MOUNTAIN-PLAINS CONSORTIUM

MPC 19-405 | P. Romero

Prevention of Low Temperature Cracking of Asphalt Pavements Using the Bending Beam Rheometer

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October 2019

Acknowledgments

The author acknowledges the Utah Department of Transportation (UDOT) for funding this research, and the following individuals from UDOT on the Technical Advisory Committee for helping to guide the research:

- Scott Andrus
- Howard Anderson
- Steve Anderson
- Kevin Nichol

The author also acknowledges the following individuals and their work. A significant portion of the information contained in this report is the result of their hard work. This includes the following current and former graduate students:

- Abu Sufian Mohammad Asib
- Faramarz Safazadeh
- Daniel Sudbury, M.Sc.
- Yang Li, M.Sc.

The following people also provided value input for this work:

- Tim Biel from PEPG (formerly CME)
- Michael VanMilligen, from PEPG (formerly CME)
- Clark Allen from Utah Department of Transportation

The author also acknowledges the financial contribution from the Mountains-Plains Consortium.

ABSTRACT

An evaluation of the ability of the BBR as a test to determine changes in the low temperature properties of asphalt mixture parameters was conducted, along with the possible implications of adopting this test for low temperature pavement performance. It was found that the creep modulus and the m-value from the BBR are able to detect changes in binder content and air voids. The test indicates that RAP is detrimental to the overall expected performance of the mixtures when compared with a mixture with no RAP. The BBR appears to be a sensitive test capable of capturing the effect of aging and RAP on the material.

It was found that aging of the loose mixture at 135°C prior to compaction shows a more consistent trend than aging the compacted specimen at 80°C. One hour of loose mix aging at 135°C results in the same mechanical changes as 47 to 55 hours of compacted mix aging at 80°C.

Based on the results, it is concluded that adoption of the BBR as a required test might not affect the overall binder content of the mixtures but might affect the overall amount of RAP. The BBR appears to be capable of capturing the effect of aging and RAP on the material. Thus, adoption of the BBR as a specification test would likely result in changing the mixture design process to favor mixes with lower RAP content and less sensitivity to aging.

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LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
BBR	Bending Beam Rheometer
CME	Construction Materials Engineering
CoV	Coefficient of Variation – Percent Ratio of the Standard Deviation to the Mean
FHWA	Federal Highway Administration
FI	Flexibility Index AASHTO TP-124
HWT	Hamburg Wheel Tracking Test, AASHTO T-3
IFIT	Illinois Flexibility Index Test, AASHTO TP-124
ITS	Indirect Tensile Strength, ASTM D6931
LSU	Louisiana State University
MEPDG	Mechanistic Empirical Pavement Design Guide
ME	Mechanistic Empirical
PG	Performance Grade, AASHTO M-320
RAP	Recycled Asphalt Pavement
SCB	Semi-Circular Bending Test
SGC	Superpave gyratory Compactor, AASHTO T-312
UDOT	Utah Department of Transportation
VFA	Voids Filled with Asphalt
VMA	Voids in the Mineral Aggregate
VTM	Voids in the total mix
VECD	Visco-elastic Continuum Damage

EXECUTIVE SUMMARY

A research project was conducted to determine the ability of the Bending Beam Rheometer (BBR) to evaluate the effects of mix design factors such as binder content, air voids, RAP content, and laboratory aging on the predicted mixture performance at low temperatures. The goal of this research was not only to understand the capability of the test to relate to performance, but also to evaluate what effect adopting the test will have on asphalt mixtures produced in Utah. The experiment was separated into two parts: i) changes in binder content and air voids, and ii) RAP content and aging.

In regard to the air voids and binder content, it was found that the creep modulus, or m-value, is only moderately sensitive to changes in binder. A decrease in creep modulus was observed with increased air voids. In regard to the RAP content, the test indicates that RAP is detrimental to the overall expected performance of the mixtures when compared with virgin mix. Based on these observations, the BBR appears to be a sensitive test to capture the effect of aging and RAP on the material.

It was found that aging of the loose mixture at 135°C prior to compaction shows a more consistent trend that aging the compacted specimen at 80°C. An index valued, developed as part of this study for the BBR, combines both changes in modulus and changes in m-value. Using this index, equivalent times were obtained between both conditioning procedures. One hour of loose mix aging at 135°C results in the same mechanical changes as 47 to 55 hours of compacted mix aging at 80°C.

Based on the results from the low temperature test (BBR), it was determined that increases in binder content are beneficial to the overall performance of the mixture (at least at low temperatures). However, deficiencies in binder content seem to be a problem for the BBR results, as they indicate a desirable condition (lower modulus, same m-value) that is contrary to accepted knowledge. It is believed that adoption of the BBR as a specification for mixtures would not necessarily result in mixtures with higher binder content being favored during design.

The data indicate that aging causes mechanical changes in the material that relate to lower performance. The data also indicate that RAP is detrimental to the overall expected performance of the mixtures when compared with virgin mixes. Based on this observation, the BBR appears to be a sensitive test to capture the effect of aging and RAP on the material. Thus, adoption of the BBR as a specification would likely result in changing the mixture design process to favor mixes with lower RAP replacement.

It is recommended that the BBR modulus and m-value be used as parameters to evaluate low temperature properties of asphalt mixtures. Using these parameters, a true performance-based specification could be developed at the mix design stage.

1. INTRODUCTION

1.1 Problem Statement

An asphalt concrete pavement is, ideally, a continuous roadway having a smooth, unbroken surface while having the capacity to carry modern loading. Asphalt pavements are subject to distresses generally falling into five general categories. They are:

- Rutting – The permanent deformation of the pavement material from loads.
- Stripping – The separation of the binder from the aggregate.
- Fatigue Cracking – The development of cracks due to repetitive loads.
- Thermal Cracking – The development of cracks due to thermal contraction.
- Aging – The permanent change in the ability of the asphalt material to perform as designed, usually caused by oxidation or other chemical changes.

The design requirement that an asphalt pavement be continuous brings with it some challenging materials properties. One of the most interesting is the requirement that the pavement be able to expand and contract under temperature variation without breaking. This slow but repeated application of force will fracture even the strongest of materials; for example, a continuous steel rail track will break if curves are not provided, allowing contraction to move the track transverse to the alignment while maintaining some continuity. An asphalt material is able to deal with these forces by its ability to relax stresses. As long as the stress relaxation is faster than the stress buildup, the material can relieve energy through flow and heat rather than with the creation of new surfaces.

It is known that the ability of asphalt to relax stresses is reduced as the temperature decreases and as the rate of load application increases; therefore, testing of asphalt materials must consider both the temperature and the rate of load application. This requirement makes testing of asphalt materials more complicated in comparison with other construction materials. Since asphalt binder is the material that gives asphalt concrete its ability to relax stresses, many researchers have attempted to test the binder alone and link the behavior of asphalt binder to that of the asphalt concrete composite. However, this approach often fails to capture the interactions that occur between the asphalt binder and the aggregates and, more importantly, the effect of recycled asphalt pavement (RAP) and other additives. There has been only moderate success in this area and thus there is a need to develop practical tests of the asphalt concrete mixture (Mangiafico et al., 2016).

As the temperature increases and the speed of load application decreases, the behavior of asphalt materials changes and its ability to resist deformation decreases. This behavior leads to rutting. Over the past 30 years, many highway agencies, including UDOT, have given priority to rutting. UDOT has adopted the Hamburg Wheel Tracking (HWT) test to ensure sufficient rut resistance and to determine stripping susceptibility. Every mixture placed on Utah roads is tested for rut resistance at the design stage.

Emphasis on rutting behavior leads to the idea that rut resistant mixtures with high modulus could lead to thinner asphalt surfaces and cheaper pavements (Hajj et al., 2005). However, actual field projects have shown that when highly stiffened asphalt concrete is used, cracking occurs, moisture enters the pavement structure, and the underlying layers weaken leading to premature pavement failure. An example of this behavior observed in 2012 on SR 201 and 3200 West ramp in Salt Lake City, UT, is shown in Figure 1.1.

In response to the unbalanced mixture designs resulting from the emphasis on rutting, UDOT investigated the use of the Bending Beam Rheometer (BBR) in mixtures. Work done at the University of Utah and the University of Minnesota has shown that the BBR is a good alternative for asphalt mixture testing at low temperature (Zofka, et al., 2005; Ho and Romero, 2011; Romero, 2016).

The BBR places a constant load on a small asphalt mixture beam (12.5 x 6.75 x 127 mm [0.5 x 0.25 x 5 in]) and measures its deformation at mid-span; this process is described in detail in AASHTO TP125. The modulus of the material and the slope of the modulus versus time curve at 60 seconds have been successfully related to low temperature cracking performance (Jones et al., 2014; Romero, 2016). However, it is generally recognized that not all aspects of asphalt pavement performance can be addressed by measuring the modulus of the material. Some measurement of the strength or resistance to cracking of the material is also needed.

(a) Ramp facing north (b) Close-up of road showing cracks

Figure 1.1 Example of severely cracked road surface

Given that UDOT has addressed the rutting and stripping behavior of its asphalt materials through the HWT tests, it is important to concentrate on the other distresses. The modulus and m-value at 60 seconds from the BBR and the FI from the IFIT have the potential to address thermal cracking. However, to allow for a better understanding of the optimum asphalt mixture properties, a conjoint evaluation of both tests is desirable. Such an approach would lead to balanced asphalt mixtures, reducing premature failures, and improving pavement performance.

1.2 Objectives

The objective of this research is to develop an understanding of asphalt mixture performance at low temperature using the BBR and the effect that adopting this test might have on mixture design and subsequent pavement performance.

Specific objectives are:

1. Determine how the introduction of a low temperature test will affect the mixtures currently being used by UDOT in terms of binder content, RAP content, and aging.
2. Evaluate potential changes in mixture design resulting from the incorporation of low temperature tests.
3. Verify the ability of the BBR tests to detect changes in mixture components.

1.3 Scope

This study consists of the evaluation of asphalt mixture properties at one temperature using the BBR. The BBR addresses the cold temperature properties of asphalt mixtures. The test will explore the effects of increased or reduced binder content, increased RAP content, and increased laboratory aging on the same materials. Data will be produced by preparing samples appropriate to the BBR and testing them based on the established protocols.

Aggregates from local sources and a commonly used asphalt binder will be used in this study.

2. LOW TEMPERATURE TESTING OF ASPHALT MIXTURES

2.1 Overview

The performance requirements for asphalt pavements listed in Section 1.1 present a very interesting challenge in that asphalt mixtures must be evaluated based on mechanical tests that attempt to quantify the properties that are more relevant to the specific distress based on our understanding of material behavior. This is not always easy since there is the added requirement placed on test developers in that whatever test is implemented it will be perceived as practical for routine use. Furthermore, the mixtures used for evaluation must also represent the properties of materials placed on Utah roads. This section describes the testing of asphalt mixtures and the selection of materials to accomplish such tasks.

2.2 Low Temperature Testing of Asphalt Mixtures

Testing of asphalt mixtures will be done using the BBR. This test has been previously evaluated by researchers and showed promise in balancing the rigor with the practicality for determining mixture performance at low temperatures. A short description is presented next.

The BBR, shown in Figure 2.1 and in Figure 2.2, produces the creep modulus and the stress relaxation capacity (slope of the modulus versus time curve in a log-log scale), also called m-value, by applying the elastic solution to a simply supported beam. These values obtained in asphalt binders have been used to evaluate low temperature performance in pavements (Bahia and Anderson, 1995; Marasteanu, 2004). Using the BBR to test asphalt mixtures in place of binder was originally proposed by Marasteanu et al. (2009) and further advanced by Ho (2010), Romero et al. (2011), Ho and Romero (2011), and Clendennen and Romero (2014), who determined that BBR testing of small amounts of material can produce behavioral results that are representative of the entire mixture.

Figure 2.1 Cannon Bending Beam Rheometer

Prior to testing, each sample is soaked in the temperature-controlled bath for 60 minutes to ensure the entire beam is brought to test temperature. Each test produces a series of data that includes force and deflection as a function of time. These values are then used to calculate creep modulus and the m-value (slope).

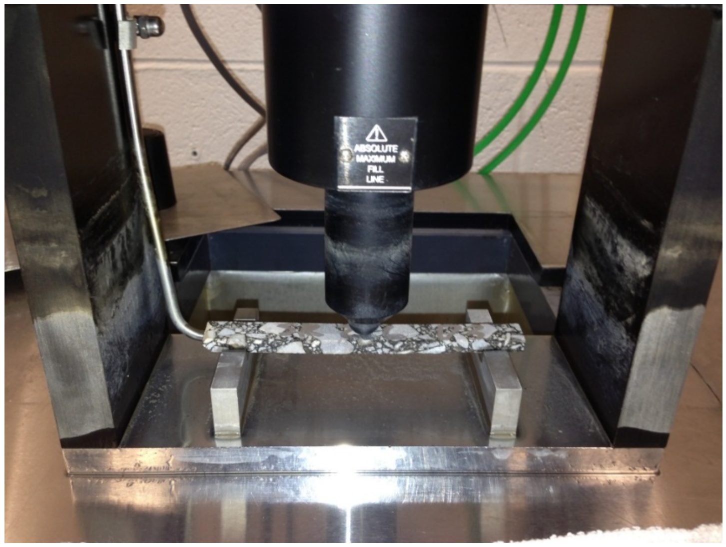


Figure 2.2 Sample beam in the BBR testing position (pictured out of bath for clarity)

2.2.1 Data Analysis

The BBR automatically records the load and the deformation of the beam. Knowing the beam dimensions and using beam elastic solutions along with elastic-viscoelastic correspondence principle, the creep modulus as a function of time of the material is determined. Standard software provided with the BBR automatically calculates the creep modulus and m-value at the end of the test and highlights these values at 60 seconds. Therefore, even though other times can be used, due to software convenience and consistency with binder testing, creep modulus and m-value at this specific loading time have been used to evaluate expected mixture performance.

More specific details of the BBR testing can be found in AASHTO Temporary Procedure TP 125-16: Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Mixtures Using the Bending Beam Rheometer. The procedure is available at the AASHTO website.

2.3 Selection of Asphalt Mixtures

In order to evaluate how the BBR might affect mixture designs, the same materials were used to perform all testing. Two different virgin mixture designs that met Superpave requirements were obtained from local contractors. One of these mixes, referred to as Mix A, is a 19-mm nominal maximum aggregate size (NMAS), 100 gyration Ndes; the other, referred to as Mix B, is a 12.5-mm NMAS, 75 gyration Ndes. A single asphalt binder graded as PG 64-28-UT was also selected to represent typical material used in the state, and a local source of RAP was obtained and used for all mixture variants. RAP binder content was approximately 5.2% by mass of the RAP with minor variation in the stockpile. The collected quarry aggregate was separated into individual sieve sizes. Sieve size #200 was washed to control the amount of dust filler entering the mix. One percent hydrated lime, based on the virgin aggregate weight, was added in a 3:1 slurry to all mixes. The gradations of mixes A and B are shown in Figure 2.3. Mix A is made with a low absorption limestone, and Mix B is made with a mixture of quartzite and granite. Tests done using the Hamburg Wheel Tracking (HWT) during mixture design indicated that both virgin mixes are rutting and stripping resistant, with HWT tests exhibiting less than 5-mm of rut depth and no secondary deformation slope in 20,000 passes at 50°C.

As part of the air voids and binder content investigation, a variant of Mix A had to be used. The adjustment in gradation came from not meeting volumetric properties set by AASHTO R35 Superpave specifications, as both the number of gyrations used for compaction and the binder content were varied. The amount passing the coarse aggregate sieves was increased, while the percent passing the fine aggregates sieves was decreased to create more of an “S” shape curve and support the changes. However, because each combination either received different compaction effort or different binder content, it was not practical to meet AASHTO R35 specifications for each sample. The actual details of the mixture variants are discussed in Section 3.2 of this report.

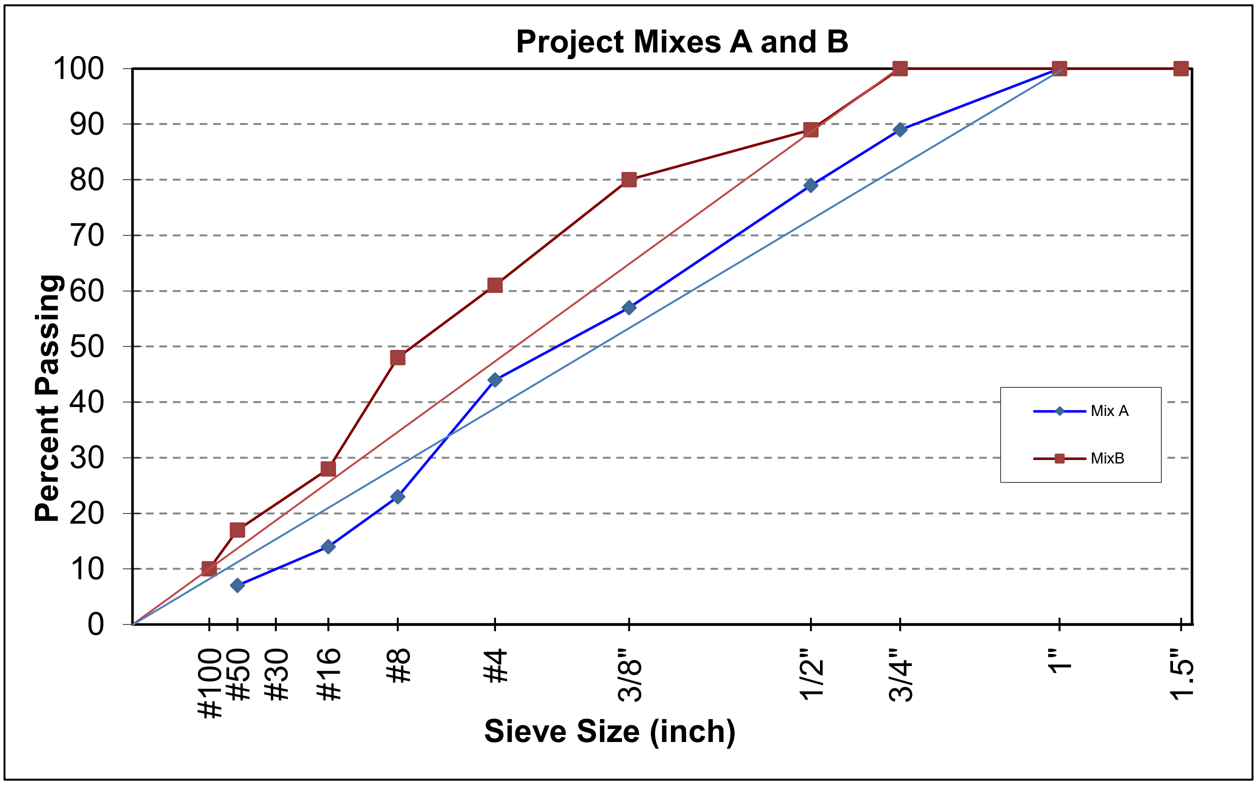


Figure 2.3 Base Mixture Gradations

2.4 Summary

This chapter presented a background of the testing procedures used to characterize the low temperature properties of asphalt mixtures. A short description of the BBR was given; however, a more detailed description can be found in previous UDOT reports.

3. EFFECT OF BINDER CONTENT AND AIR VOIDS

3.1 Overview

The binder content and the air voids of an asphalt mixture are two variables known to affect the mechanical behavior of the materials. It is important, therefore, to evaluate the ability of any test to capture the effects of both binder content and air voids. Alternatively, it is desirable to know the tolerances regarding these two variables when performing any test or if the tolerances, as proposed, yield accurate results.

An experiment was set up in which both the binder content and the air voids were varied. Ideally, those two factors are isolated; however, varying one will affect the other so both binder content and air voids were evaluated simultaneously. The results are discussed in this section.

3.2 Procedures

The experimental design for the BBR consisted of two experiments: varying compaction level while keeping binder content constant, and varying binder content while keeping compaction level constant. For each variation, Superpave gyratory compacted (SGC) cylinders were prepared at the University of Utah. The cylinders were cut into beams for testing on the BBR using the procedures outlined in AASHTO TP125.

After cutting, the beams were placed in a sealed container and tested after 24 hours. This was done to eliminate any variation that might be caused by steric hardening. Because the measured air voids of the SGC cylinders are not applicable to each individual cut beam, an alternative method had to be developed. Given the size of the beams (6.25x12.5x101 mm, ~25 g) and typical asphalt absorption of 0.5%, it was not possible to perform the AASHTO T166 bulk density test with the available analytical balance. Instead, the density of each beam was estimated by dividing the mass over the volume of the prismatic beams. The volume was measured using calipers accurate to 0.02 mm and the mass using a balance sensitive to 0.01 g. This density was compared with the theoretical maximum density determined according to AASHTO T209. These density values were used to calculate air voids where appropriate.

After labeling and volumetric measurements, 12 random samples were selected and evaluated for any possible damage, excessive air voids, or compaction that could likely affect test results. The two most excessively damaged samples were then removed from the sample population, and the flexural creep modulus of the remaining beams was measured on the BBR. Each beam was conditioned in the BBR bath at the low temperature of -18°C (PG+10°C) for 60 minutes prior to testing. The creep modulus and the m-value at 60 and 120 seconds were recorded and used for analysis. Based on the time temperature superposition principle, this is equivalent to testing the same binder at two different temperatures or testing two binders of different grades at the same temperature.

3.2.1 Mixture Properties

As was discussed in Section 2.3, two variations of Mix A were used in this experiment. The gradation is almost the same as that shown in Figure; however, due to the changes in both binder content and air voids, each sample had slightly different volumetric properties, which are shown in Table 3.1 and Table 3.2.

Table 3.1 Volumetric Properties of Samples for the Air Void Experiment

Mix A Variant I						
Binder Content, %	**Pb**	4.2				
Binder Grade	**PG**	64-28				
Design Gyrations	**N_{des}**	70	60	60	40	30
Air Voids, %	**VTM**	2.3	4.5	4.5	5.4	6.2
VMA, %	**VMA**	11.55	13.62	13.62	14.42	15.07
VFA, %	**VFA**	80.08	66.96	66.96	62.55	58.87
Dust Proportion	**D/B**	1.3				
Bulk SG	**G_{mb}**	2.432	2.375	2.375	2.353	2.225
Max. SG	**G_{mm}**	2.488				

Table 3.2 Volumetric Properties for the Binder Content Experiment

Mix A Variant II							
Binder Content, %	**Pb**	5.0	5.5	4.7	4.4	4.1	3.8
Binder Grade	**PG**	64-28					
Design Gyrations	**N_{des}**	75					
Air Voids, %	**VTM**	0.6	0.5	1.7	3.4	3.9	6.4
VMA, %	**VMA**	12.93	13.11	12.80	13.36	13.16	14.38
VFA, %	**VFA**	95.36	96.18	86.72	74.55	70.36	55.49
Dust Proportion	**D/B**	1.10	1.07	1.20	1.30	1.40	1.60
Bulk SG	**G_{mb}**	2.416	2.424	2.412	2.389	2.387	2.346
Max. SG	**G_{mm}**	2.431	2.436	2.453	2.472	2.483	2.507

3.2.2 Air Voids

In this experiment, compaction level was varied while binder content was held constant (at optimum) as shown in Table 3.1. Optimum binder content on the variant mixtures was found to be 4.2% after a sweep was performed. Five SGC cylinders were compacted ranging from 30-70 gyrations at increments of 10 gyrations for each cylinder. The bulk density of each cylinder was measured using AASHTO T166 and compared with the theoretical maximum density of 2.488 obtained from the mixture design based on AASHTO T209. The measured cylinder air voids ranged from 2.3% to 6.2% as shown in Table 3.3.

The cylinders were then cut into bricks, which were further reduced to beams for testing on the BBR as described in AASHTO TP125. As previously mentioned, for each SGC sample, 12 beams were randomly selected and the mean estimated air voids were measured. Air void measurements in Table 3.3 show the difference in air voids between beams and cylinders is about 0.5%. This is within typical ranges observed in prior research (Romero et al., 2011) and is believed to be the result of the smooth cut faces.

Table 3.3 SGC Cylinder Air Voids and Mean Estimated Air Voids in Beams

Gyrations	Compacted Height, mm*	G_{mb}	Air Voids, %	
			Measured Cylinder	Estimated Beam
70	110.7	2.432	2.3	2.1
60	114.3	2.375	4.5	5.1
50	114.2	2.375	4.5	6.0
40	115.5	2.353	5.4	6.0
30	116.3	2.335	6.2	6.8

*All samples had approximately the same mass

3.2.2.1 Air Void Results

Figure 3.1 shows that creep modulus increases with increasing compaction effort. It is believed that the space from the increased air voids at lower compaction levels allows for greater movement and thus results in a lower creep modulus. Figure 3.2 shows there is a general trend of decreasing modulus with increasing air voids at both 60 and 120 seconds. In contrast, the 60- and 120-second m-values for beams in Figure 3.3 seem to show no discernable trend in m-value with increasing air voids.

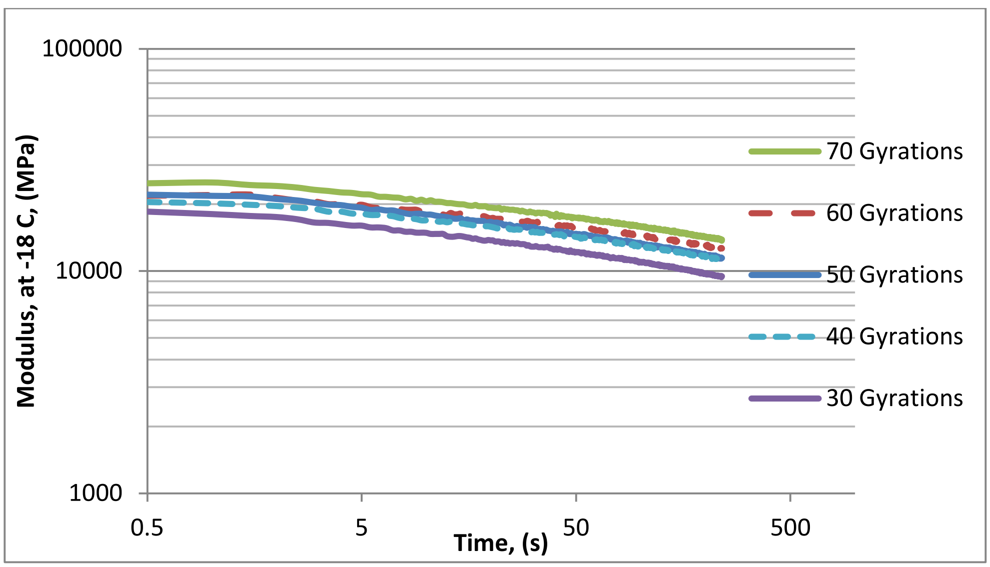


Figure 3.1 Average BBR results for varying compaction effort, binder content constant

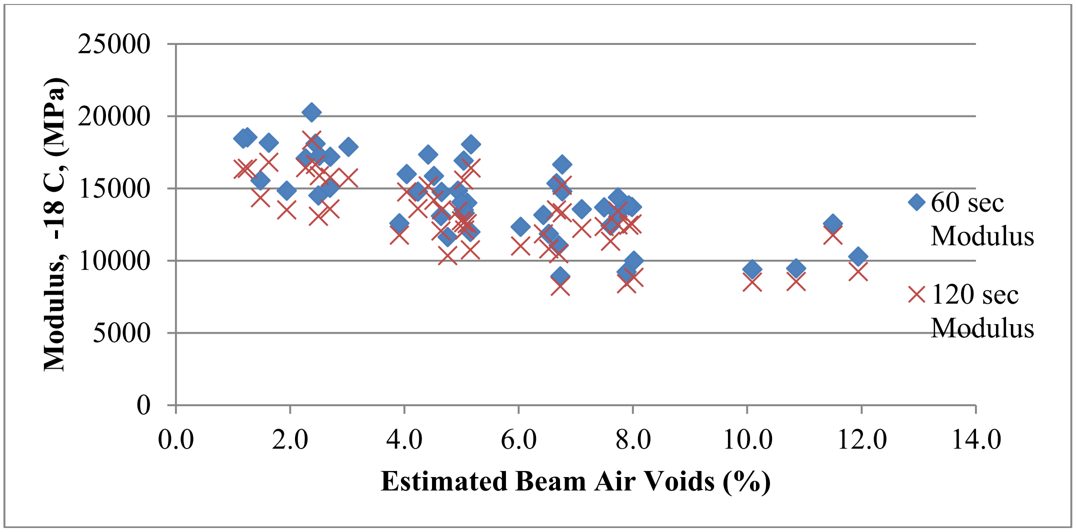


Figure 3.2 Beam stiffness with varying compaction effort, binder content constant

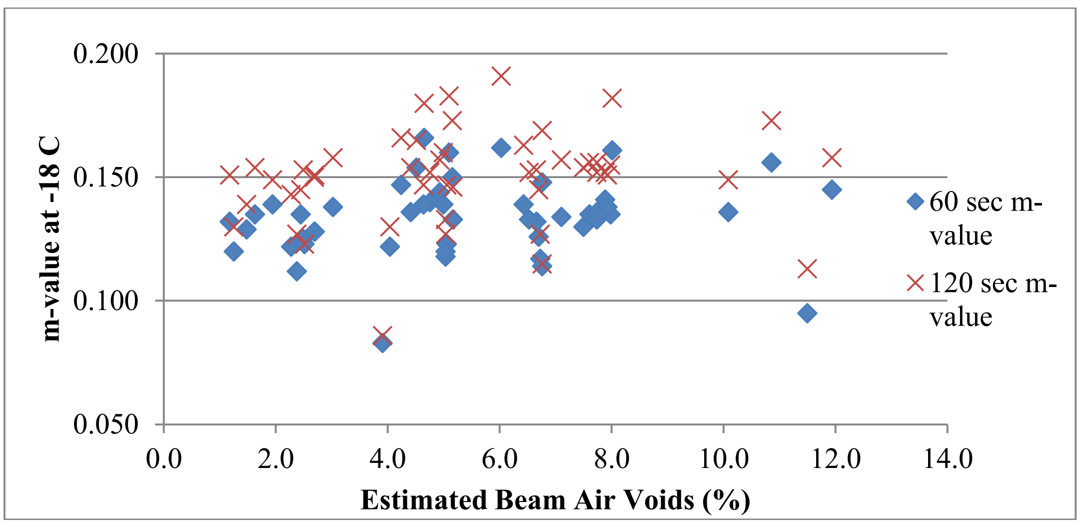


Figure 3.3 Beam m-value at varying compaction effort, binder content constant

To aid in the analysis and reduce some of the noise, the air voids were separated into discrete groups of 2% increments. This is shown in Figures 3.4 and 3.5. It is evident that the creep modulus decreases as the air voids increase. However, the same is not observed in the m-value as there is no discernable trend.

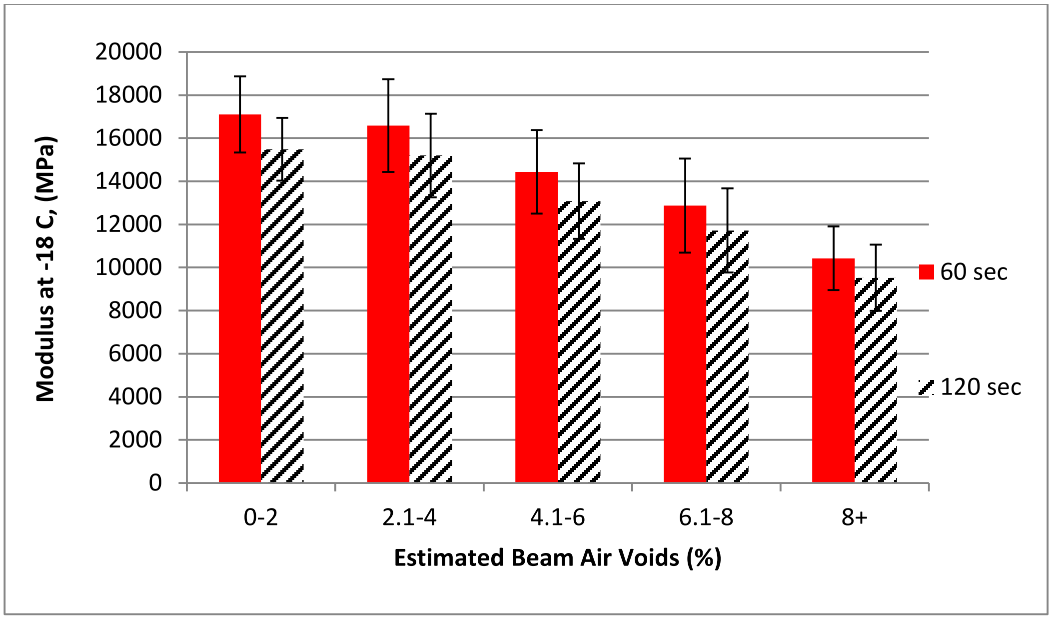


Figure 3.4 Average stiffness per air void grouping, binder content constant
Error bar represents 1 S.D.

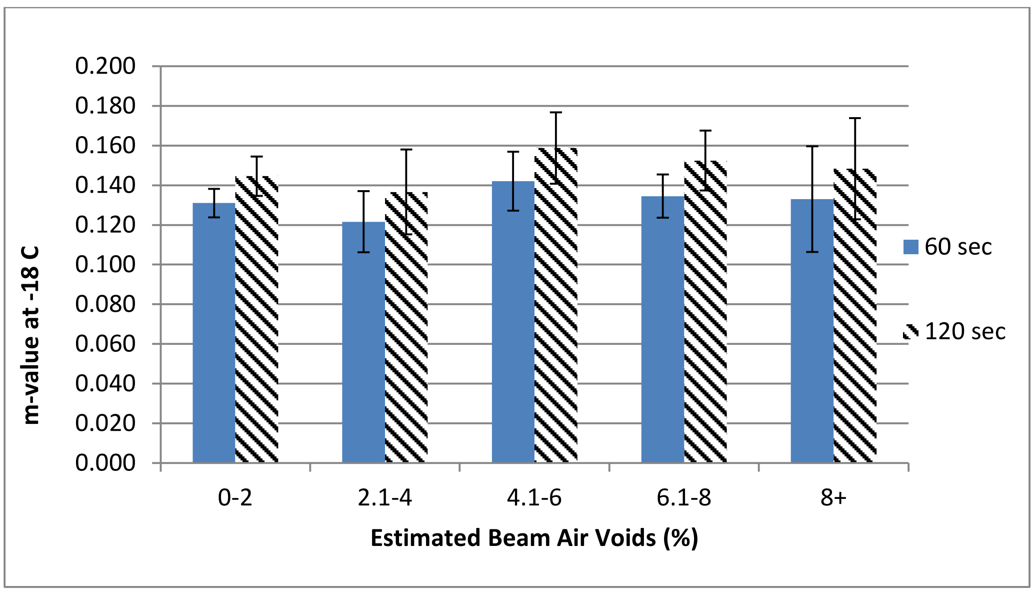


Figure 3.5 Average m-value per air void grouping, binder content constant
Error bars represents 1 S.D.

3.2.3 Binder Content

In this part of the experiment, the binder content was changed while the number of gyrations remained constant at 75. This resulted in compacted specimens with different properties as shown in Table 3.4. A binder sweep of the mixture was performed as shown in Table 3.2. In the binder content experiment, the cylinders used to determine the optimum binder content were the same samples used for the binder sweep. Binder content varied from 3.8% to 5.5% and air voids ranged from 0.5% to 6.4%.

Table 3.4 SGC Cylinder's Air Voids and Estimated Air Voids in Beams, Varying Binder Content

Binder Content, %	Gyrations	Compacted Height, mm	G_{mb}	G_{mm}	Air Voids, %	
					Measured Cylinder	Mean Estimated Beam
5.0	75	112.4	2.416	2.430	0.6	0.0
5.5	75	111.8	2.424	2.436	0.5	2.9
4.7	75	111.6	2.412	2.453	1.7	1.6
4.4	75	113.8	2.389	2.472	3.4	4.5
4.1	75	112.9	2.387	2.483	3.9	3.0
3.8	75	115.7	2.346	2.507	6.4	7.7

*Mass of aggregate was the same but total mass varied according to binder content

3.2.3.1 Binder Content Results

In the binder content experiment, with optimum binder at 4.2%, creep modulus values were highest for values closer to optimum. Figure 3.6 shows that the 4.1% binder content had the highest modulus followed by 4.4%. Creep modulus decreased with both increasing and decreasing binder content (from optimum). With increasing asphalt content, more asphalt is available to "flow," while decreasing asphalt content results in more voids and thus increased deflection. Figure 3.7a shows changes in creep modulus with air voids for different binder contents. The lowest binder content of 3.8% shows a greater spread of air voids. This is most likely because the binder distribution in the beams was uneven because there was an overall deficiency in binder content. The 120-second measurements in Figure 3.8a show similar results.

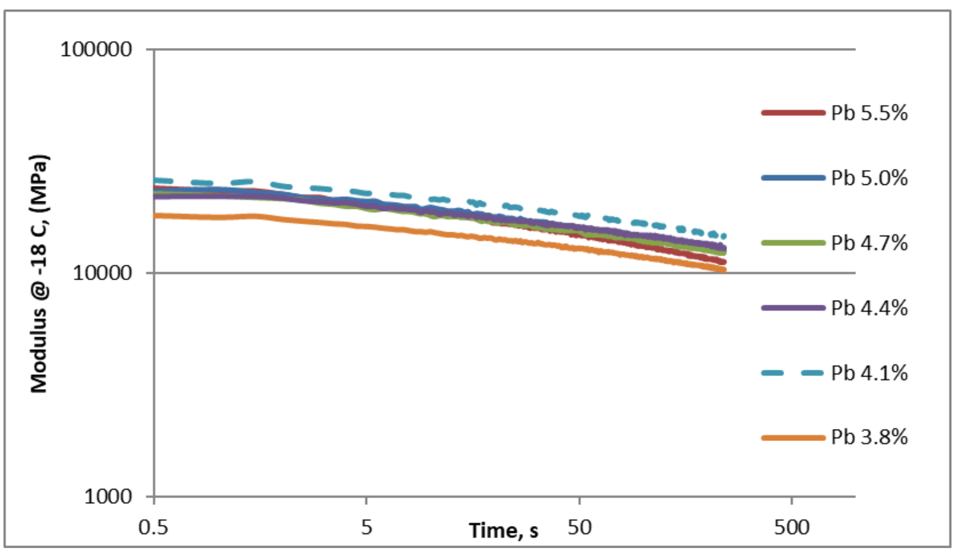


Figure 3.6 BBR creep modulus for varying binder content, compaction constant

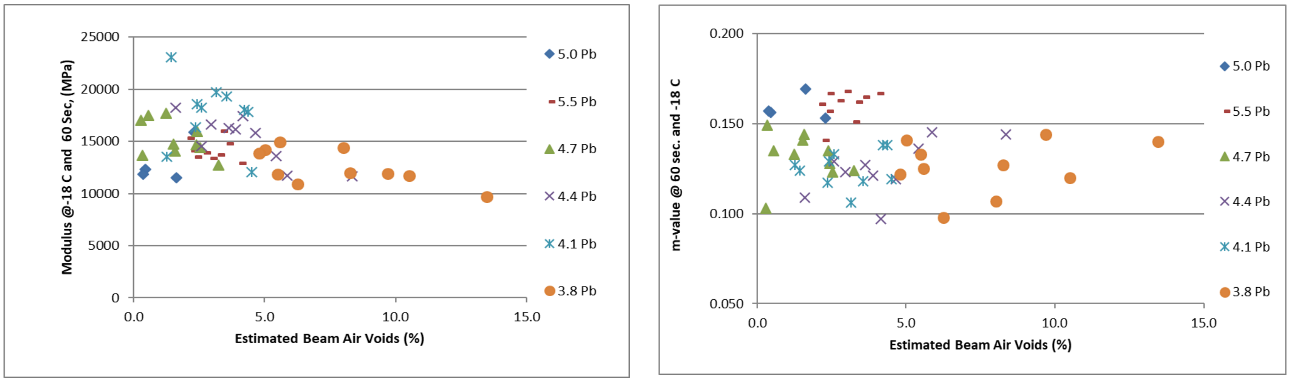


Figure 3.7a Creep modulus and b. m-value at 60 sec. varying binder contents, compaction constant

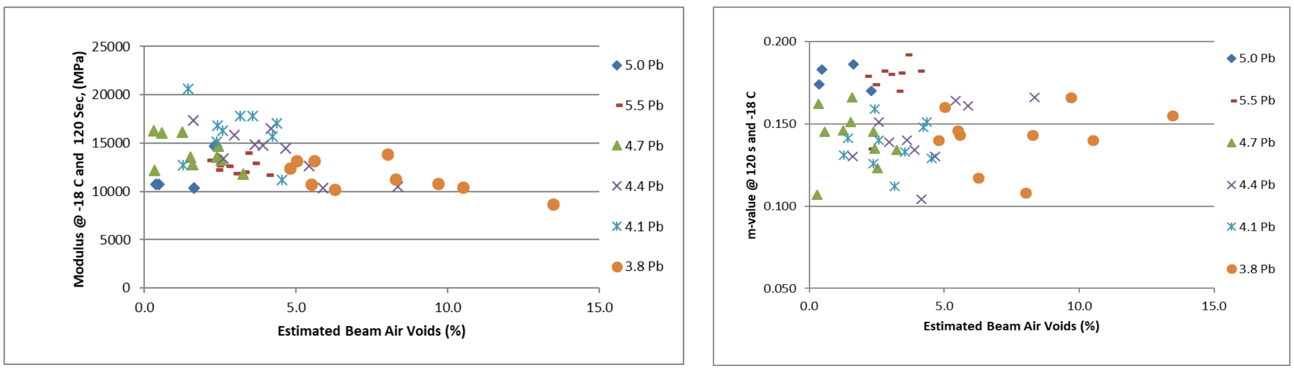
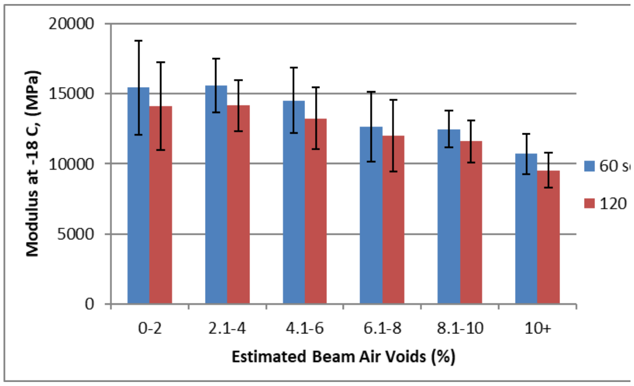


Figure 3.8a Creep modulus and b. m-value at 120 sec. varying binder content, compaction constant

Similarly to what was done with the air voids experiment, the data were separated into discrete values of air voids that resulted from the changes in binder content. Figure 3.9a shows a trend of decreasing creep modulus with decreasing air void groups. In contrast, evaluation of the m-value in Figure 3.9b for air void grouping shows that negligible change occurs at different air void contents and no clear pattern is observed.

Figure 3.10 shows the average values for different binder contents. For binder content above the optimum (4.2% for gradation and compaction), only a small decrease in creep modulus is observed. A small decrease in binder content below optimum (4.1%) shows a noticeable increase in creep modulus; further reduction in binder content to 3.8% reverses the trend showing an actual decrease in modulus. This is similar to what is observed in Figure 3.6. The reason for this behavior is believed to be changes in film thickness and how it changes the ability of the aggregates to move in relation to one another; however, at some point, there is a loss of cohesion resulting in a lower modulus. Thus, the amount of asphalt binder available plays a significant role in the creep modulus of binder deficient mixtures but not so much in mixtures with excess binder. It is not known if this behavior applies to different gradations or if it is specific to the mixture used in this portion of the study. Analysis of the m-value shows only slight variations as the binder content changes. The m-value is related to the relaxation capacity of the material, and this property does not change with air voids or film thickness.



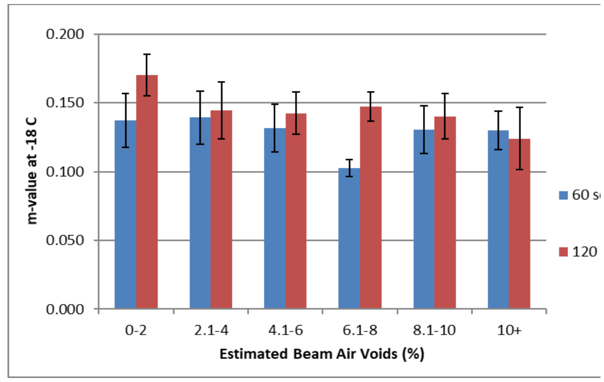


Figure 3.9a Average creep modulus, and b. average m-value per air void grouping at 60 and 120 sec., binder content varied. Error bars represent 1 S.D.

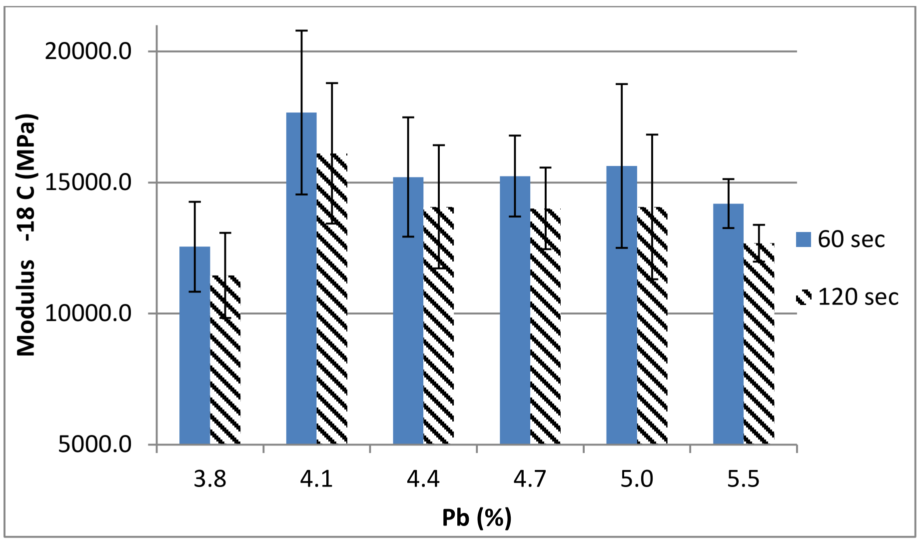


Figure 3.10 Average creep modulus per binder content grouping, compaction constant Error bars represent 1 S.D.

3.3 Summary

Based on the analysis of the BBR results, the following can be determined:

1. 60- and 120-second creep modulus from SGC samples varying compaction with binder content constant: From beams measuring 0% to 2% air voids compared to beams with greater than 8% air voids, creep modulus roughly decreases by 30%. The 120-second creep modulus follows the same trend.
2. M-values at 60 and 120 seconds are not affected by air void content.
3. 60- and 120-second creep modulus from SGC samples varying binder content with compaction level held constant: The creep moduli are approximately constant with binder contents close to the optimum of the mixture design. At great deficiencies or excessive quantities of binder contents, creep modulus values differ significantly. A greater difference in creep modulus is seen in mixes deficient in binder content compared to mixes with excessive binder content. A mixture deficient in binder content can have decreased results on the magnitude of 30%, while a mixture with excessive binder content will have a difference of about 15% or half of the deficient binder mix.
4. M-value is independent of binder content.

By looking at the results from the BBR, it is clear that an increase in binder content is beneficial to the overall performance of the mixture (at least at low temperatures). As the binder content increases, the BBR results show a slight decrease in creep modulus; this condition is associated with better performance. Deficiencies in binder content seem to be a problem for the BBR results as they indicate a desirable condition (lower modulus, same m-value), which is contrary to accepted knowledge. A decrease in creep modulus was measured with increased air voids.

Finally, while the test shows variations in results with changes in volumetrics (binder content and air voids), the test is not expected to be used for volumetric verification as there are better tools available for this purpose.

4. EFFECT OF RAP AND AGING

4.1 Overview

In this part of the study, the effect of RAP and aging on the low temperature performance of asphalt mixtures was investigated using the mixtures described in Section 2.3. Aging and RAP content were studied together given that the binder in the RAP has already been aged in the field and it is common practice to assume a portion of that binder will blend with the virgin binder. The process and amount of blending that actually occurs is not well understood, but will depend, among other factors, on the temperatures the mixtures are subjected to. The same elevated temperatures will also age the virgin binder.

Understanding the effects of aging in asphalt binders and how the virgin binder is replaced with aged material is important for controlling the low and intermediate temperature cracking behavior of pavements. It is believed that increasingly aged binders have detrimental effects in the performance of asphalt mixtures once placed in the field; therefore, any test used in asphalt mixtures must be able to capture the addition of RAP and progressive aging. In this study, an experimental matrix, shown in Table 4.1 was developed to look into increased aging and aged binder replacement.

Table 4.1 Experimental Matrix

Binder	**Gradation**	**Aggregate Type**	**RAP, %**	**Aging Protocols**	
				Loose Mixture At 135 °C, hours	Compacted Mixture At 80 °C
PG 64-28	A 19mm NMAS	Limestone	0, 15, 25, 35	0, 3, 6	48, 120, 168 hours (2, 5, 7 days)
	B 12.5 mm NMAS	Granite			

4.2 BBR Testing

For the low temperature part of this study, 48 mixture pucks were prepared using standard procedures for Superpave gyratory compacted (SGC) asphalt mixtures and tested as described in Section 2.2.1. The samples were made using varying RAP content and laboratory aged for different intervals both before and after compaction, as shown in Table 4.1.

4.2.1 Procedures

As shown in Table 4.1, three RAP contents, 15%, 25%, and 35%, were selected for this study in addition to the normal control mixtures, which are designated as 0% RAP mixtures. To investigate the effect of long-term aging, the samples were subjected to two different temperatures either before or after being compacted. For those being aged prior to compaction (i.e., loose mix), a temperature of 135ºC was used; the mixtures were aged for an additional three hours and six hours before compaction. These mixtures are called loose mixtures. The rest of the mixtures were compacted and placed inside a forced-draft oven at 80ºC for periods of two, five, or seven days. Following the aging protocols, the compacted samples were then cut into beams for BBR testing. With four different RAP contents and six different aging periods, 24 different combinations of mixtures were obtained for each aggregate source; therefore, a total 48 asphalt concrete mixtures were used for this part of the experiment.

4.2.2 Results

A summary of results of the effect of aging for different RAP content are shown on Appendix Data Table A.1 and Table A.2. As seen in the tables, the data are very consistent; in all cases, the coefficient of variation (standard deviation divided by the mean) was below 15% and quite often below 10% for both the modulus and the m-value. This is consistent with previous reports and is an indication of the quality of the results, the ease of testing, and the reliability of the test.

The data for each condition were plotted showing the change in creep modulus and the change in m-value for each of the mixtures tested. No error bars are shown on the figures but, as previously stated, the coefficient of variation was below 15%.

The results in Figure 4.1 show that, as the RAP content increases, the creep modulus also increases at each aging condition. The increase in Mix A's creep modulus to the addition of 35% RAP is almost 30% (Figure 4.1b); while Mix B shows an increase in creep modulus of almost 50% for the same RAP content (Figure 4.1d). This indicates that the interaction between RAP and virgin material is probably mixture dependent. Mix B has more binder than Mix A, thus it is not unreasonable to expect greater changes. It could be argued that binder replacement (i.e., less virgin binder in the mix and not complete blending) could be responsible for some of the changes observed. However, it was shown in Section 3.2.3 that the magnitude of the change in the modulus is not likely from a change in binder content alone; therefore, the changes observed are the results of aging the binder and some blending of the RAP with the virgin mix.

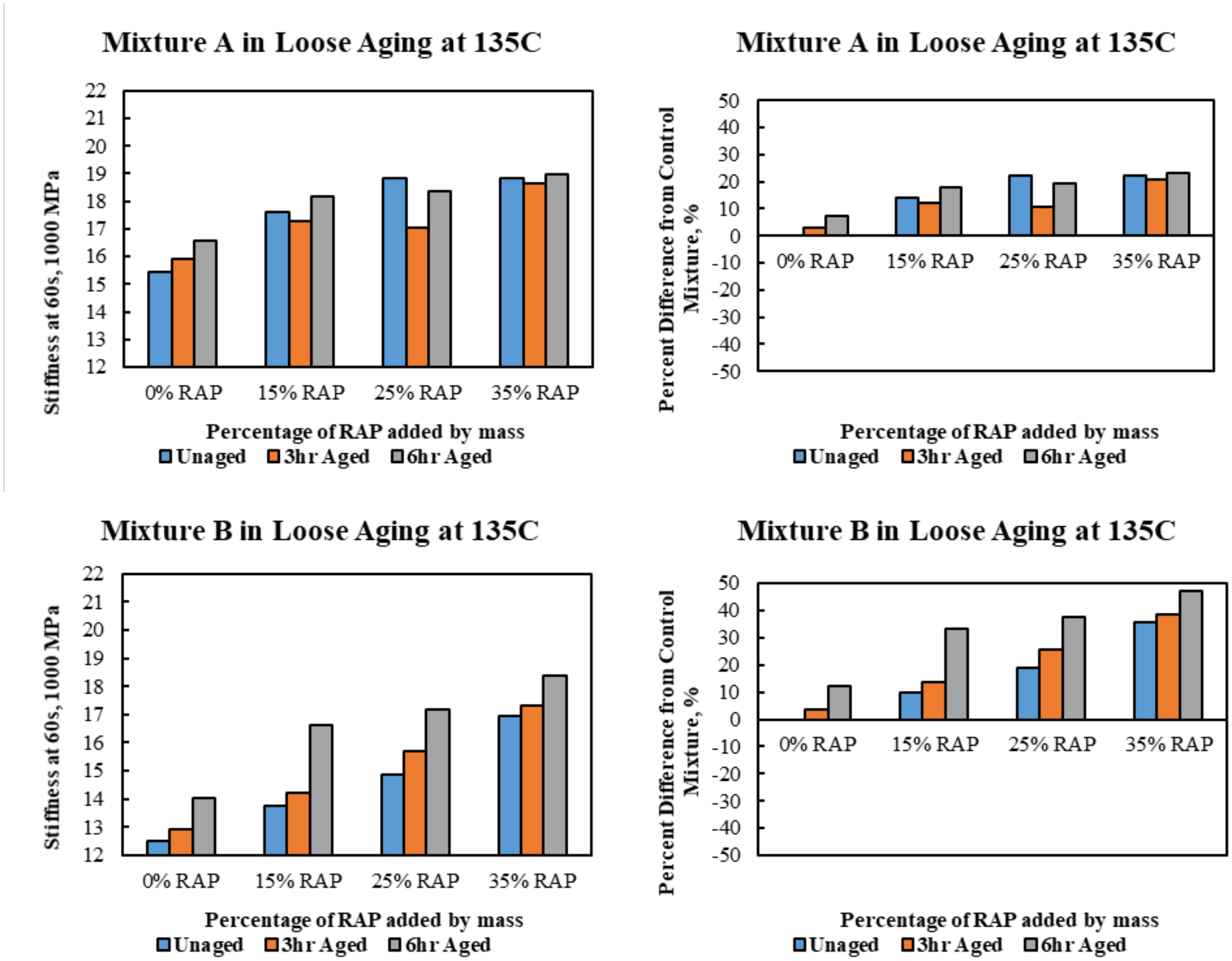


Figure 4.1a-d Effect of RAP on creep modulus for different aging times

Aging of the loose mixture at 135°C for three or six hours results in an increase of modulus regardless of the RAP content. However, Figure 4.1a and Figure 4.1b show that, when RAP is added to Mix A and the loose mixture is aged, a reduction in creep modulus can be observed between the unaged to the three-hour aged condition. The reason for this is not clear, but it is not believed that it represents an improvement in expected performance. Perhaps this behavior could be caused by loss of cohesion from the loss of volatiles in the binder. Mix A is a coarser mixture with lower binder content as compared with Mix B. Mix A also has an overall higher creep modulus, so perhaps there is a limiting or asymptote value around 18,000 MPa that must be considered.

Figure shows results for the m-value. The data show that an increase in RAP decreases the m-value and, just as was seen for the modulus, the effect of loose mixture aging is not consistent for Mix A (Figure 4.2a and Figure 4.2b); but a consistent decrease in m-value for Mix B is seen with increased RAP content (Figure 4.2c and Figure 4.2d).

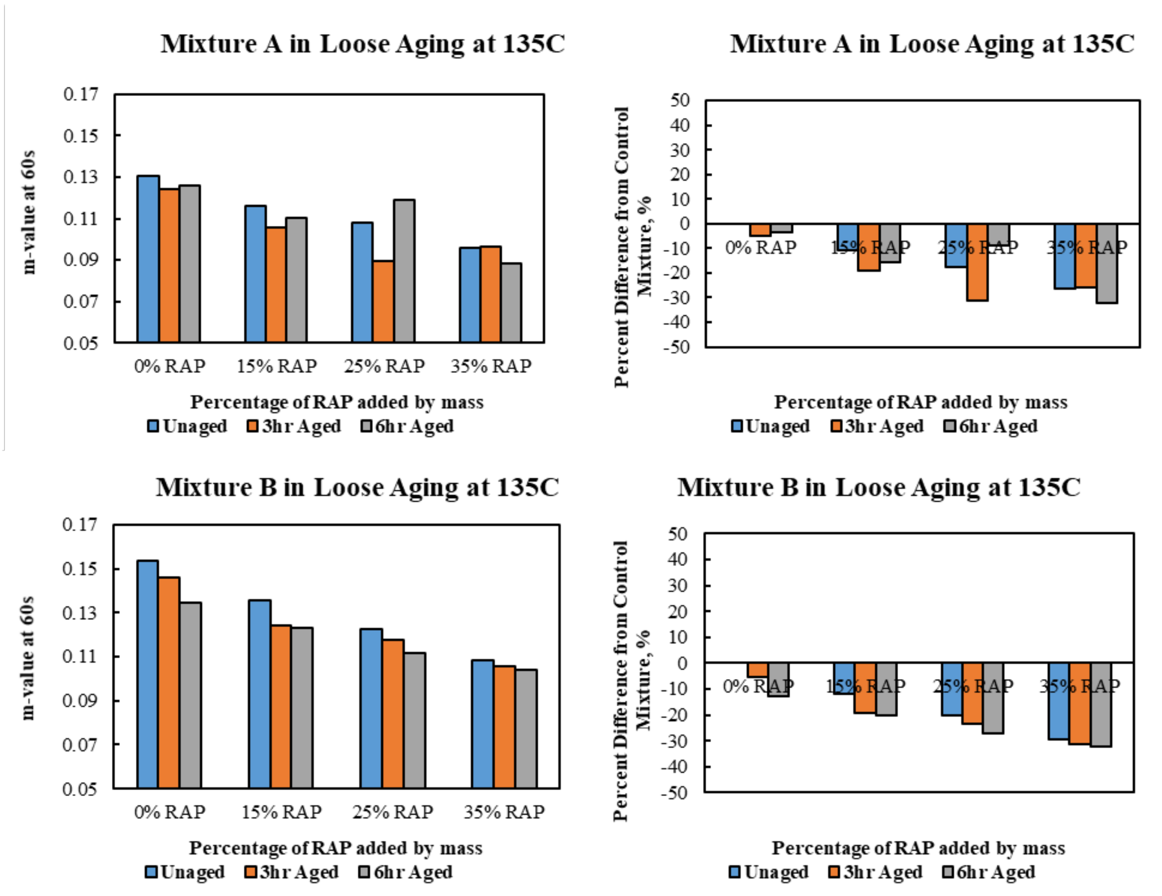


Figure 4.2a-d Effect of RAP on m-value for different aging times

When evaluating the overall trend, it is evident from the results that adding RAP to a mixture increases the creep modulus and decreases the m-value. These changes mean that even a moderate amount of RAP, as low as 15%, can be captured by the BBR tests. The test predicts that the addition of RAP is detrimental to the low temperature mixture performance.

Figure 4.3 shows the effects of increased RAP content on the creep modulus but with aging done on the compacted samples at 80°C. Mix A shows some scatter in the results with some cases having a decrease in modulus after aging (Figure 4.3a). For example, mixtures with 15% and 25% RAP have a lower modulus after seven days of oven aging than the same mixtures with no aging. Mix B shows a consistent trend of increased modulus with increased RAP content. It is believed that the scatter observed in Mix A is related to the lower binder content.

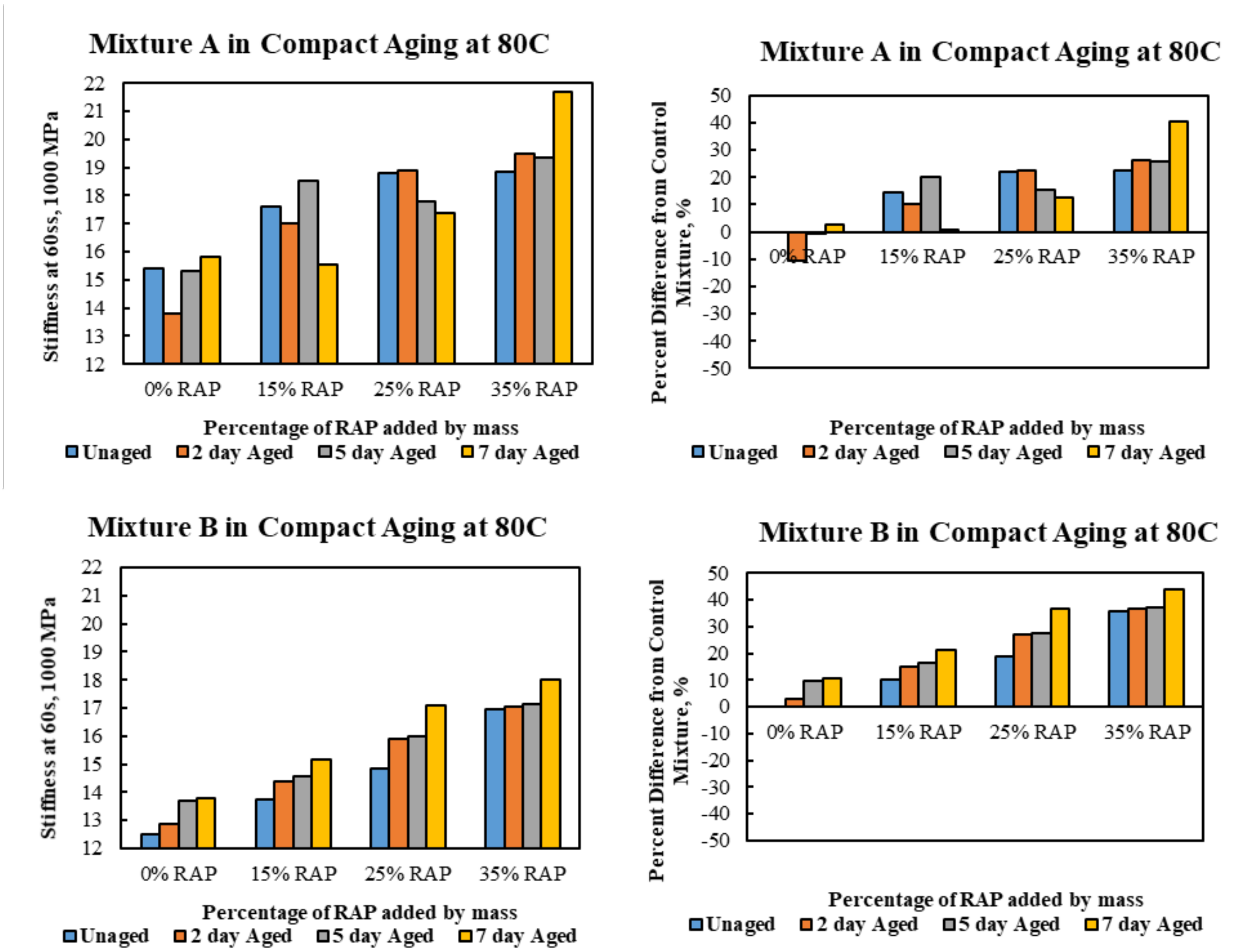


Figure 4.3a-d Effect of RAP on creep modulus at different aging days

Figure 4.4, shows the changes in the m-value from oven aging and increased RAP content. This parameter decreases with oven aging time and increased RAP content for both Mix A and Mix B. Evaluating both modulus and m-value leads to this conclusion: from oven aging of compacted mixtures as RAP is added to the mix, a decrease in performance is expected.

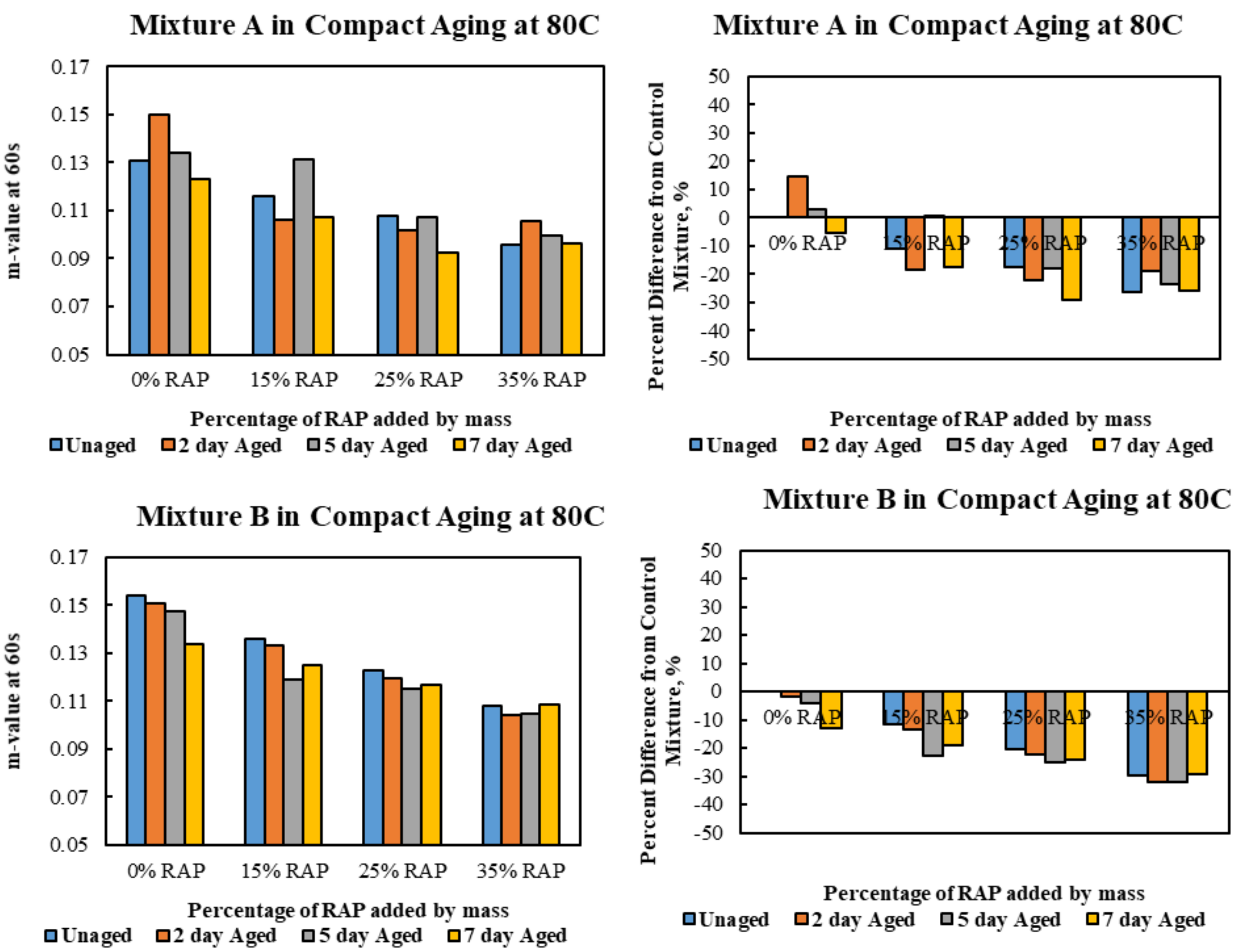


Figure 4.4a-d Effect of RAP on m-value for different aging days

4.2.2.1 Practicality of Aging Procedures

Based on this experiment, and from a practical perspective, aging of the loose mixture at 135°C is preferable to aging the compacted mixture at 80°C since loose mixture aging conditions the material in a much shorter time while yielding similar conclusions, albeit different numbers, for creep modulus and m-value. An equivalency between both aging methods can be determined; however, to develop such a relation, the combined effect of change in modulus and change in m-value must be understood. This is investigated in the next section.

4.2.3 Aging Index

The results shown in the previous section indicate that both the creep modulus and the m-value are adversely affected by increases in RAP content and aging conditioning. In order to gain a better understanding of the process, the two variables, modulus and m-value, were combined into a single index value. Previous work has shown that both values play a role in mixtures performance; so for this analysis, the changes in both values were given the same weight (i.e., a 10% increase in modulus has the same effect as a 10% decrease in m-value). This assumption needs to be verified with further studies, but it would not change the observed trends.

The index value is determined as the absolute difference between the given condition (RAP content, aging time/condition) and the control condition (no RAP, no lab aging) for that mixture. It considers both the change in creep modulus and the change in m-value.

The index is calculated based on the following equations,

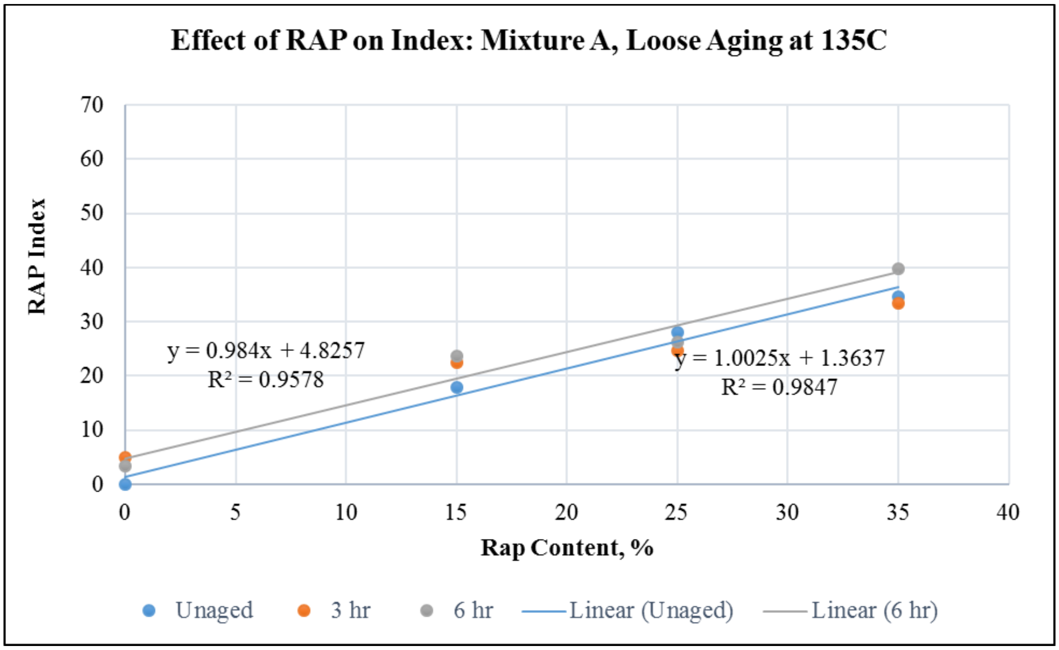
$$\boldsymbol{\Delta_{modulus}} = \frac{\boldsymbol{Modulus_{time/RAP} - Modulus_{Control}}}{\boldsymbol{Modulus_{Control}}}$$ Equation 0-1

$$\boldsymbol{\Delta_{m-value}} = \frac{\boldsymbol{m-value_{time/RAP} - m-value_{Control}}}{\boldsymbol{m-value_{Control}}}$$ Equation 0-2

$$\boldsymbol{Index} = \sqrt{(\boldsymbol{\Delta_{Modulus}})^2 + (\boldsymbol{\Delta_{m-value}})^2}$$ Equation 0-3

The data were separated into two graphs, RAP content for different aging conditions (Figure 4.5 and Figure 4.6) and aging time for different RAP contents (Figure 4.7 and Figure 4.8). While these are essentially the same data, just plotted with a different X-axis, the index was labeled as RAP Index and Aging Index, respectively, to separate the different treatments and try to better understand their effect.

Figure 4.5 and Figure 4.6 show a linear relation between RAP content and RAP Index. A regression line resulted in very high r-squared values (97% or higher). It should be noted, however, the intersect of the regression equations was not forced through zero; this is the result of using the control mix as a reference for all cases. Thus, only the slope of the line will be discussed, as it represents the overall (modulus and m-value) rate of change caused by each variable studied. For clarity, only two conditions are shown with regression lines.



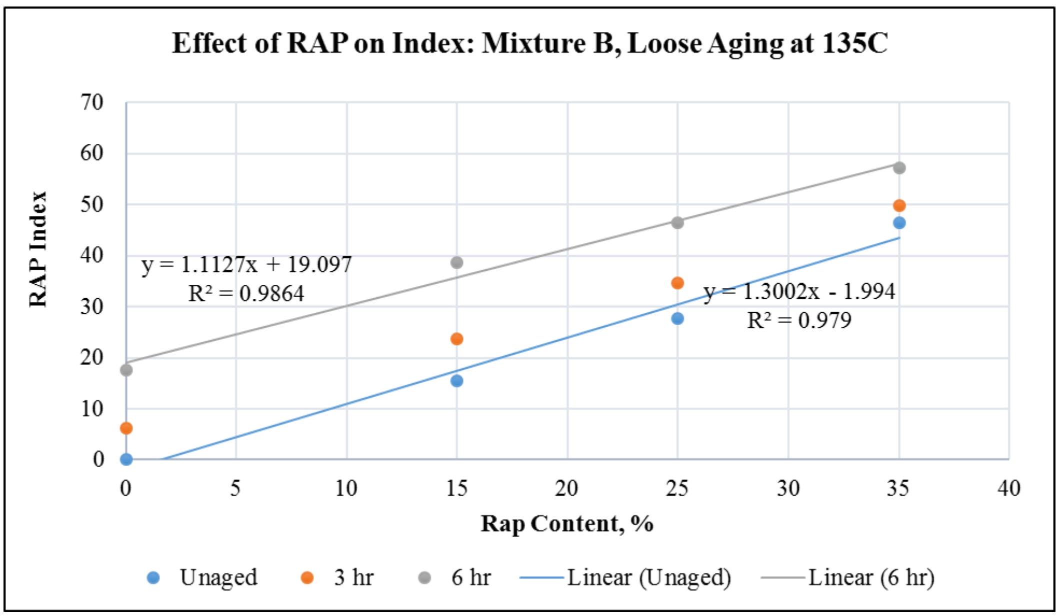
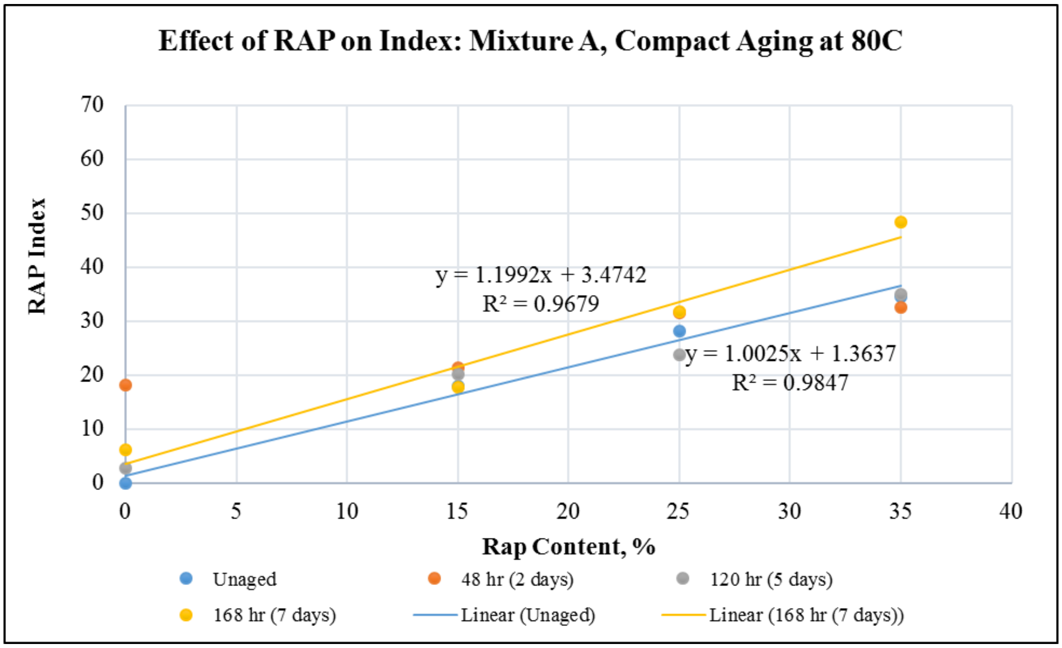


Figure 4.5a-b Effect of RAP content on index for loose mix aging

Figure 4.5 shows the RAP index as a function of RAP content for different loose mixture aging condition times. Mix B shows higher sensitivity for RAP having a slope for the unaged condition of 1.3 versus 1.0 for Mix A. For six hours of aging, the slopes were 1.1 for Mix B versus 0.98 for Mix B. However, as was shown in Figure 4.1, Mix B has a lower creep modulus than Mix A with no RAP and no aging (12,000 MPa versus 15,000 MPa) and higher m-value (Figure 4.2). The data suggest that the starting value of modulus and m-value for the baseline condition has an influence on the rate of change.



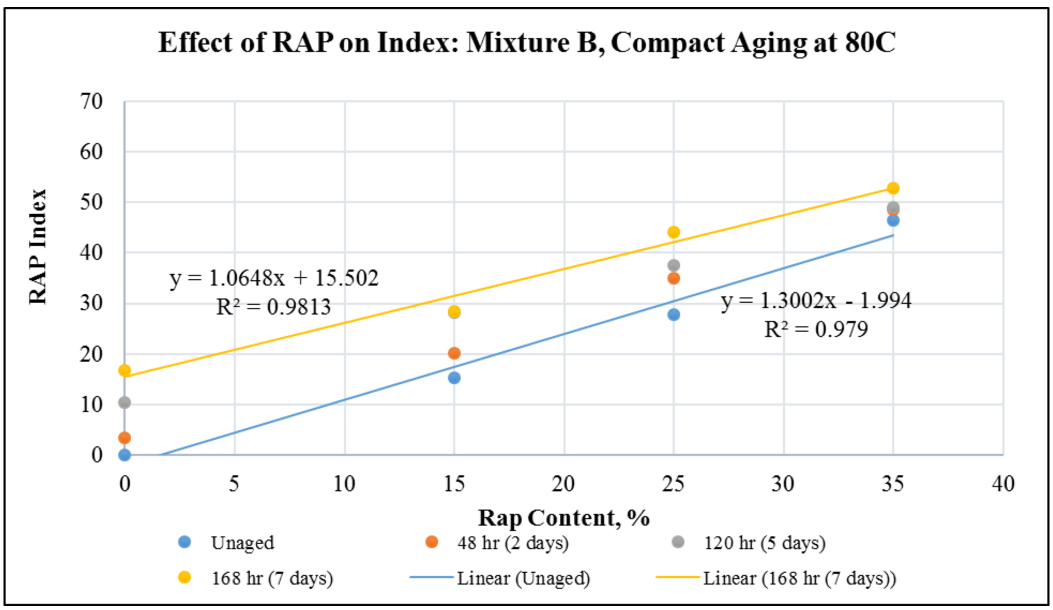
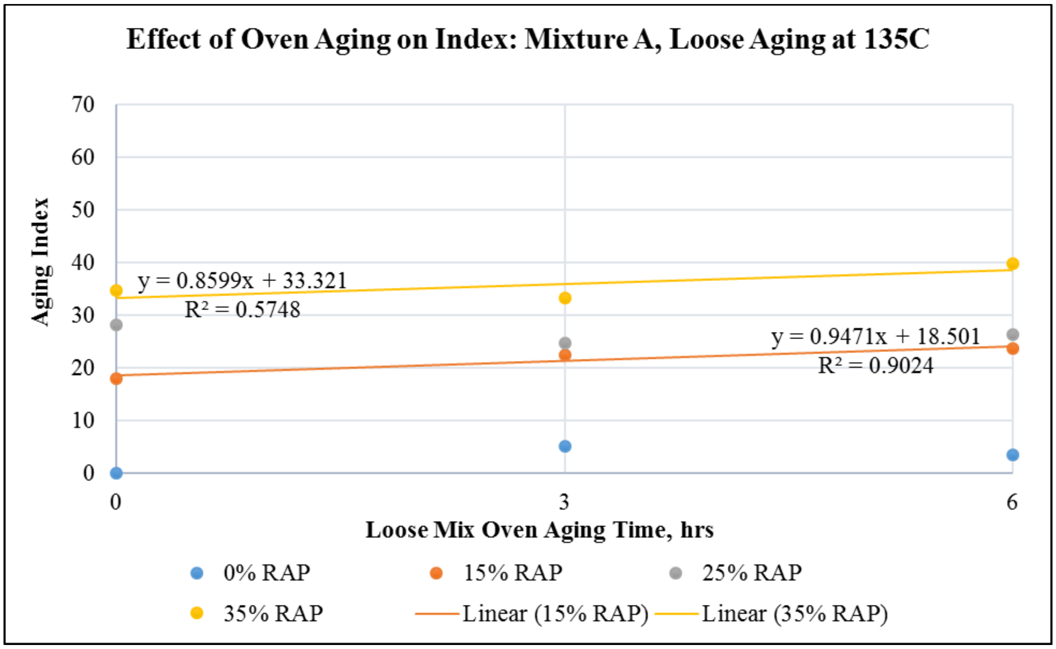


Figure 4.6a-b Effect of RAP content on index for compacted aging

Figure 4.6 shows the effect of RAP content on the RAP index for different compacted aging times. For the unaged condition, Mix B has higher sensitivity to the addition of RAP than Mix A with a slope of 1.3 versus 1.0; however, after 120 hours of aging at 80°C the role reverses with Mix A now having a slightly higher slope of 1.2 versus 1.1. The sensitivity of this index is not known; therefore, no statement is made regarding the significance of such change.



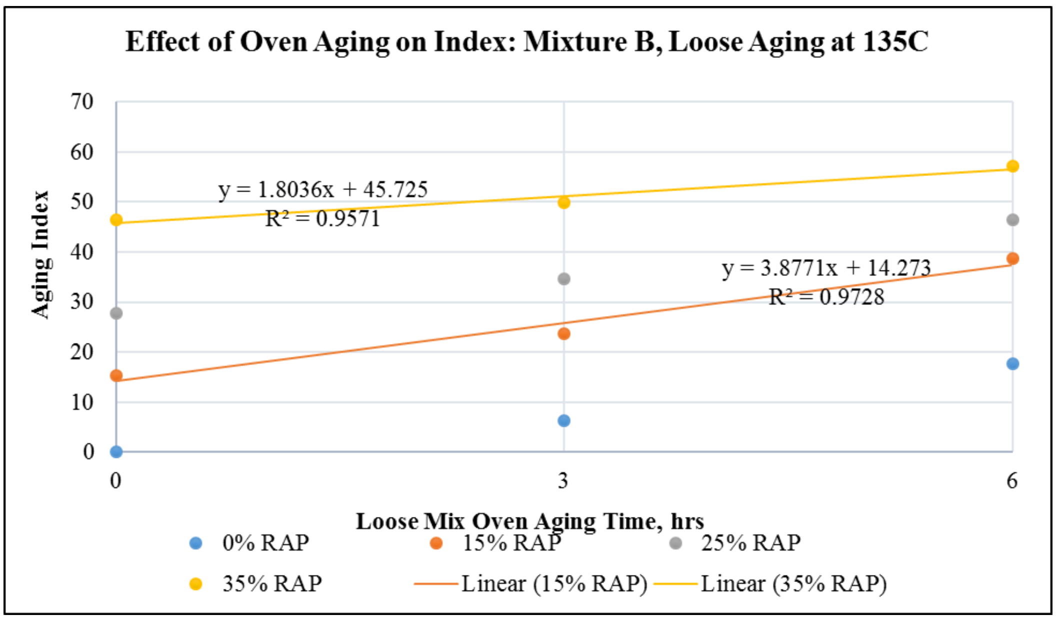


Figure 4.7a-b Effect of loose mix aging on index for different RAP contents

Figure 4.7 shows the aging index as a function of loose mixture oven aging time at 135°C. Mix A shows a lower sensitivity to aging time with a slope of 0.9, while Mix B shows a slope of 3.8 for 15% RAP and 1.8 for 35% RAP. As in the case with the RAP index, it seems a mixture that starts with low performance expectations (high modulus and low m-value) would not change dramatically, as compared with a mixture with good performance expectation. This was previously discussed in Section 4.2.2.

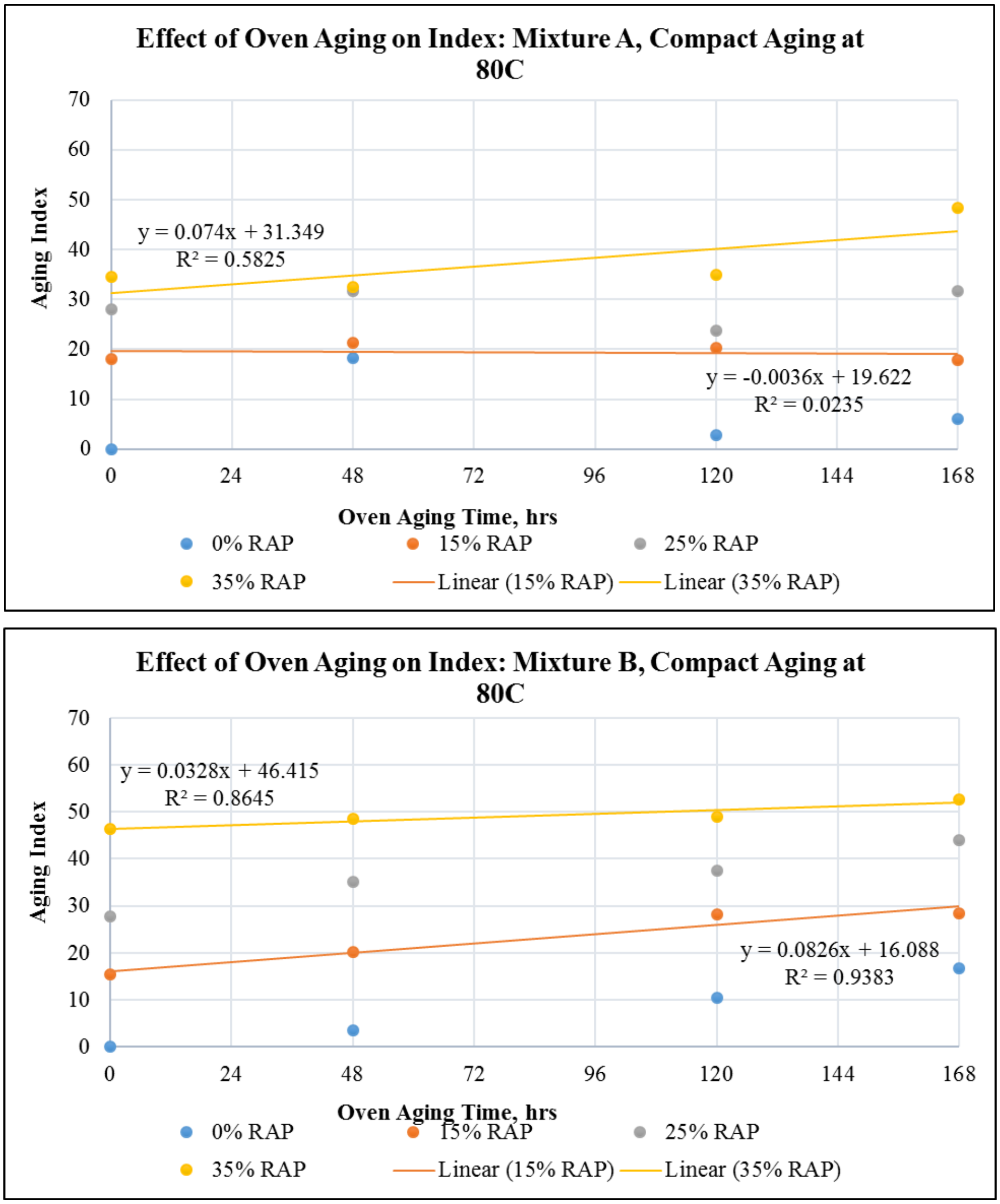


Figure 4.8a-b Effect of compacted aging on index for different RAP content

Figure 4.8 shows the aging index as a function of compacted aging time. Mix A shows significantly more scatter in the results, resulting in a low r-squared for the regression line. The low value for the slope of the regression in both mixes shows there is low sensitivity to this type of laboratory aging. The lower temperature and the fact that the mixtures are compacted might make it more difficult for the blending of RAP and virgin material to occur and for the volatiles in the virgin material to change.

Of interest is a comparison of the effects of aging conditioning of loose mixture versus compacted mixes. As was mentioned in Section 4.2.2.1, there is a significant advantage, from a time perspective, in aging the mixture before compaction than aging it after compaction. Furthermore, the results indicate that aging of loose mixtures induces more changes in the BBR parameters than aging of compacted specimens in a shorter amount of time.

By comparing Figure 4.7b and Figure 4.8b for 35% RAP (the most clear data), the equivalent time of compacted aging at 80°C required to obtain the same aging index for one hour of loose mixture aging at 135°C can be calculated as 55 hours (1.8036/0.0328). For no RAP this value is 47 hours (3.8771/0.0826). This shows the advantage of loose mixture aging versus compacted mixture aging when time is a concern. Furthermore, loose mixture aging shows less variability than compacted aging, and even though the higher temperature might lead to chemical changes in the asphalt binder, the fact that the mixture is already at the compaction temperature makes this option very more attractive for everyday use.

4.2 Summary

In this section, samples were prepared with different amounts of RAP and aged for different periods before and after compaction. In general, the test shows a decrease in expected performance with the addition of RAP and with increased aging time.

The following results were obtained from BBR testing:

1. Laboratory aging produced significant changes in the modulus and m-value of the asphalt mixtures and should be considered during mixture design.
2. Two different aging procedures were evaluated and loose mixture aging at 135°C gave the most consistent results in a reasonable amount of time.
3. Based on one of the mixes studied, one hour of loose mixture aging at 135°C provides the same change in material properties as 47 to 55 hours of aging of the compacted mixture at 80°C.
4. The introduction of RAP to the mixture adversely affects both the modulus and the m-value of the mixes studied; however, the magnitude of the changes is mixture specific and probably related to overall binder content.
5. Changes in modulus and m-value can be combined into a single index. This index is linearly related to the amount of RAP introduced to the mix.
6. The mixture with the high modulus (Mix A) had the smallest change in properties when RAP was introduced or when aged in the lab. The mixture with the low modulus (Mix A) had the largest change in modulus or m-value; however, the fact that the modulus was relatively low for the control condition indicates this mixture should have acceptable performance once placed on the field.

The data from the BBR indicate that aging causes mechanical changes in the material that relate to lower performance. The tests also indicate that RAP is detrimental to the overall expected performance of the mixtures when compared with virgin mix.

Conditioning the loose mixture at 135°C prior to compaction seems to be a practical method to accelerate the effect of aging when compared with conditioning the compacted specimen at 80°C. Even though 135°C could change the chemical composition of the binder, from the mechanical response, an equivalency can be established between field aging and laboratory aging that balances rigor and practicality.

5. CONCLUSIONS

5.1 Summary

Adoption of any mixture test that relates to pavement performance requires an understanding of all aspects of mixture design. Factors such as binder content and addition of RAP are known to play a key role in the durability of pavements. These factors were evaluated using the BBR. The goal was not only to understand the capability of the test to relate to performance, but also to evaluate what effect it will have on asphalt mixtures produced in the state.

Specifically, this work aimed at answering the following questions:

1. How does the introduction of a low temperature test will affect the mixtures currently being used by UDOT in terms of binder content, RAP content, and aging?
2. What are the potential changes in mixture design resulting from the incorporation of a low temperature test?
3. Can mixture parameters (binder content, RAP content) be optimized using a low temperature test (BBR)?
4. What is the ability of the BBR test to detect changes in mixture components?
5. The experiment was separated into changes in binder content and air voids and RAP content and aging. The findings of these experiments are summarized next.

5.2 Findings

5.2.1 Binder Content and Air Voids

- For constant binder content, the higher the air voids the lower the modulus with no change in m-value
- Changes in binder content above optimum results in no significant changes in modulus or m-value. Changes in binder content below optimum results in the reduction of the modulus but no change in m-value.

5.2.2 RAP Content and Aging

- Both modulus and m-value are sensitive to changes in laboratory aging.
- Aging of the loose mixture at 135°C prior to compaction shows a more consistent trend than aging the compacted specimen at 80°C. Using the index valued developed in this study, equivalent times can be obtained between both conditioning procedures. One hour of loose mix aging at 135°C results in the same mechanical changes as 47 to 55 hours of compacted mix aging at 80°C.
- The magnitude of the change in modulus and m-value resulting from aging is mixture dependent, but it seems that for mixes with higher modulus, the rate of change is lower.
- Both modulus and m-value are sensitive to the additions of RAP. Even small quantities, like 15%, result in an increase in modulus and a decrease in m-value.

The test results indicate that RAP is detrimental to the overall expected performance of the mixtures when compared with virgin mix.

5.3 Conclusions

Based on the work presented, the following conclusions are reached:

1. The results from the low temperature test (BBR) indicate that increases in binder content are beneficial to the overall performance of the mixture (at least at low temperatures). Deficiencies in binder content seem to be a problem for the BBR results as they indicate a desirable condition (lower modulus, same m-value), which is contrary to accepted knowledge.
2. The data from the BBR test indicate that aging causes mechanical changes in the material that relate to lower performance. The tests also indicate that RAP is detrimental to the overall expected performance of the mixtures when compared with virgin mixes. Based on this observation, the BBR appears to be a sensitive test to capture the effect of aging and RAP on the material. **Adoption of the BBR would likely result in changing the mixture design process to favor mixes with higher binder content with high RAP replacement.**
3. Conditioning the loose mixture at 135°C prior to compaction seems to be a practical method to accelerate the effect of aging when compared with conditioning the compacted specimen at 80°C. Even though 135°C could change the chemical composition of the binder, from the mechanical response, an equivalency can be established between field aging and laboratory aging that balances rigor and practicality**. Knowing the relationship between the different mixture parameters and the changes induced by aging gives the ability to optimize parameters such as binder and RAP content using the BBR.**

5.4 Limitations and Challenges

The results from this work are limited to the conditions and materials used during this research. As more data become available, some of the limitations can be better understood.

6. RECOMMENDATIONS AND IMPLEMENTATION

6.1 Recommendations

It is recommended that the BBR modulus and m-value be used as parameters to evaluate low temperature properties of asphalt mixtures. Using these parameters, a true performance-based specification can be developed at the mix design stage. The amount or condition of the test can be determined in an incremental manner. For example, if the proposed mixture results in low modulus and high m-value, then no further testing would be required. If the proposed mixture results in high modulus and low m-value, then it would be rejected and must be redesigned. Finally, if the modulus and m-value fall within a transition zone, three hours of loose mixture aging at 135°C would be required prior to compaction. If after the aging conditioning the proposed mixture is still below the allowed modulus and above the minimum m-value, then the mixture would be acceptable; otherwise, it must be redesigned. As an example, data for a low design temperature of -22°C are shown in Figure 6.1 based on previous published work (Report No. UT-16.09).

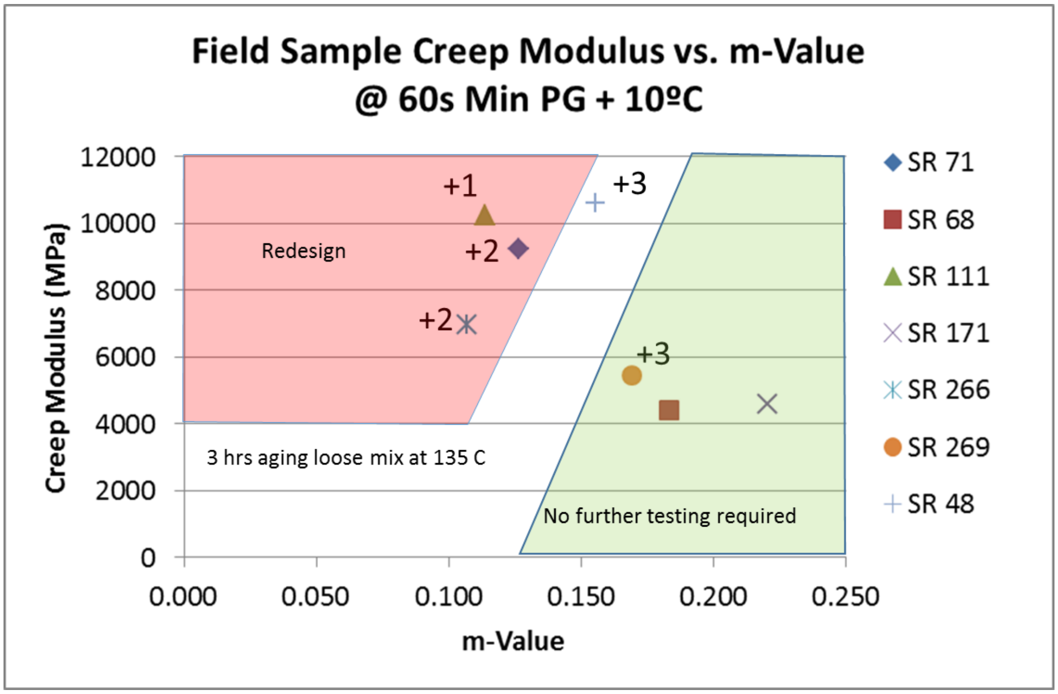


Figure 6.1 Proposed modulus and m-value limits at -12°C for mixtures prepared for a PG64-22 binder environment

The number next to the markers represent how many years since construction for cracks to appear.

Figure 6.1 shows three areas based on field performance: 1) accept with no further testing required, 2) redesign (i.e., reject), and 3) age the loose mix for three hours at 135°C then compact and test in the BBR. Unfortunately, limits for other temperature regions cannot be determined as part of this work since field data with results at the design temperature of -28°C are not available. Therefore, it is recommended that testing of field materials at -18°C be performed.

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APPENDIX A: DATA

BBR Results and Data Management

All data from BBR testing were collected using electronic data acquisition of force, displacement, and temperature sensors. The data were collected in non-proprietary CSV format as generated by the BBR data acquisition system. Spreadsheets were used to summarize and analyze the data. The raw data, called primary data, have been preserved and archived at Zenodo (https://zenodo.org/), an international repository/archive of research outputs from across all fields of research. Zenodo is listed as conforming with the USDOT Public Access Plan (https://ntl.bts.gov/publicaccess/repositories.html). According to Zenodo's policy, data entries remain accessible forever.

The data are accessible at the following link: http://doi.org/10.5281/zenodo.1035944

Romero, Pedro. (2017). Balanced Asphalt Concrete Mix Performance Phase II: Analysis of BBR Tests [Data set]. Zenodo.

A README file, including the metadata/information required to repeat the research, is included along with the data in the archive. Zenodo will provide proper citation for users to incorporate the data into their publications and will have a memorandum of understanding (MOU) stating that users may not re-release the data to a third party, but direct them back to the repository.

Summarized data, called secondary data, are presented in the following tables. The mixture ID refers to the mixture used (Mix A or Mix B) follow by RXX (RAP content, in percent), L for loose mixture, and C for compacted mixture and then either the hours at 135°C (for loose mix) or the days at 80°C (for compacted mix). Fox example, AR15C5d stands for Mixture A with 15% RAP aged in the compacted state for five days.

Table A.1 BBR Results for Mixture A

Bending Beam Rheometer Test Results of Mixture A specimens							
Mixture ID	Samples Tested	Trimmed Stiffness, Mpa (Omitting Max and Min)			Trimmed m-value (Omitting Max and Min)		
		Average	Standard Deviation	CoV (%)	Average	Standard Deviation	CoV (%)
CAR0	24	15418	1256	8.15	0.131	0.010	7.56
AR0L3h	18	15900	2076	13.06	0.124	0.014	11.66
AR0L6h	18	16581	1687	10.17	0.126	0.014	11.08
CAR15	18	17606	1555	8.83	0.116	0.009	7.58
AR15L3h	19	17265	2365	13.70	0.106	0.014	13.29
AR15L6h	18	18175	2176	11.97	0.110	0.011	10.10
CAR25	18	18813	2655	14.12	0.108	0.010	9.47
AR25L3h	18	17061	1976	11.58	0.090	0.009	9.98
AR25L6h	17	18373	1636	8.90	0.119	0.021	17.71
CAR35	19	18844	1470	7.80	0.096	0.010	9.98
AR35L3h	18	18644	1765	9.46	0.097	0.010	10.82
AR35L6h	17	18988	2104	11.08	0.088	0.010	11.00
AR0C2d	18	13775	2102	15.26	0.150	0.011	7.15
AR0C5d	20	15306	1880	12.28	0.134	0.012	9.18
AR0C7d	17	15793	1390	8.80	0.123	0.014	11.36
AR15C2d	17	17007	1623	9.55	0.106	0.009	8.22
AR15C5d	18	18531	1657	8.94	0.131	0.013	10.17
AR15C7d	18	15563	1453	9.34	0.107	0.011	10.69
AR25C2d	15	18877	2547	13.49	0.101	0.005	5.31
AR25C5d	18	17794	2235	12.56	0.107	0.011	10.45
AR25C7d	19	17372	1279	7.36	0.093	0.009	9.89
AR35C2d	18	19467	2895	14.87	0.106	0.010	9.17
AR35C5d	17	19360	2647	13.67	0.100	0.010	10.16
AR35C7d	18	21680	2465	11.37	0.096	0.014	14.30

Table A.2 BBR Results for Mixture B

Bending Beam Rheometer Test Results for Mixture B specimens							
Mix ID	Samples Tested	Trimmed Stiffness, MPa (Omitting Max and Min)			Trimmed m-value (Omitting Max and Min)		
		Average	Standard Deviation	CoV (%)	Average	Standard Deviation	CoV (%)
CBR0	24	12504	1241	9.92	0.154	0.013	8.29
CBR15	17	13747	1200	8.73	0.136	0.012	8.42
CBR25	18	14863	1221	8.22	0.123	0.011	9.27
CBR35	18	16963	1610	9.49	0.108	0.011	9.96
BR0L3h	18	12944	1186	9.17	0.146	0.011	7.28
BR15L3h	18	14206	2148	15.12	0.124	0.009	7.44
BR25L3h	17	15680	1182	7.54	0.118	0.012	9.99
BR35L3h	18	17338	1953	11.26	0.106	0.007	6.50
BR0L6h	17	14038	1965	14.00	0.134	0.015	11.33
BR15L6h	18	16644	2219	13.33	0.123	0.006	4.84
BR25L6h	16	17186	2169	12.62	0.112	0.013	11.63
BR35L6h	16	18400	2048	11.13	0.104	0.008	7.40
BR0C2d	18	12863	933	7.25	0.151	0.009	5.58
BR15C2d	18	14400	1345	9.34	0.133	0.012	9.20
BR25C2d	18	15900	1664	10.46	0.120	0.010	8.77
BR35C2d	18	17056	1705	10.00	0.104	0.008	7.70
BR0C5d	18	13694	1274	9.31	0.147	0.009	6.15
BR15C5d	18	14581	1492	10.23	0.119	0.010	8.45
BR25C5d	18	15969	1464	9.17	0.115	0.009	7.78
BR35C5d	18	17136	1185	6.92	0.105	0.010	9.55
BR0C7d	17	13800	1500	10.87	0.134	0.012	8.90
BR15C7d	17	15160	1579	10.41	0.125	0.013	10.46
BR25C7d	17	17107	2071	12.11	0.117	0.012	10.58
BR35C7d	17	17987	1817	10.10	0.109	0.016	14.92