University of Nevada, Reno

Develop a Laboratory Mixing Procedure for Hot Mix Asphalt Containing RAP Materials

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
Civil and Environmental Engineering

By

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August 2011

University of Nevada, Reno
Statewide • Worldwide

THE GRADUATE SCHOOL

We recommend that the thesis
prepared under our supervision by

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entitled

Develop A Laboratory Mixing Procedure For Hot Mix Asphalt Containing RAP Materials

be accepted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE

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August, 2011

Abstract

The use of reclaimed asphalt pavement (RAP) has become more prevalent with the rising costs of virgin materials and the recent push to develop more environmentally friendly and sustainable roadways. The use of RAP decreases the costs of constructing new pavements by limiting the amount of virgin materials required. For this reason there is a significant amount of research being conducted to examine the effects of using high amounts of RAP in the new HMA mixtures.

The primary objective of this study is to develop a mixing procedure for the laboratory that best simulates the plant-produced samples after their mixing and production process. Three distinct methods for incorporating the RAP material into the mixing process will be examined and compared to the plant produced samples provided by Granite Construction. The general descriptions of the three methods are as follows:

Method A: The virgin aggregate, the virgin asphalt binder and the RAP material will all be heated to the appropriate mixing temperature as dictated by the virgin asphalt binder grade.

Method B: The virgin aggregate will be superheated in accordance with NAPA's recommendations from Information Series 123. The virgin asphalt binder will be heated to the appropriate temperature dictated by the performance grade. The RAP material will be dried and added at the ambient temperature.

Method C: The virgin aggregate is superheated in accordance with NAPA's recommendations from Information Series 123. The virgin asphalt binder will be heated to the appropriate temperature dictated by the performance grade. The RAP material will be moisturized to the appropriate moisture content and added at the ambient temperature.

To be able to determine which method of incorporating the RAP material into the laboratory mixing process will produce the mixture that most closely simulates the plant-produced mixture several characteristics will be analyzed. This thesis will examine the mixing temperatures over the duration of the mixing process for each method. This will provide insight into how effectively the virgin aggregate is transferring heat to the RAP material.

Additionally a short term oven aging analysis will help determine the appropriate aging time in the laboratory the replicate the aging experience by the plant-produced mixtures. To assess the different aging levels, the asphalt binder will be extracted from the plant-produced and laboratory-produced mixtures and graded according to the Superpave performance grading system. Lastly, compacted samples will be created for each mixing method as well as for the plant-produced laboratory-compacted mixtures to conduct an analysis of the volumetric properties and dynamic modulus.

Acknowledgements

I would like to express my sincerest thanks to Dr. Elie Hajj for all of his guidance and assistance throughout the completion of this thesis.

I would like to thanks Dr. Peter Sebaaly for all his support and guidance.

A special thanks and appreciation to Mr. Pete Folk and Mr. Chris Campbell of Granite Construction for all their valuable information and help.

I would like to acknowledge my committee members Dr. Raj Siddharthan and Dr. Jim Carr for their assistance.

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Chapter 1: Introduction

When asphalt pavements exceed their performance life; no longer being able to provide a safe and functional surface they still retain a significant value. The asphalt layer can be recycled through milling or heating of the layer and removing the softened asphalt. Once removed the reclaimed asphalt pavement (RAP) can be used in the production of hot mix asphalt (HMA), recycled in the base layers or used in warm mix applications. The components of RAP: the aggregate and the binder still have value so recycling utilizes that value lessening the financial burden of building new roadways. Recognizing the value in the recycled aggregate and binder saves taxpayers an average of $300 million dollars annually *(1).*

By using recycled aggregate the contractor can save on the cost of blasting, crushing, washing and stockpiling virgin aggregates. While the cost of acquiring virgin aggregates can get very expensive it is savings in asphalt binder that really provide the basis for extensive research and interest into new techniques and methods to incorporate higher percentages of RAP into new HMA designs. Crude oil prices have been steadily rising sitting at just over $100 per barrel and projected be over $116 per barrel within a year *(2),* In addition to the ever increasing oil prices; the current push to become more environmentally friendly has helped RAP become the United States' leader in recycled materials *(1).* 90 million tons of RAP are recycled each year; doubling the total amount of paper, glass, aluminum and plastic combined.

Providing cost effective solutions is always a top priority of engineers but if saving money means sacrificing the quality of product it may not always be a more effective

solution. Fortunately, the research conducted on mixtures incorporating RAP show that the performance is close to or better than that of mixtures containing all virgin materials. Most research pertaining to RAP is now focusing on incorporating 25% or more RAP material into new HMA designs and trying to develop effective laboratory processes to produce these high RAP designs. It is important to have laboratory methods that simulate the actual field processes in order to produce results and findings in the laboratory that can be applied to real world solutions.

Typically when incorporating RAP material into a mixture in the plant the virgin aggregates are superheated. The RAP material is then added at the ambient temperature and relies on heat transfer from the superheated aggregates to reach an equilibrium that should be within the range of mixing temperatures for the virgin binder grade selected for the mix. In the push to create more sustainable pavements it seems that incorporating higher percentages of RAP material into the new HMA designs is an obvious choice, but without an effective laboratory mixing process that simulates the actual plant mixing conditions progression will be slow.

1.2 Objective

The objective of this study is to develop a mixing procedure for the laboratory that most closely simulates the actual process that occurs in the plant while most closely replicating the product created in the field. The typical method for incorporating RAP material into the mixing process is to add the RAP at the ambient temperature to the virgin aggregates that have been superheated. This process relies on heat transfer to heat the RAP to the appropriate temperature for mixing according to the design binder grade. This study will

evaluate three different mixing processes in the laboratory. Each process will have a different method for incorporating the RAP material into the mixing process. Certain characteristics and properties will be measured regarding temperature, aging levels, volumetric properties and stiffness to determine which method best replicates the current field practice.

Chapter 2: Background

Reclaimed asphalt pavement can be obtained from a variety of methods. The existing pavement can be cold milled or heated which softens the pavement before removal. It can also be obtained directly from the hot mix asphalt plant in the form of reject material. While the existing pavement may have exceeded its performance life it still retains significant value when incorporated into a new HMA design. Recycling the RAP material reduces the need to quarry more virgin aggregates, reduces the cost of processing and transporting virgin aggregates and most importantly reduces the virgin asphalt binder demand. The asphalt binder accounts for a significant percentage of the total cost of producing an asphalt pavement. So being able to decrease the amount of virgin asphalt binder required could dramatically decrease the price of constructing new pavements.

RAP material can also be used for base material, fill and shoulders, but is most beneficial when incorporated back into new HMA. Using RAP materials can have many benefits but it also requires that additional measures be taken to adequately account for the RAP in the mix design. The NCHRP 9-12 developed guidelines for incorporating RAP material into the Superpave design as well as an accompanying manual *(3,5).* The RAP and aggregate mixture must still meet the gradation and other necessary aggregate properties. In addition to the aggregate properties it is very important to know the properties of the existing aged binder, including binder percentage and PG grade. These will affect the design virgin binder grade. Depending on the age of the roadway from which the RAP material was obtained the binder could be extremely stiff. From the time

of mixing and production throughout the service life to the time of removal the binder has become aged through the oxidation process.

To account for the aged binder a three tiered approach was proposed based on the percentage of RAP material to be used in the mixture *(4)*. The 'Black Rock Study' studied the interaction between the RAP binder and the virgin asphalt binder. The three-tier approach provides some guidelines for selecting the virgin binder grade.

- Tier 1: RAP < 15% by mass of the total mixture. The RAP binder is assumed to have little or no effect on the mixture properties; hence the determination of the virgin asphalt grade should be based on the climate and traffic criteria for the specific project.
- Tier 2: For RAP contents between 16% and 25% by mass of the total mixture. There are two options for mixtures incorporating this range of RAP. The first option is to drop the virgin asphalt binder grade by one level. The second option is to use the blending charts.
- Tier 3: For RAP contents > 25% by mass of the total mixture. The blending charts are required for this option to determine the appropriate virgin asphalt binder.

Another important consideration when using RAP material is the mixing process. Unless the RAP material was obtained from plant reject, the RAP binder has already been extensively aged so further aging the binder should be avoided. A study completed by Nguyen *(8)* from the University of Nottingham examined some of these mixing processes. The concept behind the study was that the current laboratory practice of

heating the RAP for extended periods of time in the oven before mixing could be softening the material creating a better blending between the RAP binder and the virgin binder than is actually possible in the field. If this is true then the current practice is overestimating the performance of the mixtures containing RAP in the field.

The mixing study evaluated 4 different mixing techniques:

- Black Rock – The black rock method assumes that there is no interaction between the RAP binder and the virgin binder. To simulate this phenomenon the RAP binder is extracted from the aggregate then the aggregate is mixed only with virgin binder. The aggregate is heated at 135°C for 8 hours while the asphalt binder is heated at the same temperature for 2 hours. Mixing takes place in a heated chamber at 135°C for 2 minutes.
- Complete Blending – The complete blending method assumes that there is total blending between the RAP binder and the virgin binder. To simulate this, the RAP binder is extracted and mixed directly with the virgin binder. Virgin aggregates were used to ensure that there was no residual binder. The aggregate is heated at 150°C for 8 hours while the asphalt binder is heated at the same temperature for 2 hours. Mixing takes place in a heated chamber at 150°C for 2 minutes.
- SHRP – For the SHRP method the RAP is preheated at 110°C for two hours before being mixed with the virgin aggregate and binder. Virgin aggregates are heated to 150°C for 8 hours and the mixing process is completed at 135°C. The

preheated RAP and virgin aggregates are mixed for 30 seconds before the addition of the virgin binder for an additional 2 minutes of mixing.

- Field Simulation – This method is supposed to replicate the process used in the field. The virgin aggregate is superheated to 215°C while the RAP is added at the ambient temperature, 25°C. The study also looked at different mixing durations for this method. RAP material and the virgin aggregate were mixed for durations of 2,4,6 and 8 minutes. Then mixed with the asphalt binder for 2 minutes.

The study completed by Nguyen concluded that the mixing time between the superheated aggregates and the RAP material had a significant impact on the segregation of the materials within the mixture and uniformity of the stiffness results *(8)*. The longer mixing times resulted in less segregation observed in cross sections of the compacted specimens. The segregation observations were possible because the virgin binder used was died a different color than the RAP binder, making them easily identifiable.

The stiffness values from the indirect tensile test also suggested that the longer mixing times created a more uniform mixture leading to more consistent and repeatable stiffness values between replicates. It was also found that the longer the mixing time the closer the stiffness came to approaching the complete blending stiffness results, which were the highest. The stiffness of the black rock case was significantly lower suggesting that the RAP binder does have an effect on the stiffness of the overall mixture. However it was noted that if the mixing time is not long enough the effect of the RAP binder may not be captured since it did not have enough time to soften and interact with the virgin binder. The SHRP method seemed to overestimate the stiffness of the recycled mixtures every

time. This can be directly related to the long preheating time which would never be possible in the field. Nguyen concluded that the field simulation method best replicates the process occurring in field mixers. With regards to aging and binder testing the study found that the only method to significantly age the binder was the SHRP method during which the RAP was preheated for 2 hours at 110°C.

A study completed by Stephens et al on the preheating time of RAP concluded that the longer the RAP was preheated the higher the strength of the entire mixture when subjected to the indirect tensile test *(6)*. In addition to the preheating time there are other variables present in the laboratory that make it difficult to replicate actual field or plant mixing process. In the field mixing is typically done in rotating drum mixers. This allows all the material to be constantly moving in all directions coming in contact with as many other particles as possible. In the laboratory the mixing is done by a rotating head. This allows the aggregate to only move horizontally and limits movement of all the individual particles. Secondly in the field the drum is never opened to the air to add material or take temperature readings. The closed drum allows for a uniform temperature with almost no temperature loss. These differences between the field and the laboratory might be the basis for the acceptable longer mixing times in the laboratory to create the same product that the drum mixer can create in 45 seconds to a minute.

The preheating time of RAP before incorporating it into the mixing process was the subject of research completed under NCHRP 9-46. The purpose of the study was to evaluate the effects on the asphalt binder of different heating methods. The initial true grade of the RAP binder was 85.1 – 15.7. The asphalt content in the RAP material was

4.87%. Four different scenarios were considered. In order to consider only the effects on the RAP binder, the RAP was 'dry' mixed with the virgin aggregate. The batches were prepared with half virgin aggregate and half RAP material. The four heating scenarios considered were:

1. RAP and virgin aggregate heated together for three hours at 355°F. Material was then dry blended for 2 minutes.
2. RAP and virgin aggregate heated for 16 hours at 355°F. Material was then dry blended for 2 minutes.
3. Virgin aggregate heated for 3 hours at 355°F while the RAP was heated at 355°F for the last 30 minutes before mixing. Material was dry mixed for 2 minutes..
4. Virgin aggregate was superheated to 500°F for three minutes. RAP at the ambient temperature was mixed with the superheated virgin aggregate for 2 minutes.

The RAP binder was extracted from each mixture using trichloroethylene. It should be noted that there have been findings that the rheological properties of the asphalt binder can affected by using trichloroethylene as an extraction solvent. Trichloroethylene tends to soften the asphalt binder. The asphalt content of the mixes where the RAP was preheated for 16 hours had significantly lower binder content. It is possible that the preheating time hardened the RAP so it couldn't be extracted easily. The results for the binder grading are shown in Table 1 *(7)*. With the exception of the RAP added at the ambient temperature the replicates were pretty uniform. The study theorized that adding

the RAP at the ambient temperature it is possible that portions of the binder were more oxidized as a result of non-uniform heating.

The extracted RAP binder grading results showed that only scenario 3 did not increase the high grade of the RAP binder during the mixing process. All other scenarios yielded results that were significantly different (higher). For the low grade of the RAP binder, scenario 1 and 3 did not significantly affect the binder grade leading the research team to suggest that RAP material can be heated from 30 minutes to 3 hours without drastically affecting the low binder grade of the RAP. It was determined that scenario 3 had the least affect overall on the binder properties.

Another study completed by Anderson et al. *(9)* examined the asphalt binder properties in relation to non-load related cracking. The study found that when an asphalt binder has been significantly oxidized it becomes strongly m-controlled when determining the critical low temperature using the Bending Beam Rheometer (BBR). The BBR results produce two critical temperatures, the more conservative of the two is chosen as the design critical temperature for a specific asphalt binder. The critical temperature for stiffness is temperature when the specification limit of 300 MPa is met at the 60 second loading point. For the m-value the critical temperature occurs when the specification limit of exactly 0.300 is met at the 60 second loading period.

The study found that at a given stiffness level for a specific binder tested at different aging levels it became increasingly more difficult for the binder to relax the thermally induced stresses. So the m-value is much more sensitive to oxidation and aging than the stiffness. This conclusion suggests that asphalt research may have been over estimating

the importance of limiting stiffness while underestimating the importance of the binder ability to relax the stresses. This becomes extremely important in environments such as desert climates where the temperature range can be very large and cooling can occur over a very short period of time. Even a slow cooling rate is much more beneficial for new or virgin binders than for significantly aged binders.

Oxidation occurs most prevalently at the surface of the pavement *(9),* so the rheological properties of the asphalt will vary with depth. This creates further issues because the higher levels of oxidation at the surface coincide with the fact that the thermal gradients and cooling rates are also largest at the surface. This enables a scenario that is extremely susceptible to cracking starting at the surface during the winter months and propagating downwards.

Chapter 3: Experimental Program

This research was conducted under the subtask E2b-3 titled Develop a Mix Design Procedure as part of a larger project being conducted by the Asphalt Research Consortium *(10)*. The emphasis of this research was to develop a laboratory mixing process that closely simulates the actual conditions in the asphalt plant under which reclaimed asphalt pavement (RAP) materials are incorporated into mixing of HMA mixtures. The typical plant production of HMA mixtures using RAP relies on the heat transfer to effectively heat the RAP material. During this process the virgin aggregates are superheated to a temperature well above the typical mixing temperature for the design binder grade while the RAP material is added at the ambient temperature. The concept behind this is that the superheated aggregate will transfer heat to the RAP material in such a way that when the temperature reaches an equilibrium it should be near the ideal mixing temperature for the specific virgin asphalt binder grade. The reason for adding the RAP at the ambient temperature is to attempt to prevent aging the RAP binder.

This experiment will assess the most effective laboratory process to mix the virgin aggregate and virgin asphalt binder with the RAP material. The experiment will be conducted using three different methods for incorporating RAP into the mixing process.

- Method A: The virgin aggregates and the RAP materials will be heated to the appropriate mixing temperature for the virgin asphalt binder grade. RAP will be placed in the oven towards the end of the heating period for just enough time, 30 – 45 minutes, to reach the mixing temperature, so the RAP temperature must be monitored closely.

- Method B: The virgin aggregates are superheated to the appropriate temperature based on the NAPA recommendations provided in Information Series 123, Recycling Hot Mix Asphalt Pavements *(11)*. The chart produced by NAPA for superheating temperatures can been seen in Figure 2. The RAP material will be added at the ambient temperature in the dry condition. The virgin asphalt binder will be heated to the appropriate temperature for the virgin asphalt binder grade.
- Method C: The virgin aggregates are superheated to the appropriate temperature based on the NAPA recommendations provided in the Information Series 123, Recycling Hot Mix Asphalt Pavements. The RAP materials will be added at the ambient temperature in the wet condition. The virgin asphalt binder will be heated to the appropriate temperature for the virgin asphalt binder grade.

To determine the effectiveness of each mixing process for simulating the actual conditions in the asphalt plant, samples will be taken from the two individual projects to help evaluate each method. Plant-produced mixtures for each project were shipped to the University of Nevada, Reno along with virgin aggregates, virgin asphalt binder and RAP materials. The laboratory samples were created in accordance with the mix design provided for each project. To evaluate the different mixing processes the following characteristics were evaluated.

- The temperatures of the mixtures were monitored throughout the mixing process. This allowed for the evaluation of the heat transfer between the virgin aggregates and the RAP materials.

- The laboratory and plant-produced mixtures were subjected to different levels of short term oven aging to identify the level that most closely simulates the actual short term aging exhibited by the mixtures during the plant mixing process.
- The asphalt binder was extracted and recovered from each of the plant and laboratory-produced mixtures after subjecting the mixtures to the various short term oven aging periods. The solvent used in the extraction recovery process was a mixture of 85% toluene and 15% ethanol. From the recovered asphalt binder a small sample was shipped to Texas where the carbonyl testing will be completed. The remaining recovered binder was graded using the Dynamic Shear Rheometer and the Bending Beam Rheometer.

- The Superpave volumetric properties were measured for each of the laboratory created mixtures and compared to the plant mixed-laboratory compacted samples.
- Dynamic Modulus testing was conducted for all laboratory and plant-produced mixtures.

Chapter 4: Materials and Mix Designs

This section is going to summarize the project specific details pertaining to each of the two projects that were used for this study. The experiment was conducted on material from two separate projects from Utah, one from northern Utah which will be referred to as State Route 201 (SR 201) and one from southern Utah to be referred to as Washington Field (WF). Figure 1 is a map showing the location of the two projects. Both projects incorporated 25% RAP material. The construction dates were September 29, 2010 for the SR 201 project and December 3, 2010 for the WF project.

For each of these projects samples of the plant-produced mixtures were collected in metal buckets at the production plant by Granite Construction and shipped to the University of Nevada, Reno (UNR). The plant produced samples were mixed using Gencor counter flow drum mixers. Virgin aggregate, virgin asphalt binder and RAP material were also collected and shipped to UNR. Both projects incorporated the use of lime. The properties discussed in this section were provided by the Utah Department of Transportation. The laboratory produced samples will be compared to the plant-produced laboratory-compacted samples later in the report.

4.1 Climate and Environmental Data

From the location map, Figure 1, it can be seen that the SR 201 project is from northern Utah and the WF project is located in southern Utah. The climate and environmental data was obtained using the LTTPBIND software at locations that are very near the project locations used in this study. The SR 201 project is located in a Wet Freeze region and

receives more than 500 mm of precipitation per year. The WF project in southern Utah is in a Dry Freeze region and receives about 300 mm or precipitation.

4.2 Aggregates

The virgin aggregates and RAP material were obtained from Cottonwood Heights for the SR 201 project and from the Snowfield Pit for WF. A summary of the physical aggregate properties can be found in Table 3 for the SR 201 project and in Table 4 for the WF project. Since both projects were completed in the state of Utah the same properties and specifications were used for each set of aggregates. The RAP material from both projects consist of two sizes, material retained on the #4 sieve and material passing the #4 sieve. A summary of the gradation and control points used for the SR 201 project is shown in Table 5 while a graphical representation with the limits based on the UDOT Volumetric Design Procedure can be seen if Figure 2. The same information for the WF project is found in Table 6 and Figure 3.

4.3 Asphalt Binder

The Superpave Performance Grading was used for the asphalt binders. This allowed the appropriate binder to be chosen to meet the climatic and traffic needs of the projects. The total asphalt binder content including the contributions from the RAP binder was 5.0% by the total weight of the mix. The mix design sent with the field mixtures, virgin materials and RAP materials included detailed binder testing for the virgin binder, blended binder and RAP binder which were verified in the laboratory. The virgin asphalt binders used in the two projects were a PG58-34 for SR 201 and a PG64–34 for WF, both supplied by

Peak asphalt. The ranges for gyratory mixing and compaction temperatures for projects completed in Utah are a function of both PG grade and supplier.

PG58-34	Mixing Range:	306°F – 320°F
	Compaction Range:	275°F – 293°F
PG64-34	Mixing Range:	316°F – 329°F
	Compaction Range:	284°F – 302°F

4.4 Lime

Lime was included in the total gradation for both of the projects used in the experiment. The hydrated lime was added to the dry aggregate at a rate of 1% of the dry weight of the aggregate. The hydrated lime slurry was created and mixed in the laboratory in accordance with section 00852 of the Utah Department of Transportation's Standards and Specifications *(12)*. The lime slurry was created using one part lime to three parts water. Per conversations with officials in Utah it was determined that there would be no marinating time; so the aggregate-lime mixture would be placed immediately back in the oven to dry and prepare for the mixing process.

4.5 Mix Designs

A Superpave mix design was conducted by Garco Testing Laboratories of Granite Construction for each project. NCHRP 9-12 provides detailed guidelines for performing mix designs when using reclaimed asphalt pavement *(4)*. Both mixtures had a nominal maximum aggregates size of 0.5 inch and a recommended total asphalt content of 5.0%

by the total weight of the mix. A summary of the mix design characteristic can be found in Table 6.

Chapter 5: QC/QA and Project Specific Information

This section will cover the QC/QA data that was conducted to ensure that the plant produced mixtures conform to the specifications laid forth in the mix design completed by Garco Testing Laboratories. Quality control data was provided with the sampled materials for the gradation, asphalt content, voids in mineral aggregate (VMA) and air voids. The quality control data was compared to the quality assurance completed by the Utah Department of Transportation (UDOT). A summary of this data can be seen in Figures 4 and 6 for SR 201 and Figures 5 and 7 for WF. The plot of the gradations are directly on top of each other, but at a few of the points you can set two sets of error bars. The reason the gradations look slightly different for the WF plot is because the QA data was not provide for every sieve, but the sieves it was provided for were nearly identical to the QC data. The laboratory creates samples according to the mix design so knowing that there is little variability in the plant-produced mixtures allows for conclusions to be drawn in the laboratory without having to worry about variability of the plant-produced mixtures.

5.1 Superheating Temperatures

In order to apply the NAPA recommendations for superheating the virgin aggregate it is necessary to know the RAP percentage to be used in the mixture, the moisture content within the RAP and the discharge temperature one would like to achieve for this mixture. For both projects used in this study a discharge temperature of 280°F was chosen. That is

the highest temperature provided in the table and most near the compaction temperature range for both of the virgin asphalt binders. After these three factors are determined Table 2 is used to choose the appropriate superheating temperature. Since 25% RAP was incorporated at various moisture contents for the two projects interpolation was used to determine the correct temperature.

5.2 Moisture Contents

The moisture contents for the individual stockpiles were provided by Garco Testing Laboratories. These values were used to determine the moisture content levels to be used for conditioning the RAP material in the laboratory. A summary of the average moisture contents is shown in Table 8. For the WF project the provided values of 2.1% moisture for the + #4 RAP material and 2.7% for the - #4 were used. Due to the large variability associated with the values provided for the SR 201 project more reasonable moisture contents of 1% and 3% were chosen for the + #4 and -#4 RAP material, respectively.

5.3 Project Specific Asphalt Binder Grading and Blending Charts

The virgin asphalt binder used for the SR 201 project was a PG64-34 which was verified in the laboratory UNR. A summary of the asphalt binder testing and blending data conducted by the Garco Testing Laboratories and UNR laboratory for SR 201 is shown in Table 9. The target grade for the blended binder is PG64-28. Both laboratories graded the blended binder to be very similar, however it was graded to be a PG70-28. The blending chart created by the UNR laboratory is shown in Figure 8.

The virgin binder grade used for the WF project was graded to be PG70-34 by the Garco laboratory and PG70-28 by the UNR laboratory. The summary for the WF asphalt binder

grading and blending is shown Table 10 and Figure 9 for the blending chart. The target grade for the blended binder is PG70-28. The UNR laboratory blend is a little stiffer due to the difference in the original binder grade but still was graded close to the target grade. In addition to the blending charts a laboratory blended binder was created at UNR. The SR 201 blended binder was created using 77% virgin asphalt binder and 23% extracted RAP binder. The WF blend was created using 80% virgin asphalt binder and 20% extracted RAP binder. A summary of the performance grade of the laboratory blends compared to the blending chart blends is shown in Table 11. For both projects the UNR blending charts and laboratory created blends are more stiff that then blended binder grading provided by Garco Testing Laboratories. For both projects the extracted RAP binder graded at UNR had a higher low critical temperature than provided by Garco, directly affecting the blending charts and the laboratory created blends.

Chapter 6: Discussion of Laboratory Processes and Testing

Since the objective of this experiment was to develop a mixing procedure for HMA mixtures incorporating RAP materials; it is important to discuss all the intricacies related to the different mixing processes. Each one required a slightly different procedure which will be summarized in this section. All of the laboratory produced samples were created using the gradations provided with the mix design and the design virgin binder content used during production of the plant-produced samples. Mixing was completed in the laboratory using steel whips and bowls with a Hobart mixer. Throughout the mixing process two heaters were placed beneath the mixing bowl. The variations between the methods are discussed within this section.

Another important characteristic that was monitored closely was the moisture content of the RAP material. In the laboratory it is easy to monitor the temperature of the RAP and it is assumed that once the RAP meets the mixing temperature all the moisture has been removed. This is important because the gradations used in the mix design are based on the dry weight of the aggregate. Any moisture within the material also carries additional weight causing the improper amount of material to be added during the mixing process. This becomes even more important in the field where the moisture contents tend to be higher because the stockpiles are exposed to the environment. If moisture contents become too high, the superheating temperature required for the virgin aggregate will increase creating the need for additional energy to superheat the aggregates. This increase in energy negates some of the benefits of incorporating RAP as it will increase the cost of production in the field. One of the methods used in this experiment looked at using RAP with moisture and will be discussed in this section.

6.1 Mixing Methods

In an attempt to simplify the description of each method, flowcharts have been created outlining the details. The flowcharts for Methods A, B and C are shown in Figures 3, 4, and 5, respectively. Since both of these projects required the addition of the hydrated lime slurry the aggregates had to be mixed with lime before the start of each individual mixing process. The methods described in the figures do not account for the addition of lime because there are different ways to incorporate lime into the mixture and mixtures that do not call for the addition of lime at all. The objective of this study is to develop a mixing procedure that can be used universally for all laboratory-produced HMA mixtures that incorporate RAP so any state or agency specific procedures for adding lime to the mixture should be followed before starting the mixing processes outlined below.

Method A: This is the simplest method with no significant additional work required to produce the mixtures. After the virgin aggregate has been mixed with the lime slurry it was placed in the oven with the virgin binder at the appropriate mixing temperature for that specific virgin asphalt binder. The mixing temperature was provided with the Superpave design summary and verified with UDOT for the specific binder type. UDOT provides suggested mixing temperature ranges based on binder grade and supplier. RAP material was batched and placed in the oven after the aggregate had dried and was nearing the mixing temperature. The temperature was then monitored and once the RAP material has reached the desired mixing temperature the materials were removed from the oven and mixed for 3 minutes. It typically took between 30 and 45 minutes for the RAP to reach mixing temperature in the oven. The RAP material was batched for each sample

to speed up the mixing process so the RAP portions were small in comparison to the batched aggregates.

Method B: This method requires the aggregate to be superheated according to NAPA recommendations provided in the Information Series 123. The virgin binder was heated to the appropriate temperature as discussed in Method A. The RAP material was dried in front of a fan until no mass change was recorded so it could be added in the dry condition. Once the virgin aggregate and virgin asphalt binder reached the desired temperatures they were removed from the oven, placed in the mixing bowl where the RAP was then added at the ambient temperature. The ambient temperature in the laboratory was usually around 77 degrees Fahrenheit. These samples were then mixed for 3 minutes. This mixing time was determined to be adequate because all the virgin aggregate appeared to be coated with binder and allowed adequate time for temperature measurements.

Method C: This method required the most time to prepare for. The virgin materials were prepared the same as the previous methods however the RAP preparation required extra time to moisturize to the wet condition. It was decided that drying the RAP first would make it possible to best simulate the exact moisture conditions that were present in the field at the time of production. The + #4 RAP and - #4 RAP materials had different moisture contents and had to be moisturized separately. To make sure the RAP was moisturized to the desired level, the RAP was first dried in front of a fan and then mixed with the appropriate amount of water necessary to reach the desired moisture content. After mixing RAP and water, the mixture was placed in a sealed container to moisturize for 16 hours to achieve uniform moisture throughout the RAP. After the moisturizing

period the process is the same as described in Method B. The virgin binder is heated to the appropriate temperature, the virgin aggregate is superheated according to NAPA recommendations and the moisture conditioned RAP will be added at the ambient temperature. The superheating temperature for this method is even higher than the temperature used in Method B to account for the moisture now present in the RAP material

6.2 Mixing Temperatures

As mentioned earlier the temperature was monitored to evaluate the heat transfer between the materials. To find a process to monitor the temperature that would be easily repeatable it took a few trials. The first process attempted was to remove all material from the oven, place it in the steel mixing bowl, place the bowl in the mixer and then start the timer. This method proved to be flawed. The amount of time it took to get the material from the ovens into the bowl and placed on the mixer was not always the same, so an effective measure of heat transfer versus time was difficult to determine. The time variability also created large variability in the temperatures that were recorded because the first 60 seconds account for most of the heat lost in the mixture.

The second method was to start the timer as soon as the materials were removed from the oven. Then the first temperature would then be recorded around the 45 second mark. This method also proved to be flawed. The 45 second time limitation did not provide enough time for the heat transfer process to take place so the temperature readings were not consistent, especially for the methods where the RAP wad added at the ambient temperature. The temperatures were taken using an infrared laser gun so if one reading it

was pointed at a virgin aggregate the reading would be much higher than if it was focused on a portion of RAP material that had been added at the ambient temperature. Additionally, in order to achieve a good temperature reading the mixer had to be stopped and stopping the mixer that early in the mixing process made it difficult to get all the aggregates evenly coated with virgin binder. This was probably due to the loss in temperature of the virgin binder while the temperature reading was being taken. The temperature loss created a more viscous binder that made it more difficult to coat the aggregates.

The process that was ultimately chosen was to start the timer as soon as the material was removed from the oven. Then the bowl was placed in the mixer around the 45 second mark after all the materials had been combined in the mixing bowl, however now the mixer was allowed to run until the 90 second mark before being stopped for a temperature reading. This provided a better gauge of the temperature lost before the material was being mixed and more reliable readings to gauge the heat transfer between the materials. A good portion of the mixing was done at this point so the remaining temperature variations were due to temperature loss or heat transfer.

6.3 Short Term Oven Aging

A short term oven aging analysis was also conducted to help determine the laboratory aging level that best represents the actual aging that occurred during mixing and production of the plant mixtures. The experiment looked at two separate aging levels. One considered no further aging after the mixing process while the other subjected samples to additional short term oven aging. These provide a basis for determining what

the actual aging time in the laboratory should be to best represent the plant-produced mixtures after production. The short term oven aging was conducted at the compaction temperature for the virgin asphalt binder.

6.4 Extraction and Recovery

Extraction and recovery becomes necessary when the percentage of RAP in the new HMA design exceeds 25%. When percentages are this high the blending charts are required to determine the virgin binder grade. For this experiment the blending charts were verified in the laboratory. To create the blending charts the RAP binder had to be extracted and graded as if it were a virgin binder. Once the RAP properties have been obtained in order to complete the blending charts it is necessary to know either the critical temperatures of the virgin binder or the percentage of RAP in the mixture *(3).* The blending charts are assumed to be linear so if only the RAP percentage is available the virgin binder critical temperatures could be solved for.

In order to evaluate the different aging levels the asphalt binder had to be extracted from both the plant and laboratory produced mixtures. The extraction was completed using a solvent mixture consisting of 85% toluene and 15% ethanol. Once the asphalt binder had been extracted it was recovered using the Rotovap recovery apparatus. From the recovered asphalt binder a small portion was set aside for carbonyl testing. This testing is used to determine the extent of the oxidation of the asphalt. The remaining portions of the recovered asphalt binders for each mixture are then graded in accordance with the AASHTO procedures for the Dynamic Shear Rheometer, AASHTO T 315, and the Bending Beam Rheometer, AASHTO T313.

These binder grades are used to help determine if one of the mixing methods produces a binder aging level that best represents the plant-produced mixtures. Since the method of extraction and recovery was chosen to evaluate the binders; for this study it is assumed that there is total blending of the RAP binder and the virgin binder which may or may not be the case in the actual field conditions. However in reality it is very difficult to determine the actual interaction between the two binders because there are many factors that can affect the blending.

6.5 Volumetric Analysis

A volumetric analysis will be completed to determine if the mixing method has an effect on the volumetric properties of the laboratory-produced mixtures. The properties that will be examined and compared to the mixture design criteria are air voids, voids in the mineral aggregate (VMA) and voids filled with asphalt (VFA). The following equations from AASHTO R 35 will be used to calculate the properties.

Air Voids: $V_a = 100\ x\ \left(1 - \left(\frac{G_{mb}}{G_{mm}}\right)\right)$

Voids in Mineral Aggregate: $VMA = 100\ x\ \left(1 - \frac{G_{mb}P_s}{G_{sb}}\right)$

Voids Filled with Asphalt: $VFA = 100\ x\ \left(\frac{VMA - V_a}{VMA}\right)$

$G_{mb} = Bulk\ Specific\ Gravity$

$G_{mm} = Theoretical\ Maximum\ Specific\ Gravity$

$P_s = Percent\ of\ Aggregate\ in\ the\ Mixture$

$G_{sb} = Bulk\ Specific\ Gravity\ of\ Combined\ Aggregates$

To determine the volumetric properties, samples of about 4800 grams were mixed and compacted using the Superpave Gyratory Compactor for each mixing method as well as the plant-produced lab-compacted samples. Separate G_{mm} values will be determined for each method to determine if the individual mixing methods will have an effect.

Chapter 7: Laboratory Evaluation

This section will cover the results and findings of the laboratory testing beginning with the analysis of the mixing temperatures for each of the three methods. There will be an extensive discussion on the binder grading and short term oven aging because this is how the appropriate aging levels in the laboratory to simulate the aging during mixing and production of the plant mixed samples will be determined. Lastly, there will be a section outlining the results for dynamic modulus testing.

7.1 Mixing Temperatures

As mentioned before the mixing temperatures were monitored for each method to determine the effectiveness of superheating the aggregates. Once all materials were added to the mixing bowl they were allowed to mix for 30 to 45 seconds before a temperature reading was taken. At that point the temperature was recorded at 30 second intervals for the remainder of the mixing process. The total time allowed for mixing starting with the removal of all the materials from the oven was 4 minutes. For mixing Method A both the aggregate and the binder were heated to the mixing temperature as dictated by the virgin asphalt binder. The RAP was added to the oven shortly before the mixing time. The temperature of the RAP material was monitored and mixing began as soon as it reached the mixing temperature. This could take anywhere from 30 to 45 minutes depending on the size of the batched sample of RAP material.

The data for the two projects had to be analyzed separately because different virgin binders were used requiring different mixing temperatures. The initial temperature of each component of the mixture is shown in Table 12. The asphalt binder was always

heated to the appropriate mixing temperature for that specific performance grade. With the exception of Method A when the RAP has a small preheating time it is always added at the ambient temperature of the laboratory which was around 77°F.

The mixing temperature analysis examines the recorded mixing temperatures over the duration of the mixing period. A summary of the average recorded mixing temperatures for Method A for the SR 201 project is shown in Table 13 and Figure 13. The initial temperature of all the materials was 313°F and the final temperature after 4 minutes of monitoring was 286°F. It appears that most of the temperature loss occurred in the minute that it took to combine all the materials and start the mixing process. The limited loss in temperature over the remaining monitoring time could be due partially to the two heaters placed beneath the bowl during mixing.

The Washington Fields mixing temperatures for Method A follow the same trend. The data is tabulated in Table 14 and shown graphically in Figure 14. Once again most of the temperature loss occurred in the time allotted for combing the materials in the bowl. The final temperature at the end of the mixing time was 289°F. The slight increase in final temperature is directly related to the higher mixing temperature for the WF virgin binder. It should be noted that the final temperature for both Method A analyses fell within the compaction temperature range. So if future research were to find that no short term aging time will be required it would be possible to compact right after mixing.

For mixing Method B, it was necessary to use two different ovens. One oven was used for superheating the virgin aggregate and the other for heating the virgin asphalt binder to the correct mixing temperature. The RAP was added in its ‘dry’ condition at the ambient temperature which is normally pretty close to 77°F in the laboratory. The temperatures

recorded for the SR 201 mixtures are shown in Table 13 and Figure 15. The aggregate was superheated to 379°F and the first recorded temperature was 301°F; hence a significant amount of heat was consumed by the RAP material. Over the rest of the monitoring period just over 7°F was lost. The average final temperature for the SR 201 mixtures was 293°F.

The data for the WF mixtures with regards to the mixing temperatures for Method B can be found in Table 14 and Figure 16. From the data it can be seen that the mixing temperatures remained almost constant. The first recorded temperature averaged out to be 292°F and the average final temperature was 291°F. The overall steadiness of the temperatures may mean that all necessary heat transfer from the superheated aggregate to the RAP material has already been completed by the time it was possible to begin taking temperature readings.

The last mixing method, Method C, required that the aggregate be superheated even hotter than method B and that the RAP material be moisturized to the appropriate moisture contents. For SR 201 the moisture contents were 1% for the coarse (+ #4) RAP and 3% for the fine (- #4) RAP. The RAP material was first dried in front of a fan as to ensure that the beginning moisture content was zero. The appropriate amount of moisture was then added to the batched samples of RAP. The newly moisturized samples were then placed into cylinders and sealed to create uniform moisture throughout the sample. The samples were left in the cylinders for 16 hours at ambient temperature.

This method exhibited the greatest loss of temperature from the superheated virgin aggregate. For the SR 201 project the aggregate was superheated to 413°F and the average first recorded temperature was 299°F. This was the highest of the first recorded

temperatures. Throughout the monitoring process, shown in Table 13 and Figure 17, the temperature drops until the 2 minute mark and then steadily increases to a final temperature of 306°F. This could be a result of the interaction between the moisturized RAP and the aggregate trying to vanquish the moisture and steadily heat the RAP material.

The same trend is seen in the WF mixtures, Table 14 and Figure 18. However, in this scenario the temperature doesn't begin to rise until just after the three minute mark. This delayed jump in temperature could be due to the higher amount of moisture in the RAP material. The moisture contents for the WF project were 2.1% for the coarse RAP and 2.7% for the fine RAP. This added moisture may have taken longer to burn off before more significant heat transfer could occur between the aggregate and the RAP. Also supporting this point is the increase in temperature loss. The virgin aggregate was superheated to 420°F and the average first recorded temperature was 298°F. From there the temperature continues to decrease before rebounding to a final average temperature of 298°F.

A summary of the temperature loss from the original superheated aggregate temperature is shown in Table 15. The table compares the initial aggregate temperature with the 1st and final recordings once the temperature was monitored. It also looks at the loss in temperature over the course of the monitoring period. As the temperature of the aggregate increases the greater the loss of temperature from the initial aggregate temperature. This is to be expected because the superheated aggregate is responsible for heating the RAP material for Method B and burning off the moisture and heating the RAP in Method C.

Another note is that the final temperature averages correlate with the initial aggregate temperatures. For both projects Method A produced the lowest final temperature and had the lowest initial temperature for the virgin aggregate. This may mean that for laboratory purposes the NAPA recommendations for superheating the aggregate are in excess of what is actually required.

Additionally, from Table 15 it can be seen that throughout the monitoring process from the 1st reading to the final reading, Method A exhibited the greatest loss in temperature, followed by Method B. Method C actually gained in temperature throughout the process for the Washington Fields project. The only discrepancy in the data in this table is with Method B. The temperature lost from the first reading to the final reading for SR 201 is 8.7 degrees and 0.9 degrees for the WF project. The difference of about 8 degrees is not a huge but it could mean that the WF aggregate was more effective at transferring the heat to the RAP.

Figures 19 and 20 compare the mixing temperature for the SR 201 and WF projects, respectively. Both figures show that the temperatures for Method C do in fact increase towards the end of the monitoring period. However, between the two projects only Method A exhibits the same general trend over the entire period. Method A slowly decreases in temperature the whole time. A look at the plots for Method B and C show that there is a lot of variability during the early temperature readings but they follow the same trend towards the end of the period. This could easily be attributed to all the different temperatures in play for each of those methods since all the components of the mixture are added at different temperatures. This creates a situation where until the

temperature of the mixture has reached an equilibrium temperature readings may be sporadic.

7.2 Short Term Oven Aging Analysis and Binder Grading

To quantitatively analyze the different levels of aging and to be able to compare the effect each mixing method has on the asphalt binder the extracted binders were graded using the Superpave performance grading system. The extracted binder was treated as 'original'. Using the Dynamic Shear Rheometer in accordance with AASHTO T 315 it is possible to characterize the viscous and elastic behavior of asphalt binders at high temperatures. The binders are tested at the same temperatures they are expected to encounter in the field. The high temperature tests on the DSR predict the binder's ability to resist deformation. The main early life distress is rutting so this test is used to help predict and allow the engineer to recommend an asphalt binder to perform adequately given certain environmental conditions.

The extracted binder was then short term aged in the rolling thin film oven (RTFO) in accordance with AASHTO T 240. This procedure short term ages the binder using a combination of heat (325°F) and air while keeping the binder in constant motion on a rolling rack. There is a significant amount of aging that occurs within the asphalt binder during production and placement; so this test in theory recreates that same aging in a laboratory setting. A portion of the RTFO aged binder is tested on the DSR. There is another specification for RTFO aged binder that must be met for an asphalt binder and the lower of the critical high temperatures between the original and RTFO binders is chosen at the true high temperature grade for that specific asphalt binder.

The remaining portion of RTFO aged binder is further aged using the pressure aging vessel (PAV). This test follows the standard AASHTO R 28 for accelerated aging of asphalt binders. During this test the asphalt binder is subjected to heat (212°F for moderate climates) and pressure (305 psi) for 20 hours. This aging in theory represents the long term in service aging of the pavement over a 7 to 10 year period *(13)*. The high pressure and lower heat combination allow for the main mode of aging, oxidation, to dominate this aging process. The RTFO which is run at a much higher temperature simulates the volatization portion of the aging. After the production process is complete there is little to no aging due to volatization because the in service temperatures are significantly lower than the production temperatures.

Of the many distresses associated with hot mix asphalt a large amount of them become more significant in old pavements. The PAV aged binder provides a basis to begin investigating how a particular binder will perform under the conditions for which it is to be used. From the performance grading standpoint used in this experiment there are two tests that were run on the long term aged binder for this analysis: the DSR and the Bending Beam Rheometer (BBR). The DSR on the PAV aged binder is used to predict the fatigue performance of the binder at intermediate temperatures. The BBR is used to determine the critical low temperature. The BBR uses specific criteria for both stiffness and the ability of the binder to 'relax' when it encounters stresses. An additional analysis was conducted looking into the controlling criteria for the critical low temperature.

For each project the virgin, RAP and laboratory blended binders were graded according to AASHTO M323. The RAP binder was also graded as an 'original' following AASHTO M320 and as expected yielded a performance binder grade with much higher

low and intermediate critical temperatures so those values were not used for this experiment. The performance grades of the virgin, RAP and laboratory blended binders were used to provide perspective for comparison and analysis of the extracted binders. The extracted binder grades for the SR 201 project can be seen in Table 16 and Figure 21. The extracted binder grade for the 0 hour aging level for all three mixing methods is relatively close to the grade of the laboratory blended binder for the high, intermediate and low critical temperatures. That is to be expected because all the asphalt binder used for those analyses have been heated to the same temperature for the same amount of time. Method B and Method C have slightly larger critical high temperature values. This could be attributed to having come in contact with the superheated aggregates during the mixing process.

For the SR 201 project, 2 and 4 hour short term oven aging was completed on loose portions of the plant-produced mixture. Examining the extracted binder grades of those mixtures it is apparent that the 4 hour aging level is too long for plant-produced mixtures because it grades out much higher than any of the laboratory-produced blends at 0 or 2 hours of short term aging. The plant-produced mixture that was aged for 2 hours was slightly stiffer than the 2 hour short term oven aged laboratory-produced mixtures. It was about 1.5 degrees higher at all critical temperatures. So for the SR 201 project it seems that in order to replicate the same binder grades in the laboratory and the plant-produced mixtures there will be two different aging levels. The plant-produced mixture should be aged for about an hour at the compaction temperature while the laboratory-produced mixtures should be aged for 2 hours at the compaction temperature. This discrepancy could be created during the splitting time required for the plant-produced mixtures since

they were shipped in 50 pound buckets that had to be heated before splitting into workable sizes. This splitting time of 2.5 to 3 hours may have been enough to slightly age the binder.

The same general trend can been seen in the WF project regarding the similarities in binder grading between the laboratory blended binder and the extracted binder grades for the 0 hour aging level for each mixing method. This is supported in Table 17 and Figure 22. However, when comparing the laboratory-produced mixtures to the plant-produced mixtures there are a few differences. The 0 hour aged plant-produced mixture has higher critical temperatures than the 0 hour laboratory-produced mixtures. This suggests that the plant-produced mixture was more aged during its initially production and splitting process than the plant-produced mixture for the SR 201 project. For this project the aging level at which the binder grades for the plant-produced and laboratory-produced mixtures most closely resemble each other is two hours.

A look into the effect of the 2 hour aging level on the extracted binder grades, Figures 23 and 24, show that for both projects the critical high temperature experiences the greatest change. The intermediate and low critical temperatures are less affected. This is probably attributed to the long term aging process the asphalt binder experiences while in the PAV. It suggests that asphalt binder aging is always increasing but at a decreasing rate. So the original binders will be more affected by the short term oven aging. The long term aging of the binder for the low and intermediate binder testing most likely masks the effect that the short term aging had on the binder.

Lastly, there has been some interest in the controlling factor regarding the critical low temperature. This topic was discussed in the background section; with the main premise being that as binder's age they tend to become more m-value controlled, while the stiffness is less affected by the aging. This same fact was seen in the critical low temperature results for both projects. The data supporting this claim is found in Tables 19 and 20 with supporting Figures 25 and 26. As was expected, the virgin asphalt binder is the least affected while the extracted RAP binder is affected the greatest. For the WF project the variation is low critical temperature is 3.9 degrees for the original binder and 13.3 degrees for the RAP. With the 2 hour short term aging level for the field and each of the three mixing methods the binders become more m-value controlled. Another conclusion is that for each corresponding binder between the two projects every binder for the WF project is more m controlled. This is most likely due to the virgin binder grade. The WF project was designed and constructed with a stiffer virgin asphalt binder. It should be noted that the extracted RAP binder was found to not have been polymer modified. This was determined using the Multiple Stress Creep Recovery (MSCR). Polymer modified binders tend to have larger recovery values. The extracted RAP binders tested for this analysis had very low recovery values, suggesting that neither RAP material was originally constructed with polymer modified asphalt.

7.3 Volumetric Analysis

A volumetric analysis was conducted for the SR 210, Table 21, and the WF, Table 22, to compare the effects of the mixing methods. The tables also contain multiple values for Gmm, theoretical maximum specific gravity, since it was determined early on during the

study that increasing the absorption time for the loose mixtures would increase the Gmm value. This phenomenon is shown graphically in Figure 27. Multiple absorption levels were completed in an attempt to closely replicate the Gmm of the plant-produced mixtures. The tables also include information for bulk specific gravity, air voids, voids in the mineral aggregate and the voids filled with asphalt.

Regarding bulk specific gravities for the SR 201 project, only Method B produced a value identical to the plant-produced mixture of 2.384. Method A had a lower value at 2.384 and Method C had a higher value at 2.392. Concerning the Gmm values all three methods had values higher than the plant-produced mixture. The design Gmm for this project was 2.494. The plant-produced mixture Gmm after being placed in the oven for 3 hours for splitting and 0.5 hours for heating was near that at 2.491. Method A with 0 hours aging recorded a Gmm of 2.494 followed by Method B with 2.497 and Method C at 2.503. There appears to also be an increase in Gmm with the increase in mixing temperature. So the superheated aggregate may be further heating the binder allowing for more absorption during the mixing process.

As mentioned earlier the Gmm value increased with an increase in the curing or absorption time that the loose mixture was subjected to in the oven. The air voids for SR 201 obviously increase with an increase in the Gmm since the same value for Gmb was used, Figure 28. An increase in the air voids led to a decrease in the VFA while the VMA remained fairly constant; Figures 29 and 30 show plots of the VMA and VFA versus the curing time of the Gmm samples. It should be noted that all the relationships of curing time versus volumetric properties used the single average value for Gmb. If the Gmb is affected by curing time it may sway these conclusions. However, for all three

mixing methods the laboratory-produced samples with no additional short term oven aging after the mixing process most closely replicate the plant-produced volumetric properties.

For the WF projects all the Gmm values from the three mixing methods seem to replicate the plant-produced mixture pretty closely. The design value for this project was 2.447, which was replicated exactly in the plant-produced mixture that underwent three hours of splitting time at 275°F with no additional short term oven aging time. The Gmm for Method A with no additional short term oven aging was 2.448, Method B was 2.445 and Method C was 2.446. The two hour aging level Gmm value leads one to conclude that the aging period affected each of the mixing methods differently because Methods A and C saw a much larger jump in Gmm due to the absorption or curing time than Method B did.

The bulk specific gravity analysis did not yield the same results for the WF project as occurred in the SR 201 project. For the SR 201 project only Method B produced a value nearly identical to the plant-produced mixture, but in the WF project Method C assumed that role. The plant-produced mixture had a Gmb of 2.331 while Method C had a value of 2.339. The other two Methods A and B has values of 2.373 and 2.377, respectively. I recommend further analysis be completed on more projects before drawing any conclusions from the volumetric properties of the mixtures using the three different mixing methods. The results thus far the results have not followed identical trends but with only two sources it is difficult to determine a source of error.

7.4 Dynamic Modulus Testing

The dynamic modulus testing was conducted using the AMPT (Asphalt Mixture Performance Tester). The samples were created in accordance to AASHTO TP 62. However, the samples were not aged according to AASHTO R 30. To set the aging levels for the samples the data from the extracted binders was analyzed. The objective of this experiment is to develop the laboratory mixing process that most closely simulates the actual plant-produced mixtures. To keep aligned with this objective the chosen aging levels try to match the extracted binder grades of the plant-produced mixtures as well as each of the mixing methods. The mixtures and corresponding aging levels that were used in sample creation are summarized in Table 23.

For both projects it became clear the plant-produced mixtures should be tested at the 0 hour short term oven aging level. The 0 hour short term oven aging level for this experiment refers to the plant-produced mixture immediately after it has been split. This is extremely difficult to achieve in the laboratory because the plant-produced mixtures must be split from buckets weighing over 50 pounds. Warming this much material to a temperature where the material can be easily split can take hours. Splitting was aided by the fact that the virgin binders used were fairly soft. To split the plant-produced mixtures, buckets were placed in the oven at 275°F. The buckets were split at the 2.5 hour mark and the samples placed back in the oven at the compaction temperature. The compaction temperature was reached within an hour so the total heating time for the field samples before compaction was roughly 3.5 hours.

The laboratory-produced samples for the different mixing methods were mixed according to the procedures discussed earlier in this report. After mixing, the samples were placed

in pans in the oven at the compaction temperature for 2 hours. Once the loose mix samples had been short term oven aged they were compacted using the Superpave Gyratory Compactor (SGC). The samples were 150 mm in diameter and compacted to a height of 170 mm. The samples were then given adequate time to cool down before being cored and cut down to the dimensions of 100 mm in diameter and 150 mm tall. The studs, each separated by 120°, were glued on the samples. The samples were then placed in an environmental chamber to achieve the desired test temperature. Four different test temperatures were used, beginning with the lowest temperature. The test temperatures used were 4°C, 21°C, 37°C and 54°C. At each testing temperatures the samples were testing over a range of frequencies including 0.1Hz, 0.5 Hz, 1 Hz, 5 Hz, 10 Hz and 25 Hz.

The master curves from both projects are shown in Figures 31-34. The curves were created for 70°F and 100°F. From the figures it can be seen that there is a very small difference between the three different mixing methods. For both projects at the lower frequencies the plant-produced mixtures with no additional aging has slightly lower E* values. For the Washington Field project values were also obtained for the plant-produced mixture with 2 hours of short term oven aging, but it is clear that the additional aging time for that mixture resulted in stiffness values greater than all the mixing methods that also had 2 hours of short term oven aging. This phenomenon is easier to see in Figure 36.

Figures 35 and 36 show the dynamic modulus values for each mixture over the range of frequencies at 70°F. For the specific temperature all of the laboratory produced mixtures had stiffness values very close to those of the plant-produced mixtures.

Referencing back to Figures 22 and 23, there are some interesting observations to note. For both projects Method B produced a mixture more stiff than Method A and more stiff than the plant-produced mixtures. This could be attributed to the superheated aggregate aging the virgin asphalt binder during the mixing process, but this doesn't explain the results for Method C between the two projects. For the SR 201 project Method C yielded stiffness values even greater than Method B, but in the WF project Method C produced the least stiff mixes. The only explanation I could think of for this phenomenon relates back to the interesting trend in the mixing temperatures.

For both projects the mixing temperatures decreased to a point and then began to increase for the Method C mixtures. But in the WF project, the one with the higher moisture content in the RAP that increase occurred later in the temperature monitoring period. This resulted in a lower overall mixing temperature presumably because more heat had to be expended to dry the RAP before it could superheat it. The drying-superheating process most likely occurs simultaneously but undoubtedly more energy or heat will be required to expel the larger moisture content. So all this together coupled with the fact that the RAP was not preheated as was the case in Method A; the asphalt binder blend for Method C may have been subjected to the least amount of heat creating a softer binder. This softer binder assumption could directly explain the lower stiffness values for Method C for the WF project.

In Figures 37 and 38 the dynamic modulus values are plotted versus the frequency for 100°F. The higher temperatures appear to capture different stiffness behavior between the mixtures and some interesting notes. First of all for the SR 201 project at 100°F Method A produced the least stiff mixture while for the WF project it was the most stiff

mixture. Once again Method B was more stiff the plant produced mixtures for both projects. At the higher temperature Method C is closest to representing the plant produced mixtures from a stiffness perspective. As was noticed at 70°F for the SR 201 project Method C was less stiff than the plant produced mixtures while it was more stiff for the WF project.

Chapter 8: Conclusions and Recommendations

8.1 Mixing Temperatures

- All three methods seemed to retain enough heat to adequately mix the laboratory mixtures.
- Superheating recommendations provided by NAPA may be overestimated for laboratory purposes since the final temperature for these methods was higher than method A.
- High variability at the early temperature recordings for Methods B and C did not seem to affect the final readings. The final temperatures for both projects had Method C with the highest and Method A with the lowest.

8.2 Binder Grading Analysis

- There was not a significant difference between the extracted binder grading for the three mixing methods. For the WF project Method B yielded a binder slightly softer at the high temperature (2 degrees), but a nearly identical grading at the low temperature.

- Coming in contact with superheated aggregate did not have a significant effect on the binder grade. This may have been an issue if the binder had been heated to the superheated aggregate temperature, but since it was only heated to the design mixing temperature no effect of aging was noticed.
- For all methods, the 2 hour short term oven aging level has the greatest effect on the high critical temperature grade. The intermediate and low critical temperatures were much less affected. The long term aging of the PAV most likely masks the effect of the short term aging.
- For all binders, the critical low temperature became more m controlled after the short term aging period.
- With no large differences between the binder grades due to mixing method, Method A would be recommended due to simplicity in the laboratory.

8.3 Volumetric Analysis

- It was found that the theoretical maximum specific gravity, Gmm, increases with an increase in absorption time in the oven.
- Due to the variations in the bulk specific gravities in both projects I recommend further analysis be completed on more projects before drawing any conclusions from the volumetric properties of the mixtures using the three different mixing methods. The results thus far have not followed identical trends but with only two sources it is difficult to determine is a source of error.

8.4 Dynamic Modulus Analysis

- All three mixing methods produced pretty similar master curves to the plant-produced mixtures.
- The higher temperature captures more variability between the laboratory mixtures and the plant-produced mixtures.
- Method B produced the stiffest mixture for both projects, so superheating the aggregate may have directly affected the binder.
- Higher moisture contents within the RAP could possibly produce less stiff mixtures.
- Aging the loose plant-produced mixtures for additional time in the laboratory produced mixtures that were more stiff than mixtures for any of the three mixing methods that had been short term aged for 2 hours.

In conclusion, based on the findings from this research, I would recommend Method A be instituted in the laboratory for mixing HMA mixtures containing RAP materials. It proved to be the simplest method without requiring excessive superheating temperatures which can be difficult to reach and maintain in the laboratory setting. I would however, strongly encourage the temperature of the RAP be monitored so it does not heat for extended periods of time in the oven. The NCAT study summarized earlier in the report highlighted the effect that excessive preheating times can have on the RAP material. So in an attempt to avoid aging the RAP any more than it already has been it is important to preheat the RAP material for ease of mixing purposes but not long enough for significant aging to occur. I would recommend batching the RAP material for individual samples so the amount of RAP material required to heat is small and preheating for 30 minutes to 45

minutes as used in this study. Method A also produced the mixture with a stiffness that most closely resembled the stiffness shown in the plant-produced mixtures at 70°F. Although, the variability of Method A at the higher temperature could be cause for some concern.

The superheating temperatures for Methods B and C were sometimes hard to reach and even more difficult to maintain when mixing multiple samples. This introduces more factors for variability within the laboratory setting that could possibly affect the mixture. That variability was another pitfall of Method C and the moisture conditioning of the RAP material. It is easy to replicate moisture content in the laboratory and ensure uniform moisture, but the sample created in the laboratory may not actually replicate the plant conditions. Uniform moisture throughout a stockpile is not possible in the field and moisture contents are constantly fluctuating. I would suggest that more research be completed with varying moisture contents to determine the true effect of the moisture in the RAP before suggesting this method is used.

Chapter 9: Future Work

The main objective of the study that encompasses this small portion is to develop a mix design procedure for new HMA pavements that incorporate RAP materials. The emphasis of this study was on the laboratory mixing process and trying to determine the most effective and representative way to incorporate RAP material in the laboratory setting. Just at the completion of the overall objective is still a way off, so is the completion of all research avenues concerning the laboratory mixing process. Further research should include but not limited to the following:

- Incorporating higher percentages of RAP. The current push is to incorporate upwards of 50%. This study only used 25% RAP material in the mix design. While it is a good start, incorporating larger percentages of RAP could definitely effect the outcome of the analyses done in this study.
- Further analysis on the effect of varying moisture contents. It was seen in the E* data that the moisture content may have had an effect but that was between two different projects. Further research varying the moisture contents of individual projects could produce more sound results.
- Assess the effect of different types of plant or field mixing procedures. A large portion of this study was devoted to the extracted binder grading and trying to determine a short term oven aging period in the laboratory setting that replicated the aging level of the plant produced mixtures. With that said, different plant or field mixing techniques may produce mixtures with varying levels of aging.
- The RAP binder in this study was found, using the MSCR, to not have been polymer modified. Another possible avenue for further research could try to find

the difference, if any, to how a RAP material that does include polymer modified binder should be treated in the laboratory.

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Tables

Table 1 - NCHRP Extracted Binder Grading

Scenario	Virgin Heating Time	Virgin Temperature	RAP Heating Time	RAP Temperature	True Grade	PG Grade
N/A	Initial RAP asphalt binder grade				85.1–15.7	82-10
1	3 hours	355 °F	3 hours	355 °F	89.5-14.5	88-10
	3 hours	355 °F	3 hours	355 °F	89.1-13.3	88-10
2	16 hours	355 °F	16 hours	355 °F	N/A	N/A
	16 hours	355 °F	16 hours	355 °F	N/A	N/A
	16 hours	355 °F	16 hours	355 °F	N/A	N/A
3	3 hours	355 °F	30 minutes	125 °F	84.9-16.9	82-16
	3 hours	355 °F	30 minutes	125 °F	84.9-17.4	82-16
	3 hours	355 °F	30 minutes	125 °F	85.3-19.0	82-16
4	3 minutes	500 °F	0	Ambient	97.5-9.8	94-4
	3 minutes	500 °F	0	Ambient	95.1-8.7	94-4
	3 minutes	500 °F	0	Ambient	92.3-11.6	94-4

Table 2 - NAPA recommendation for superheating virgin aggregates.

Reclaimed Material Moisture Content (%)	Recycled Mix Discharge Temperature, °F			
	220°F	240°F	260°F	280°F
A. Ratio: 10% RAP / 90% Aggregate				
0	250	280	305	325
1	260	290	310	335
2	270	295	315	340
3	280	300	325	345
4	285	305	330	350
5	290	315	335	360
B. Ratio: 20% RAP / 80% Aggregate				
0	280	310	335	360
1	295	320	350	375
2	310	335	360	385
3	325	350	375	400
4	340	365	390	415
5	355	380	405	430
C. Ratio: 30% RAP / 70% Aggregate				
0	315	345	375	405
1	335	365	395	425
2	360	390	420	450
3	385	415	445	475
4	410	440	470	500
5	435	465	495	525
D. Ratio: 40% RAP / 60% Aggregate				
0	355	390	425	460
1	390	425	460	495
2	425	460	495	530
3	470	500	535	570
4	500	535	570	610
5	545	575	610	645
F. Ratio: 50% RAP / 50% Aggregate				
0	410	455	495	540
1	465	515	550	590
2	520	560	605	650
3	575	620	660	705
4	640	680	715	760
5	690	735	775	820

Table 3 - Aggregate Physical Properties – State Route 201

Property	Standard	Result	UDOT Specification
One Fractured Face	AASHTO TP 61	98	95% Min
Two Fractured Faces	AASHTO TP 61	97	90% Min
Fine Aggregate Angularity	AASHTO T 304	47	45 Min
Flakiness Index	AASHTO MOI 933	16	17% Max
Los Angeles Wear	AASHTO T 96	19.8	35% Max
Sand Equivalent	AASHTO T 176	67.0	60 Min
Plasticity Index	AASHTO T 89/90	Non-Plastic	Non-Plastic
Unit Weight	AASHTO T 19	110.7 pcf	75 pcf Min
Soundness (Coarse)	AASHTO T 104	0.3	16% Max
Soundness (Fine)	AASHTO T 104	1.9	16% Max
Clay Lumps	AASHTO T 112	1.0	2% Max

Table 4 - Aggregate Physical Properties – Washington Field

Property	Standard	Result	UDOT Specification
One Fractured Face	AASHTO TP 61	100	95% Min
Two Fractured Faces	AASHTO TP 61	100	90% Min
Fine Aggregate Angularity	AASHTO T 304	49	45 Min
Flakiness Index	AASHTO MOI 933	17	17% Max
Los Angeles Wear	AASHTO T 96	24.0	35% Max
Sand Equivalent	AASHTO T 176	67.0	60 Min
Plasticity Index	AASHTO T 89/90	Non-Plastic	Non-Plastic
Unit Weight	AASHTO T 19	110.9 pcf	75 pcf Min
Soundness (Coarse)	AASHTO T 104	2.4	16% Max
Soundness (Fine)	AASHTO T 104	5.8	16% Max
Clay Lumps	AASHTO T 112	0.7	2% Max

Table 5 - Aggregate Gradation – State Route 201

Nominal Maximum Aggregate Size, mm				19.0
Aggregate Bulk Specific Gravity, G_{sb}				2.669
Sieve Size	Virgin Aggregates w/ Lime	Total Blend w/ RAP	Control Points	
	%Passing		Min	Max
37.5 mm (1 1/2")	100.0	100.0	--	--
25.0 mm (1")	100.0	100.0	--	--
19.0 mm (3/4")	100.0	100.0	100	--
12.5 mm (1/2")	94.0	95.0	90	100
9.5 mm (3/8")	85.0	87.0	--	90
4.75 mm (No. 4)	41.0	45.0	--	--
2.36 mm (No. 8)	24.0	28.0	28	58
1.18 mm (No. 16)	17.0	20.0	--	--
0.3 mm (No. 50)	8.0	12.0	--	--
0.075 mm (No. 200)	4.60	6.50	2	10
Aggregates	Material Description			Bin %
Aggregate 1	3/4" Rock			9.0%
Aggregate 2	7/16" Chip			29.0%
Aggregate 3	1/4" Chip			14.0%
Aggregate 4	Type 3 Sand			13.0%
Aggregate 5	Washed Sand			9.0%
Aggregate 6	Coarse RAP			13.0%
Aggregate 7	Fine RAP			12.0%
Aggregate 8	Lime			1.0%

Table 6 - Aggregate Gradation – Washington Field

Nominal Maximum Aggregate Size, mm				19.0
Aggregate Bulk Specific Gravity, G_{sb}				2.630
Sieve Size	Virgin Aggregates w/ Lime	Total Blend w/ RAP	Control Points	
	%Passing		Min	Max
37.5 mm (1 1/2")	100.0	100.0	--	--
25.0 mm (1")	100.0	100.0	--	--
19.0 mm (3/4")	100.0	100.0	100	--
12.5 mm (1/2")	94.0	95.0	90	100
9.5 mm (3/8")	90.0	89.0	--	90
4.75 mm (No. 4)	46.0	48.0	--	--
2.36 mm (No. 8)	22.0	28.0	28	58
1.18 mm (No. 16)	11.0	18.0	--	--
0.3 mm (No. 50)	6.0	11.0	--	--
0.075 mm (No. 200)	4.10	6.50	2	10
Aggregates	Material Description			Bin %
Aggregate 1	3/4" Rock			9.0%
Aggregate 2	7/16" Chip			20.0%
Aggregate 3	7/16" Chip 'Dirty'			15.0%
Aggregate 4	Screened Type III Sand			30.0%
Aggregate 5	Coarse RAP			12.0%
Aggregate 6	Fine RAP			13.0%
Aggregate 7	Lime			1.0%

Table 7 – Summary of Mix Designs

Property	State Route 201	Washington Fields
Nominal Maximum Aggregate Size	19	19
Design ESALs, millions	0.3 to <30	3 to <30
N_{inital}	8	8
N_{design}	100	100
N_{max}	160	160
Recommended Virgin Asphalt Content	3.90	4.00
Recommended Total Asphalt Content	5.00	5.00
Hydrated Lime, %	1.5	1
Virgin Asphalt Binder Grade	PG58-34	PG64-34
Max Theoretical Specific Gravity, G_{mm}	2.492	2.447
Bulk Specific Gravity, G_{mb}	2.403	2.447
%Gmm at N_{ini}	85.8	85.2
%Gmm at N_{des}	86.4	86.5
%Gmm at N_{max}	97.5	
Air Voids, %, at Ndes	3.6	3.5
VMA, %	14.5	14.8
VFA, %	75.3	76.4
Specific Gravity of Aggregate, Gsb	2.669	2.634
Specific Gravity of Binder	1.024	1.028
Absorbed Binder, Pba	0.357	0.07
Dust Proportion, $P_{0.075}/P_{be}$	1.4	1.3
RAP Binder Grade	PG82-22	PG82-16
RAP Binder Content (%)	1.15 %	1 %

Table 8 - Moisture Contents of Individual Stockpiles

Project	Stockpile	Moisture Content (%)
State Route 201	3/4"	0.80
	7/16" Chip	0.78
	Type III Sand	2.07
	Washed Sand	4.21
	1/4" Chip	1.49
	+4 RAP	3.17
	-4 RAP	4.38
Washington Field	3/4"	1.30
	7/16" Chip	1.90
	Dirty 7/16"	2.00
	Type III Sand	4.30
	+4 RAP	2.10
	-4 RAP	2.70

Table 9 – Design Binder Grades - State Route 201

Property	Garco Testing Laboratories				UNR Laboratory		
	Target	Virgin	RAP	Blend	Virgin	RAP	Blend
High Temperature, °C	64.0	65.3	87.6	70.4	65.0	89.0	70.5
Intermediate Temperature, °C	22.0	11.6	25.2	14.7	11.8	33.4	16.8
Low Temperature, °C	-28.0	-35.3	-22.0	-33.4	-33.8	-17.9	-30.1

Table 10 – Design Binder Grades – Washington Field

Property	Garco Testing Laboratories				UNR Laboratory		
	Target	Virgin	RAP	Blend	Virgin	RAP	Blend
High Temperature, °C	70	70.2	86.7	73.5	71.6	88.7	75
Intermediate Temperature, °C	25	12.2	26.2	15	12.8	32.0	16.6
Low Temperature, °C	-28	-34.9	-20	-32.5	-30.7	-12.1	-27

Table 11 – Comparison of Blended Binder Grades

Property	State Route 201			Washington Field		
	Blending Chart		Lab Blend	Blending Chart		Lab Blend
	Garco	UNR	UNR	Garco	UNR	UNR
Critical High Temperature, °C	70.4	70.5	68.4	73.5	75	73.3
Intermediate Critical Temperature, °C	14.7	16.8	16.3	15	16.6	17.6
Low Critical Temperature, °C	-33.4	-30.1	-29.4	-32.5	-27	-25.3

Table 12 - Initial Mixing Temperatures

Mixing Temperatures				
Project	Method	Virgin Aggregate	Virgin Asphalt Binder	RAP Material
State Route 201	A	313	313	313
	B	379	313	77
	C	413	313	77*
Washington Field	A	329	329	329
	B	379	329	77
	C	420	329	77*
Compaction Temperatures				
State Route 201	284°F			
Washington Field	293°F			

*Moisture Conditioned at Ambient Temperature

Table 13 - Average of Recorded Mixing Temperatures – State Route 201

Method	Time (seconds)	Average Temperature	Standard Deviation	Count	95% Confidence Interval
A	90	296.2	3.94	7	2.92
	120	292.6	5.82	8	4.03
	150	289.4	8.75	8	6.06
	180	286.5	4.17	8	2.89
	210	288.4	7.14	8	4.95
	240	285.7	7.03	8	4.87
B	90	301.4	13.95	6	11.16
	120	298.8	7.96	8	5.52
	150	295.2	4.47	8	3.10
	180	291.4	8.30	8	5.75
	210	292.0	6.23	8	4.32
	240	292.7	6.64	8	4.60
C	90	299.3	2.60	9	1.70
	120	297.7	4.83	10	2.99
	150	300.2	5.20	10	3.22
	180	302.1	5.04	10	3.13
	210	305.1	3.78	10	2.35
	240	306.3	4.79	10	2.97

Table 14 - Washington Fields Mixing Temperatures

Method	Time (seconds)	Average Temperature	Standard Deviation	Count	95% Confidence Interval
A	90	304.5	5.09	9	3.32
	120	299.0	6.33	11	3.74
	150	295.2	5.85	11	3.46
	180	293.8	4.53	11	2.68
	210	289.9	6.28	11	3.71
	240	288.5	6.23	11	3.68
B	90	292.2	4.12	10	2.55
	120	289.6	6.09	10	3.78
	150	292.7	3.72	10	2.30
	180	291.2	3.72	10	2.30
	210	291.4	3.37	10	2.09
	240	291.3	4.94	10	3.06
C	90	297.8	6.07	8	4.20
	120	297.6	8.03	8	5.57
	150	298.1	5.37	9	3.51
	180	294.8	2.33	9	1.52
	210	294.4	2.96	9	1.94
	240	297.1	4.81	9	3.14

Table 15 - Comparison of Mixing and Superheated Aggregate Temperatures

Project	Method	Recording	Temperature °F	Aggregate Temperature °F	Loss From Aggregate Temperature	Loss from 1st to Final Recording
State Route 201	A	1st	296.2	313	16.8	10.5
		Final	285.7	313	27.3	
	B	1st	301.4	379	77.6	8.7
		Final	292.7	379	86.3	
	C	1st	299.3	413	113.7	-7.0
		Final	306.3	413	106.7	
Washington Fields	A	1st	304.5	329	24.5	16
		Final	288.5	329	40.5	
	B	1st	292.2	379	86.8	0.9
		Final	291.3	379	87.7	
	C	1st	297.8	420	122.2	0.7
		Final	297.1	420	122.9	

Table 16 - Summary of Binder Grading - State Route 201

Binder	STO Aging of loose mix @ 284°F	True High Grade	True Intermediate Grade	True Low Grade	PG Grade
		Temp, °C	Temp, °C	Temp, °C	Temp, °C
Original	N/A*	65.0	11.8	-33.8	64 - 22
Lab Blend	N/A*	68.4	16.3	-29.4	70 - 28
Rap	0	89.0	33.4	-17.9	88 - 12
Field	0	71.5	18.9	-27.0	70 - 22
	2	74.5	20.0	-25.6	70 - 22
	4	76.7	22.0	-22.9	76 - 22
Method A	0	68.7	17.3	-28.3	64 - 28
	2	73.0	18.1	-27.4	70 - 28
Method B	0	70.1	17.3	-29.0	70 - 28
	2	72.7	19.2	-27.5	70 - 28
Method C	0	69.6	17.3	-28.4	70 - 28
	2	72.7	18.5	-27.2	70 - 28

Table 17 - Summary of Binder Grading - Washington Fields

Binder	STO Aging of loose mix @ 293°F	True High Grade	True Intermediate Grade	True Low Grade	PG Grade
		Temp, °C	Temp, °C	Temp, °C	Temp, °C
Original	N/A*	71.6	12.8	-30.7	70 - 28
Lab Blend	N/A*	73.3	17.6	-25.3	70 - 22
Rap	0	88.7	32.0	-12.1	88 - 6
Field	0	75.5	21.0	-24.2	70 - 22
	2	77.8	21.4	-22.3	76 - 22
Method A	0	73.0	19.2	-24.3	70 - 22
	2	78.3	20.4	-22.4	76 - 22
Method B	0	72.9	20.4	-25.4	70 - 22
	2	76.2	21.3	-22.7	76 - 22
Method C	0	74.1	19.7	-25.1	70 - 22
	2	78.8	20.2	-23.8	76 - 22

Table 18 - Effect of 2 Hours Aging on Critical Temperatures

Project	Method	Δ High Grade °C	Δ Intermediate Grade °C	Δ Low Grade °C
State Route 201	Field	2.9	1.1	1.5
	A	4.3	0.8	0.9
	B	2.6	1.9	1.5
	C	3.2	1.2	1.1
Washington Fields	Field	2.3	0.3	0.8
	A	5.3	1.1	1.9
	B	3.4	0.9	2.7
	C	4.7	0.5	1.3

Table 19 - Low Temperature Characteristics - State Route 201

Binder	STO Aging of loose mix @ 284°F	Low Temperature Characteristics					True Low Grade
		Criteria	Temp, °C	Δ T. °C	Controlling		Temp, °C
Original	N/A*	Stiffness	-23.8	0.7	Stiffness	-23.8	-33.8
		M - Value	-24.5				
Lab Blend	N/A*	Stiffness	-21.5	2.1	M - Value	-19.4	-29.4
		M - Value	-19.4				
Rap	0	Stiffness	-16.5	8.5	M - Value	-7.9	-17.9
		M - Value	-7.9				
Field	0	Stiffness	-20.5	3.4	M - Value	-17.0	-27.0
		M - Value	-17.0				
	2	Stiffness	-19.8	4.2	M - Value	-15.6	-25.6
		M - Value	-15.6				
	4	Stiffness	-19.4	6.5	M - Value	-12.9	-22.9
		M - Value	-12.9				
Method A	0	Stiffness	-21.2	2.9	M - Value	-18.3	-28.3
		M - Value	-18.3				
	2	Stiffness	-20.5	3.1	M - Value	-17.4	-27.4
		M - Value	-17.4				
Method B	0	Stiffness	-20.8	1.8	M - Value	-19.0	-29.0
		M - Value	-19.0				
	2	Stiffness	-20.4	2.9	M - Value	-17.5	-27.5
		M - Value	-17.5				
Method C	0	Stiffness	-20.9	2.5	M - Value	-18.4	-28.4
		M - Value	-18.4				
	2	Stiffness	-20.7	3.5	M - Value	-17.2	-27.2
		M - Value	-17.2				

Table 20 - Low Temperature Characteristics - Washington Fields

Binder	STO Aging of loose mix @ 293°F	Low Temperature Characteristics					True Low Grade
		Criteria	Temp, °C	Δ T. °C	Controlling		Temp, °C
Original	N/A*	Stiffness	-24.7	3.9	M - Value	-20.7	-30.7
		M - Value	-20.7				
Lab Blend	N/A*	Stiffness	-21.3	5.9	M - Value	-15.3	-25.3
		M - Value	-15.3				
Rap	0	Stiffness	-10.8	8.7	M - Value	-2.1	-12.1
		M - Value	-2.1				
Field	0	Stiffness	-20.0	5.8	M - Value	-14.2	-24.2
		M - Value	-14.2				
	2	Stiffness	-19.2	6.9	M - Value	-12.3	-22.3
		M - Value	-12.3				
Method A	0	Stiffness	-19.3	4.9	M - Value	-14.3	-24.3
		M - Value	-14.3				
	2	Stiffness	-18.7	6.3	M - Value	-12.4	-22.4
		M - Value	-12.4				
Method B	0	Stiffness	-19.8	4.4	M - Value	-15.4	-25.4
		M - Value	-15.4				
	2	Stiffness	-18.7	6.0	M - Value	-12.7	-22.7
		M - Value	-12.7				
Method C	0	Stiffness	-19.5	4.4	M - Value	-15.1	-25.1
		M - Value	-15.1				
	2	Stiffness	-18.9	5.2	M - Value	-13.8	-23.8
		M - Value	-13.8				

Table 21 - Volumetric Summary - State Route 201

Mix	Gmb				Gmm				VA (%)	VMA (%)	VFA (%)
	Reheat for Splitting	STO aging of loose mix at 284 F (hours)	Rep	Mean	Reheat for Splitting	STO aging of loose mix at 284 F (hours)	Rep	Mean			
Field	2.5 hours at 275F	0.5	2.417	2.413	2.5 hours at 275F	0	2.493	2.490	3.08	14.1	78.1
			2.410				2.487				
	3 hours at 275F	2	2.387	2.384	3 hours at 275F	0.5	2.489	2.491	4.28	15.1	71.7
							2.493				
	3 hours at 275F		2.381		3 hours at 275F	2	2.512	2.511	5.04	15.1	66.7
							2.510				
Method A	N/A*	2	2.383	2.378	N/A*	0	2.497	2.494	4.66	15.4	69.7
							2.491				
					N/A*	2	2.509	2.510	5.25	15.4	65.8
			2.373				2.511				
					N/A*	4	2.518	2.514	5.42	15.4	64.7
							2.511				
Method B	N/A*	2	2.386	2.384	N/A*	0	2.494	2.497	4.54	15.2	70.0
							2.500				
					N/A*	2	2.503	2.505	4.84	15.2	68.1
			2.381				2.507				
					N/A*	4	2.515	2.514	5.17	15.2	65.9
							2.512				
Method C	N/A*	2	2.396	2.392	N/A*	0	2.501	2.503	4.47	14.9	70.0
							2.506				
					N/A*	2	2.507	2.509	4.67	14.9	68.6
			2.387				2.511				
					N/A*	4	2.518	2.515	4.92	14.9	66.9
							2.513				

Table 22 - Volumetric Summary - Washington Field

Mix	Gmb				Gmm				VA (%)	VMA (%)	VFA (%)
	Reheat for Splitting	STO aging of loose mix at 293 F (hours)	Rep	Mean	Sample Reheat	STO aging of loose mix at 293 F (hours)	Rep	Mean			
Field	3 hours at 275F	2	2.333	2.331	3 hours at 275F	0	2.446	2.447	4.77	15.9	70.1
							2.449				
			2.328		3 hours at 275F	2	2.448	2.450	4.88	15.9	69.4
							2.452				
Method A	N/A*	2	2.375	2.373	N/A*	0	2.448	2.448	3.05	14.4	78.8
							2.448				
			2.372		N/A*	2	2.454	2.456	3.37	14.4	76.6
							2.458				
Method B	N/A*	2	2.379	2.377	N/A*	0	2.443	2.445	2.79	14.3	80.4
							2.448				
			2.375		N/A*	2	2.450	2.449	2.95	14.3	79.3
							2.449				
Method C	N/A*	2	2.337	2.339	N/A*	0	2.448	2.446	4.36	15.6	72.1
							2.444				
			2.341		N/A*	2	2.456	2.454	4.66	15.6	70.2
							2.451				

Table 23 - Summary of Testing for E* Samples

Project	Mixture	Short Term Aging Time (hours)	
		0	2
State Route 201	Field	X	X
	Method A		X
	Method B		X
	Method C		X
Washington Field	Field	X	
	Method A		X
	Method B		X
	Method C		X

Table 24 - Summary of Dynamic Modulus Values @ 70°F

Frequency		25	10	5	1	0.5	0.01
Washington Fields	Method A	889	684	554	314	243	130
	Method B	956	730	587	328	251	133
	Method C	976	748	601	341	262	139
	Field (0hrs)	894	693	561	318	245	127
State Route 201	Method A	1049	825	673	386	300	164
	Method B	1075	854	705	425	338	194
	Method C	1005	787	644	377	296	166
	Field (0hrs)	1025	815	676	404	320	178
	Field (2hrs)	1124	913	770	486	395	232

Figures

Figure 1 - Map of Projects

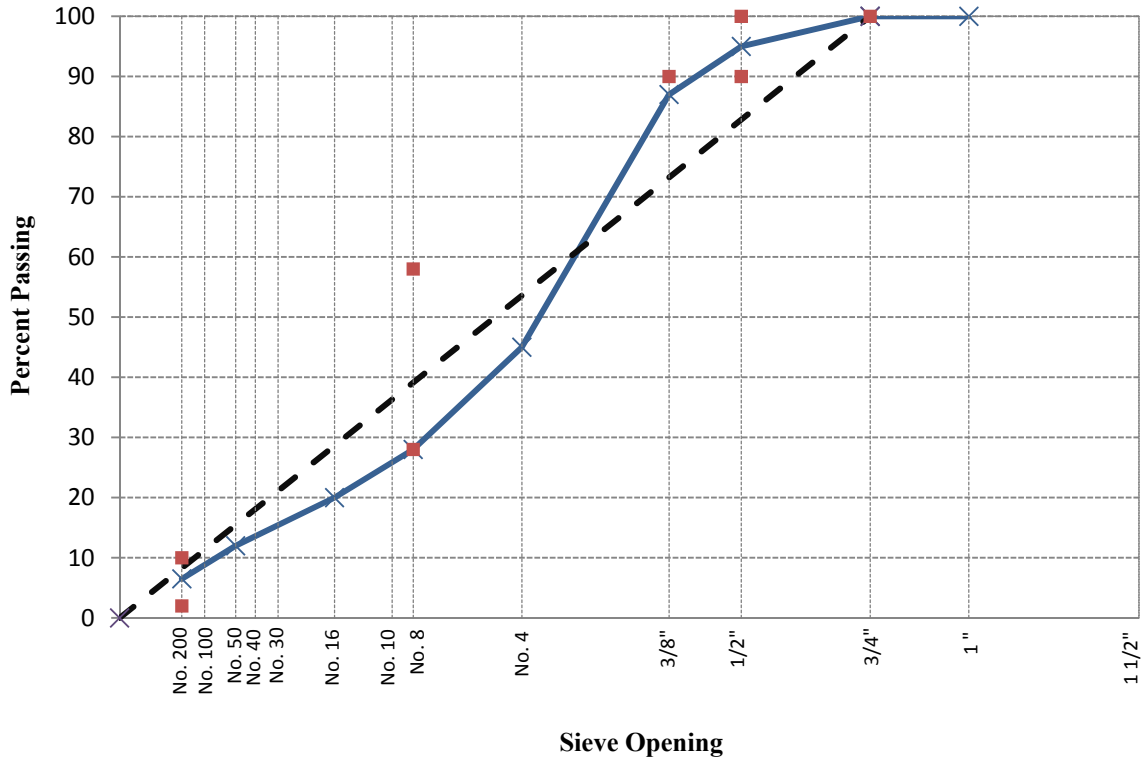

Figure 2 - Gradation - State Route 201

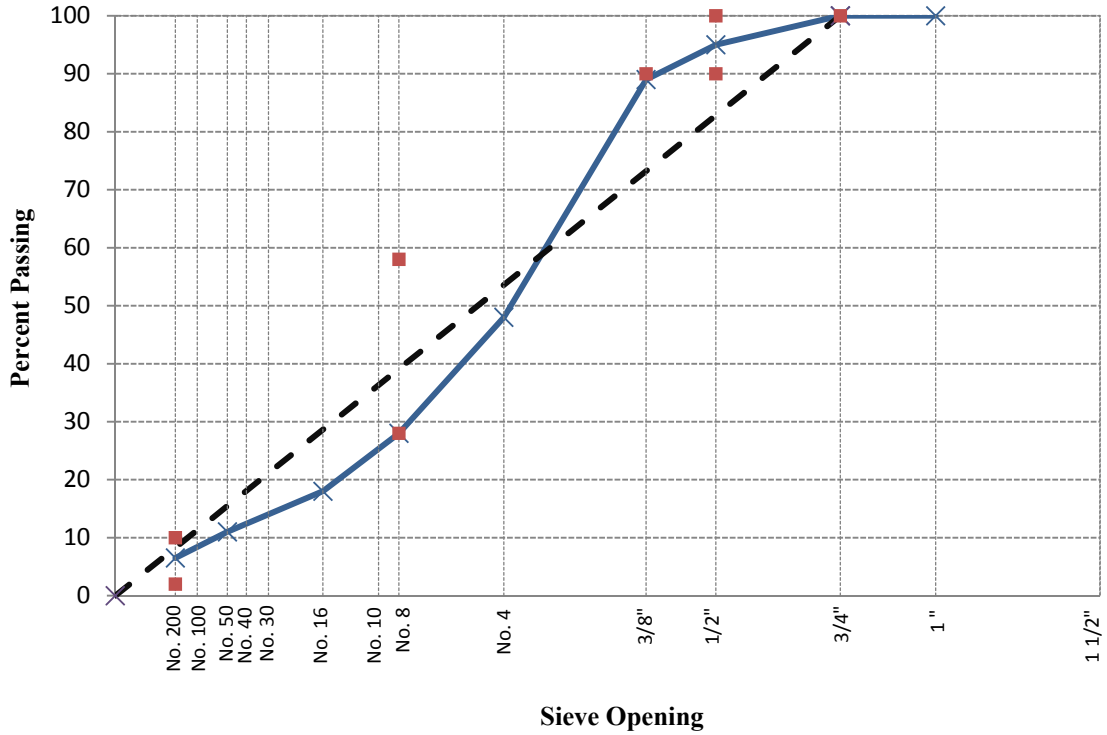

Figure 3 - Gradation - Washington Fields

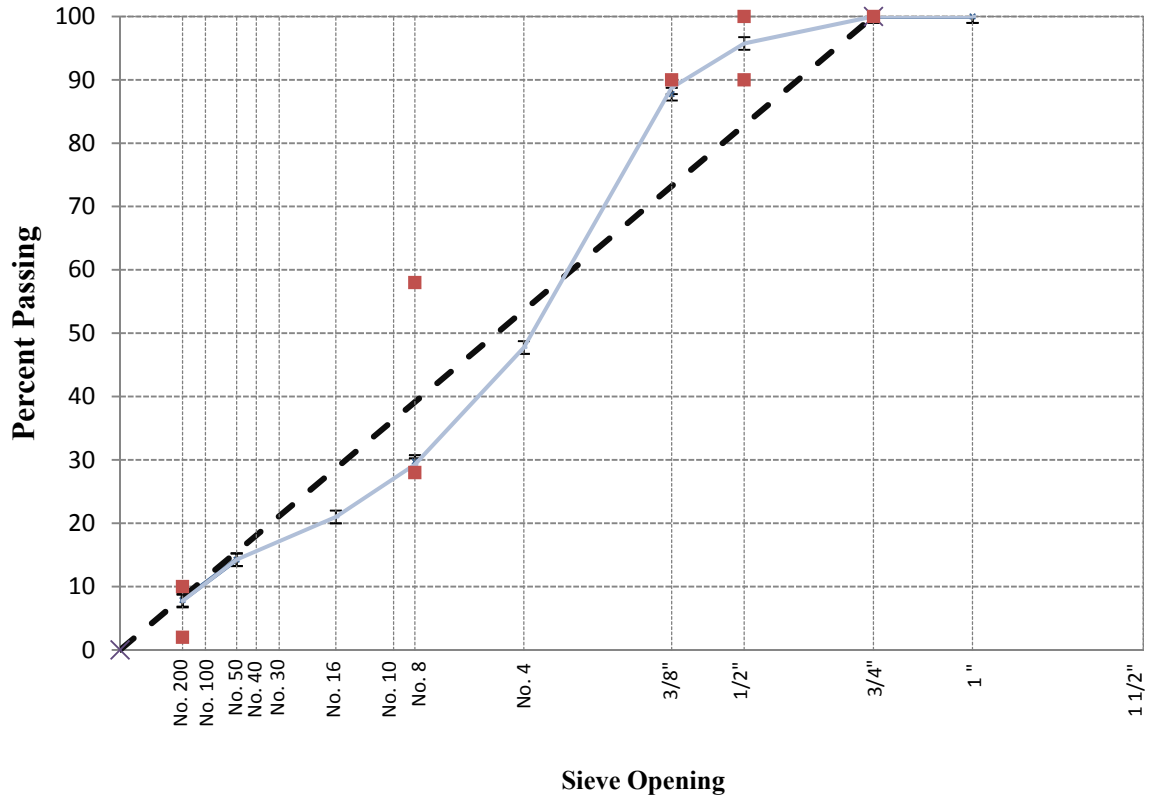

Figure 4 - QC/QA of Gradation - State Route 201

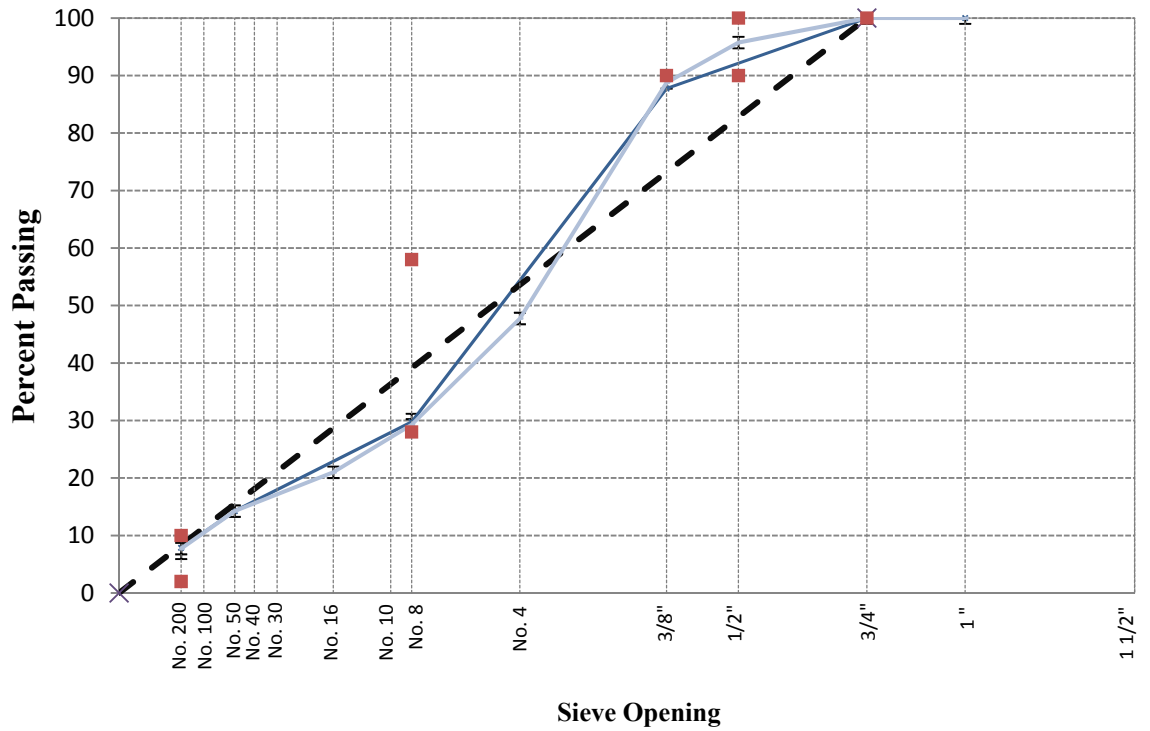

Figure 5 - QC/QA of Gradation - Washington Fields

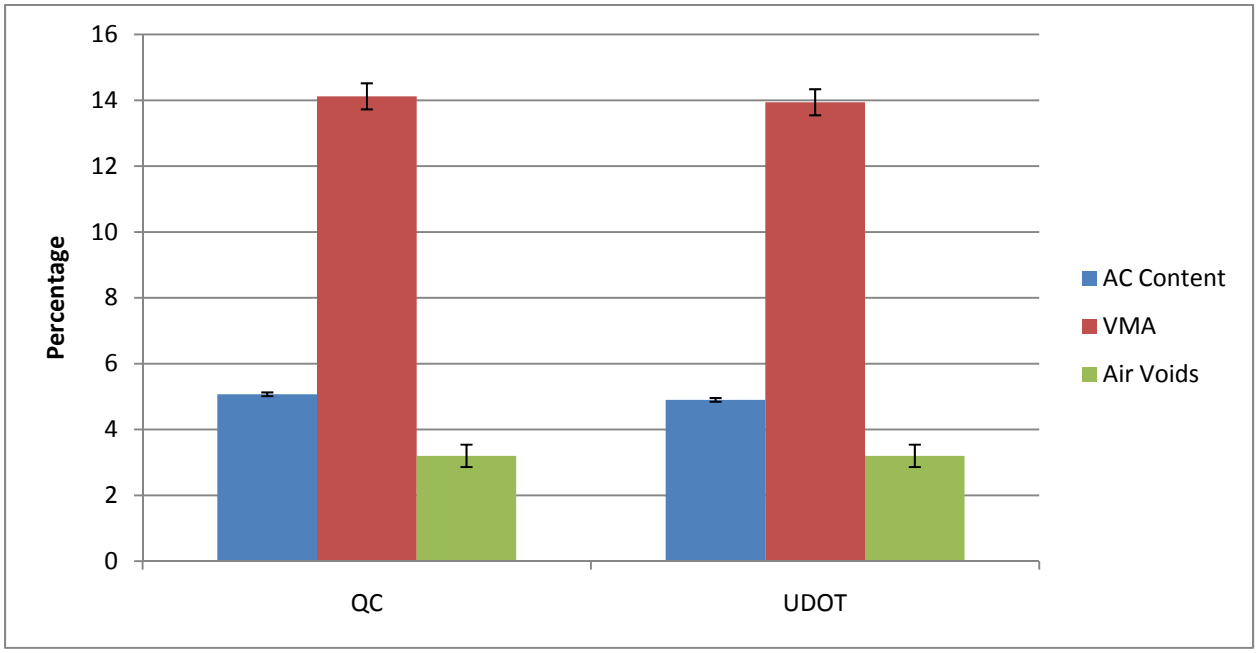

Figure 6 - QC/QA of Volumetric Properties - State Route 201

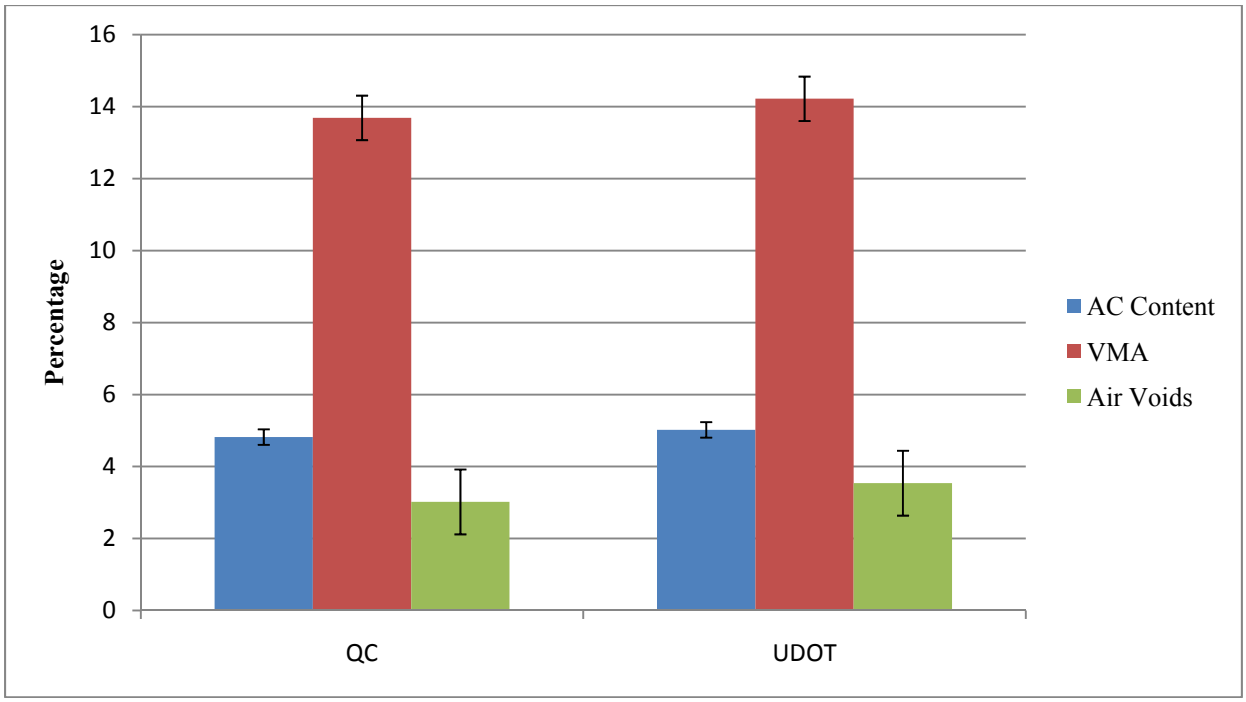

Figure 7 - QC/QA of Volumetric Properties - Washington Field

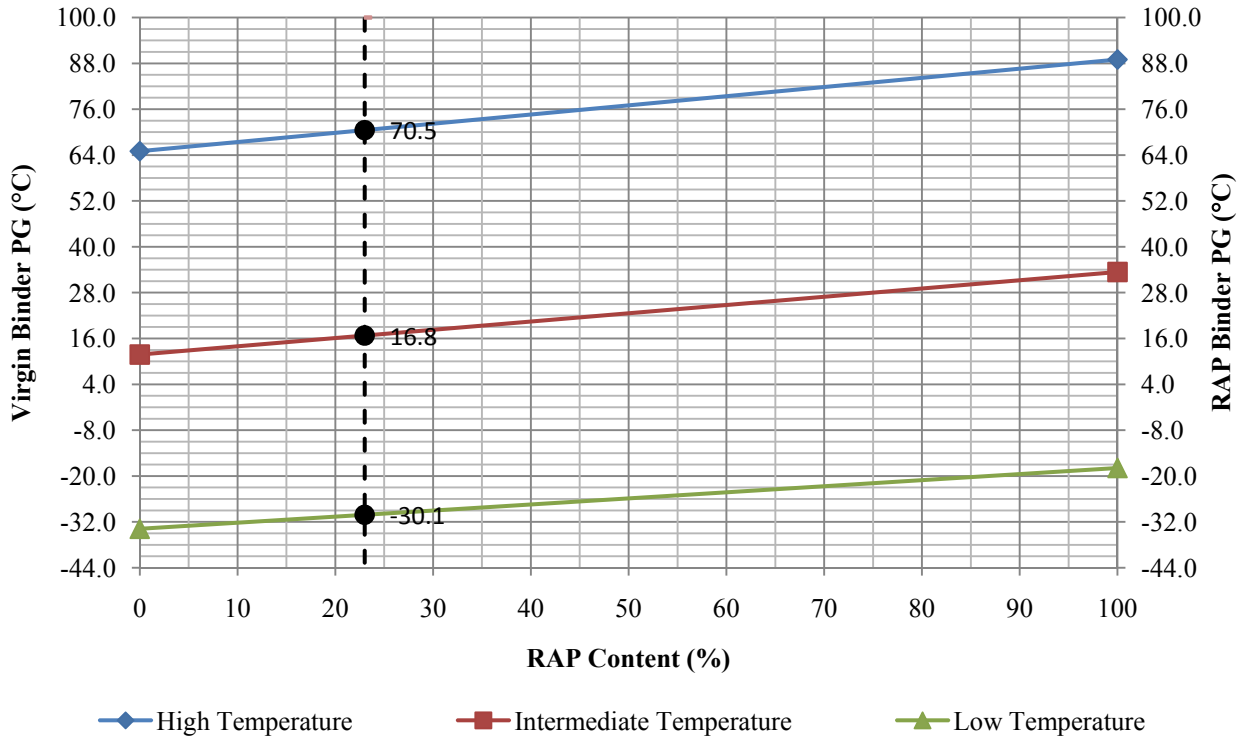

Figure 8 - UNR Blending Chart - State Route 201

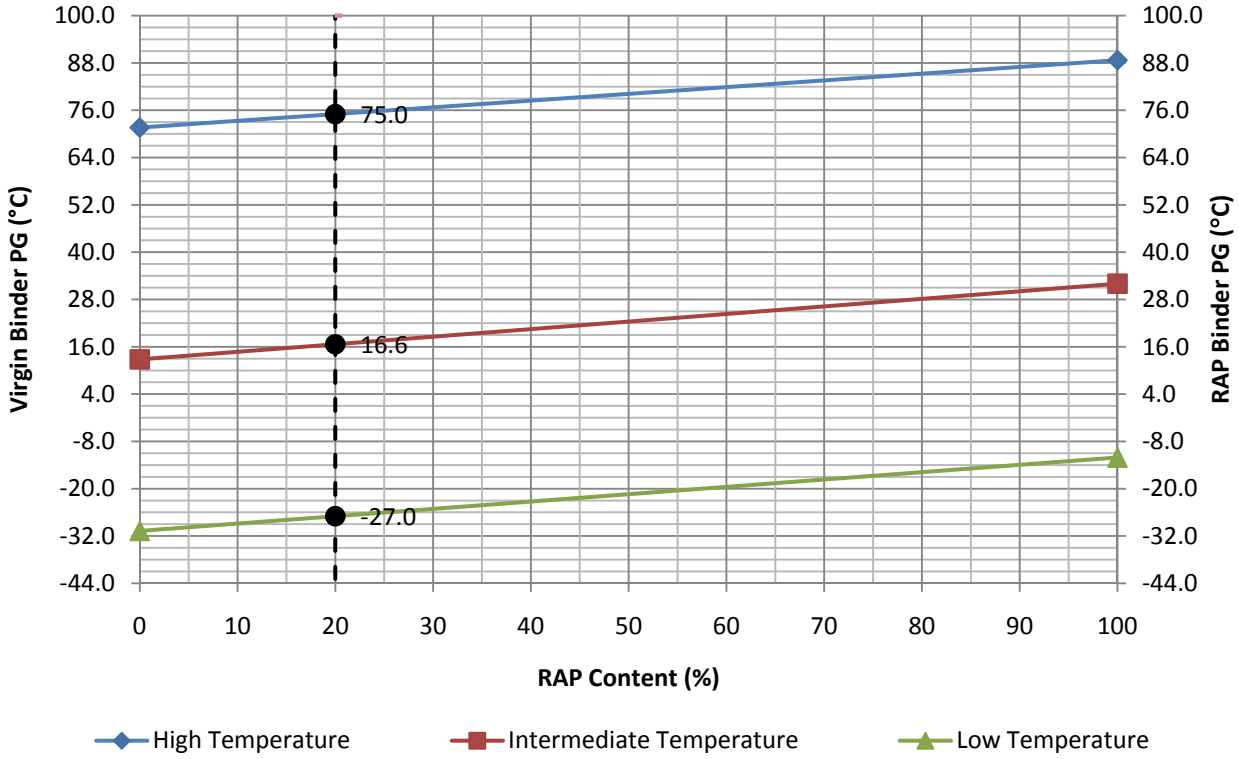

Figure 9 - UNR Blending Chart - State Route 201

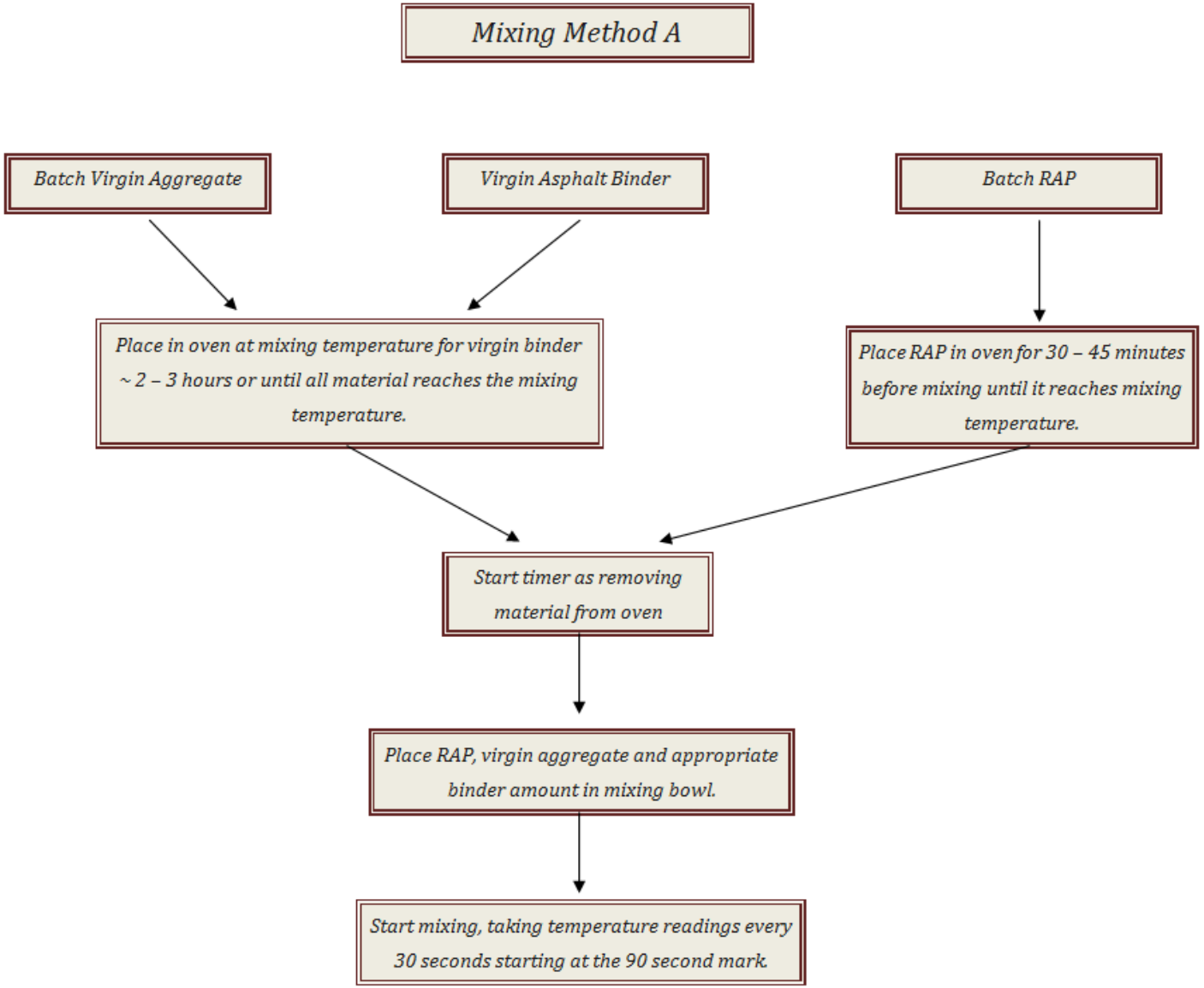

Figure 10 - Mixing Method A

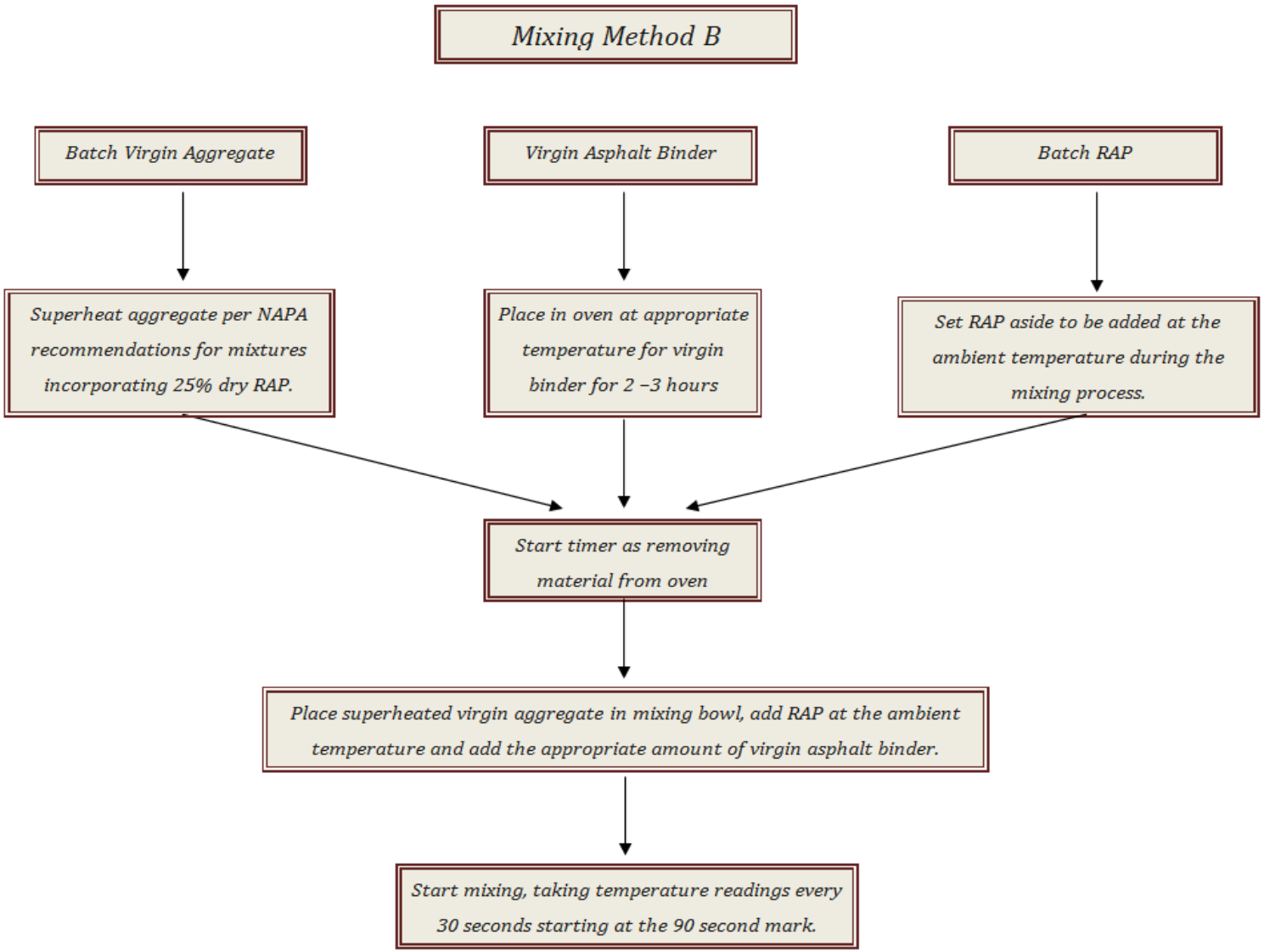

Figure 11 - Mixing Method B

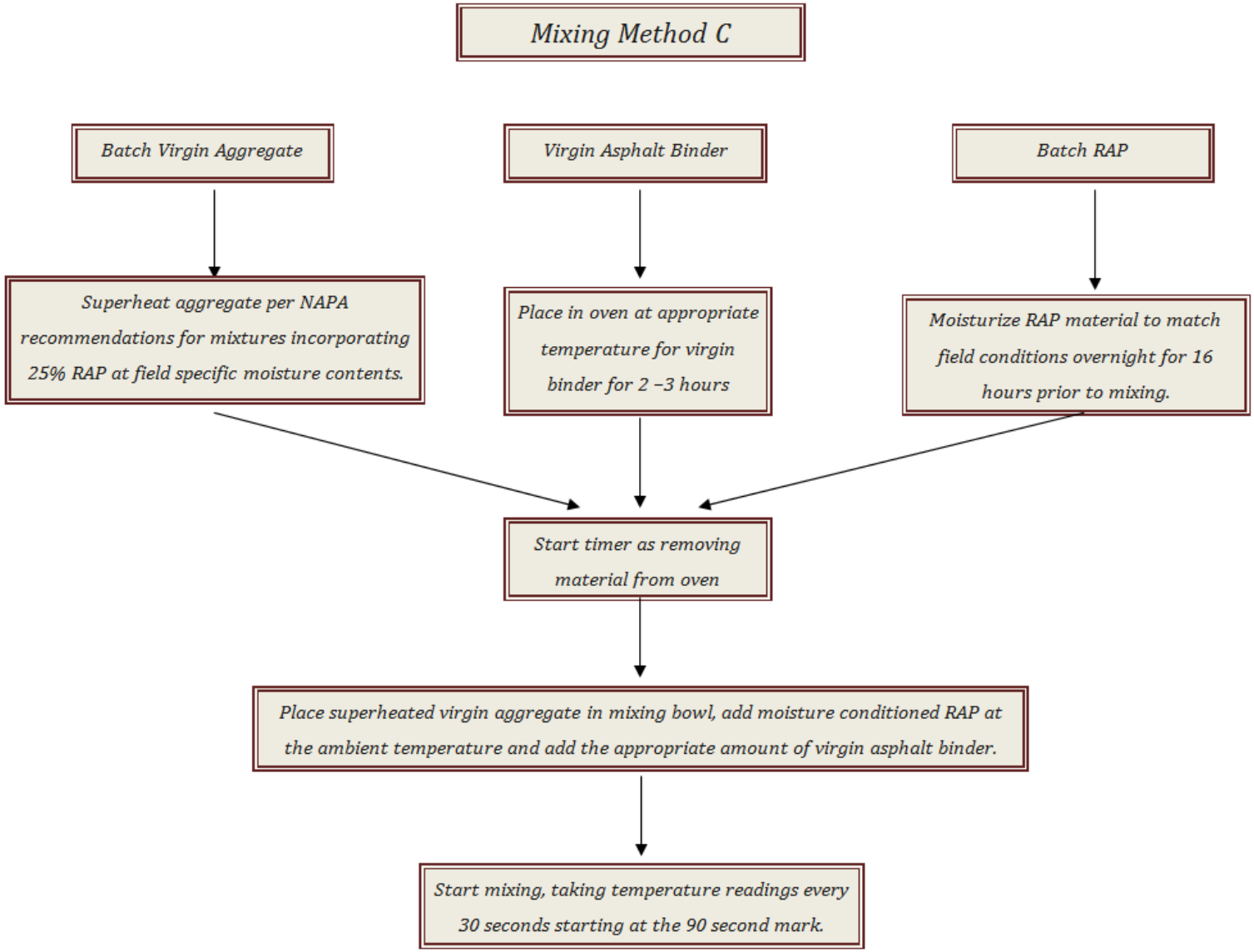

Figure 12 - Mixing Method C

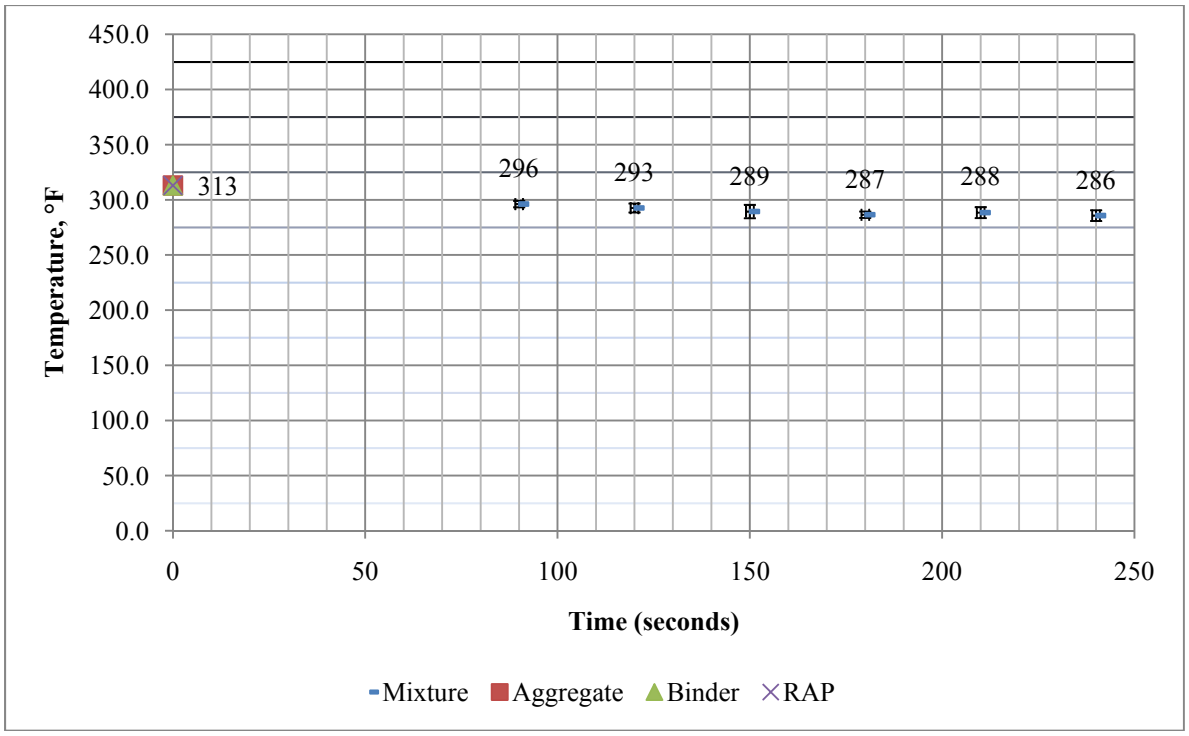

Figure 13 – Recorded Mixing Temperatures for Method A - State Route 201

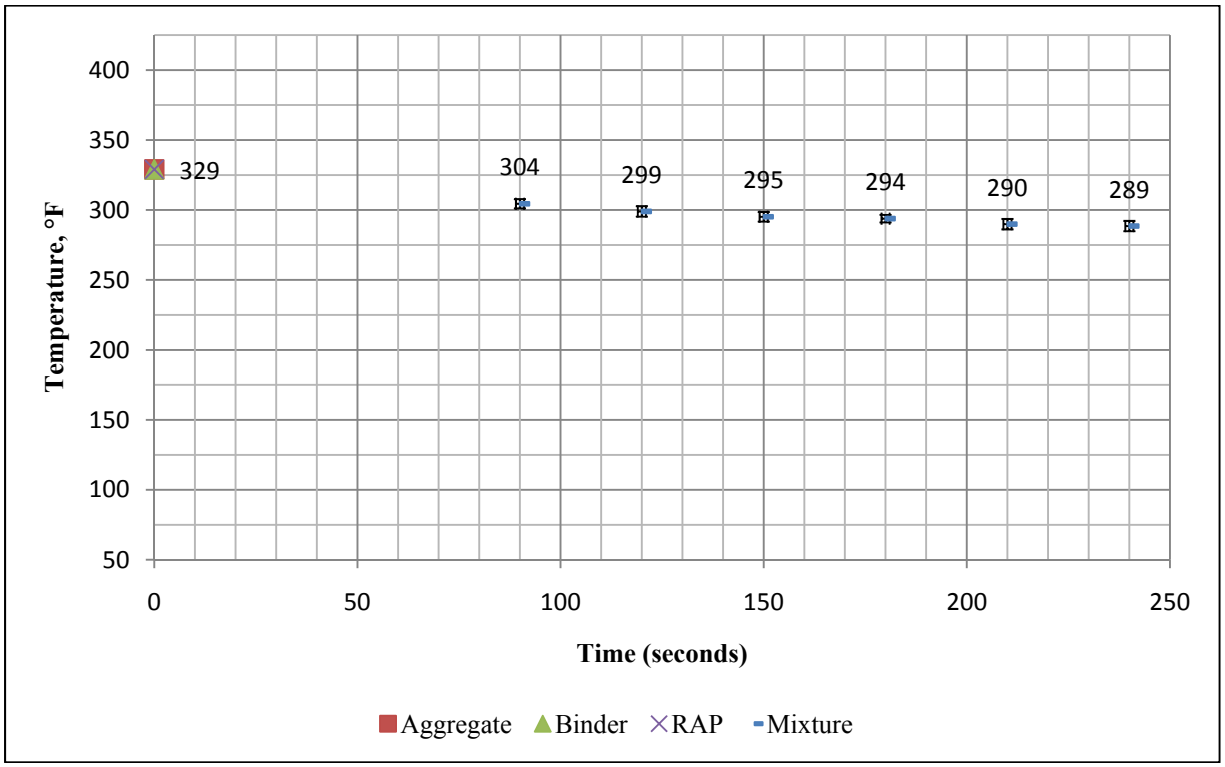

Figure 14 – Recorded Mixing Temperatures for Method A - Washington Fields

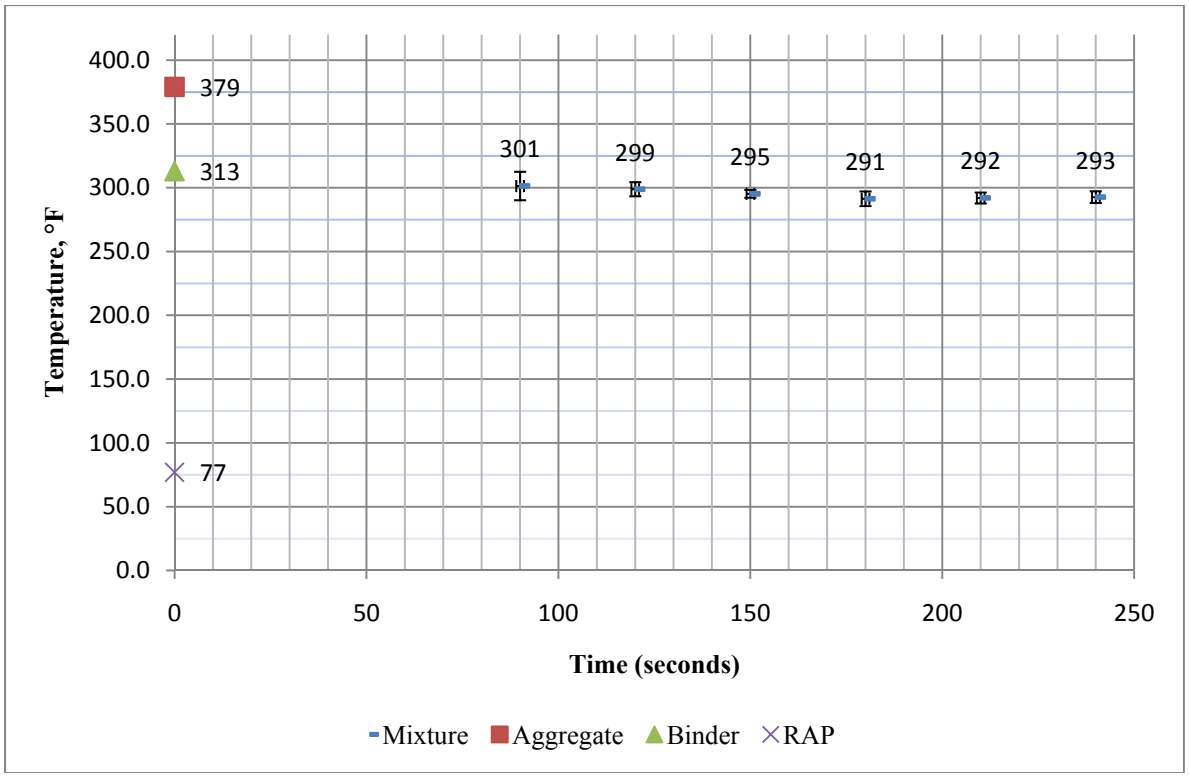

Figure 15 – Recorded Mixing Temperatures for Method B - State Route 201

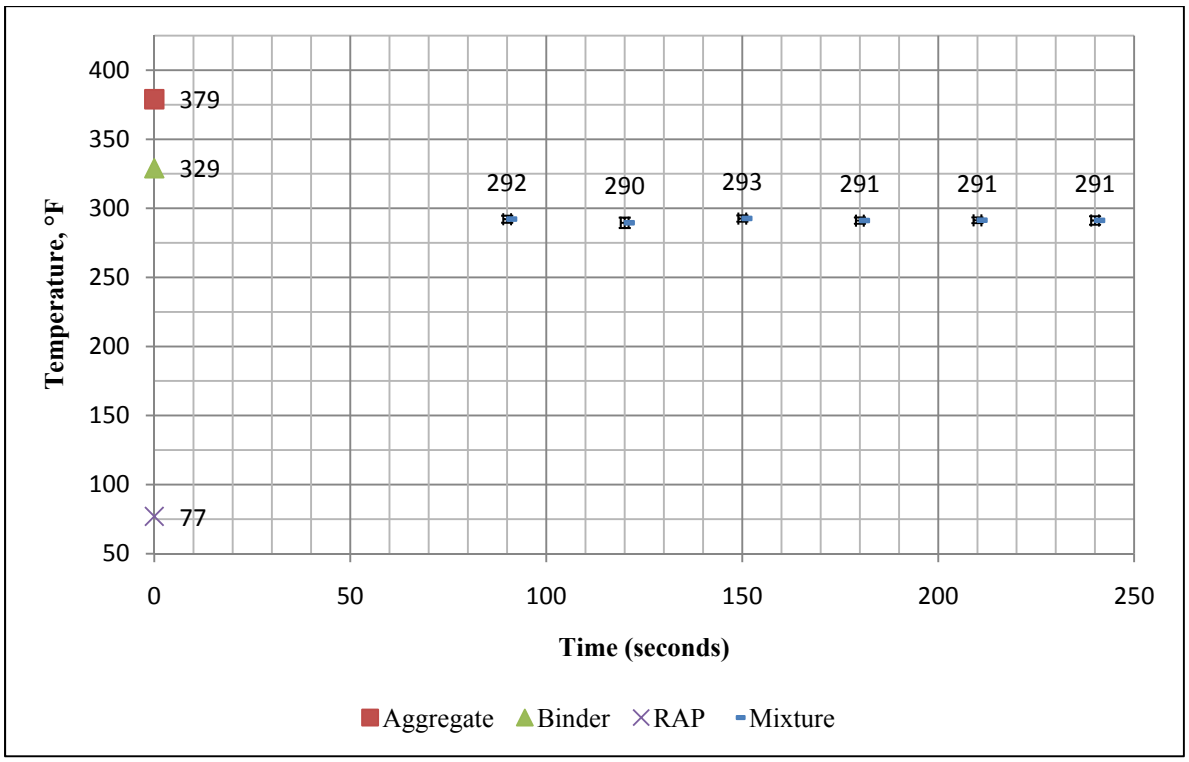

Figure 16 – Recorded Mixing Temperatures for Method B – Washington Fields

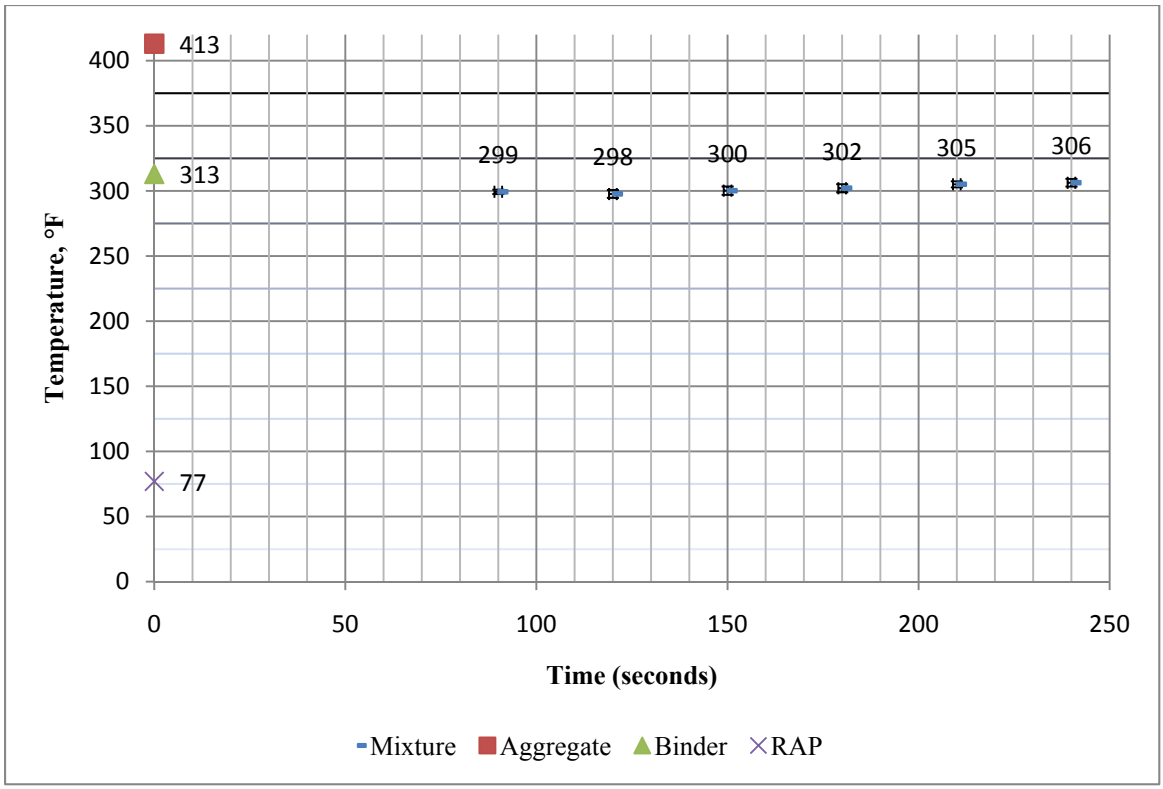

Figure 17 – Recorded Mixing Temperatures for Method C - State Route 201

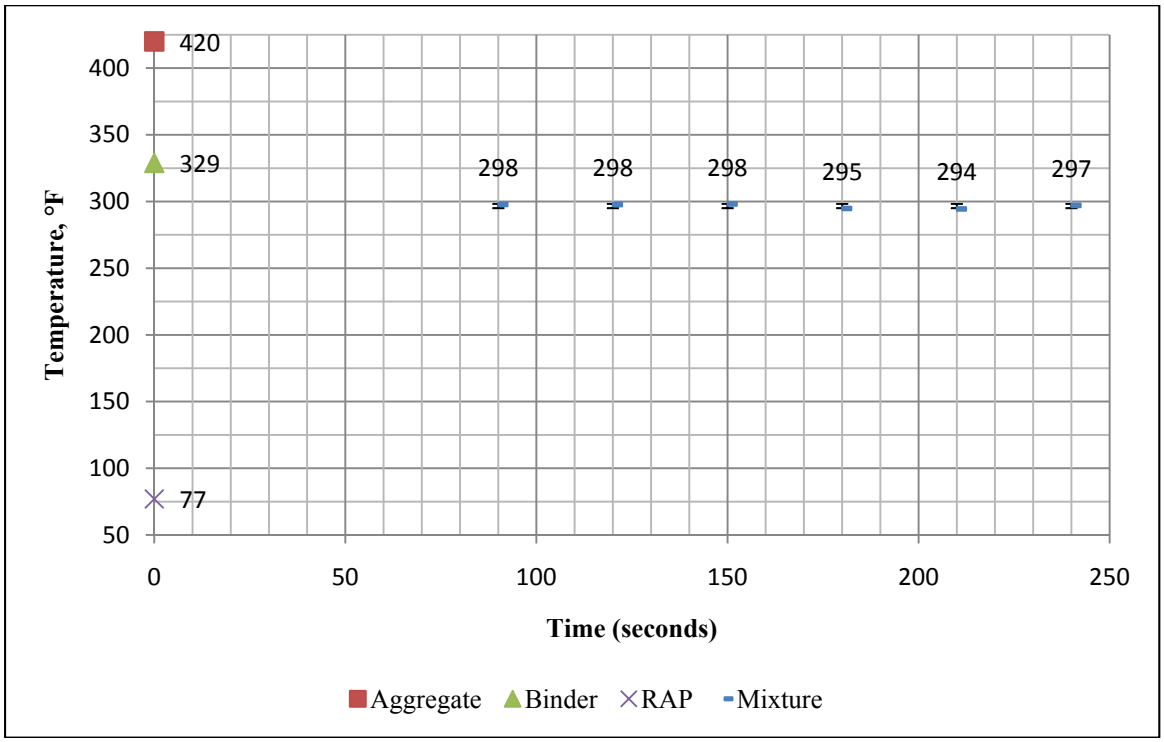

Figure 18 – Recorded Mixing Temperatures for Method C - Washington Fields

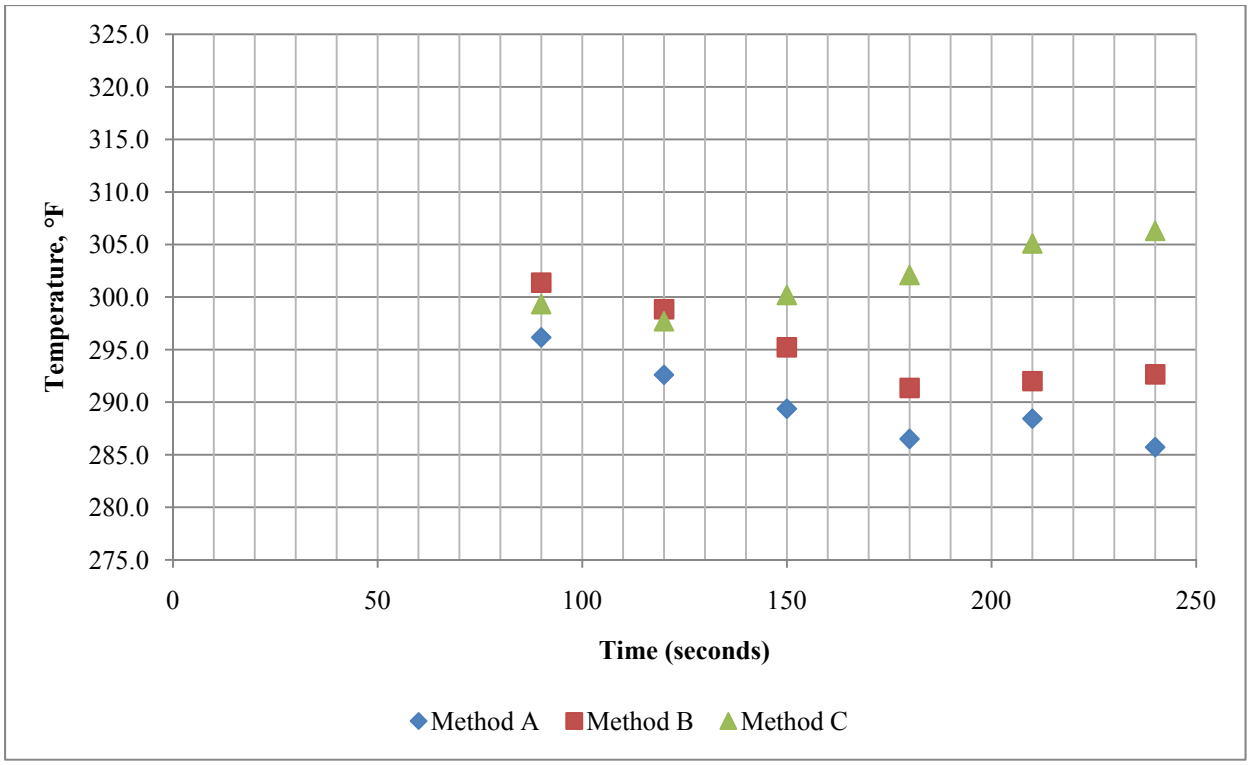

Figure 19 - Comparison of Mixing Temperatures - State Route 201

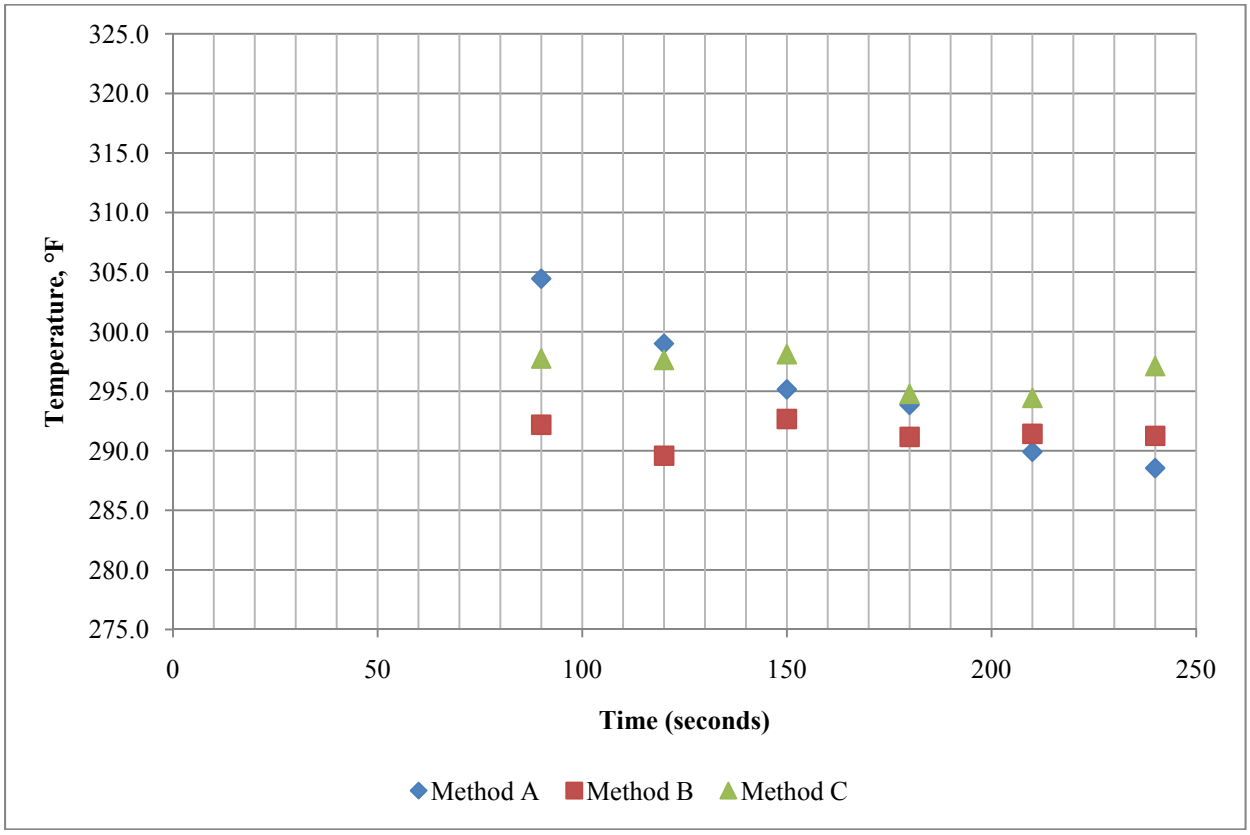

Figure 20 - Comparison of Mixing Temperatures - Washington Field

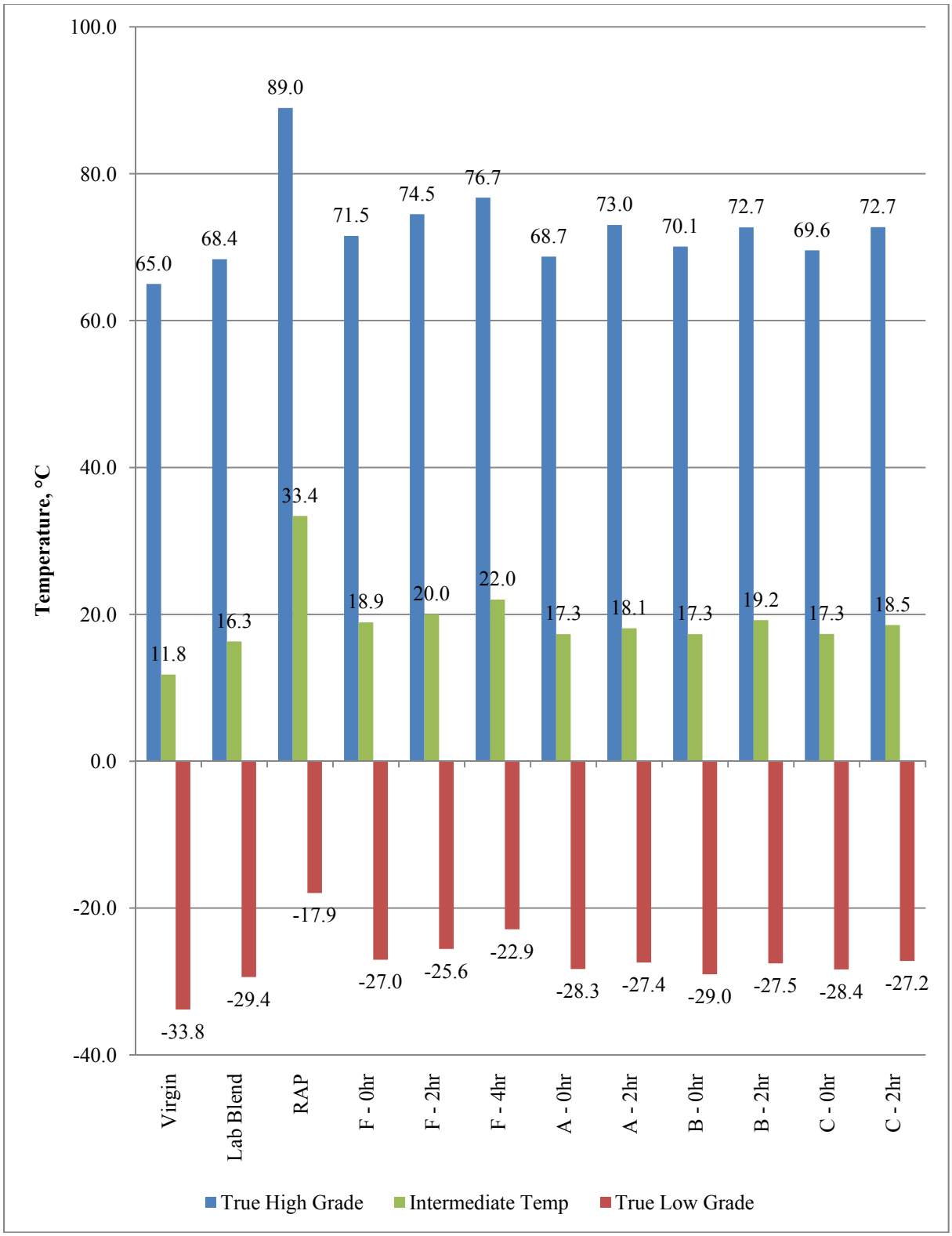

Figure 21- Summary of Binder Grading - State Route 201

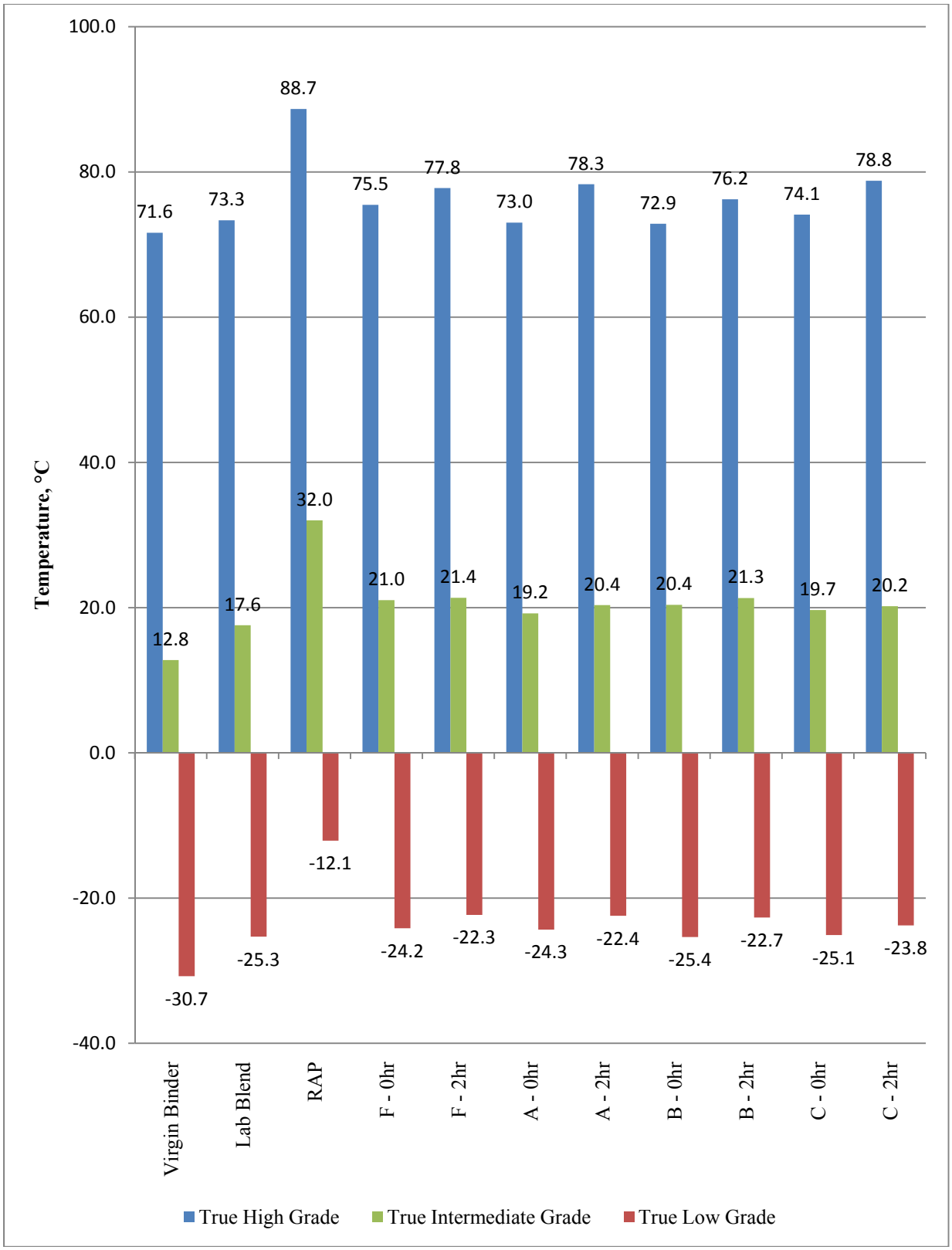

Figure 22 - Summary of Binder Grading - Washington Fields

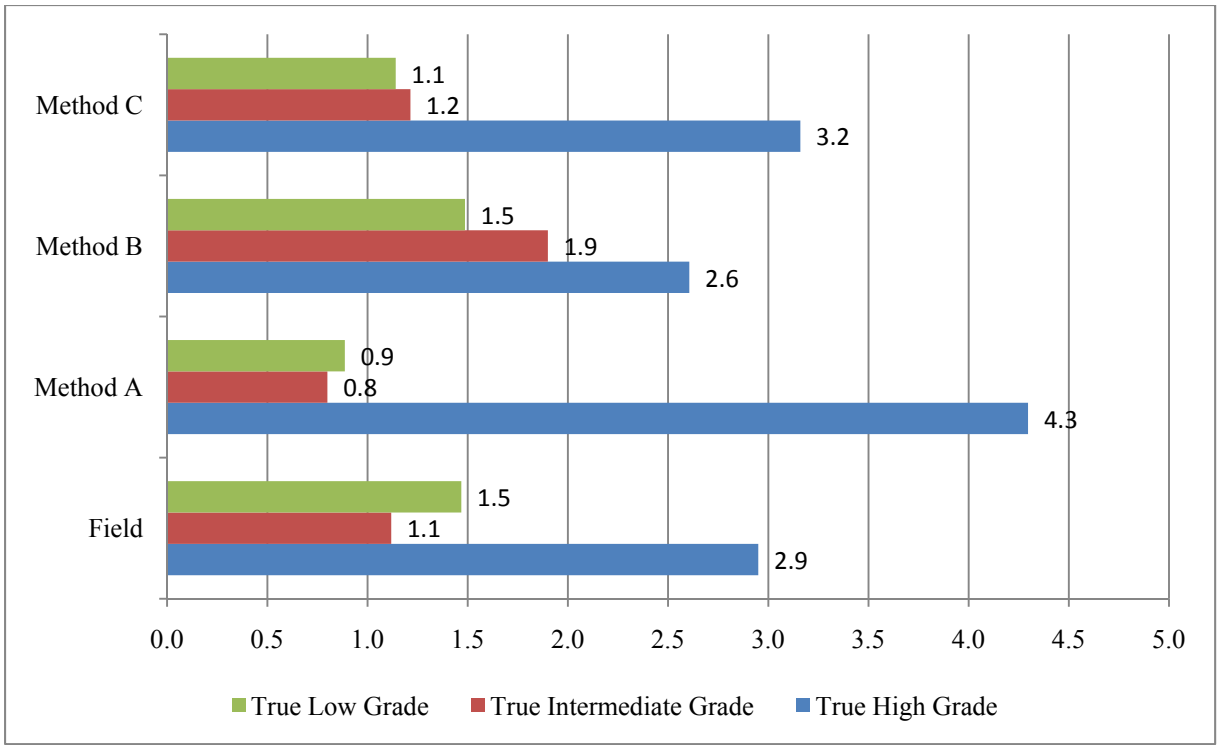

Figure 23 - Effect of 2 hours aging on True Grades - State Route 201

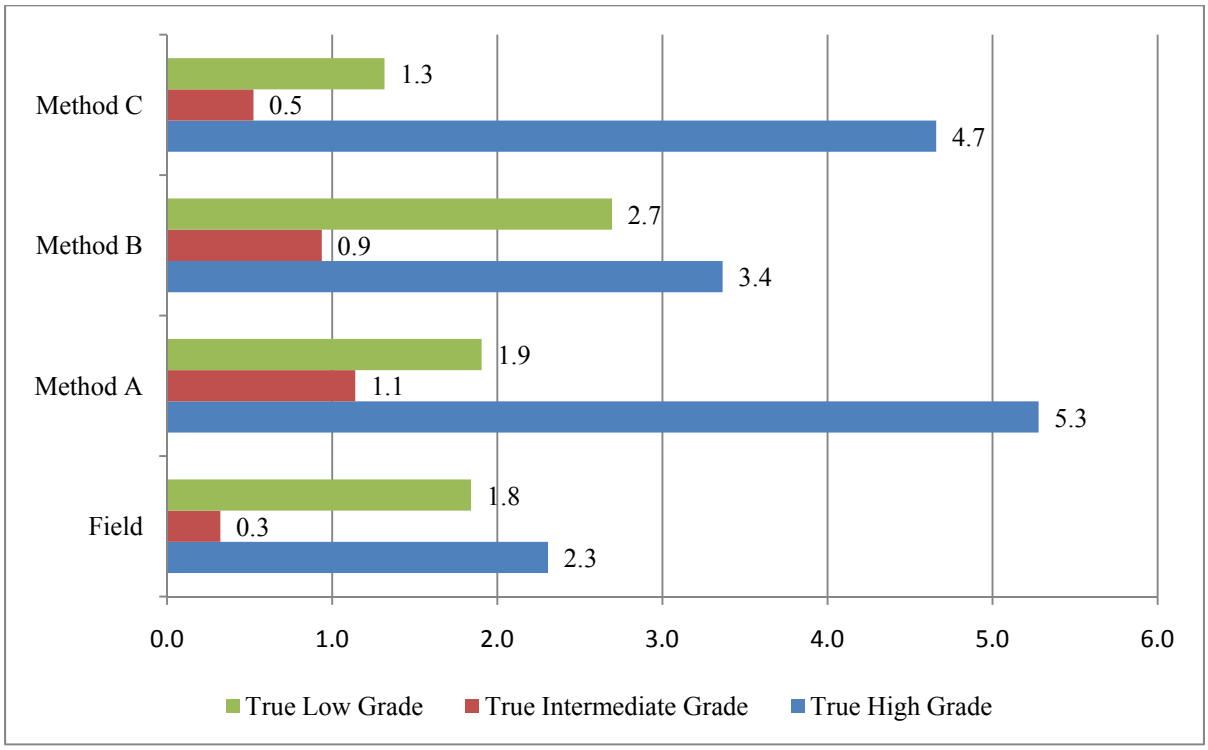

Figure 24 - Figure 15 - Effect of 2 hours aging on True Grades - Washington Fields

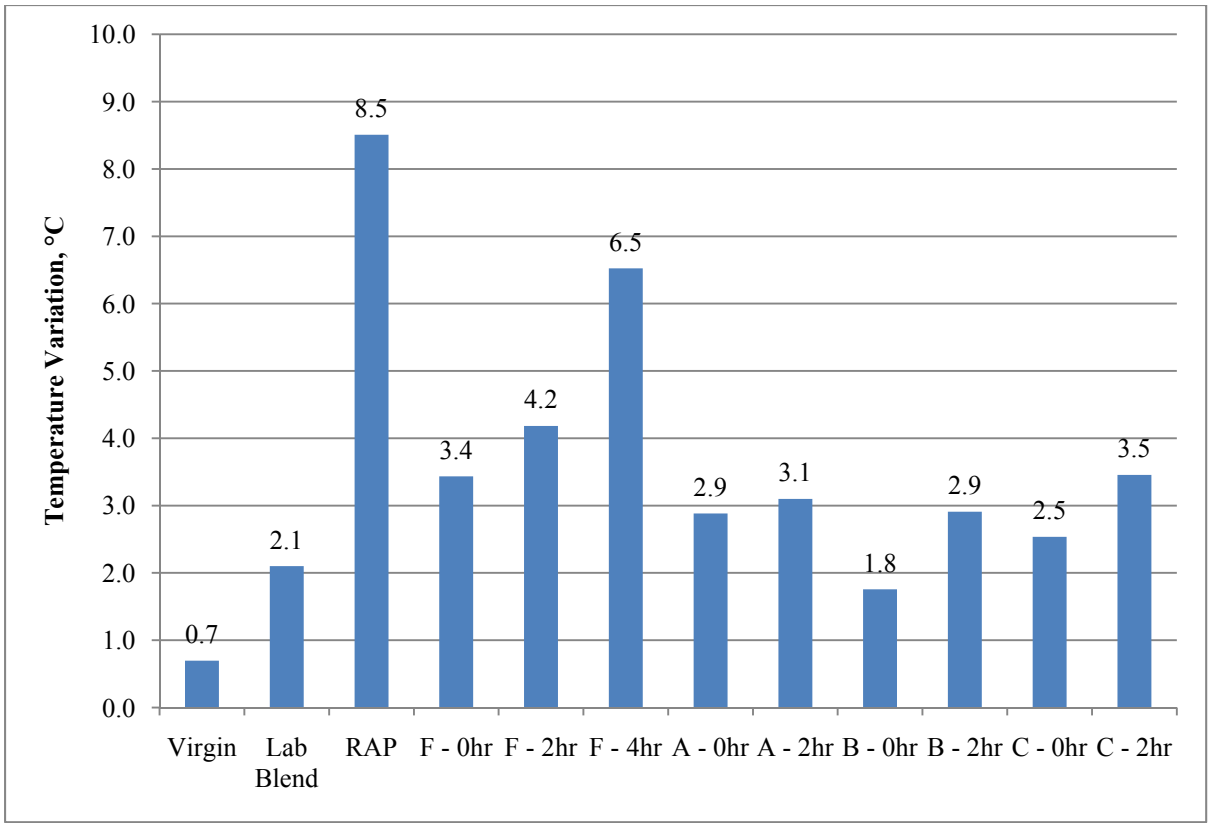

Figure 25 - Differences in Critical Low Temperature - State Route 201

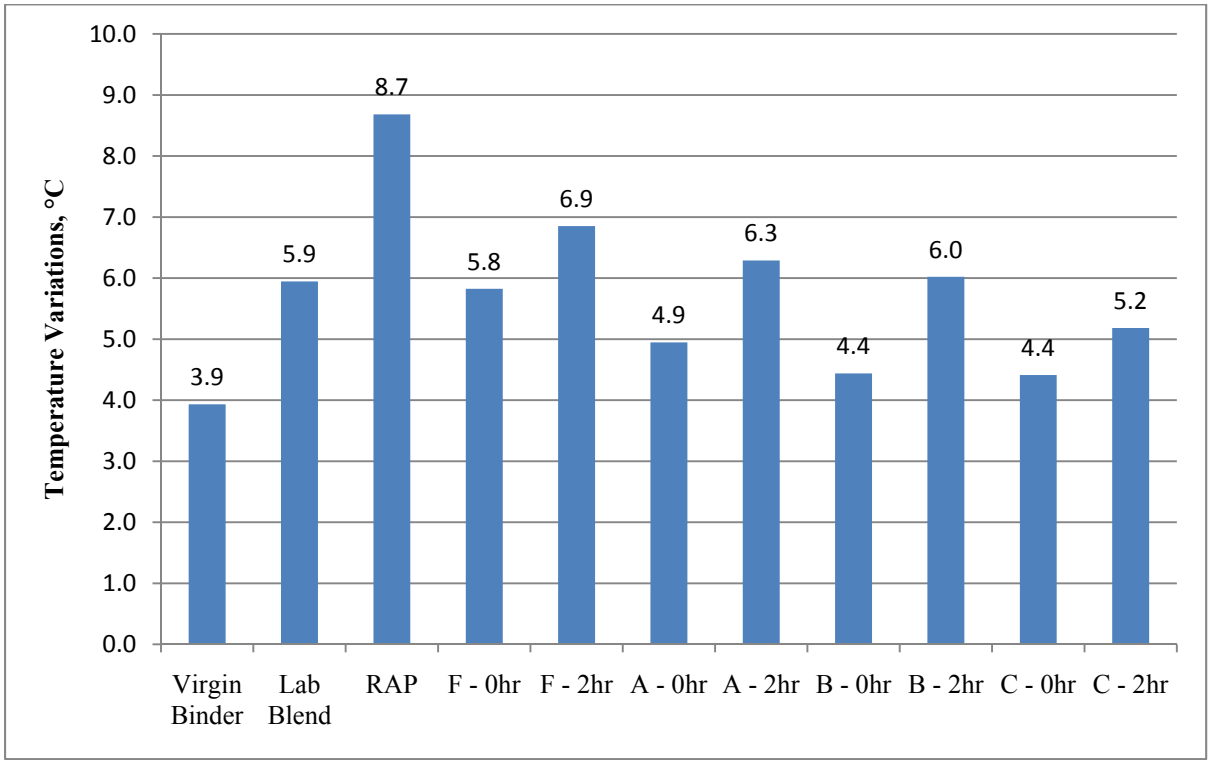

Figure 26 - Differences in Critical Low Temperature - Washington Fields

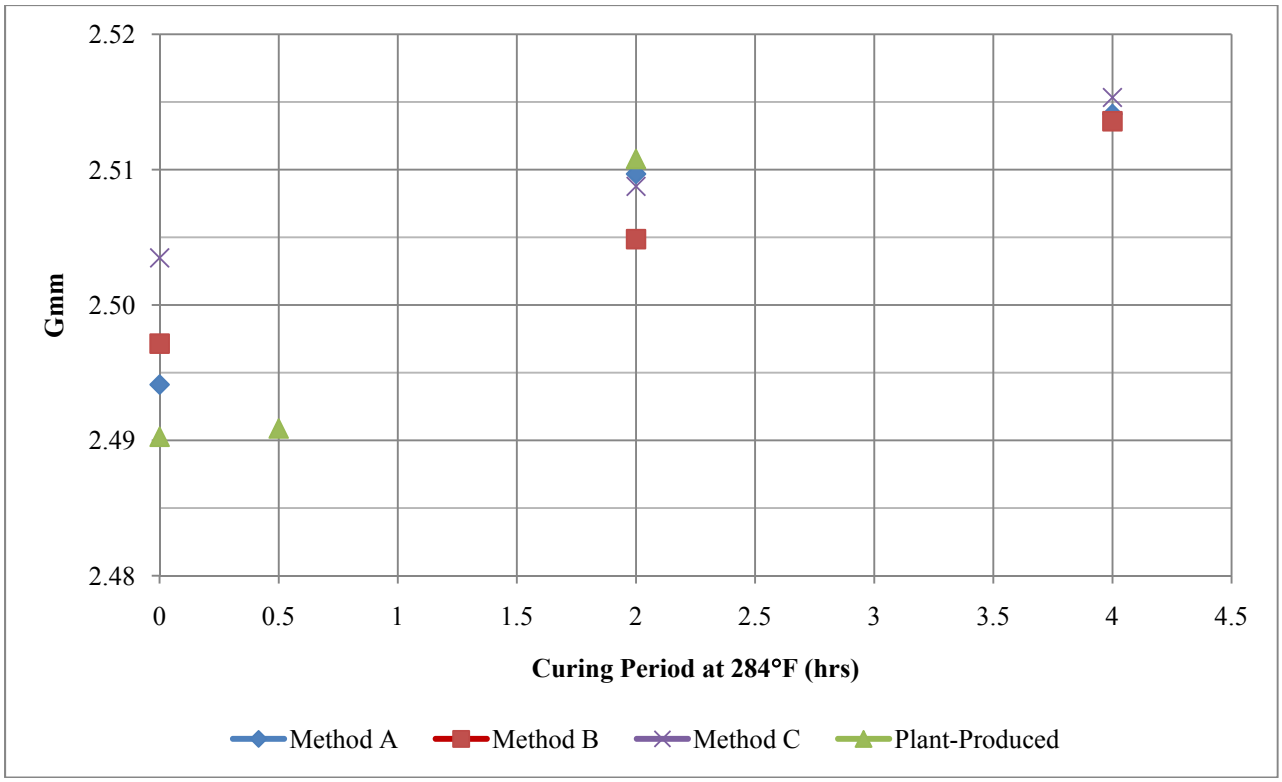

Figure 27 - Effect of Curing Time on Gmm

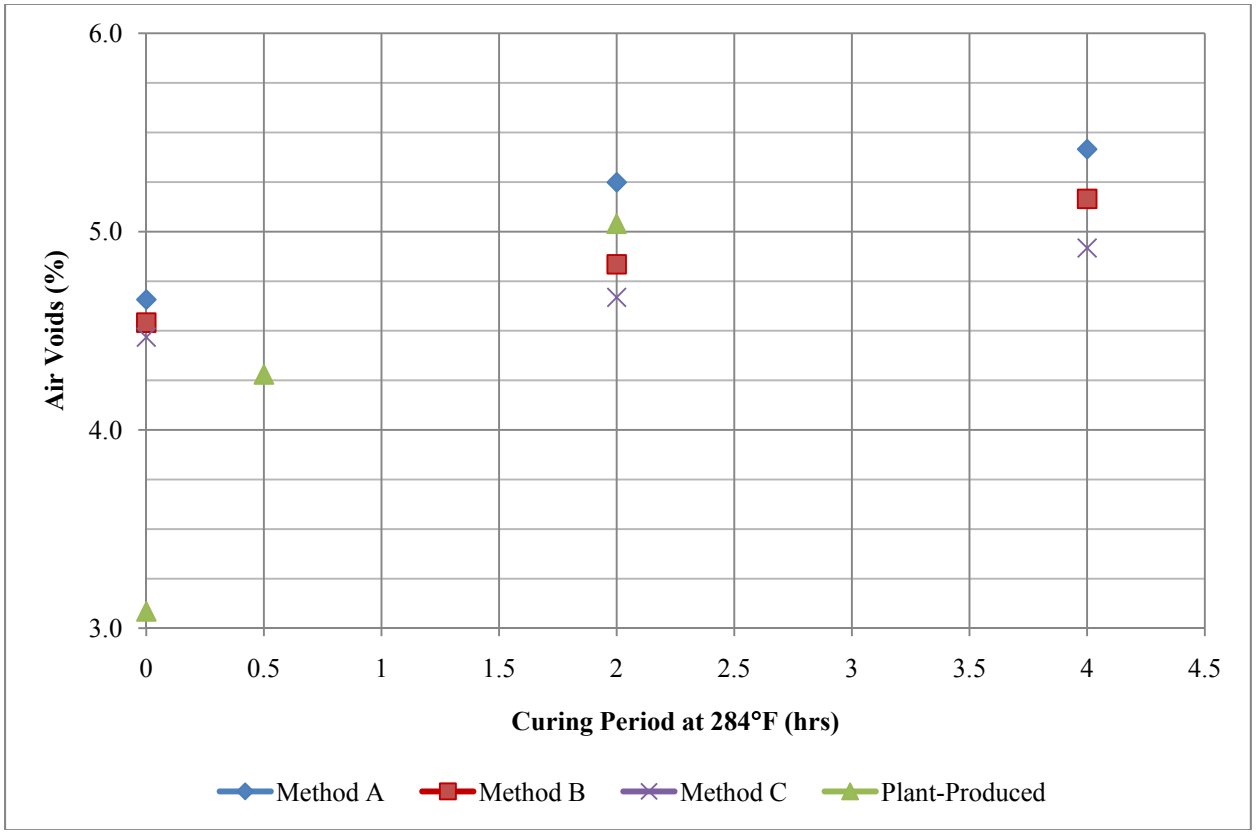

Figure 28 - Effect of Curing Time of Gmm on Air Voids

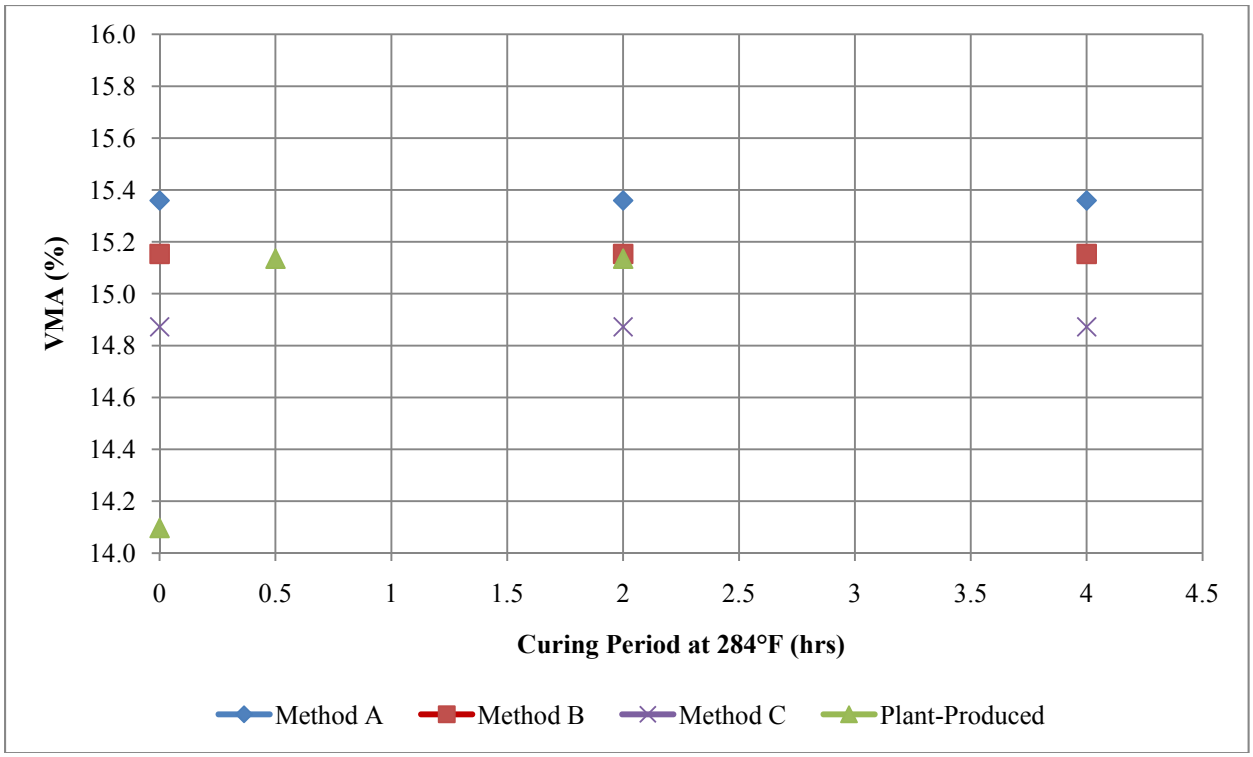

Figure 29 - Effect of Curing Time of Gmm on VMA

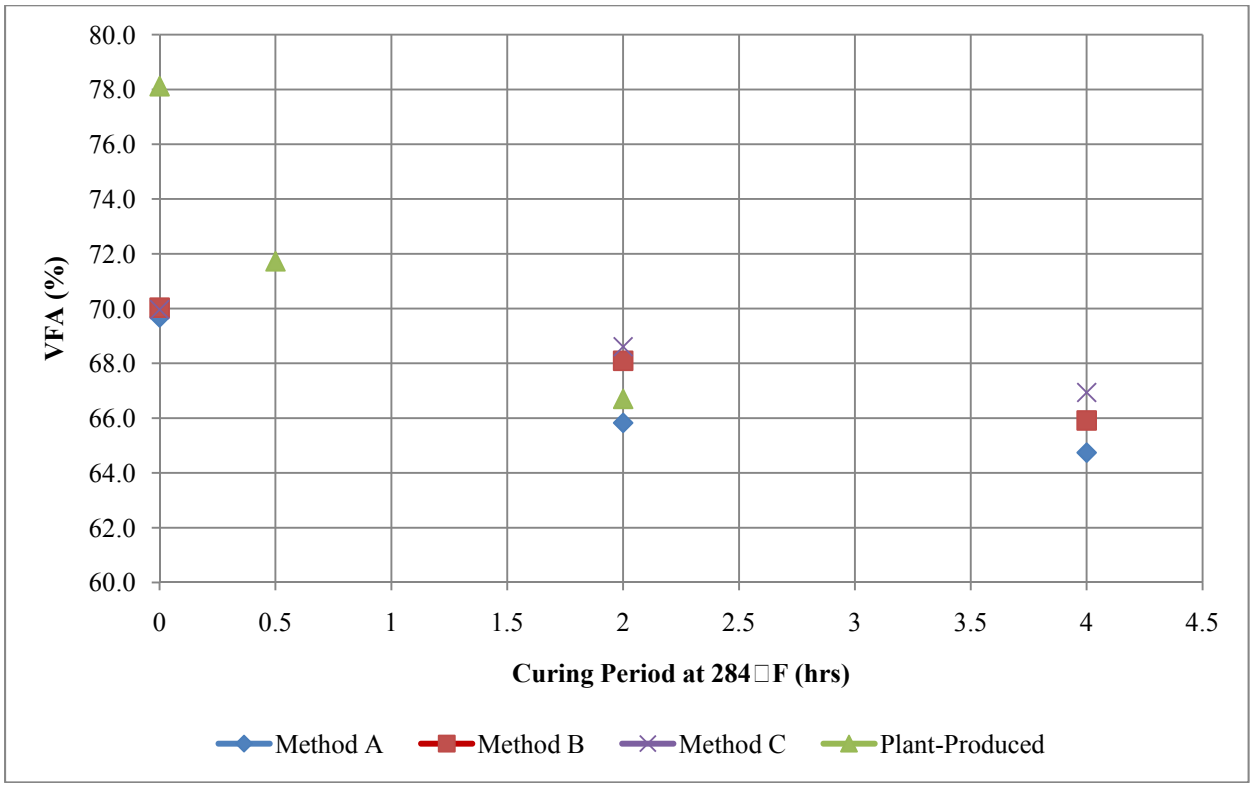

Figure 30 - Effect of Curing Time of Gmm on VFA

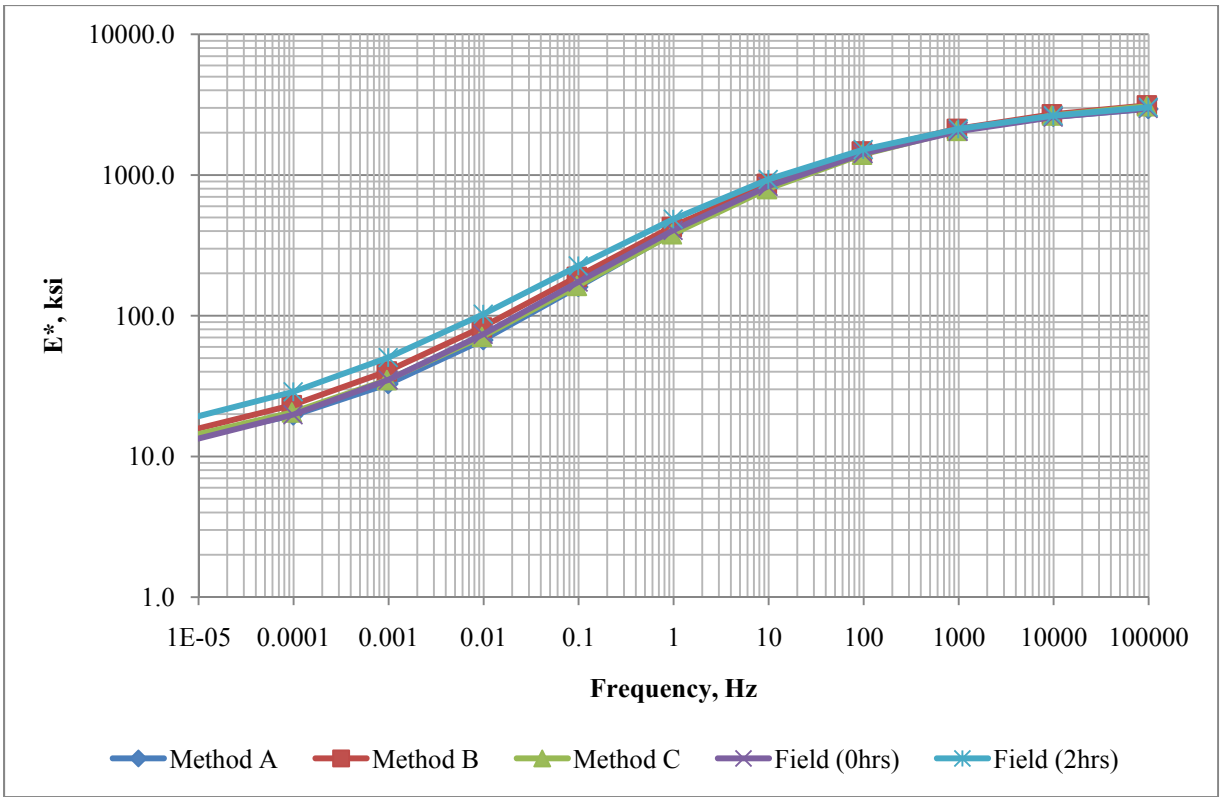

Figure 31 - Dynamic Modulus @ 70 °F – State Route 201

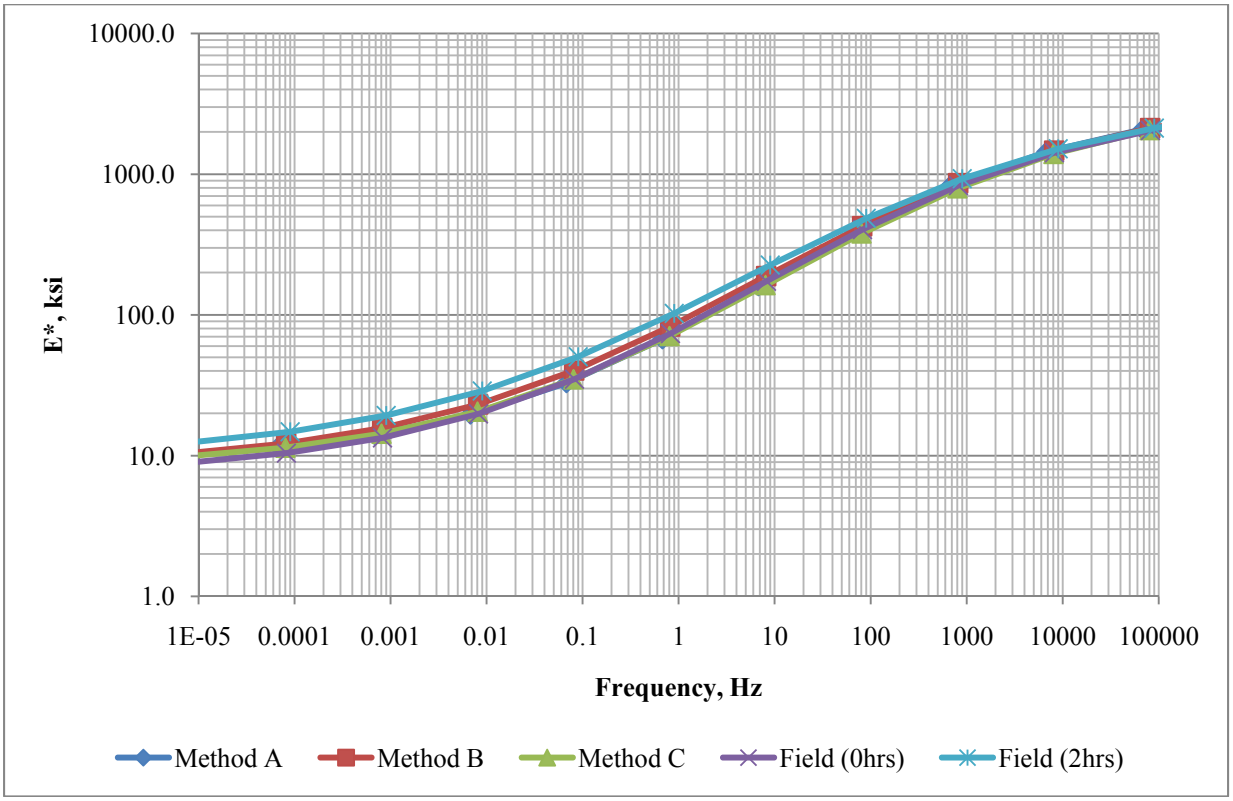

Figure 32 - Dynamic Modulus @ 100°F – State Route 201

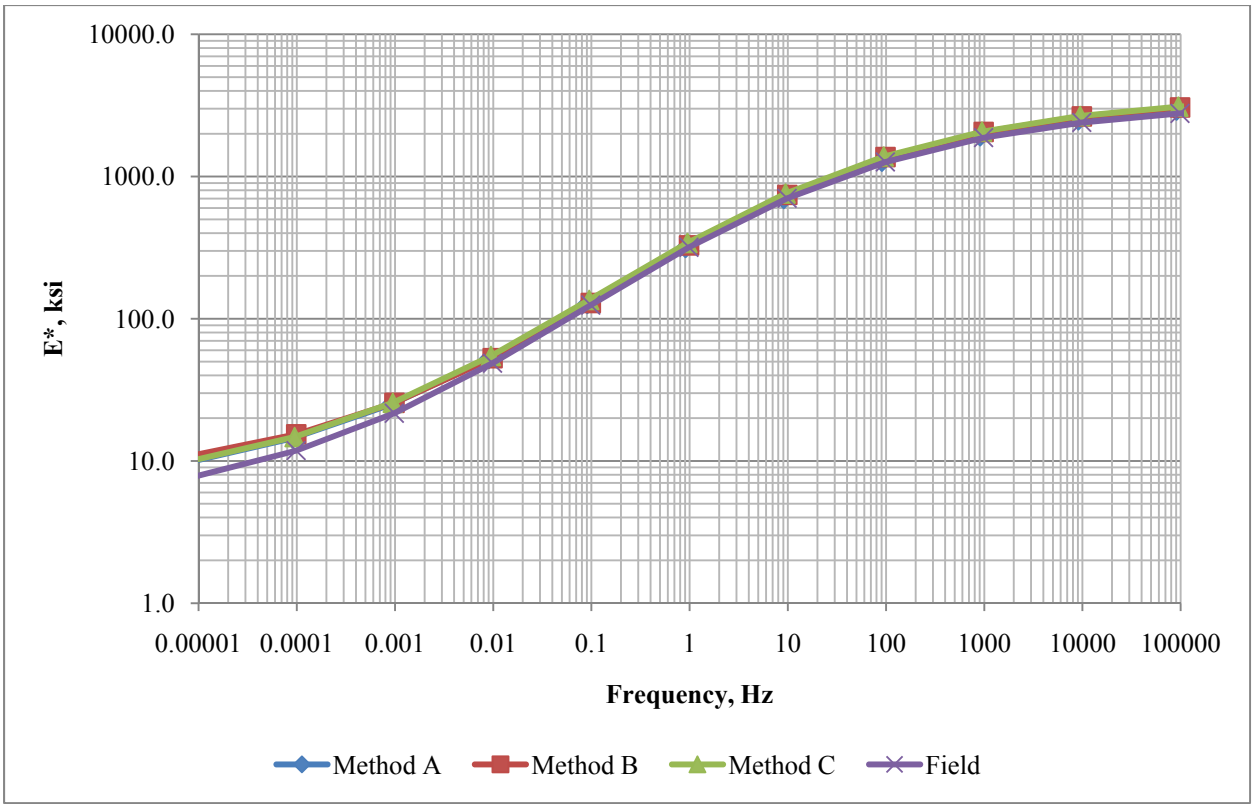

Figure 33 - Dynamic Modulus @ 70°F – Washington Fields

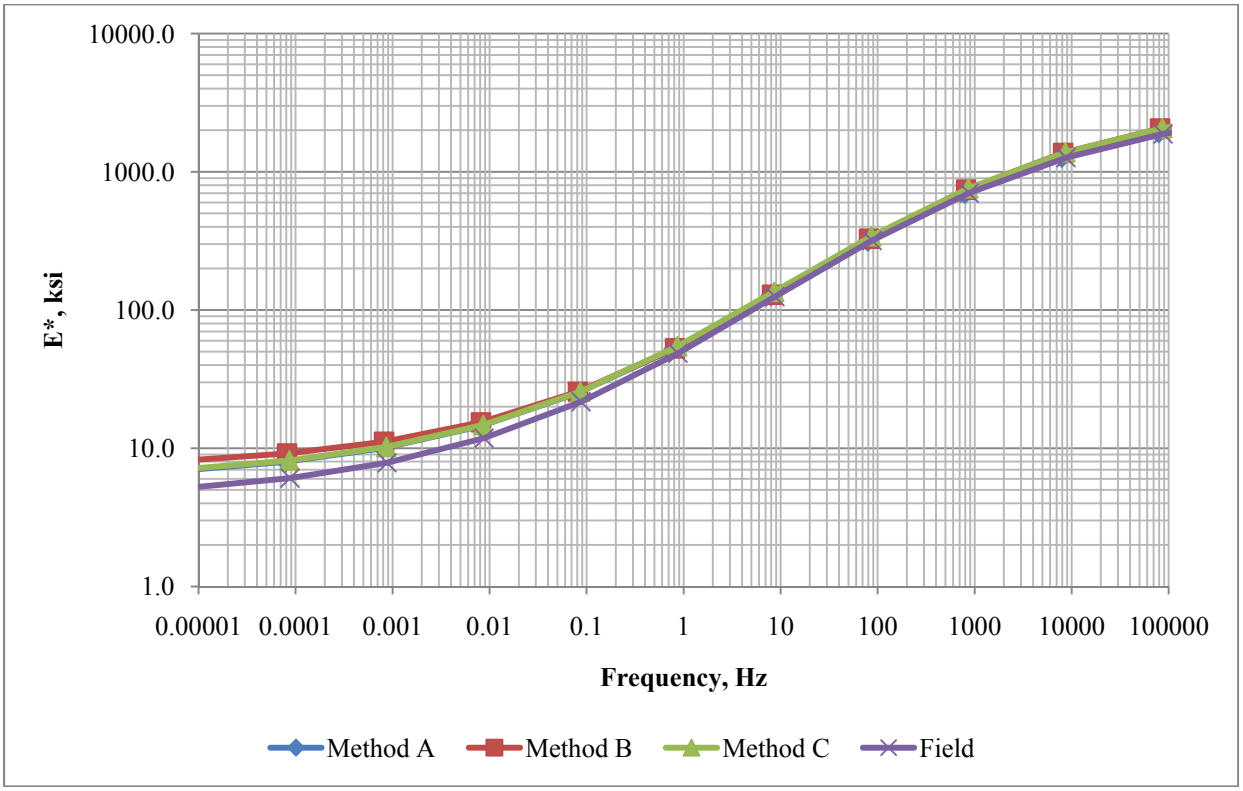

Figure 34 - Dynamic Modulus @ 100°F – Washington Fields

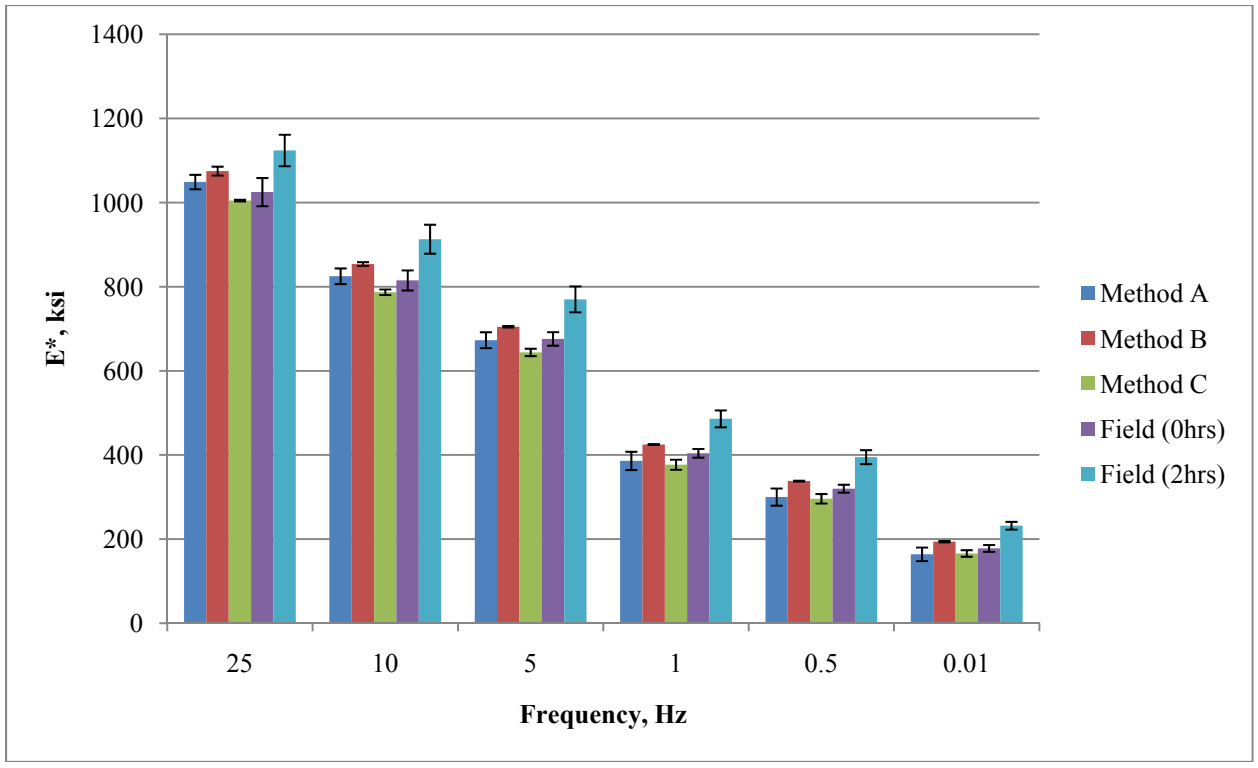

Figure 35 - Summary of E* Values @ 70°F - State Route 201

Error Bars represent minimum and maximum value of 2 replicates.

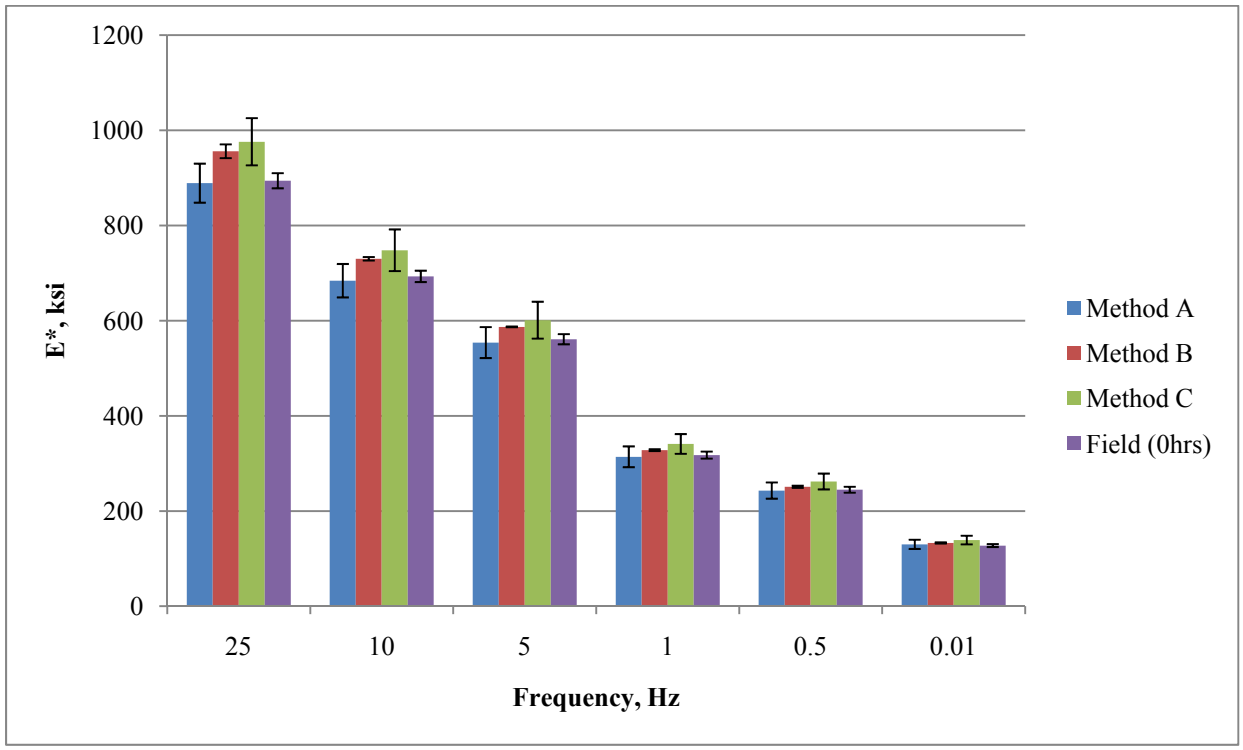

Figure 36 - Summary of E* Values @ 70°F - Washington Field

Error Bars represent minimum and maximum value of 2 replicates.

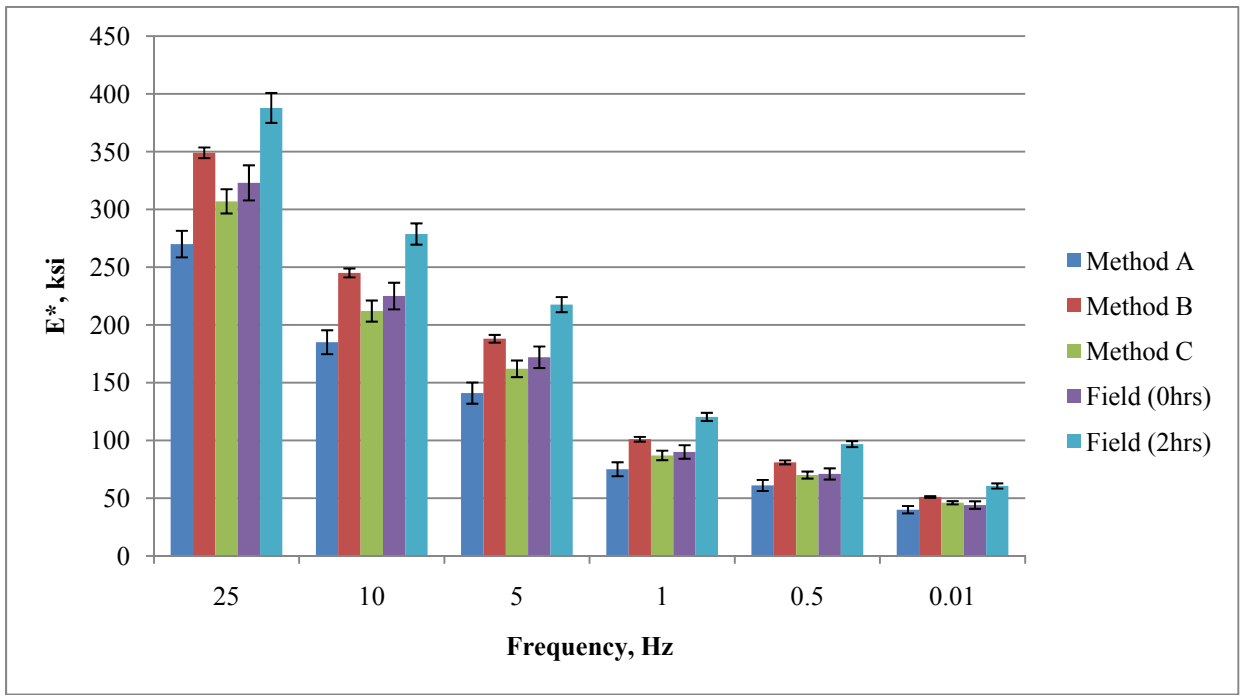

Figure 37 - Summary of E* Values @ 100°F - State Route 201

Error Bars represent minimum and maximum value of 2 replicates.

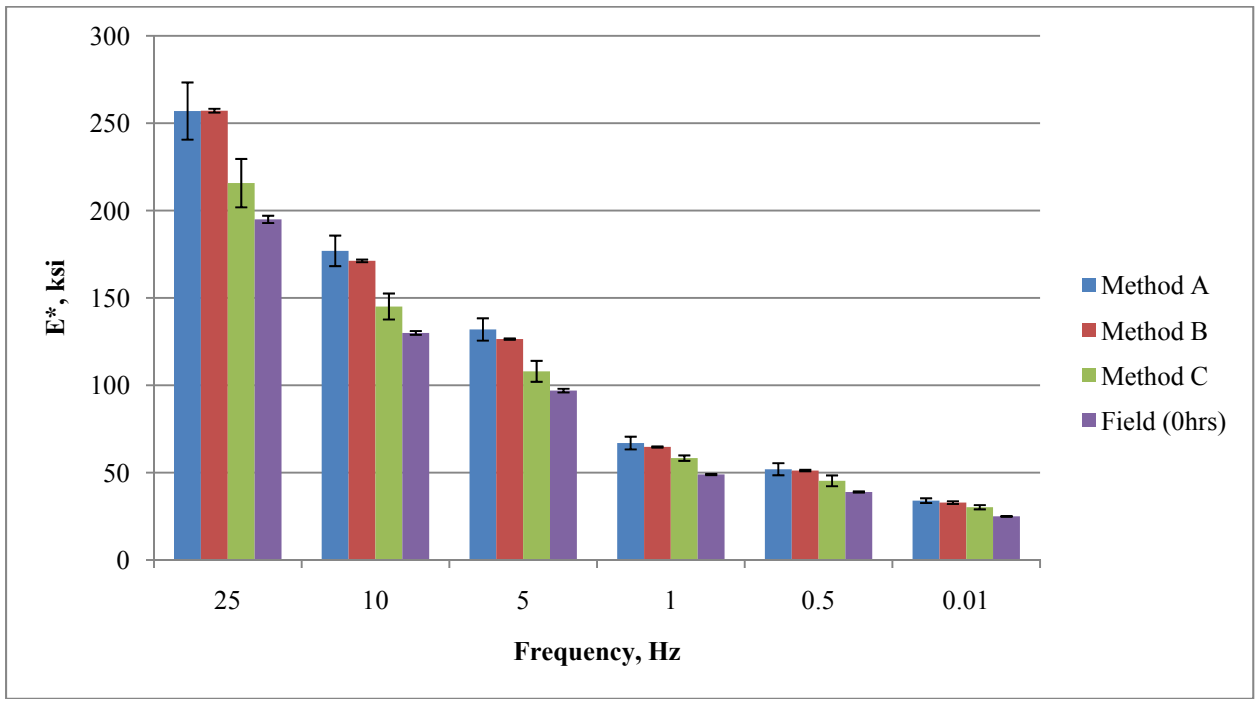

Figure 38 - Summary of E* Values @ 100°F - State Route 201

Error Bars represent minimum and maximum value of 2 replicates.