibility Results (5000 & 8000 cycles, Temperature 54C)

Figure 7.9 shows low-FAA mixture located on the top of the plot, indicating a rut-susceptible mixture. The high-FAA mixture is located along the bottom, indicating a relatively rut-resistant mixture. The remaining two mixtures have nearly the same plots, even though their FAA values vary by over 2 points.

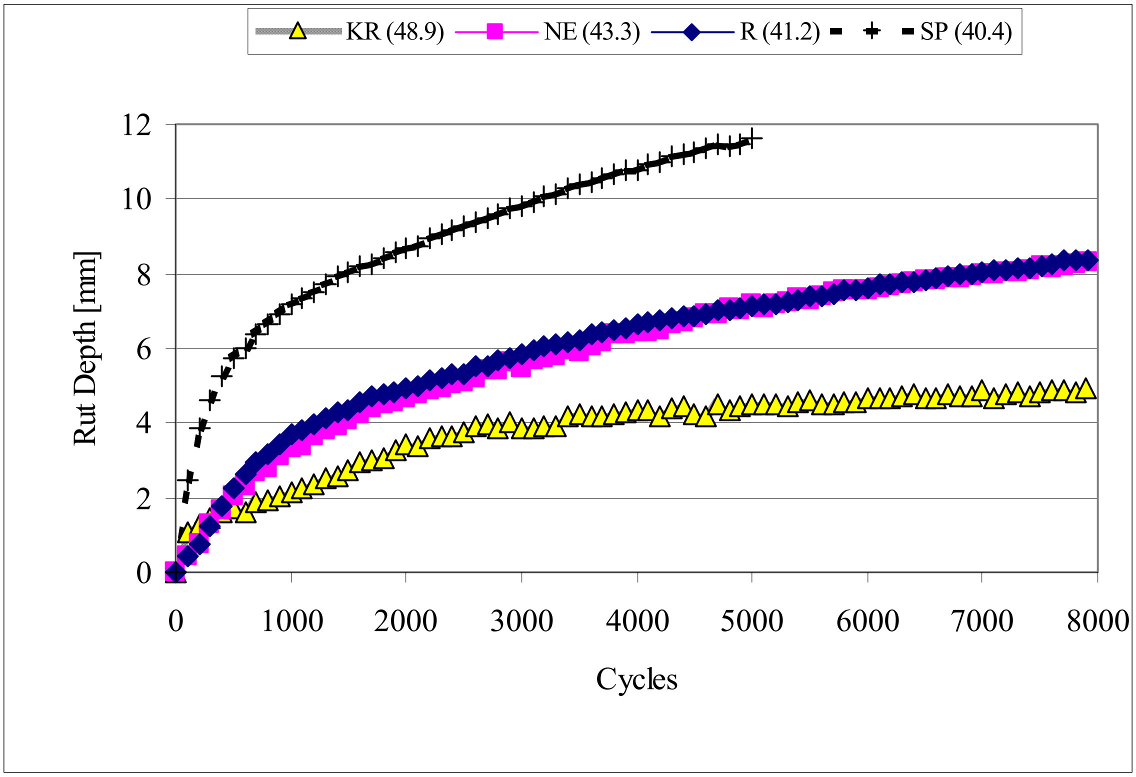

Figure 7.9 Mixture APA Rut Development at 54C

CHAPTER 8: ANALYSIS OF LABORATORY RESULTS

8.1 Introduction

Four asphalt mixtures were designed for the purpose of analyzing the contribution of Fine Aggregate Angularity (FAA) to mixture rutting resistance. Mixtures included high-quality aggregate products from Minnesota sources. A testing program for evaluating the effect of FAA was developed and presented in Chapter 5. The program included dynamic modulus (|E*|) compressive testing using an MTS machine. Rut susceptibility testing was also performed using an Aspahlt Pavement Analyzer (APA). This work was done in addition to the funded work plan; the research team thought that this extra work would benefit the project findings. 16 dynamic modulus and 8 rutting specimens were used for data collection. Data was presented in Chapter 7. Other additional work included evaluation of aggregates using a FAA-funnel flow time experiment and characterization with digital imaging methods.

8.2 Dynamic Modulus

Dynamic modulus data was collected for a range of test temperatures and frequencies.

The principle of Time-Temperature Superposition and the use of nonlinear regression techniques are means by which master curves may be developed from modulus-frequency-temperature data. Nonlinear analysis tools can develop curves by fitting dynamic modulus data to a nonlinear sigmoidal function (18):

$$\log\left|E^*\right| = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log(t_r))}}$$

Where t_r is the time of loading at the reference temperature, δ is the minimum value of |E*|, $\delta + \alpha$ is the maximum value of |E*|, and β and γ are parameters describing the shape of the sigmoidal function (22).

This function allows data to shift in relation to a predetermined reference temperature. For the purposes of this report the statistical software Sigma Stat (21) was used to develop master curves.

8.2.1 Dynamic Modulus Analysis Inputs

Input data for regression analysis was developed in Chapter 7, and consisted of dynamic modulus data averaged according to the following:

- Group data according to temperature and test frequency
- Eliminate unrealistic values by analyzing for outliers and checking mean and median trends
- Calculate mean values for modulus and test frequency

8.2.2 Dynamic Modulus Master Curve Results

The low frequency portion of the master curve is of greatest interest since mixture performance at low frequencies corresponds to performance at high temperatures and, as a consequence, master curve plots were developed at a reference temperature of 54C. Modulus curves were fitted for all mixtures at 54C using Sigma Stat. Results for all mixtures are shown in Figure 8.1. Figures 8.2–8.5 show fitted curves and shifted data for each mixture. Modulus vs. Frequency plots include values for frequencies beginning at 0.01-Hz. The upper limit of the shifted data is 39,000-Hz. The general appearance of these plots shows modulus curves maintaining their relative position up to about 10,000-Hz. From 0.01 to 10,000-Hz (corresponding to higher temperature conditions) modulus ordered from high to low appear in the following order: Mix 1 (KR) (48.9), Mix 3 (RI) (41.2), Mix 4 (SP) (40.4), Mix 2 (NE) (43.3).

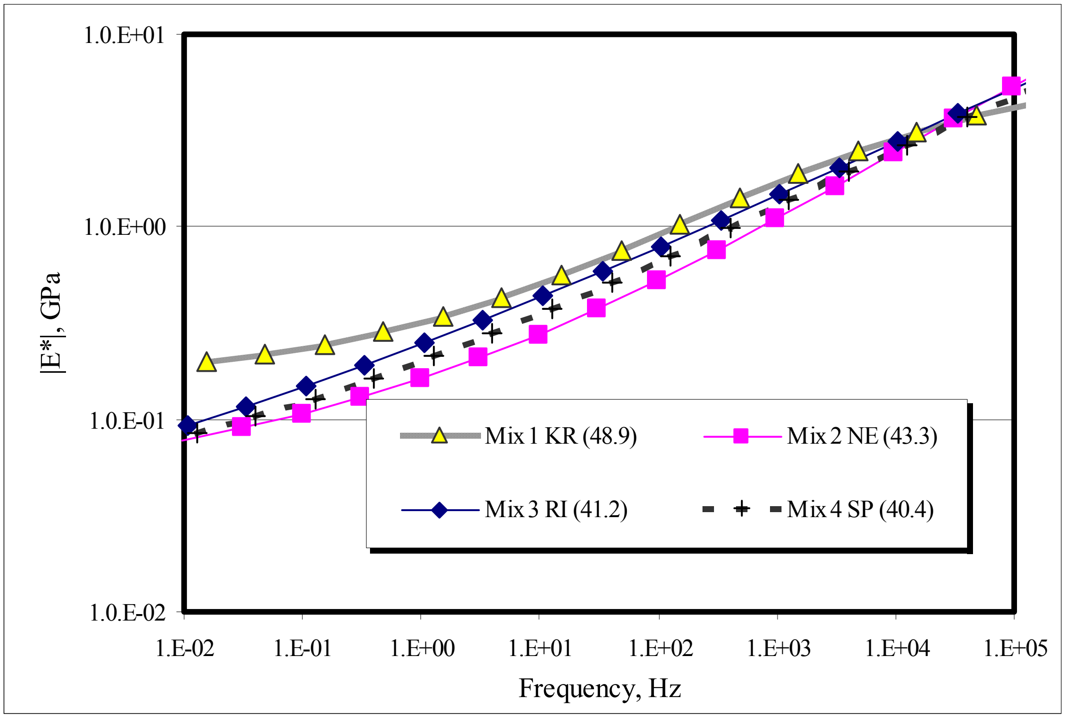

Figure 8.1 Fitted Dynamic Modulus Master Curves for 4 FAA Mixtures at 54C

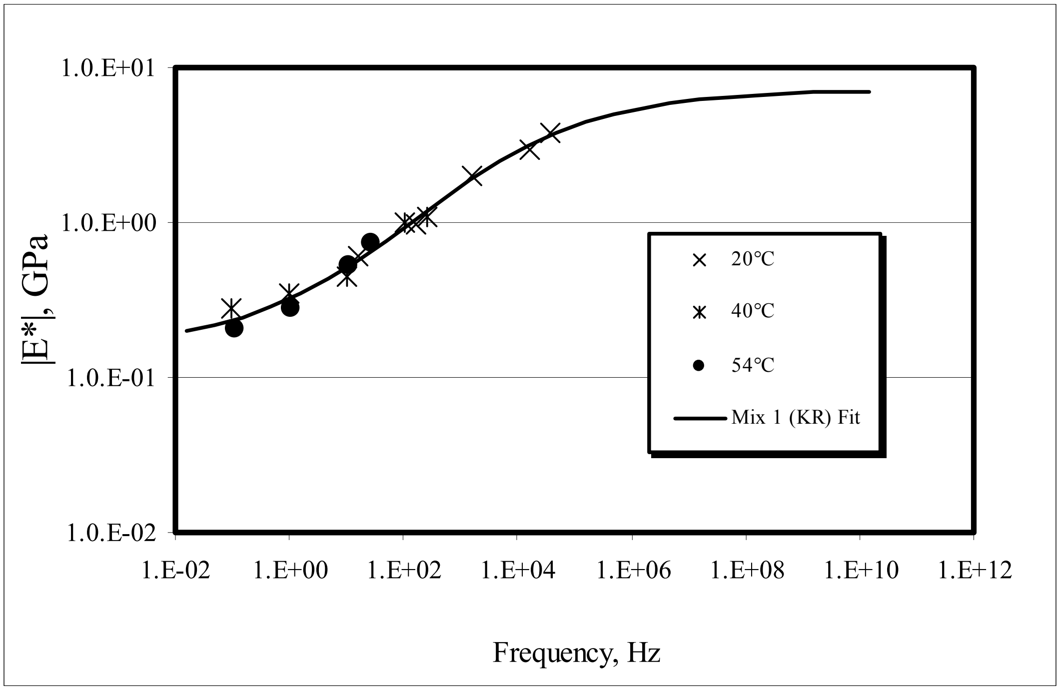

Figure 8.2 Mix 1 (KR) Fitted |E*| Curve and Shifted Data at 54C

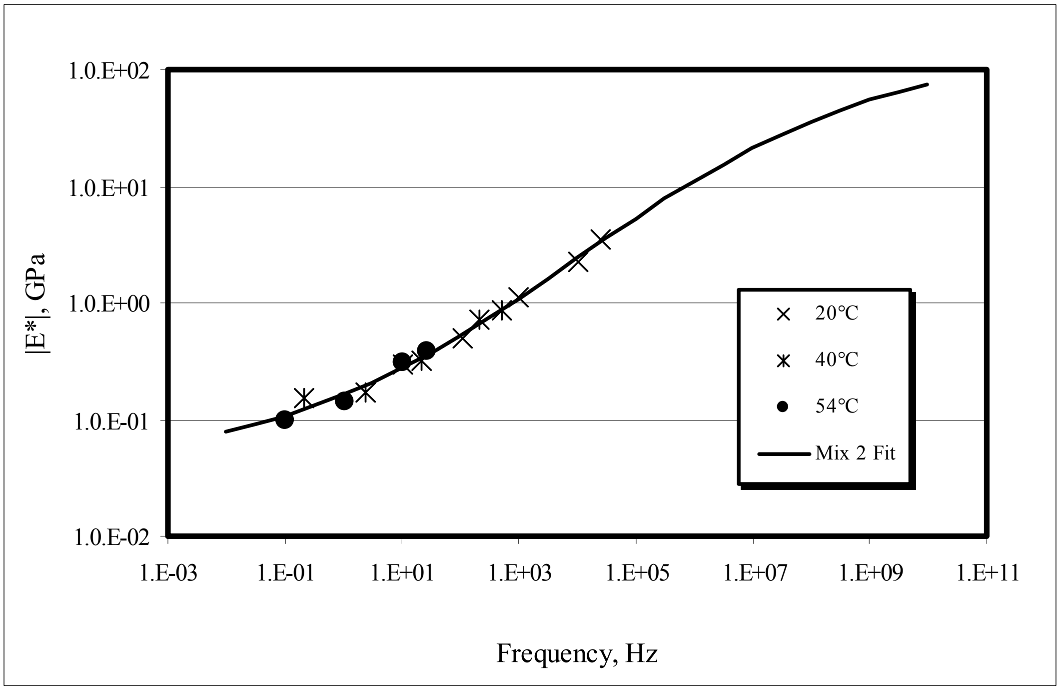

Figure 8.3 Mix 2 (NE) Fitted |E*| Curve and Shifted Data at 54C

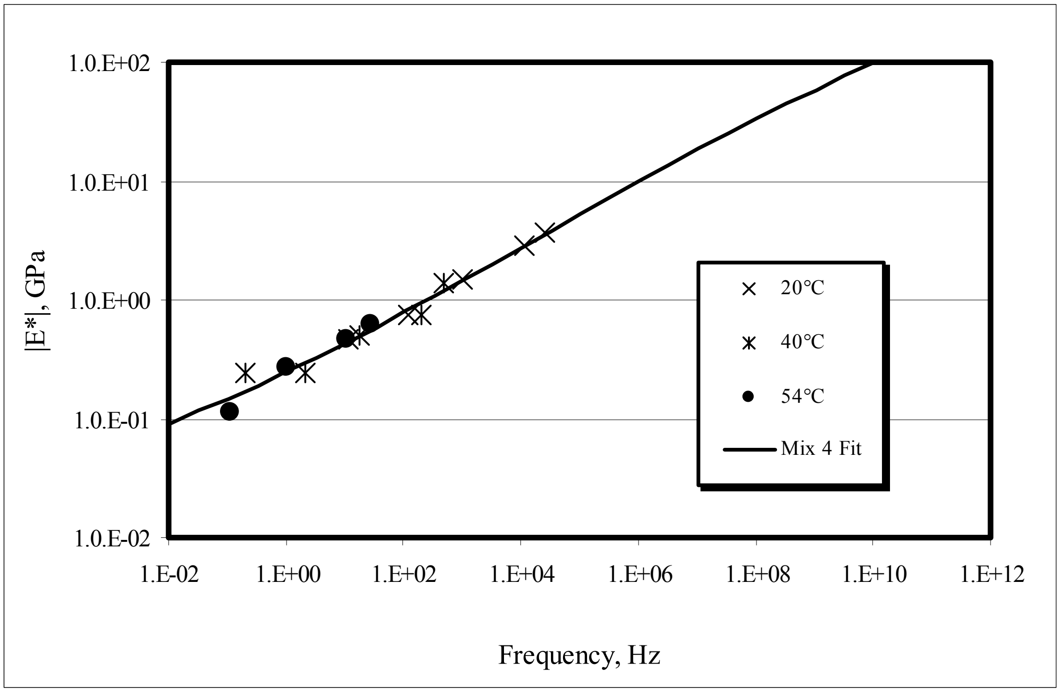

Figure 8.4 Mix 3 (RI) Fitted |E*| Curve and Shifted Data at 54C

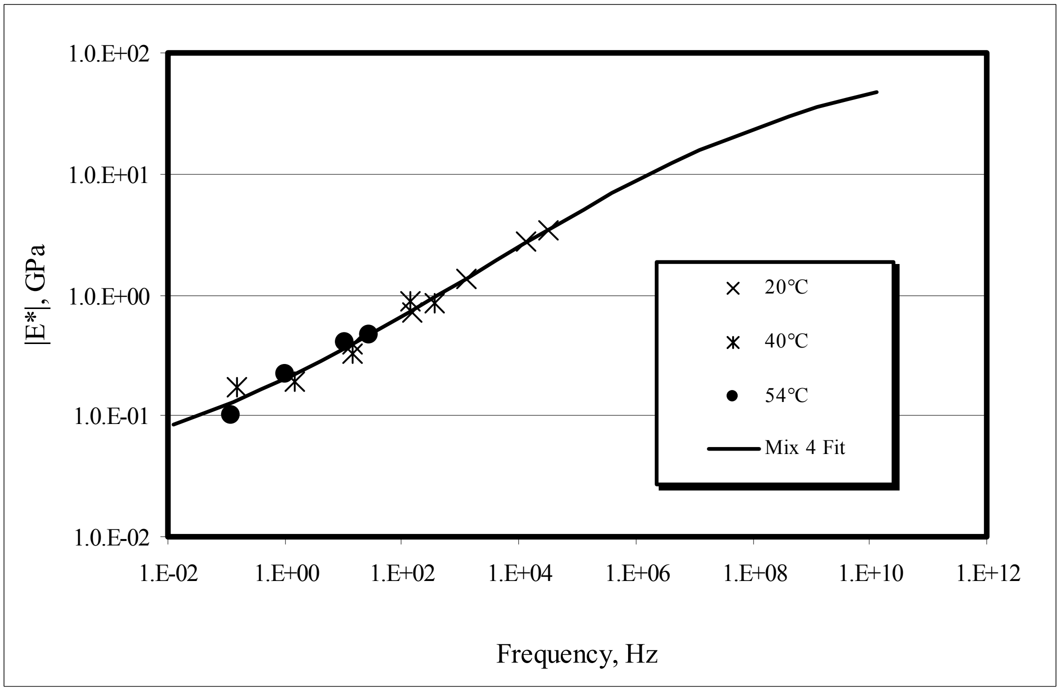

Figure 8.5 Mix 4 (SP) Fitted |E*| Curve and Shifted Data at 54C

Figure 8.6 shows a plot of |E*| fitted/measured values. The plot shows some scatter from 0.8 to 1.2. Several greater values occur at 0.1-Hz in Mixtures 3 and 4.

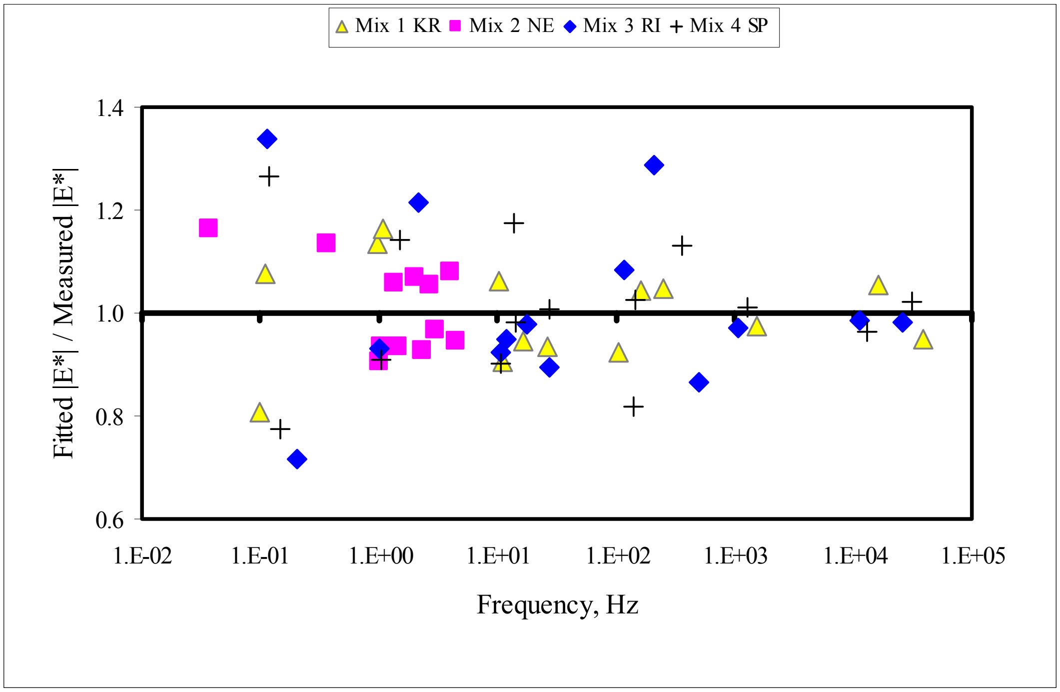

Figure 8.6 |E*| Fitted/Measured Values at 54C for the 4 Mixtures Investigated

The preceding plot of fitted-to-measured ratios shows that ratios decrease with increased frequency. The larger fitted-to-measured ratios occur because greater levels of technical difficulty are commonly encountered when gathering low-frequency, high-temperature dynamic modulus data. This is true because of the resolution limitations of the testing equipment.

The following plots of |E*| ratios in Figures 8.7–8.10 show that at low temperature and high frequency the high-FAA mixture (Mix 1) performs better that the other mixtures.

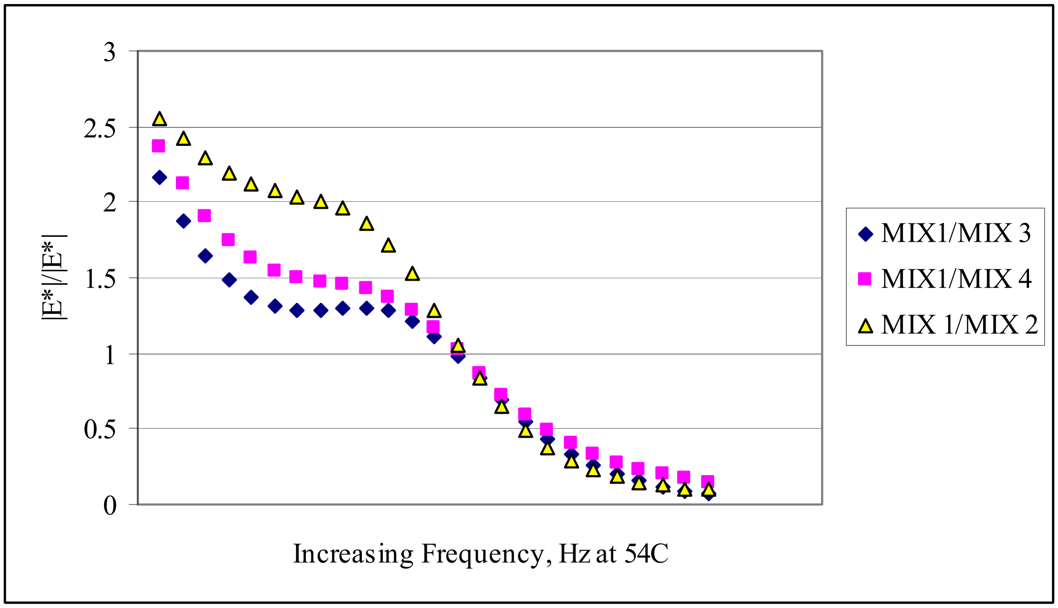

Figure 8.7 Performance Ratios for Mix 1

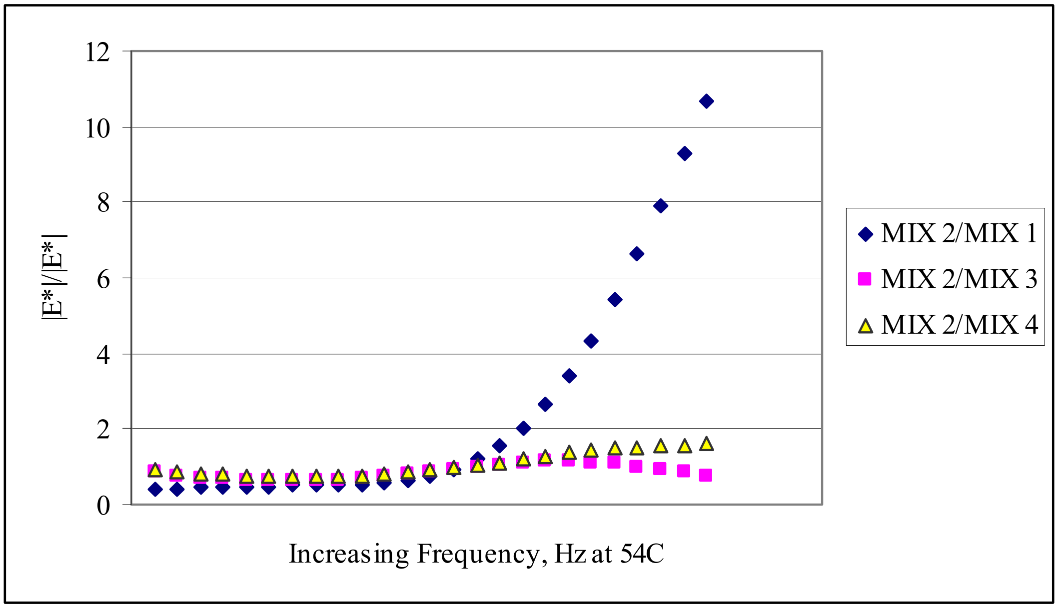

Figure 8.8 Performance Ratios for Mix 2

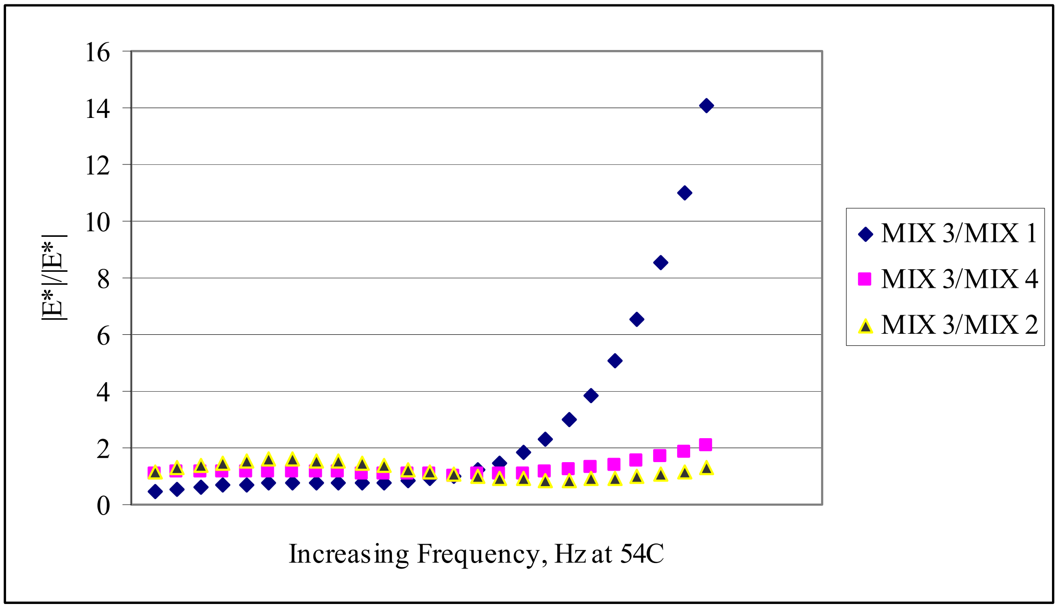

Figure 8.9 Performance Ratios for Mix 3

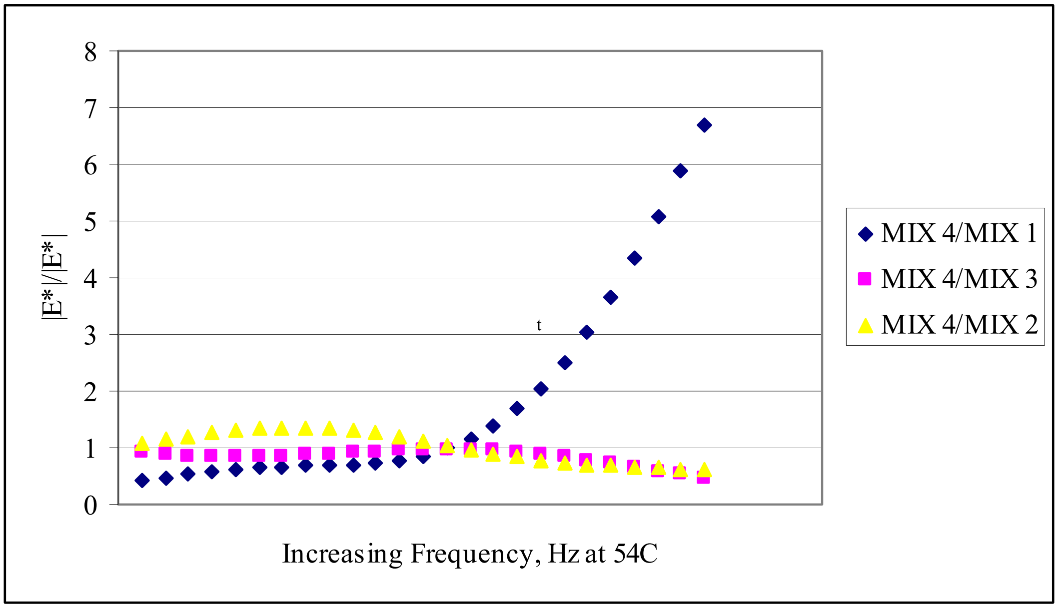

Figure 8.10 Performance Ratios for Mix 4

8.3 Asphalt Pavement Analyzer Rut Susceptibility

APA testing results were described and presented in Chapter 7. Results and rankings are given in Table 8.1 and Figure 8.11. Blend FAA is given in parenthesis in Figure 8.11. Table 8.1 shows rut depths obtained from averaging the results from two specimens per mixture and ranks the mixtures according to performance at 8000 cycles. Figure 8.11 shows mixture rut development per test cycle. Note the similarities in Mix 2 and Mix 3.

Table 8.1 Asphalt Pavement Analyzer Test Results (rut depth in mm).

	Mix 1 (KR)	**Mix 2 (NE)**	**Mix 3 (RI)**	**Mix 4 (SP)**
1 Cycle	0.906965	-0.41532	-0.14741	0.36382
5000 Cycles	4.513769	7.091806	7.11396	11.60078
8000 Cycles	4.566852	8.373692	8.42322	--
Mixture FAA	48.9	43.3	41.2	40.4
APA Rank at 8000 Cycles	1	3	2	4

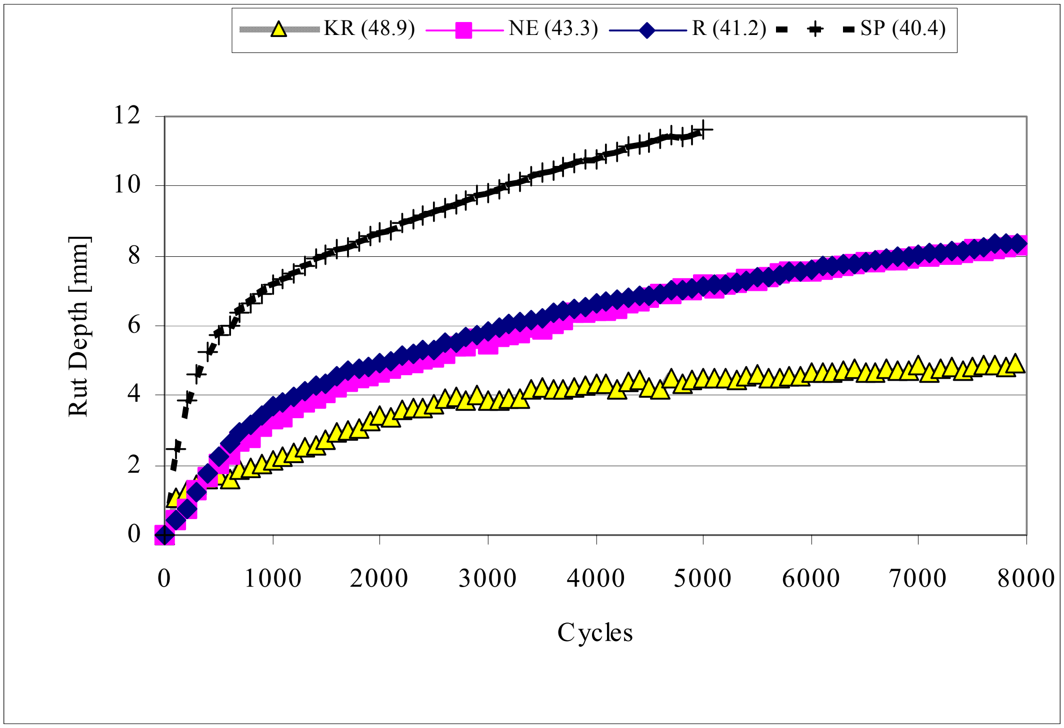

Figure 8.11 APA Rutting Curves at 54C

8.4 Mixture FAA Flow Time

The method of least squares shows that the flow time of a standard FAA sample through the FAA test apparatus is strongly related to FAA. According to the Chapter 4 experimental results, $R^2 = 0.91$ for the equation: TIME (FAA) = 0.1556(FAA)–1.5098. Using this result, measured blend FAA's, standard error of the prediction, and t-distribution critical values, FAA flow time may be estimated for mixture blends 1–4. Table 8.2 shows standard error of the prediction, and 95% confidence intervals for (n–2) = 9 degrees of freedom. Figure 8.12 shows predicted vs. measured timing values. The prediction for Mix 1 is an extrapolated value.

Table 8.1 FAA Flow Timing Prediction (95% CI, 9 df)

	FAA	prediction (sec)	SE prediction	t * SE prediction	Meas Time
Mix 1 KR	48.9	6.59	0.231	0.52	6.43
Mix 2 NE	43.3	5.66	0.224	0.51	5.73
Mix 3 RI	41.2	5.31	0.221	0.50	5.21
Mix 4 SP	40.4	5.18	0.220	0.50	5.19

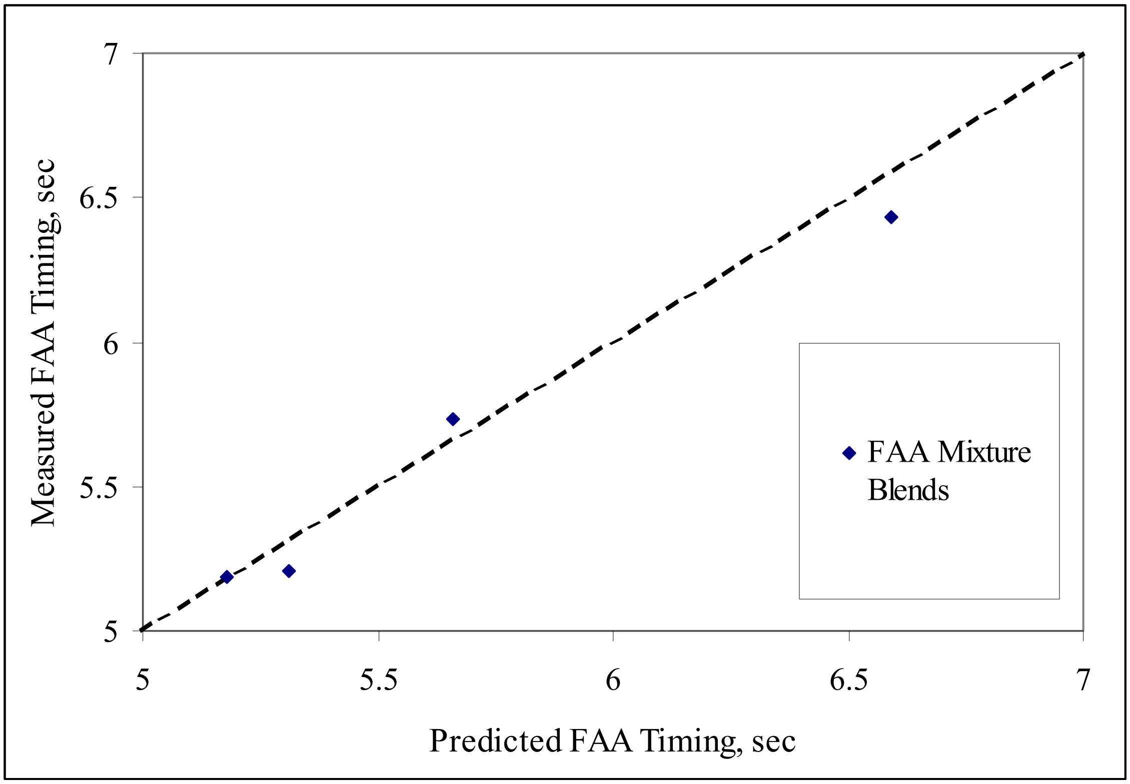

Figure 8.12 Blend FAA, Measured vs. Predicted FAA Timing

8.5 Analysis of Experimental Data

Analysis is presented in three parts. Part one discusses and analyzes APA data with respect to rate of rutting. Part two ranks mixtures in terms of performance according to the effect of FAA, aggregate type, and manufacture method. Part three correlates APA Rut Depth and all variables discussed in this study.

8.5.1 APA Data Analysis

Data is collected for each APA loading cycle. It is therefore possible to analyze the APA Rut Test data shown in Figure 8.11 for rate of rutting. Table 8.3 and the associated plot in Figure 8.13 describe trends in rut depth along various portions of the APA rutting curve.

Table 8.2 APA Rutting Rate, Test Temperature 54C

		Mix 1 (KR)	**Mix 2 (NE)**	**Mix 3 (RI)**	**Mix 4 (SP)**
		Rutting Rate [mm/Cycle]			
Max Rutting Rate Value		0.0110	0.0054	0.0053	0.0244
Mean Slope	0 – 500 Cycles	0.0034	0.0041	0.0045	0.0114
	500 – 1000 Cycles	0.0009	0.0028	0.0032	0.0032
	1000 – 2000 Cycles	0.0013	0.0014	0.0014	0.0016
	2000 – 3000 Cycles	0.0005	0.0009	0.0009	0.0012
	3000 – 5000 Cycles	0.0002	0.0007	0.0007	0.0009
	5000 – 7000 Cycles	0.0001	0.0004	0.0005	NA
	7000 – 8000 Cycles	0.0002	0.0004	0.0004	NA
Max Difference Between Concurrent Rutting Rate Values		0.0040	0.0035	0.0016	0.0019

Table 8.3 shows averages of the highest-FAA mixture rutting are approximately one quarter the rate of the lowest-FAA mix. Note that the high-angularity mixture exhibits both the lowest rate of rutting throughout the test and the maximum difference in concurrent rate values. This difference is an indicator of the noise present in the rutting rate plot. Both high angularity mixtures have the more noise, especially after 4000 APA test cycles. It may be speculated that the noise in the rutting rate curve is present due to rearrangement of the aggregates.

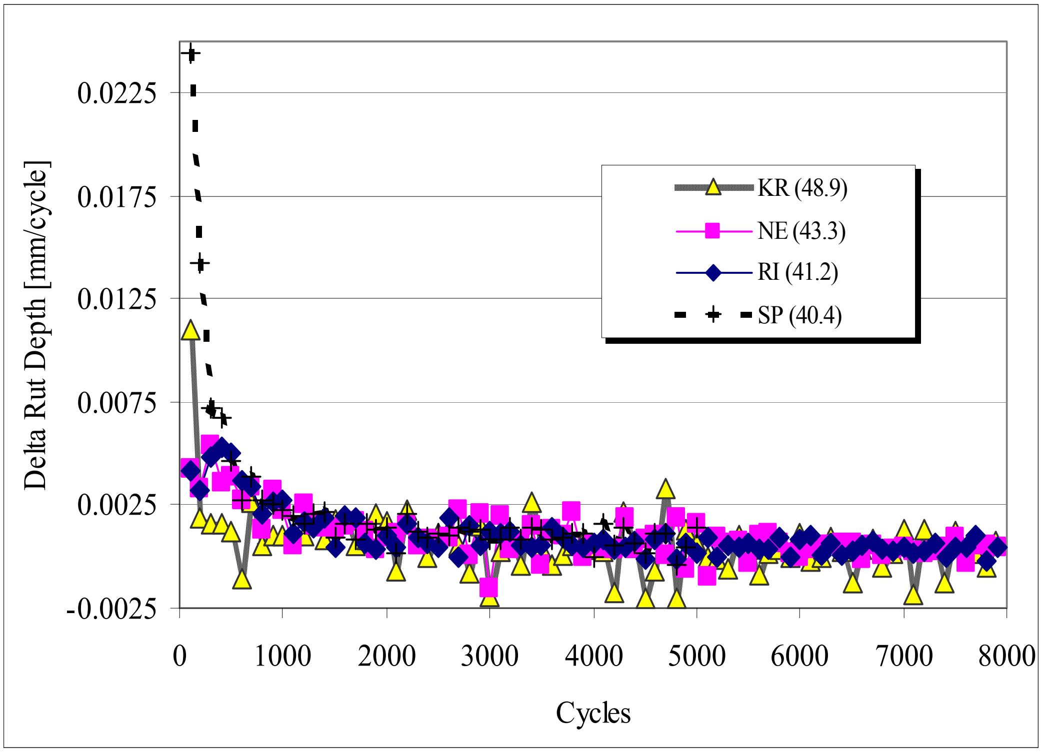

Figure 8.13 APA Rutting Rate per Test Cycle, Temperature 54C

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8.5.2 Performance Ranking

Tables 8.4–8.6 give performance rankings in terms of effect of FAA, aggregate type, and manufacture method.

Test results suggest that at high temperatures the effect of FAA will be as presented in Table 8.4. Based on least squares analysis of test results, there appears to be a slight performance benefit from increasing mixture FAA. Recall that Superpave FAA criterion is 40<FAA<45. The FAA value of Mixture 2 (43.3) nears the upper end of this criterion. The plot of Modulus vs. FAA in Figure 8.14 shows the variation in average |E*| explained by FAA correlates at $R^2 = 0.85$ for a |E*|[GPa] = 0.0138 (FAA)–0.4876. The plot of APA Rut Depth vs. FAA in Figure 8.15 shows a best-fit line correlates at $R^2 = 0.91$ for APA [mm] = 0.7922 (FAA)+42.486.

Table 8.3 FAA and Related High Temperature (54C) Mix Performance Ranking

Mixture	Mixture FAA Rank	Mixture APA Rutting Performance Rank	Modulus Master Curve Performance Rank
Mix 1 KR	1	1	1
Mix 2 NE	2	3	4
Mix 3 RI	3	2	2
Mix 4 SP	4	4	3

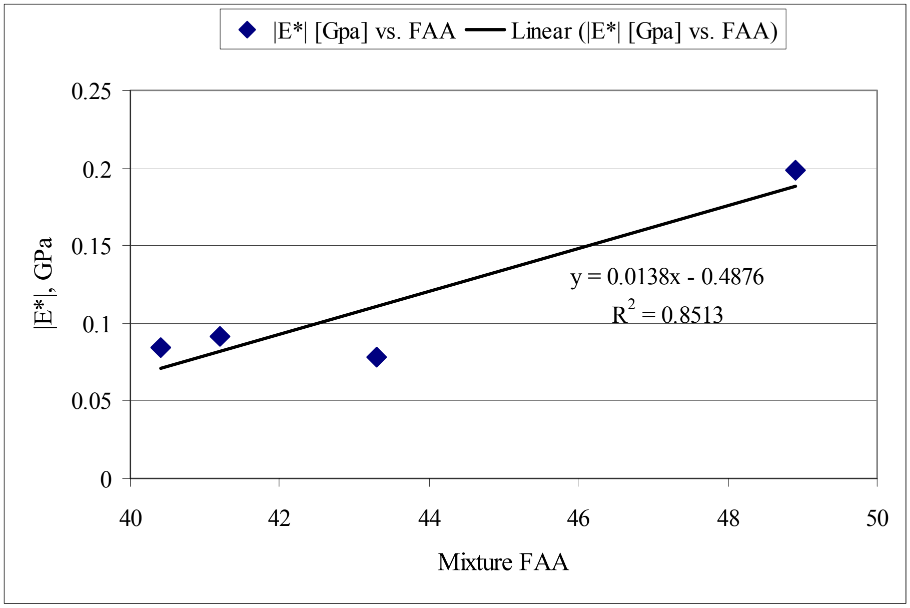

Figure 8.14 |E*| vs. FAA at 0.01 Hz and Test Temperature 54C

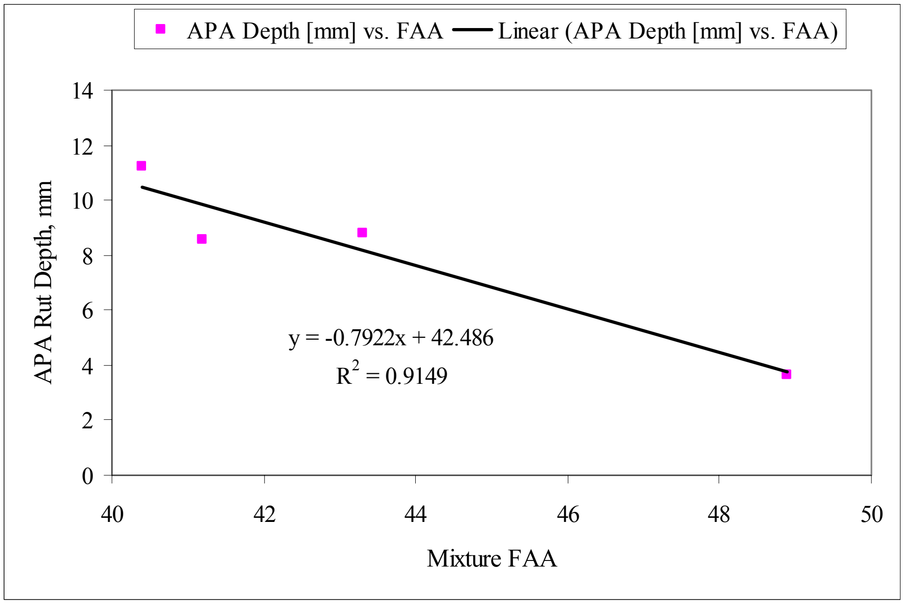

Figure 8.15 APA Rut Depth vs. FAA

The effect of aggregate type is presented in Table 8.5. Even though the Mixture 2 aggregate blend included diverse materials and a satisfactory gradation the modulus performance was low, especially when compared to the Mixture 1 blend that was composed of similar materials. This suggests poor interaction between blend components for Mix 2.

Table 8.4 Aggregate Related High Temperature (54C) Mixture Performance

Mixture	Aggregate Type	Mixture APA Rutting Performance Rank	Modulus Master Curve Performance Rank
Mix 1 KR	Limestone – Limestone	1	1
Mix 2 NE	Gravel – Granite – Limestone	3	4
Mix 3 RI	Gravel – Limestone	2	2
Mix 4 SP	Gravel – Limestone	4	3

Table 8.6 presents the effect of including crushed material in the mixture blend. Even though Mixture 2 material included crushed coarse aggregate and manufactured sand its modulus performance was low when compared with mixtures having less crushed material. As in aggregate related performance, this suggests poor interaction between blend components.

Table 8.5 Crushing Related High Temperature (54 C) Mixture Performance

Mixture	Manufactured Material in Blend	Mixture APA Rutting Performance Rank	Modulus Master Curve Performance Rank
1	100%	1	1
2	50%	3	4
3	30%	2	2
4	30%	4	3

8.5.3 Performance – Mixture Characteristics Correlation

Several kinds of mixture characteristics were examined in this project. In order to identify characteristics related to mixture performance it is important to have a method of sorting and relating mixture parameters and performance related mechanical properties. In this section Pearson correlation coefficients are used to identify characteristics that explain performance.

Table 8.7 shows Pearson correlation coefficients for APA Rut Depth and all variables discussed in this study. Values near 1 show strong positive correlation and those near –1 show strong negative correlation. Variables include: dynamic modulus at 54C and 0.01-Hz, FAA, Min., Max., Median, and quartile values obtained for blended AIMS data (reference Chapter 6), and mixture blend measured FAA Flow Timings. The table shows that rut depth is highly correlated with several variables, most notably |E*|, FAA, and Maximum Radial Angularity. Correlation results suggest that rutting performance is strongly related to the following six characteristics:

- modulus (0.01-Hz at 54C)
- FAA
- FAA Flow Time
- Radian Angularity (Minimum, 1st Quartile and Maximum)
- Gradient Angularity (Minimum and 1st Quartile)
- Form, 2-D (Minimum and 1st Quartile)

Additionally, strong relationships were observed for modulus and:

- FAA
- Gradient Angularity (Minimum), and
- FAA Flow Time.

Table 8.6 Pearson Correlation for FAA Statistics (23)

	Rut Depth	**|E*| at 0.01Hz**	**FAA**	**Rad Min**	**Rad Q1**	**Rad Med**	**Rad Q3**	**Rad Max**
|E*| at 0.01Hz	**-0.926**							
FAA	**-0.957**	**0.923**						
Rad Min	**-0.820**	0.632	0.879					
Rad Q1	**-0.875**	0.665	0.879	0.982				
Rad Median	-0.602	0.321	0.651	0.934	0.913			
Rad Q3	-0.585	0.312	0.647	0.933	0.903	0.999		
Rad Max	**-0.946**	**0.957**	**0.993**	0.817	0.816	0.556	0.554	
Grad Min	**-0.923**	**0.999**	**0.935**	0.654	0.677	0.344	0.338	0.968
Grad Q1	**-0.846**	0.730	**0.937**	0.979	0.945	0.853	0.857	0.895
Grad Median	-0.663	0.491	0.788	0.966	0.902	0.938	0.948	0.722
Grad Q3	0.029	-0.126	0.212	0.512	0.357	0.626	0.661	0.151
Grad Max	-0.721	0.680	0.883	0.900	0.819	0.756	0.772	0.858
Form Min	**-0.894**	0.808	**0.972**	0.957	0.932	0.792	0.794	0.943
Form Q1	**-0.836**	0.640	0.880	0.999	0.990	0.933	0.929	0.817
Form Median	-0.768	0.580	0.848	0.996	0.963	0.947	0.949	0.783
Form Q3	-0.419	0.098	0.458	0.826	0.804	0.973	0.972	0.350
Form Max	-0.721	0.492	0.785	0.986	0.960	0.980	0.980	0.707
FAA Time	**-0.911**	**0.865**	**0.989**	0.918	0.895	0.716	0.719	0.973

	Grad Min	**Grad Q1**	**Grad Med**	**Grad Q3**	**Grad Max**	**Form Min**	**Form Q1**	**Form Med**	**Form Q3**	**Form Max**
Grad Q1	0.755									
Grad Median	0.525	0.954								
Grad Q3	-0.074	0.509	0.716							
Grad Max	0.716	0.961	0.933	0.638						
Form Min	0.830	0.992	0.910	0.416	0.950					
Form Q1	0.660	0.973	0.953	0.474	0.881	0.953				
Form Median	0.606	0.975	0.985	0.588	0.914	0.944	0.991			
Form Q3	0.120	0.712	0.854	0.657	0.610	0.630	0.825	0.849		
Form Max	0.516	0.940	0.976	0.596	0.858	0.897	0.983	0.992	0.908	
FAA Time	0.884	0.973	0.862	0.353	0.941	0.993	0.913	0.900	0.537	0.841

Plots of FAA explaining the previously mentioned relationships are presented in Figures 8.11, 8.12, and 8.16 - 8.18.

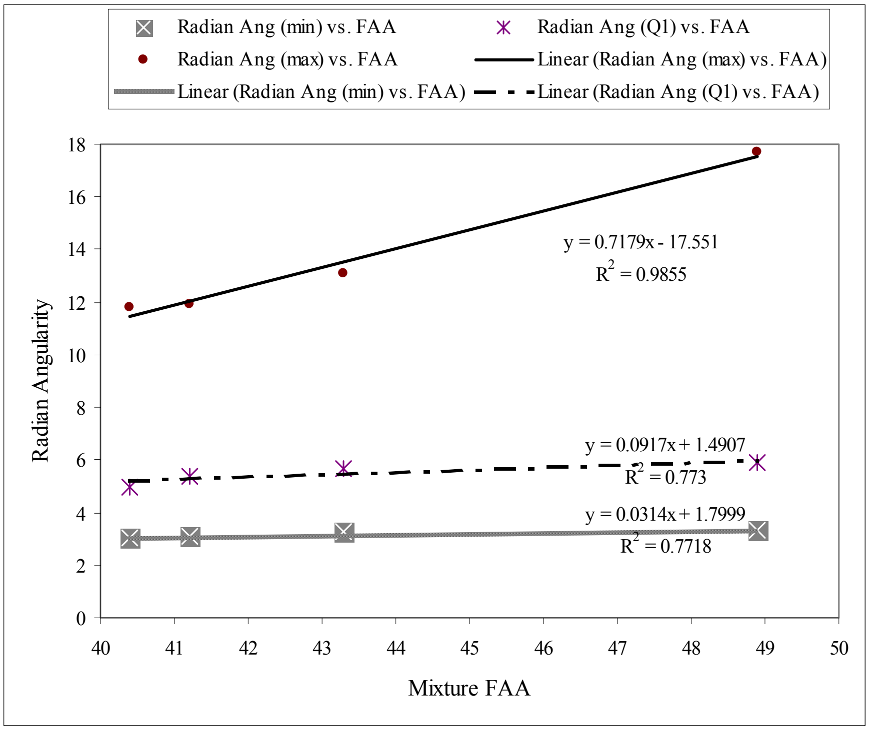

Figure 8.16 Blend Radian Angularity vs. FAA

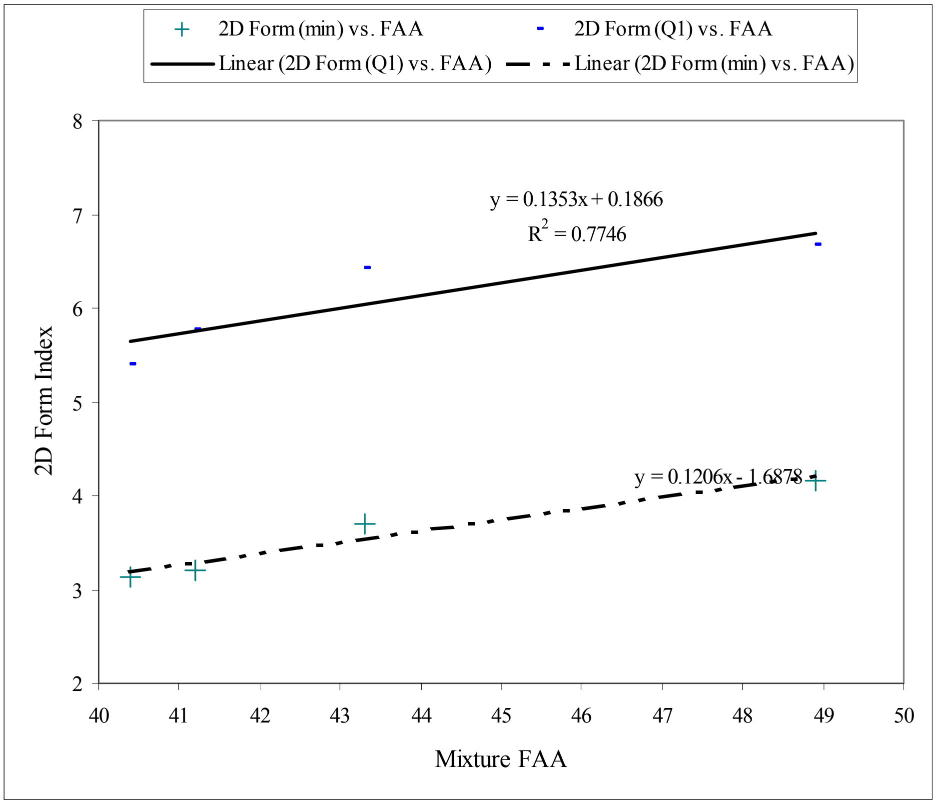

Figure 8.17 Blend Form Index vs. Blend FAA

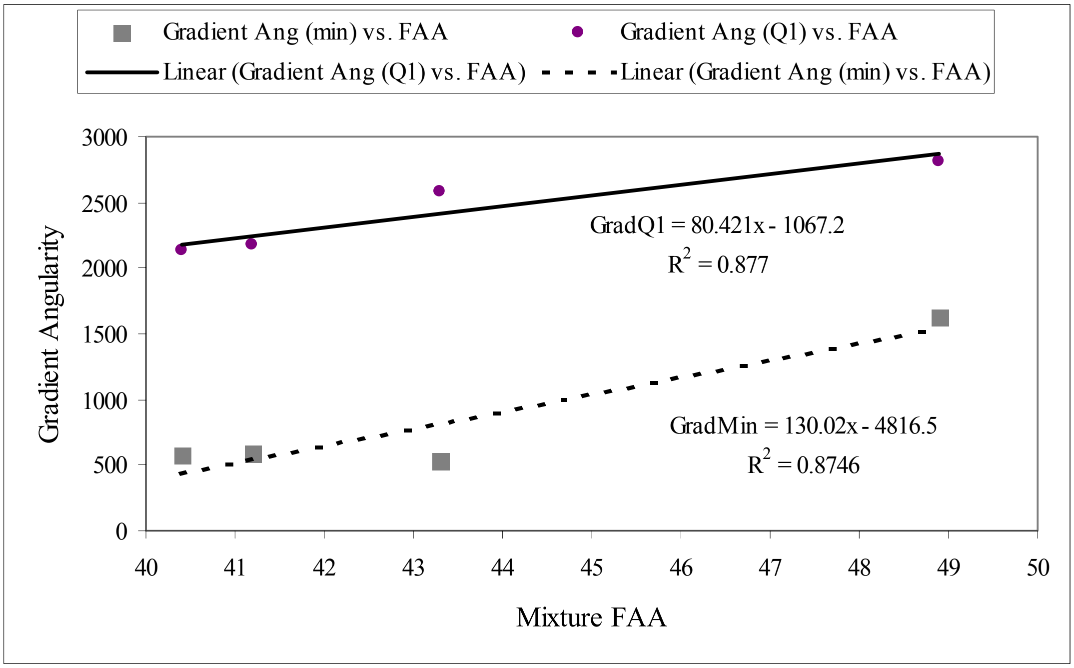

Figure 8.18 Blend Gradient Angularity vs. FAA.

The plot of APA rut depth in Figure 8.11 shows a negative dependence upon FAA. The regression of APA on FAA was fitted according to the following:

APA(mix FAA) [mm] = -0.7922(mix FAA)+42.486

$R^2 = 0.9149$

Dynamic modulus was fitted according to the following linear trend in Figure 8.11:

|E*|(mix FAA) [GPa] = 0.0138(mix FAA) - 0.4876

$R^2 = 0.8513$

This relationship holds for test temperature 54C.

Linear regression results show that for this testing scenario, APA rut depth and dynamic modulus were well represented by mixture FAA. However, notice that the variation in modulus is small (the coefficient is 0.0138) with respect to change in FAA. This suggests that blend FAA does not greatly influence modulus at high temperatures. The FAA coefficient in the APA rut depth regression equation is –0.79, which implies that rutting resistance is strongly influenced by the blend FAA magnitude.

A number of characteristics exhibited strong correlation with FAA, but also exhibited lower levels of influence when compared to APA rutting. They are listed below and are recommended for additional evaluation in future research.

Results from the FAA flow time test correlate well with modulus, APA and FAA. The test is attractive since it is easily performed. It is recommended that additional evaluation should be conducted on flow time and performance.

Radian Angularity (Minimum, 1st Quartile and Maximum), Gradient Angularity (Minimum and 1st Quartile), and 2-D Form (Minimum and 1st Quartile) correlate well with APA and FAA. These characteristics are recommended for inclusion in future research.

8.6 Conclusions

The purpose of Chapter 8 was to present an analysis of testing results for FAA validation. The testing program included several means of evaluating aggregate materials and asphalt mixtures. Four mixtures were designed and evaluated.

In previous tasks, aggregate materials were classified according to aggregate type, manufacture method, flow timing, and FAA. FAA Flow Timing descriptions were established for aggregates and aggregate blends using statistical predictions.

Superpave FAA criteria requires that aggregate materials are evaluated according to AASHTO T304 (Method A) for measurement of the uncompacted void content of fine aggregate. Digital imaging angularity and form measurements were also included for comparison with AASHTO T304.

A dynamic modulus testing program was used to evaluate the asphalt mixtures. Master curves were developed at reference temperature 54C and were obtained by inputting modulus, test frequency, and test temperature information into statistical software for nonlinear regression analysis. Regression analysis included fitting data to a sigmoidal function that has been shown to represent asphalt mixture behavior. Values from the sigmoidal master curve models were used for analysis.

Additional mixture evaluation was also performed for rutting resistance using an APA rut-testing machine, also at test temperature 54C. The analysis included ranking performance based on rut depth and modulus magnitude according to aggregate type and manufacture method. It was observed that:

- Composite aggregate blends having similar components exhibited better modulus and rutting performance,
- For these aggregate materials, the inclusion of manufactured (crushed) materials did not proportionally affect modulus or rutting performance, as shown in Table 8.6. The high-FAA mixture exhibited high modulus values and high rutting resistance but modulus and rutting did not strongly depend on FAA for mixtures having FAA below approximately 43.3.

A correlation matrix for all the material parameters measured or calculated in this study was developed using statistical software. The results shown in table 8.7 indicate that the APA rut measurements have the highest correlation with FAA (R^2 = 91.6%). For the |E*| measured at 54C and 0.01-Hz the highest correlation was obtained with Grad Min (R^2 = 99.8%), with the FAA following in third place (R^2 = 85.2%).

CHAPTER 9: SUMMARY AND CONCLUSIONS

Summary

In Chapter 2 the use of standard FAA testing was described with regard to historical implementation and post-Superpave research in research papers and nationally accepted texts. Chapter 2 also reviewed descriptions of new trends in characterizing aggregate angularity through digital imaging techniques. Traditional concepts have indicated that HMA aggregates should be angular and have a rough texture. It was found in post-Superpave research that high angularity by standard FAA did not always result in better rutting performance. Additionally, it was found through imaging techniques that crushing increases angularity but may not produce aggregate having rough texture.

A breakdown of standard FAA values obtained by Mn/DOT was given in Chapter 3. A total of 3,976 Mn/DOT standard FAA values were obtained using the State of Minnesota Database (LIMS) and Metro District production records. These records spanned the time period 2000–2002. This data set included 1,268 Superpave mixture designs, and was reduced to 980 values by setting the requirement for “useable” data as points having both a bit-record number and a project number description.

The reduced data set was sorted using project number and bitrecord. FAA values from the sorted data were then averaged. 59 averaged values were obtained. It was also possible to sort the 59 averaged values according to Mn/DOT bituminous mixture type. Four mixtures types were present, including Mn/DOT 2360 Superpave mixtures SPWEB340, SPWEB440, and SPWEB540. Mixture data was also available for MVWE35035.

Plots of averaged FAA data showed a gap in average FAA data between mixture type SPWEB340 and SPWEB440. Additionally, frequency increases for FAA values ranging from 40–41 and 44.4–45. Additionally, the plot shows a trend in decreasing frequency of FAA values between 41 and 44.4.

Mixture proportion data was obtainable from the LIMS database, and was later used as a reference to evaluate mixture designs produced by the project staff.

In Chapter 4 standard FAA data was obtained and analyzed for 11 Minnesota aggregates using AASHTO T304 Method A. Two simple experiments were also included to further examine the results of AASHTO T304. Experiment 1 included varying the testing apparatus drop height. It was observed that FAA values for a given aggregate material varied somewhat with drop distance. However, the order of FAA measurements between materials was maintained regardless of drop distance. Experiment 2 included measurement of the aggregate flow time through the FAA test funnel. A strong relation was found between FAA and flow time.

Digital Aggregate Imaging System (AIMS) characterization was included for 8 of the aggregates. Analysis was conducted by the Texas A&M Department of Civil Engineering. Fine aggregate imaging results included 2-dimensional form, gradient angularity, and radial angularity.

Chapter 5 outlined the development of a laboratory testing program for FAA validation. The program included both aggregate and mixture testing. The aggregate testing included gradation analysis, specific gravity and absorption, as well as standard FAA testing. Mixture tests included dynamic modulus (|E*|) and asphalt pavement analyzer (APA) rut testing. In order to minimize variables, |E*| and APA specimens would be designed according to Mn/DOT 2360 Superpave volumetric and traffic design criteria. The test specimens should all have similar air voids, VMA, VFA, and asphalt binder. The effect of FAA will be investigated by having 2 high-FAA mixtures and 2 low-FAA mixtures.

Asphalt mixture formulation was described in Chapter 6. Four laboratory mixture designs were produced using 2 high-FAA and 2 low-FAA aggregate blends. Mixture design was performed according to the guidelines from Mn/DOT Specification 2360. 4800-g trial mixture specimens were produced and subsequently evaluated using ASTM D 2041and ASTM D 2726.

Aggregate blends were evaluated for angularity using both measured and estimated FAA calculations. The best method of estimation was observed to be a gradation-weighted average. It is important to note that the FAA estimates are for four similar blends, having 20-30% of a single coarse material. Averaging should be used carefully when estimating the FAA of other blends. It is best to know the contribution of coarse material to FAA.

Digital imaging angularities were also calculated for each blend based upon measurements obtained for individual component aggregates. Median and quartile values were used to describe the blend imaging angularities.

Chapter 7 describes specimen fabrication and testing for FAA validation purposes. For each mixture, four 100 by 150-mm specimens were produced for |E*| testing as well as two additional 150 by 75-mm specimens for APA testing. Specimens were fabricated to Mn/DOT Specification 2360 criteria and specimen air voids were targeted at 5%.

Raw modulus data was analyzed using the SINAAT complex modulus spreadsheet for asphalt concrete. The final set of modulus values depended on statistical and graphical evaluation of potential outlying data points. Outlier evaluation included comparisons of individual data points with 1.5 by (inter-quartile range) and also plotted trends in mean and median. Using dynamic modulus data, master curves were developed at reference temperature 54C and were obtained by inputting modulus, test frequency, and test temperature information into statistical software for nonlinear regression analysis. Regression analysis included fitting data to a sigmoidal function that has been shown to represent asphalt mixture behavior. Values from the sigmoidal master curve models were used for analysis.

APA testing data was acquired for the four mixtures using an 8000-cycle test at temperature 54C. Results were reported as average rut depth.

Conclusions

A correlation matrix for all the material parameters measured or calculated in this study was developed using statistical software. The results shown in chapter 8 in table 8.7 indicate that the APA rut measurements have the highest correlation with FAA (R^2 = 91.6%). Correlation results show strong relationships between rut resistance and several other characteristics, including digital imaging characterization measurements of Gradient Angularity, Radian Angularity, and Form Index.

For the |E*| measured at 54C and 0.01-Hz the highest correlation was obtained with Grad Min (R^2 = 99.8%), with the FAA following in third place (R^2 = 85.2%).

The results obtained in this study indicate that the current FAA specification does a reasonable job in selecting the fine aggregates for asphalt mixtures with enhanced rut resistance. High correlations were found between FAA and APA rut depths and FAA and |E*| at 0.01-Hz, both measured at 54C. However, the visual inspection of linear trends (Figures 8.14, 8.15) showed that FAA had little influence on modulus variation and rut depth for the mixtures with FAA below approximately 43.3. This trend should be interpreted with caution as the results presented were based on four laboratory-produced mixtures that contained only 2 or 3 component aggregates to minimize the factors in the analysis. Mixtures found in the field often have as many as 5 or more components and tend to have more fine aggregates, which most likely will increase the effect of FAA magnitude on mixture properties.

Future research should include evaluation of both contractor-produced and laboratory-produced blends and mixtures taking into consideration additional issues such as film thickness that is not part of the current MnDOT mix design. Note that the surface area for Mixtures 1–4 was calculated to be 23.3, 21.2, 26.1, and 20.8-ft^2/lb, respectively, which according to recent calculations performed by MnDOT Office of Materials at the conclusion of the project are low in comparison to gradation blend surface areas normally observed in field mixes (around 28-ft^2/lb).

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APPENDIX A

The following table, as referenced in Chapter 3, presents a list of Mn/DOT LIMS data from year 2000 – 2002. For this data set it is possible to cross-reference bitrecord, project number and FAA.

Table A.1. 59 Mn/DOT Bit-Record and Project Numbers with FAA

P_BIT REC	Samples/P_BIT REC	P_MIX	P_PROJ NO	AVG FAA
000019	27		4001-44	40.6
000056	12		4603-38	44.0
000079	12		5203-84	42.4
000101	19		1480-127	43.6
0-2001-133	17		2785-316	45.1
0-2001-170	10		1901-137	44.8
0-2001-210	32		7007-24	45.8
0-2001-275	11	SPNWC430	0208-102	45.5
0-2001-477	18	SPWEB440	2758-60	46.4
0-2002-026	12	SPWEB540	6284-131	45.7
0-2002-042	10	SPWEB440	1913-56	44.8
0-2002-165	10	SPWEB440	6221-40	45.7
0-2002-224	14	SPNWC430	1004-24	44.7
0-2002-246	13	SPWEB440	1004-24	43.9
04-2001-033	24		5606-40	43.2
04-2002-018	22	MVWE35035	1414-02	42.7
04-2002-052	14	MVWE35035	7805-31	42.6
06-2002-148	10	SPNWB430	7408-29	45.2
07-2001-010	13		6704-16	41.8
07-2001-017	18		3206-17	41.2
07-2001-044	12		0804-72	41.3
07-2001-076	30		2280-119	46.2
07-2001-077	24		0704-78	41.1
07-2001-102	18		4001-45	41.2
07-2002-012	13	SPWEB440	7205-21	46.8
07-2002-022	16	SPWEB440	5380-112	45.4
07-2002-048	15	SPWEB340	1703-64	42.9
07-2002-055	12	MVWE35035	165-999-01	42.5
07-2002-072	11	SPWEB340	5905-21	42.5
2000-077	17		1905-24	43.7
2000-108	12		2735-160	41.4
2000-119	10		1013-70	45.5
2000-231	12		8209-41	42.5
2000-304	23		1301-87	44.9
2001-007	15		1209-20	40.8

2001-007	12		1210-09	40.5
2001-041	16		6402-20	41.1
2001-054	19		6402-20	40.9
2001-077	13		3703-21	41.3
2001-127	15	spweb540	2785-316	45.8
2001-133	47	spweb540	2785-316	45.4
2001-210	34	spweb540	7007-24	45.8
2001-329	10	spnwb440	1921-67	47.3
2002-042	13	SPNWB330	4105-08	40.8
2002-047	17	SPWEB340	4105-08	41.9
3-2000049	12		1809-49	41.5
3-2000051	27		7380-205	46.5
3-2000121	20		0116-44	41.9
3-2000143	10		1804-48	41.9
3-2000170	14		1810-82	41.3
3A-2001-049	28		8606-50	40.7
3A-2001-064	10		1814-01	40.6
3A-2001-122	27		3302-12	40.0
3A-2002-079	10	SPWEB440	1115-18	44.7
3A-2002-096	13	SPWEB340	8604-30	43.2
3A-2002-142	14	SPWEB340	7319-34	44.5
3A-2002-146	11	MVWE35035	1809-58	41.5
3A-2002-150	10	SPWEB440	1115-18	45.3
8A-2001-011	20		3411-63	40.7