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Implementing Revisions to the Allowable Maximum Recycled Binder Ratio (RBR) Specification

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16. Abstract
An increase in the use of reclaimed asphalt pavement (RAP) in the design and construction of new roads must not come at the expense of reduced durability or life cycle cost of flexible pavements. In Texas, current mixture design specifications allow the use of a binder with lower high temperature grade in lieu of the specified binder when incorporating RAP into the mixture. Referred to as *binder substitution*, it is accompanied by other constraints that limit the maximum recycled binder ratio for different mixture types and applications. The current specifications, although straightforward, have a few gaps with regards to the allowed binder substitution and recycled binder ratio. This study evaluated those gaps to determine: (i) impact of binder substitution on performance, (ii) impact of recycled binder ratio on performance, (iii) the influence of different types of RAP on the rheological and performance related properties of asphalt binder, and (iv) efficacy of agents of additives that can potentially be used to improve the properties and performance of asphalt mixtures incorporating RAP. The performance of binders and mixtures were evaluated using systematically controlled materials prepared in the laboratory as well as materials sampled from the field. The results show that addition of RAP to a substitute binder results in an increase in stiffness, non-recoverable compliance, and rutting resistance—but also show a substantial decrease in the fatigue cracking resistance and loss of low temperature grade with an increase in recycled binder content. This is especially true when using a substitute binder grade that is two high temperature grades below the specified binder or using RAP with RAS. The low temperature properties of the recycled binder from RAP can vary significantly from one source to another and have a significant effect on the properties of the binder and mixture. These results suggest that the substitute binder should have no more than one high-temperature grade lower than the specified binder and preferably also one low-temperature grade lower than the specified binder. The quality of the RAP from the specific source and interactions with the rejuvenator must also be evaluated on a case-by-case basis. This project developed fast and effective methods for such evaluation.

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EXECUTIVE SUMMARY

An increase in the demand on the existing pavement infrastructure combined with an emphasis on reduced consumption of non-renewable material resources as well as reduced life-cycle cost has led to the innovation and development of several new materials design and pavement construction technologies. One of the most significant of these is the use of reclaimed asphalt pavement (RAP) to construct and maintain pavements. However, such an increase must not come at the expense of reduced durability or life cycle cost of flexible pavements. In Texas, current mixture design specifications allow the use of a binder with lower high temperature grade in lieu of the specified binder when incorporating RAP into the mixture. This is referred to as binder substitution and is accompanied by other constraints that limit the maximum recycled binder ratio for different mixture types and applications. The current specifications, although straightforward, have a few gaps with regards to the allowed binder substitution and recycled binder ratio: (i) it implicitly assumes that the quality of recycled binders from all RAP stockpiles is the same, (ii) it may result in the use of substituted binders with little or no elastic recovery, and (iii) it does not account for the potential use and influence of recycling or softening agents.

The main goals of this study were to:

1. address the allowable substitute binder, and the maximum ratio of recycled binder to total binder to be used without compromising the durability of the mix as currently prescribed in Table 5 in Specification 2014 Items 340, 341, and 344 TxDOT (2004). This table allows for binder substitution regardless of the percentage of RAP, which is different from the general trend of using the same grade up to typically 20% RAP, and in many instances the grade lowering is restricted to only the higher grade and not the lower grade.
2. examine the influence of recycled and substitute binder on binder and mixture performance using different grades of virgin binder and percentages of RAP,
3. examine the influence of different types of RAP on the rheological and performance related properties of asphalt binder, and
4. evaluate agents or additives that can potentially be used to improve the properties and performance of asphalt mixtures incorporating RAP.

In order to achieve the aforementioned goals, the performance of binders and mixtures were evaluated using systematically controlled materials prepared in the laboratory as well as materials sampled from the field. In the case of field evaluation, four different field sections were identified from different geographic and climatic regions across Texas.

Different mixture combinations or variations were evaluated for each of the four mix designs by changing the recycled binder ratio and specified binder type. Also, field mixes were obtained at the time of construction and field cores were obtained approximately 1 to 1.5 years after construction. In the case of binder testing, parameters that were evaluated include rutting resistance, elastic recovery, intermediate temperature stiffness, cracking resistance, and thermal cracking resistance. In the case of mixture testing, mixtures were evaluated rutting resistance using the Hamburg Wheel Tracking Device (HWTD) and for their cracking resistance using the Overlay Test (OT) and Indirect Tensile Test (IDT).

Results from this study show that:

1. Substituting a softer or lower high temperature grade binder for the specified binder (without RAP) results in a reduced the high temperature stiffness, non-recoverable compliance, and rutting resistance. This is a desirable and positive effect.
2. However, elastic recovery of the substitute binder (without RAP) is generally lower than the elastic recovery of the specified binder. The lack of elastic recovery associated with the use of a substitute binder (particularly when the substitute is a PG64-22) is generally associated with lower ductility and cracking resistance in the mix and it is not desirable. This was evident in the test results.
3. The addition of RAP to the substitute binder deteriorates the low temperature properties of the binder. In most cases a combination of the substitute binder with RAP raises the low temperature grade of the blend by one grade. The loss of low temperature grade can result in a binder with lower ductility and cause premature thermal cracking and it is also an indicator of reduced resistance to intermediate temperature fatigue cracking. This effect is also undesirable and can be offset by the use of a binder with one additional lower grade than required when using RAP and/or other recycling agents/additives.
4. Three different recycling agents were used to evaluate their efficacy when using recycled binder. The effectiveness of each agent was different. In general, all agents reduced the rutting resistance based on both the MSCR and the $G^*/\sin\delta$ parameters and improved the low-temperature properties of the binder based on the S and $m-$value parameters, although some were more effective than others. However, it must be noted that when a substitute binder is being used, the reduction in stiffness and rutting resistance may more than compensate for the expected increase in stiffness and rutting resistance due to a combination of the reduced high temperature grade of the substitute binder and RAP/RAS.

5. Recycling agents did not contribute to the elastic recovery of the binder-RAP-additive blend. In other words, although the additives helped recover the low-temperature grade of the binder after the addition of RAP, they did not help recover the elastic recovery of the virgin binder.
6. Broadly, the influence of RAP-RAS is the same as RAP. However, the magnitude of the impact by allowing RAS is much higher.
7. Low temperature properties of RAP can vary significantly from one source to another and this range was approximately two grade equivalents in a sample of ten different sources of RAP. These results demonstrate that not all RAP should be treated alike and consequently the determination of substitute binder grade, RAP content, and additives should be made on a case-by-case basis.

Based on these findings, it is recommended that two grade drops in the high temperature performance grade should be avoided when using a substitute binder. The addition of RAP compromises the low PG of the binder. One way to mitigate this effect is to use a substitute binder that has one grade lower than required (e.g. if the specified binder is PG76-22 then, the substitute binder is recommended as PG70-28). A second way to mitigate this would be to use an additive (rejuvenating agent). Rejuvenating agents must be allowed for use only after examining their efficacy with RAP and the virgin binder using binder and/or mixture tests. In other words, mixture performance must be evaluated after incorporating proposed rejuvenators and RAP during the mixture design approval stage instead of approving a mix with virgin binder and allowing a substitution later. The magnitude of the impact by allowing RAS is much higher compared to RAP and typically, intermediate and low temperature performance are more severely and adversely affected when a RAP-RAS combination is used.

Finally, properties of the binder from different RAP stockpiles must be measured and evaluated on a regular basis and this information must also be incorporated in the job mix formula (JMF) and SiteManager database to develop historical data that can be used to enhance the responsible use of RAP in the future. This can be achieved using a simple and cost-effective method that was developed and presented in this report.

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CHAPTER 1. INTRODUCTION

1.1 INTRODUCTION

With increasing world population combined with urban sprawl, the demand for transportation infrastructure is rising. In the United States, a vast majority of highways pavements utilize asphalt mixes. Large portions of this roadway system are showing signs of deterioration in serviceability which explains the American Society of Civil Engineers (ASCE) evaluating the current system with a grade of D (Copeland, 2011). For example, in 2015 alone, the damage and repair costs due to poor pavement conditions totaled at $120.5 billion. This amount is a quantitative reflection of the state of our current pavement infrastructure. The deterioration and poor condition can be attributed to a combination of increased traffic loads and volume as well as under funding. It is estimated that there is a $420 billion backlog of funding to repair existing highways and $126 billion backlog of funding for system enhancement (Copeland, 2011).

An increase in the demand on the existing pavement infrastructure combined with an emphasis on reduced consumption of non-renewable material resources as well as reduced life-cycle cost has led to the innovation and development of several new materials design and pavement construction technologies. One of the most significant of these is the use of reclaimed asphalt pavement (RAP) to construct and maintain pavements.

There are different asphalt recycling methods, including hot in-place, cold in-place, cold mix recycling, and hot mix recycling, with hot mix recycling being the most widely used (Santucci, 2007). This study will only refer to RAP in the context of using reclaimed asphalt pavement to produce new asphalt mixture for new pavement construction, rehabilitation, or maintenance using the hot mix recycling method.

RAP is increasingly being used due to the cost savings that can be realized while also conserving non-renewable material resources. Using RAP reduces the amount of virgin aggregate and virgin asphalt binder consumed during the production of asphalt mixtures while also eliminating the reclaimed material from going to the landfill as waste. As public opinion for a sustainable future becomes unanimous, the emphasis to develop environment-friendly technologies in transportation infrastructure will increase. The use of RAP in asphalt mixture production, if done correctly and responsibly, can provide a solution that addresses both fiscal and environmental constraints encountered in pavement materials technologies. The following paragraphs summarize the current trends in highway agencies across the U.S. in terms of their efforts to incorporate RAP in asphalt mixture production.

In 2007, a survey was performed by North Carolina Department of Transportation (NCDOT) (Copeland, 2011), on behalf of the RAP Expert Task Group (ETG) and sponsored by AASHTO Subcommittee on Materials. The survey revealed that state DOTs intended to increase the amount of RAP used across the United States. Figure 1.1 shows the number of DOTs that used and permitted a specific amount of RAP in the intermediate layers of the pavement structure and Figure 1.2 shows the same number for surface layers. The data clearly shows that many state agencies do not use the maximum amount of RAP allowed in the state agencies respective specification. For example, in Figure 1.1, fifteen state agencies allow 30% and higher in their specification, but only 4 state agencies actually used 30% and higher in their intermediate layer. Figures 1.1 and 1.2 show that there is a difference between the amount of RAP allowed by the state agencies and the amount used. Also, the difference between RAP percentage permitted (potential) and actually used (usage) is greater when high RAP percentages are allowed. This demonstrates the potential to increase the total amount of RAP used in the United States.

A similar survey in 2009 by NCDOT (Copeland, 2011) reported increased RAP usage from 2007 to 2009 (Figure 1.3). Also, more state DOTs were permitting even higher RAP percentages in the mixture to encourage higher use of RAP usage (Figure 1.4).

Although there was an increase in the maximum allowable percentage of RAP in specifications, the actual percentage used in practice was lower (Figure 1.5). The survey results indicate a clear gap between the desire throughout the U.S. to use higher percentage of RAP and the actual percentage of RAP used on an average in projects. It is likely that this gap is driven by the reluctance of agency and/or contractor engineers to incorporate higher percentages of RAP on account of the uncertainties associated with the expected performance of the resulting mixture. In order to promote the use of RAP (in any percentage in a mix), the uncertainties associated with the used RAP must be addressed and mixtures incorporating RAP must have equal or improved performance compared to the original mixture design without any recycled material.

Previous studies demonstrate that asphalt mixtures can be produced to achieve similar or better performance by incorporating RAP. For example, a study performed by Kandhal et al. (1995) on existing pavements with RAP showed promising results. They evaluated pavements that incorporated 10-15% RAP after 1 to 2.5 years of service and recorded no signs of rutting, raveling, or fatigue cracking in any of the test sections. Expanding the study, Kandhal and Foo (1997) studied pavements with 10-40% RAP and recorded

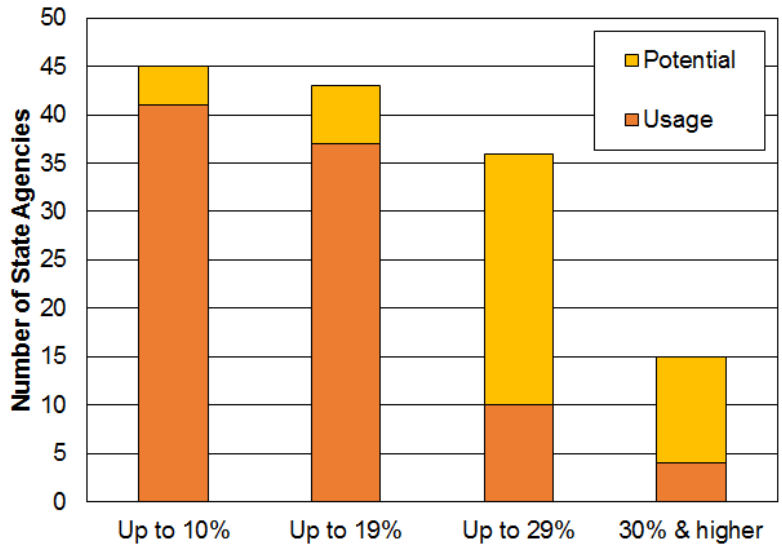

Figure 1.1. Usage and potential of various RAP percentages in the intermediate layer. Adapted from "Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice" by A. Copeland, 2011, No. FHWA-HRT-11-021, United States, Federal Highway Administration. Office of Research, Development, and Technology.

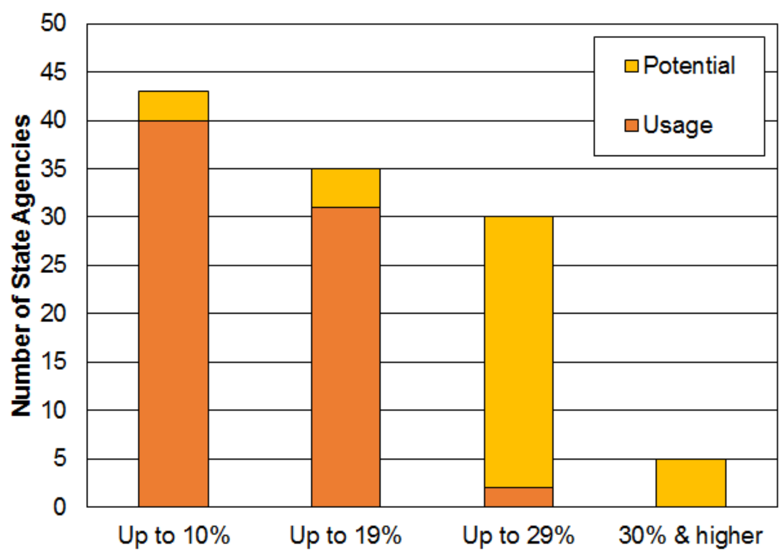

Figure 1.2. Usage and potential of various RAP percentages in the surface layer. Adapted from "Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice" by A. Copeland, 2011, No. FHWA-HRT-11-021, United States, Federal Highway Administration. Office of Research, Development, and Technology.

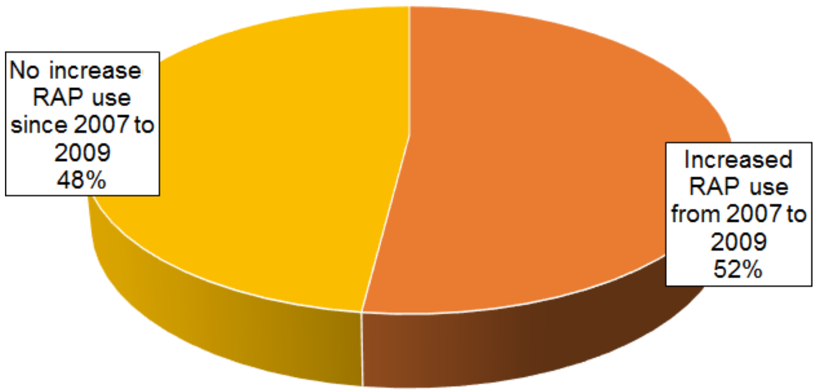

Figure 1.3. Percentage of states with increased RAP use since 2007 to 2009. Adapted from "Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice" by A. Copeland, 2011, No. FHWA-HRT-11-021, United States, Federal Highway Administration. Office of Research, Development, and Technology.

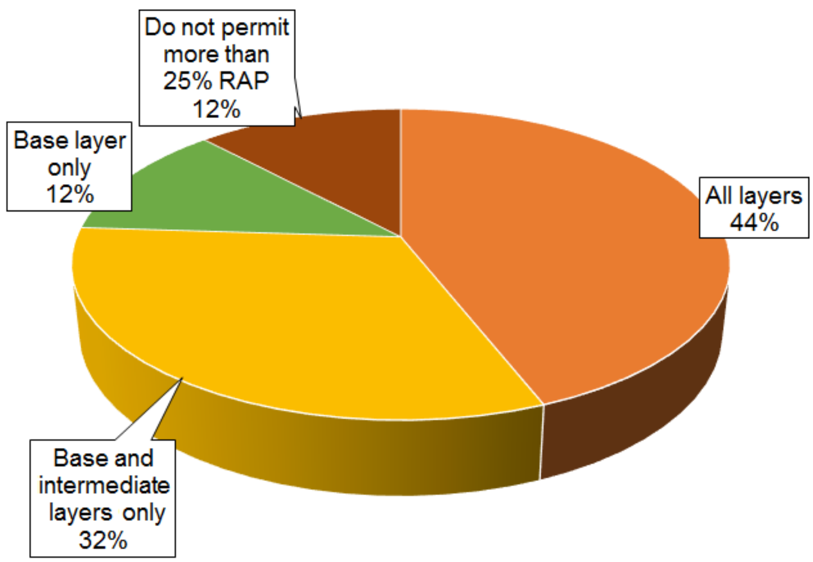

Figure 1.4. Percentage of states that permit more than 25 percent RAP in HMA layers. Adapted from "Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice" by A. Copeland, 2011, No. FHWA-HRT-11-021, United States, Federal Highway Administration. Office of Research, Development, and Technology.

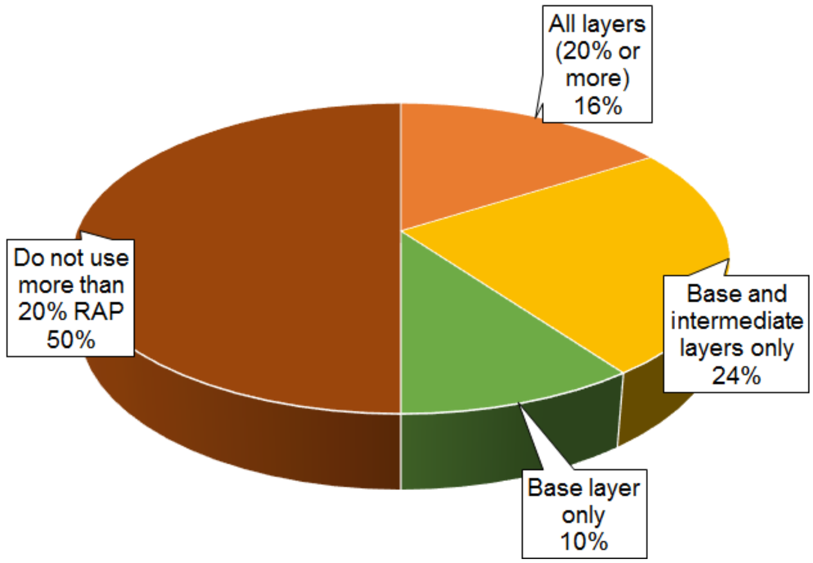

Figure 1.5. Percentage of states that use more than 20 percent RAP in HMA layers. Adapted from "Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice" by A. Copeland, 2011, No. FHWA-HRT-11-021, United States, Federal Highway Administration. Office of Research, Development, and Technology.

no significant difference in the performance of the virgin and recycled pavement sections. However, it is important to note that 1 to 3 years is not sufficient to evaluate the long-term performance of pavement sections that are typically designed for twenty or more years of service life. This is particularly important for fatigue and thermal cracking, which becomes more severe towards the end of the service life of a pavement.

Research carried out by Little and Epps (1980), also reported similar performance between mixtures incorporating RAP and virgin asphalt mixtures without any RAP. Their study looked at laboratory derived properties, such as, fatigue potential, and stability using the indirect tension test and Hveem stability value, respectively. The indirect tension tests revealed similar ultimate tensile stress between material samples incorporating RAP and control samples without RAP. The Hveem stability values of mixtures incorporating RAP were slightly lower than conventional virgin mixes, but were reported to be within a reasonable range. Therefore, the study concluded that mixtures incorporating RAP could be successfully designed to replace conventional asphalt concrete with satisfactory results.

Highway agencies typical allow the use of RAP as long as it can be done in a responsible way, i.e. by demonstrating that similar, if not better, performance characteristics can be achieved with RAP compared to mixes without RAP. However, there are a number of uncertainties and challenges that need to be overcome in order to increase the level of confidence and reliability in allowing the use of RAP. For example, inconsistencies in RAP aggregate gradation, RAP fine content, selection of appropriate bulk specific gravity of RAP aggregates, and selection of virgin binder are just a few considerations that need to be better understood and specified. To avoid some of these problems, some DOTs limit the type of RAP allowed for design, for example, RAP may be allowed for use only in specific projects or pavement types (West, 2010). In order to facilitate the use of RAP, it would help to overcome these restrictions by verifying the quality of materials in RAP with routine testing and optimizing the usage of the material. The following section presents a summary of some of the methods that have been considered for use or are currently being used to characterize RAP and optimize the design of asphalt mixtures incorporating RAP.

1.2 STATE OF PRACTICE

1.2.1 Overview

The most common method to optimize a mix design containing RAP is to use a blending chart. A blending chart helps selection of virgin binder for the design of an asphalt mixture incorporating RAP. Procedures for selecting the grade of virgin binder using such blending charts have been developed in the past (SERVAS, 1982). In 1997, Kandhal and Foo (1997) developed a procedure to select the performance grade (PG) of virgin asphalt binder to be used in asphalt mixtures incorporating RAP. The Federal Highway Administration's (FHWA) RAP ETG also developed interim guidelines for the design of Superpave asphalt mixture containing RAP in the form of a tiered approach to determine the level of testing required during the design of asphalt mixtures containing RAP. McDaniel et al. (2000) confirmed the benefits of a tiered approach for incorporating RAP in asphalt mixtures. The tiers of design mentioned above are determined based on the RAP binder grade and/or amount included: with softer RAP binders, higher percentages of RAP can be used (Bukowski, 1997). Tables 1.1 and 1.2 show that when RAP percentage is less than 15%, the virgin asphalt binder grade can be allowed to remain unchanged. When RAP percentage is in between 15 and 25%, the high and low temperature binder is "bumped" down by one grade, meaning the binder grade is reduced by one grade on both the high and low temperature end. When the proposed RAP percentage is above 25%, Superpave blending charts should be constructed to determine the desired virgin asphalt binder grade (Bukowski, 1997).

Table 1.1. Binder selection guidelines for RAP mixtures according to AASHTO M302 (2008)

Recommended Virgin Asphalt Binder Grade	RAP Percentage
No change in binder selection	<15
Select virgin binder one grade softer than normal (e.g., select PG58-28 if PG64-22 would normally be used)	15 - 25
Follow recommendations from blending charts	>25

Table 1.2. Binder selection guideline for RAP mixtures according to Superpave (2001)

Recommended Virgin Asphalt Binder Grade	RAP Percentage Recovered RAP Grade		
	PG XX-22 or lower	PG XX-16	PG XX-10 or higher
No change in binder selection	<20	<15	<10
Select virgin binder one grade softer than normal (e.g., PG58-28 if PG64-22 would normally be used)	20 - 30	15 - 25	10 - 15
Follow recommendations from blending charts	>30	>25	>15

Different DOTs have adopted their own version of the tiered system using different range of RAP percentages for each tier. Twelve states (Texas not included) have raised the lower limit for selecting a softer virgin binder grade from 15 to 20 or 25 percent (Copeland, 2011). In these cases, no change to the binder grade is required when the percentage of RAP used is below this limit (which varies from 15 to 25% for different states). Different states also have different nomenclatures to define the percentage of RAP. Percent RAP may refer to percentage based on the weight of aggregate or weight of the total mix or weight of virgin binder replaced. The percentage of RAP used in the mix can be selected by determining the contribution of the RAP binder towards the total binder in the mix by weight.

For asphalt mixtures with higher RAP percentages, a blending chart must be constructed. This blending chart can then be used in two different ways. In the first approach, the percentage of RAP that will be used in an asphalt mix is known but the appropriate virgin asphalt binder grade for blending must be determined using Equation 1.1. In the second approach, the maximum percentage of RAP that can be used with a given asphalt mixture is determined using the same virgin binder grade using Equation 1.2.

There are several pieces of information that are required to construct a blending chart. The physical properties and critical temperatures of the recovered RAP binder and either the percentage of RAP in mixture or the physical properties of the virgin binder, depending on the design method. The critical high, intermediate, and low temperatures need to be considered for both designs to determine the virgin binder or RAP content satisfying the Equation 1.1 or 1.2. The following subsections discuss the process of developing such blending charts in more detail.

$$T_{virgin} = \frac{T_{blend} - (\%RAP \times T_{RAP})}{(1 - \%RAP)} \tag{1.1}$$

$$\%RAP = \frac{(T_{blend} - T_{virgin})}{(T_{RAP} - T_{virgin})} \tag{1.2}$$

where:

T_{virgin} = Critical temperature of virgin asphalt binder (high, intermediate, or low).

T_{blend} = Critical temperature of blended asphalt binder (final desired) (high, intermediate, or low).

%RAP = Percentage of RAP expressed as a decimal.

T_{RAP} = Critical temperature of recovered RAP binder (high, intermediate, or low).

There are also questions regarding the exact contribution of RAP binder to total binder in an asphalt mixture (this is discussed again in more detail in a following section). Many researchers have demonstrated that asphalt mix designs with low RAP percentages, up to 15 to 20 percent, are not significantly affected by RAP variability (Bukowski (1997); Huang et al. (2005); Shah et al. (2007); Daniel and Lachance (2005); Li et al. (2008) and Roque et al. (2015)). However, considerable change in the performance of the asphalt mixture can be observed at higher RAP content and that the variability of the RAP has a greater influence on the performance of the mixture. For example, Daniel et al. (2005) reported similar dynamic modulus and creep compliance curves compared to those for the control mixture containing 0% RAP. While McDaniel et al. (2000) observed higher degree of blending for high quantity of RAP (40%) than the low quantity of RAP (10%). These findings are reflected in the blending guidelines created by AASHTO and Superpave, in which no specific binder testing was required for low or intermediate RAP content, while a blending chart is required for high RAP content. The AASHTO and Superpave guideline further validate the assertion that low percentage of RAP (up to 20%) has no significant impact on the mixture, but higher RAP content is depended on the variability of RAP.

1.2.2 Binder recovery methods

In order to obtain the binder properties and critical temperature for the blending chart, the first step is to extract the binder from a given sample of the RAP. Various extraction methods exist that use different procedures, equipment, and solvents. Extraction processes are often criticized for their influence on the potential properties of binder and aggregates. Some examples of extraction techniques available include centrifuge, reflux, abson and Strategic Highway Research Program (SHRP) extraction method. Procedures such as AASHTO TP2 modified, ASTM D2172 method A,B,C, D, and E utilize the extraction techniques mentioned above or some combination of these techniques. The modified AASHTO TP2 method is explained in more detail later in the section. These different extraction methods rely on different solvents, such as trichloroethylene (TCE), toluene, toluene/ethanol, or N-propyl bromide(NPB), and methylene chloride. Some disadvantages of extraction processes include the excessive operator time consumed during extraction, use of toxic solvents that are both costly to purchase and dispose, and exposure to such solvents. As mentioned previously, one of the most critical limitations with extraction methods is the effect the process has on the properties of the binder. For example, a study performed by Nosler et al. (2008) showed that there is a trace of solvent in the extracted binder and the impact of this trace can be observed in binder properties such as its softening point, penetration, and ductility.

Some researchers have also employed the use of proxy RAP binder, which is aged virgin binder to "synthesize" RAP binder in an effort to avoid the influence of the extraction process on the properties of the binders. However, it is evident that such synthetic binders can only be used in research settings to study the influence of RAP binder on the performance of the blended binder and mixture. As such, this is not relevant to characterization of realistic RAP binders from the field.

A number of studies in the literature indicate that The Strategic Highway Research Program (SHRP) extraction procedure such as (AASHTO TP2 (1999) modified method) has minimal impact on the properties of the binder (Copeland (2011); Al-Qadi et al. (2009); McDaniel et al. (2000) and Bennert (2012)). A study performed by Al-Qadi et al. (2009)

reported that the AASHTO TP2 method resulted in minimal aging to the recovered binder during the extraction process. McDaniel et al. (2000) compared the centrifuge extraction (ASTM2172 method A) and the AASHTO TP2 modified extraction procedure which are the two most commonly used methods. They used the rotary evaporator (RE) method to recover the asphalt binder following the AASHTO TP2 method. They tested the recovered binder for $G^*/sin\delta$ and concluded that the centrifuge-abson-TCE method had lower values with the poorest repeatability. The centrifuge-RE-Toluene/Ethanol method had higher values indicating possible additional aging during the process. The standard RE recovery procedure when compared to the modified AASHTO TP2 RE recovery method involves the use of a higher temperature and lower vacuum. Lower temperature may have helped minimize hardening for the AASHTO TP2 process. It was also shown that the RE recovery method was more consistent with a coefficient of variation being much less compared to the abson recovery method (5-20% compared to 38-69%). However, the AASHTO TP2 modified method is limited in the quantity that can be produced per extraction process, which is about 50 grams.

The apparatus associated with the AASHTO TP2 method consists of an extraction vessel, centrifuge, rotary evaporator (RE) with oil bath, nitrogen gas, gas tubes, and vacuum pump as shown in Figure 1.6. To briefly describe the extraction process, a RAP sample is mixed with a solvent in the extraction vessel while injecting nitrogen gas. After mixing the solvent in the vessel, it is extracted into a recovery flask under vacuum and then again into another recovery flask through a 0.020 mm cartridge filter all the while under vacuum. From the filtered solution, it is then introduced into the RE recovery flask, beginning the primary distillation under vacuum at 100 ± 2.5 °C. The process from the vessel to RE is repeated as many times as necessary using the specified solvent quantity and mixing period. Once satisfactory solution dilution and volume is obtained, the solution is put through the centrifuge and then into the RE at a higher temperature until condensation rate is less than one drip per 30 seconds (McDaniel et al., 2000).

After the extraction process, the recovered asphalt is used to determine the upper and lower critical PG temperature using a dynamic shear rheometer (DSR) at high and intermediate temperatures, and using a bending beam rheometer (BBR) at low temperatures.

1.2.3 RAP and virgin binder blending

Before proceeding with the further discussion on blending charts, it is important to briefly discuss the issue of blending of RAP and virgin binder in a mix. There are two extreme

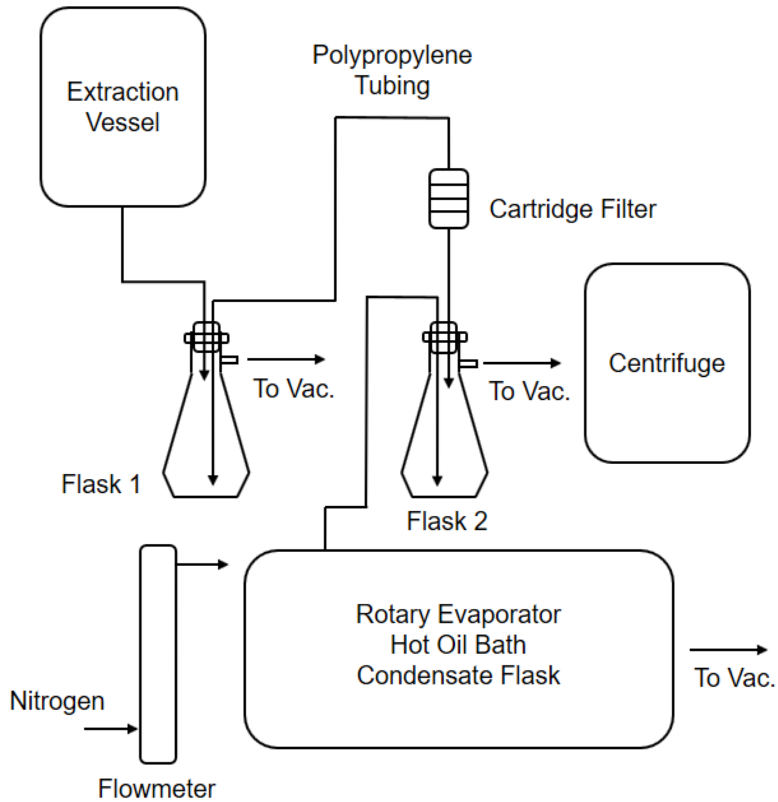

Figure 1.6. AASHTO TP2 apparatus diagram. Adapted from "Standard Test Method for the Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures" by AASHTO TP2, 1999, Washington, DC., American Association of State Highway and Transportation Officials.

schools of thought regarding the blending of the RAP binder with the virgin binder. The first extreme scenario is that the RAP acts as a black rock with essentially no blending (or concomitant contribution) of the RAP binder with the virgin binder. In this case the benefits of RAP are realized purely from the recycling of the aggregates. The second extreme scenario is that the RAP and virgin binder completely blend to form a homogeneous mix. Studies show that reality is somewhere in between depending on the time and temperature at which the loose mix exists after being produced in the asphalt mix plan and prior to compaction and cooling. Current typical practice assumes the latter, i.e. 100 percent blending, which may be inaccurate. Research performed by Al-Qadi et al. (2009) found that the actual blending is somewhere in between complete blending and black rock but there are no direct methods available to accurately determine the amount of blending that occurs.

According to Daniel and Mogawer (2010), the extent of the blending also varies with the source of the RAP. However, the effective properties of the binder in mixtures containing RAP cannot be tested directly. This is because the process of extracting the binder results in complete blending of the virgin and RAP binder. Therefore, testing must be performed on the mixtures to determine the effective properties of the binder. Other researchers have used different approaches to estimate the extent of blending as described below.

Huang et al. (2005) conducted an extensive study to determine the blending ratio between virgin binder and RAP binder through the studying of coating of mixed binder. Fine screened ($\leq$ No.4 sieve) RAP particles and coarse virgin aggregates($>$ No.4 sieve) were blended in order to be able to visually differentiate and physically separate the particles after blending. Blending of the two types of particles made it possible to distinguish the RAP binder that was released from the RAP material and coated the virgin aggregates. The asphalt content of RAP decreased from 6.8% to 6%, which is about 11%. Also, a similar decrease in the asphalt content was observed for all RAP proportions (10-30%). Huang et al. (2005) concluded that majority of RAP binder is retained on the RAP aggregate and only a small portion of blending occurs. It should be noted that the mixing time and temperature were modified from current practice to facilitate improved blending. Huang et al. (2005) also performed a staged extraction to determine the penetration depth of virgin binder on RAP aggregate with aged binder coating. The asphalt viscosity increased at both high and intermediate temperature as the depth increased. Around 40% of the outer layer showed a decrease in stiffness with lower complex shear modulus while the inner layers (60%) showed stiffness resembling that of pure RAP binder.

Research by Shirodkar et al. (2011) extended the study of partial blending performed by Huang et al. (2005). Shirodkar et al. (2011) compared the rheological properties of the binder coating the RAP aggregate and the virgin aggregate. The hypothesis was that full blending would result in similar properties of binder from virgin aggregate and RAP aggregate after blending and in the case of no blending the properties of the binder extracted from the virgin aggregates would be more similar to properties of the virgin binder and properties of the binder extracted from the RAP aggregate would be similar to properties of the binder extracted from the RAP aggregate before any blending was carried out. Equation 1.3 shows the blending ratio calculation and the degree of partial blending was calculated using the following Equation 1.4. The study found that the degrees of partial blending for 25% RAP with PG70-28 and 35% RAP with PG58-28 were 70% and 96%, respectively. Shirodkar et al. (2011) concluded that Huang et al. (2005) may have underestimated degree of blending and that degree of blending determined by the blending study is much higher than that determined by coating study.

$$Blending\,ratio = \frac{(|(G^*/sin\delta)_{blend\,binder\,virgin\,agg}) - (G^*/sin\delta)_{blend\,binder\,RAP\,agg}|)}{(T_{RAP} - T_{virgin})} \tag{1.3}$$

$$Degree\,of\,partial\,blending\,(\%) = 100 \times |1 - Blending\,ratio| \tag{1.4}$$

In a more recent study, Guo et al. (2016) studied the interaction between binder and mineral aggregate, including RAP, to gain a better understand about the behavior of different components. The role of individual ingredients of asphalt mixture such as asphalt binder and aggregates are clearly defined. However, the interaction and bonding mechanisms between these components is not as well understood. Furthermore, the interaction of virgin binder and RAP aggregate is even less clear and the study highlighted the importance of understanding the influence of interactions at the binder-aggregate interface for warm mix asphalt with RAP. Guo et al. (2016) evaluated the effect of interfacial interactions under loading in shear with sinusoidal oscillation and monotonically increasing load. An interaction parameter (IP) that indicated the degree of interaction between asphalt and aggregate showed that the mixing time and temperature significantly influence the interfacial properties of RAP aggregate surface (with a film of aged binder). Stronger interaction was observed as the curing temperature or time increased.

Although there are uncertainties related to estimating the degree of blending between virgin and RAP binder, it is generally accepted that the two will mix to a certain extent.

1.2.4 Mix design

There are several considerations that must be made while designing a mix incorporating RAP. For example, the gradation of the RAP particles is not the original gradation of the aggregate used in RAP because the binder film on RAP adds to the dimension of the aggregate. However, in practice, the gradation of the recovered RAP aggregate is used on an as-is basis for design purposes. Typical job mix formulas account for the differences in batching material gradation and the true gradation of the RAP material as well as for the binder contained in the RAP material (Copeland, 2011). The dust produced during the milling process is also a factor that limits the usage of high RAP because of the potential changes to the dust to asphalt ratio in the mix that may not be properly accounted for as well as the implications of this dust on air voids and VMA (Voids in Mineral Aggregate). Once RAP has been characterized, it is treated like any other aggregate stockpile for the purposes of developing an aggregate gradation.

One important recommendation for handling RAP in a laboratory environment is that RAP is heated before mixing with virgin materials to achieve the desired workability at a temperature of 110 °C (230 °F), but no more than 2 hours for a sample sizes of 1 to 2 kg. Higher temperature and longer heating times have been shown to change the properties of some RAPs (McDaniel et al., 2000).

1.2.5 Voids in mineral aggregate (VMA)

There is some variability associated with VMA of RAP included in asphalt mixes. There are several studies investigating the effect of RAP on the volumetric and mechanical properties of asphalt mixture reporting contradicting results. For example, Al-Qadi et al. (2009) studied six job mix formulas (JMF) with three different RAP sources at 0, 20, and 40 percent. For two of the RAP sources they reported increased VMA with increased RAP content. Daniel and Lachance (2005) also reported increased VMA with 25% and 40% RAP content. These researchers attributed this increase to the pre-heating for RAP material, which simulates real practice, to induce greater ratio of blending between RAP binder and virgin binder. If not heated sufficiently, RAP particles were more like black rock rather than mixing with virgin material. But they also found overheating cause severe aging of RAP binder that caused less blending. Daniel and Lachance (2005) reported a decrease in VMA by 0.5 percent when heating time increased from 2 to 3.5 hours, and then approximately 3 percent increase when with heating time of 8 hours. Tran and Hassan (2011) on the other hand found contrary results. The study reported a decrease in VMA with increase in RAP content while studying 0, 10, 20, and 30 percent RAP that were designed to have similar blending gradation. VMA decreased from 16.3 percent to 14.2 percent as RAP content increased from 0 to 30 percent. The decrease in VMA may be explained by the reduced design binder content and an increase in the amount of material passing through No. 200 sieve.

Paving RAP included in asphalt mixtures should present no significant difference from issues encountered when paving with conventional asphalt mixtures with virgin materials. High RAP mixtures will have increased stiffness as a result of RAP so the contractor should be aware of this during production. Higher temperatures to facilitate blending of RAP with virgin materials may be required but achieving density with RAP mixes is typically not a concern.

1.3 METHODS TO ASSESS PERFORMANCE OF RAP BINDER WITH INCREASED RELIABILITY

The gradation of the recycled aggregate changes during the milling process and the properties of the oxidized recycled binder must be reflected in the final mix design. To characterize the aged binder from RAP, the binder needs to be extracted and the rheological properties tested. Current practice only requires the rheological testing that is necessary to determine the critical high and low temperature to determine the blending ratio of RAP and virgin material. However, after a thorough review of literature and field performance, it is clear that current tests do not accurately reflect the expected performance of the asphalt binders when used in asphalt mixtures.

Researchers have demonstrated that different rheological indices can be derived using a Dynamic Shear Rheometer (DSR) tests that serve as a surrogate indicator for brittleness. Glover et al. (2005) proposed the rheological parameter, $G'/(\eta'/G')$, as an indicator of ductility based on the ductility of a mechanical analog consisting of springs and dashpots. It has been well demonstrated in the literature that this parameter is directly correlated to measured ductility for most unmodified binders. The Glover parameter can be calculated based on results obtained by conducting a DSR frequency sweep test, making it much more practical than directly measuring ductility using traditional methods. Rowe and Sharrock (2011) re-defined the Glover parameter in terms of $|G^*|$ and δ as shown in Equation 1.1 and suggested use of the parameter $|G^*| \times (cos\delta)^2/sin\delta$, termed the Glover-Rowe (G-R) parameter in place of the original Glover parameter at a specific frequency.

$$\frac{G'/(\eta'}{G'} = \frac{|G^*| \times (cos\delta)^2}{sin\delta}\omega \tag{1.5}$$

Rowe proposed measuring the G-R parameter based on construction of a master curve from frequency sweep tests conducted at 5, 15, and 25 °C in the DSR and interpolating to find the value of G-R at 15 °C and 0.005 rad/s to assess binder brittleness (Rowe et al., 2014). A higher G-R value indicates increased brittleness. It has been proposed that a G-R parameter value of 180 kPa corresponds to damage onset whereas a G-R value exceeding 450 kPa corresponds to significant cracking potential based on a study relating binder ductility to field block cracking and surface raveling by Anderson et al. (2011). It was proposed that the rheological indices be considered as simple indicator related to cracking susceptibility. However, recent studies such as Hajj et al. (2019) and Glover et al. (2005) have also shown that this parameter is not very accurate for modified binders.

The Bending Beam Rheometer (BBR) is typically used to measure the stiffness and m-value parameters of an asphalt binder at low temperatures as an indicator of the binder's resistance to low temperature cracking. However, some studies such as Anderson et al. (2011) have demonstrated that the ΔT_c, which is the difference in the critical low temperature based on the stiffness (S) criterion and the critical low temperature based on the m-value criterion is also correlated with intermediate temperature fatigue cracking resistance (e.g., as measured using the overlay tester). In contrast, other studies have shown that this parameter does not necessarily correlate with the cracking resistance of the asphalt binder (Hajj et al., 2019). Not withstanding these contradictions, it is important to evaluate and consider the low-temperature properties of the asphalt binder.

Bahia et al. (2001) demonstrated that the correlation between $G^*/sin\delta$ for asphalt binders and rutting in asphalt mixtures was weak. The repeated creep and recovery test using the DSR was explored as an alternative to overcome this limitation. The outcome of these investigations was the development of the Multiple Stress Creep and Recovery (MSCR) test protocol to measure the non-recoverable compliance of the binder J_{nr}. ε_{10} was defined as the non-recoverable strain at the end of a nine second recovery period after one second loading period. At a given temperature, a binder with a higher value of J_{nr} indicates a higher propensity to accumulate permanent deformation. D'angelo (2007) also reported that J_{nr} values correlated better with rutting compared to the $G^*/sin\delta$ parameter as prescribed by the original Superpave PG specification. This finding was later substantiated by other researchers (Bukowski et al. (2011); DuBois et al. (2014) and Guo et al. (2016)).

The time sweep test was developed in NCHRP 9-10 (Bahia et al., 2001) in an attempt to solve the limitations of the current specification in terms of its ability to predict fatigue cracking. The time sweep test consists of applying repeated cyclic loading at fixed amplitude to an 8 mm diameter asphalt binder specimen in the DSR. Changes in loading resistance with respect to number of loading cycles are used to evaluate damage resistance and determine fatigue failure. It has been demonstrated that results of binder time sweep testing are correlated with mixture beam fatigue results (Bahia et al., 2001) and direct tension testing (Hintz, 2012). However, the time sweep test has been deemed impractical for specification purposes due to the need to select an appropriate loading amplitude for testing to produce failure in a reasonable amount of time, which requires knowledge of the material's damage resistance a priori.

The Linear Amplitude Sweep (LAS) test (AASHTO TP101, 2014) has been proposed as a surrogate to the time sweep as a practical specification test (Johnson (2010); Hintz et al. (2011); Hintz and Bahia (2013)). The LAS test is similar to the time sweep in that it consists of cyclic loading in the DSR and utilizes the same specimen geometry. However, in the LAS test, loading amplitudes are systematically increased to accelerate damage. The LAS test also includes a frequency sweep to obtain a fingerprint of the material's undamaged material response, which can be run directly before the amplitude sweep, on the same specimen. Total testing time, including thermal equilibration, is approximately 30 minutes. Simplified Viscoelastic Continuum Damage (S-VECD) theory can be applied to LAS (or time sweep) results to allow for estimating fatigue life at any strain amplitude of interest. Recently, the analysis protocol has been enhanced to include a failure criterion to improve predictability (Wang et al., 2015). The new protocol includes an improved method for defining fatigue failure in the LAS test based on energy principles, which is material-dependent and is effective in capturing the benefits of asphalt modification for binder fatigue resistance. In addition, a failure criterion has been developed which can predict when the fatigue failure will occur under loading conditions other than those used in model characterization testing. Fatigue life predictions using this newly developed failure criterion coupled with the S-VECD model are able to predict measured time sweep fatigue lives reasonably well.

In addition, fatigue life predictions generally related well with the field fatigue performance measured in the FHWA-ALF study (Wang et al., 2015), as well as LTPP field performance (Hintz et al., 2011). It has also been demonstrated that when a strain ratio from mix to binder of 80 is used, fatigue life predictions from LAS results are consistent with mixture fatigue life predictions (Safaei et al., 2014).

In summary, several recent studies have demonstrated a weakness in the existing test methods commonly used as a part of the Performance Grading specification. These weaknesses are inherited and in some cases also enhanced with the use of recycled asphalt binders. Different alternatives have been presented in the previous paragraphs as potentially better indicators of the expected performance of the asphalt binder in an asphalt mixture. Some of these tests and concomitant parameters will also be used in the remainder of this study to evaluate virgin and RAP binders.

1.4 PRACTICE FOR BINDER SELECTION IN TEXAS

TxDOT standard specifications currently allow the use of RAP in all asphalt concrete mixtures with the exception of thin overlay mixtures (TOM). The maximum allowable percent of RAP by weight is limited to 30% when the mixture is used as a base or binder (level-up) course and 20% when used as the surface course. Special provisions were recently approved that allow both unfractionated and fractionated RAP to be used without requiring a plan note. Unfractionated RAP is limited to 10% for surface mixes, and 20% for base mixes. Currently some districts in Texas do not allow RAP to be used in any asphalt mixtures or in surface mixtures mainly because of the high variability associated with RAP, and therefore with the produced mixture. Other barriers to increasing the use of RAP in Texas (and in the US) include:

- Meeting voids and asphalt content with Superpave mix designs.
- Meeting skid requirements.
- Hardness of asphalt with high RAP contents potentially, leading to fatigue cracking, with the subsequent need to use softer binders that could potentially lead to rutting problems.
- Uncertainty regarding use of RAP with special mixtures, for example stone mastic asphalt (SMA).
- Uncertainty regarding use of RAP with polymers.
- Plant restrictions.

As shown before, Table 1.3 represents the blending specification required by TxDOT showing originally specified binder, allowable substitute binder, and the maximum ratio of recycled binder to total binder for a surface, intermediate or base layer of a mixture.

In summary, recycled materials are typically used in conjunction with warm mix technologies, recycling agents, and a softer substitute binder. The recycled binder ratio (RBR) is controlled through "Table 5" in Specification 2014 Items 340/341/344. However, the current specification (1) may result in the substitution of a polymer modified binder with a binder that has little or no polymer (elastomer), (2) does not account for the influence of recycling agents, and (3) does not address the potential differences in the quality of binders from different sources of RAP or recycled asphalt shingles (RAS). Also note that this table allows for binder substitution regardless of the percentage of RAP, which is different from the general trend of using the same grade up to typically 20% RAP. Furthermore, in many instances the grade lowering is restricted to only the higher grade and not the lower grade.

Table 1.3. Allowable substitute PG binders and maximum recycled binder ratios. Note: Table 5 in TxDOT specification book 2014 (TxDOT, 2004)

Originally Specified PG Binder	Allowable Substitute PG Binder	Maximum Ratio of Recycled Binder to Total Binder (%)		
		Surface	Intermediate	Base
		HMA		
76-22	70-22 or 64-22	20.0	20.0	20.0
	70-28 or 64-28	30.0	35.0	40.0
70-22	64-22	20.0	20.0	20.0
	64-28 or 58-28	30.0	35.0	40.0
64-22	58-28	30.0	35.0	40.0
76-28	70-28 or 64-28	20.0	20.0	20.0
	64-34	30.0	35.0	40.0
70-28	64-28 or 58-28	20.0	20.0	20.0
	64-34 or 58-34	30.0	35.0	40.0
64-28	58-28	20.0	20.0	20.0
	58-34	30.0	35.0	40.0
		WMA		
76-22	70-22 or 64-22	30.0	35.0	40.0
70-22	64-22 or 58-28	30.0	35.0	40.0
64-22	58-28	30.0	35.0	40.0
76-28	70-28 or 64-28	30.0	35.0	40.0
70-28	64-28 or 58-28	30.0	35.0	40.0
64-28	58-28	30.0	35.0	40.0

This study addresses the above gaps as well as methods to improve blending of recycled and virgin binders by evaluating the performance of binders and mixtures using systematically controlled materials prepared in the laboratory as well as materials sampled from the field.

CHAPTER 2. MATERIAL SELECTION AND SAMPLING

This chapter summarizes the materials selected for use in subsequent tasks for laboratory and field evaluation.

2.1 LABORATORY EVALUATIONS

In the case of laboratory evaluation, two different grades of binders that are typically recommended for asphalt pavement construction were selected as control binders (PG76-22, and PG70-22). In addition, three different types of binders were selected as substitute binders (PG70-22, PG64-22, and PG64-22* which is a polymer modified binder specifically formulated in the lab to have good elastic recovery).

Table 2.1 shows a summary of binders and RAP combinations that were used in this study. Binder recovered from two RAP stockpiles and two RAS stockpiles were used in order to create blends with different percentages of RAP, or RAP and RAS, to study the influence of RAP or RAS inclusion in binders. Also, three different additives (recycling or softening agents) were used in order to enhance the properties of the RAP modified binders.

Table 2.1. Control binders, substitute binders, recycled binder sources, and percentages for laboratory binder testing

Binder PG			RBR Percentages (A1, 2, 3 = Three different types of recycling or softening agents)							
Spec.	Sub.	Source								
76-22	70-22	RAP A	20%	40%	40% + A1	50% + A1	40% + A2	50% + A2	40% + A3	50% + A3
76-22 70-22	64-22	RAP A	20%	40%	40% + A1	50% + A1	40% + A2	50% + A2	40% + A3	50% + A3
76-22	64-22	RAP B	20%	40%	40% + A1					
76-22	64-22	RAP A + RAS A	20%	40%	40% + A1					
76-22	64-22	RAP A + RAS B	20%	40%	40% + A1					
76-22	64-22*	RAP A	20%	40%	40% + A1					
76-22	64-22*	RAP B	20%	40%	40% + A1					

Note: Suffix A and B show different sources of types of RAP/RAS recycled binders. PG64-22* is a PG64-22 binder that is polymer modified.

During the course of this study, it was recommended that more emphasis be placed on binder properties and variability in RAP instead of mixture properties. The rationale for this was that mixture properties were currently being captured by other performance based test methods. Accordingly, ten different RAP stockpiles were identified throughout the state of Texas in order to evaluate the variability in the binder properties from different RAP stockpiles. Figure 2.1 shows the locations of the ten different RAP stockpiles that were used in this study.

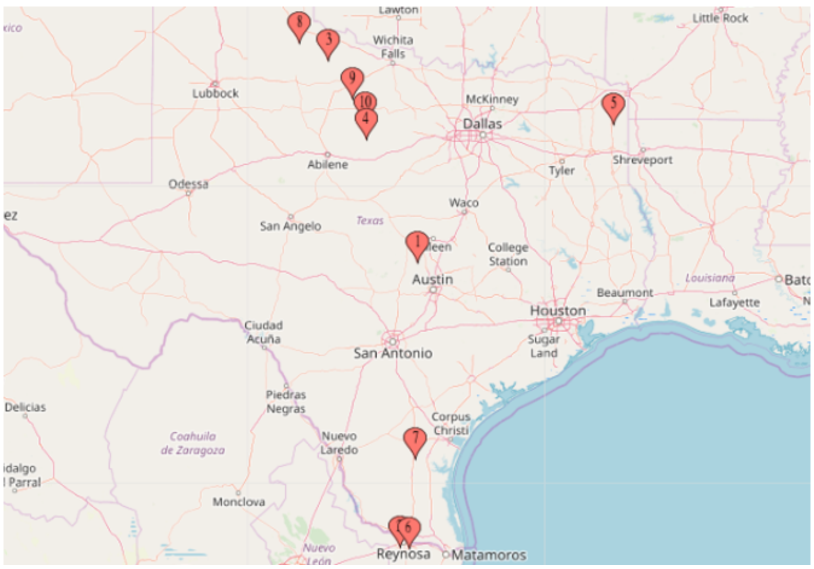

Figure 2.1. Locations of the different RAP stockpiles used in this study

Table 2.2 shows the methods and tests that were used to extract, recover, and evaluate these asphalt binders. Primarily, the interest was to evaluate the low performance grade or PG of the recovered binder using micro-extraction method and the DSR 4mm parallel plate with the intention of potentially using this on a routine basis in the long-term. The micro-extraction method is more affordable and less time consuming when compared to the regular extraction method. The objective of this exercise was to determine the variability in the recovered binder from different RAP stockpiles. In addition, two different binders (PG70-22 and PG64-22) were used to evaluate the low PG using a constant RBR percentage of 30% from five different RAP stockpiles (RAP #1 through RAP #5) after short term aging (RFTO) and long term aging (PAV).

Table 2.2. **Control RAP stockpiles used to characterize their recovered binder using micro-extraction method and materials used to evaluate a constant RBR percentage using DSR 4mm plate geometry**

Stockpile	Extraction Method	Con-trol	RBR %	Aging	Test Low Temp.
RAP #1	Micro Extraction	N/A	N/A	As is	DSR (4mm)
RAP #2	Micro Extraction	N/A	N/A	As is	DSR (4mm)
RAP #3	Micro Extraction	N/A	N/A	As is	DSR (4mm)
RAP #4	Micro Extraction	N/A	N/A	As is	DSR (4mm)
RAP #5	Micro Extraction	N/A	N/A	As is	DSR (4mm)
RAP #6	Micro Extraction	N/A	N/A	As is	DSR (4mm)
RAP #7	Micro Extraction	N/A	N/A	As is	DSR (4mm)
RAP #8	Micro Extraction	N/A	N/A	As is	DSR (4mm)
RAP #9	Micro Extraction	N/A	N/A	As is	DSR (4mm)
RAP #10	Micro Extraction	N/A	N/A	As is	DSR (4mm)
N/A	Regular Extraction	64-22	30%	RTFO/PAV	DSR (4mm)
N/A	Regular Extraction	70-22	30%	RTFO/PAV	DSR (4mm)

2.2 FIELD EVALUATIONS

Part of this study also included the evaluation of field mixes. For this purpose, four different field sections were identified representing different geographic and climatic regions across Texas. Figure 2.2 shows these locations in the Pharr, Childress, Austin, and Atlanta districts.

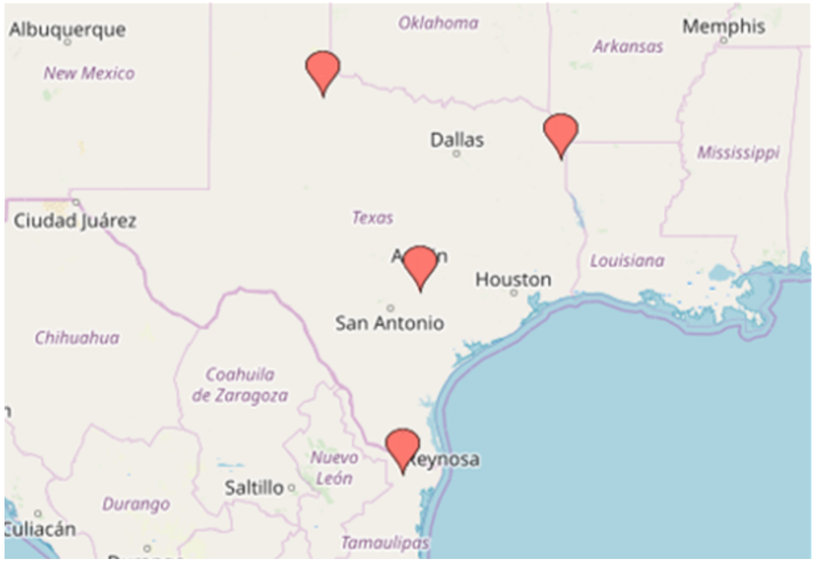

Figure 2.2. Different locations selected in the Pharr, Childress, Austin, and Atlanta districts

Figure 2.3 shows the four districts selected, that represent four different climatic regions. The Pharr district represents a dry-warm zone, Childress district represents a dry-cold zone, Austin district represents a wet-warm zone, and Atlanta district represents a wet-cold zone.

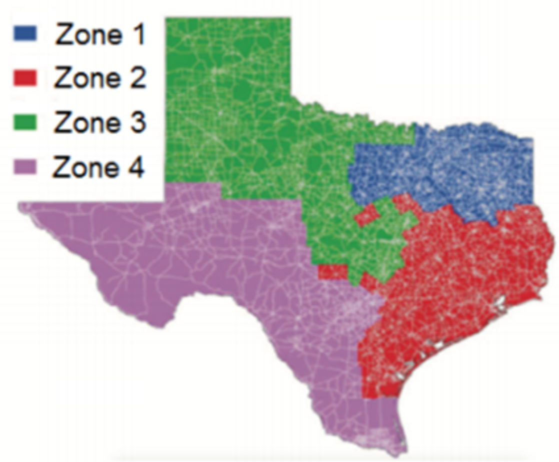

Figure 2.3. Typical climatic regions in the State of Texas; wet-cold (Zone 1), wet-warm (Zone 2), dry-cold (Zone 3), and dry-warm (Zone 4)

The different mixture combinations or variations that were evaluated for each of the four districts are summarized here.

1. Laboratory mix prepared using the job mix formula (JMF) and the specified binder and without any RAP[1].
2. Laboratory mix prepared using the JMF and the substitute binder but without any RAP (this was intended to serve as a baseline for comparison).
3. Laboratory mix prepared using the JMF and the substitute binder and RAP (this would be the mix design that was ultimately used).
4. Laboratory mix prepared using the JMF and an additional 10% RAP after making appropriate adjustments to the aggregate gradation.
5. Field mix obtained at the time of construction.
6. Field cores obtained approximately 1 to 1.5 years after construction.

Details of the mix design and component materials for each district are described in the following sections.

2.2.1 District 1

District 1 used a PG76-22 as the specified binder and a PG64-22 as the substitute binder. The JMF was a Type D mix and it included a total of eight different bins that included Grade #4, W.C.F, Cyclone Sand, Grade #6, Grade #-6, and Lime for the aggregate bin fractions; fractionated RAP, and RAS for the recycled material bin fractions. The Grade #6 and Grade #-6 were delivered as one bin, so the percentages of the two bins were not changed for different RBR ratios. Also, the quantity of RAS was kept constant as we increased the RBR by an additional 10%, because the purpose of this study was to observe the effect of specifically increasing the percentage of RAP. Table 2.3 shows the JMF for the District 1.

[1] In the context of this report RAP also includes RAS where applicable. Two districts used a combination of RAP and RAS, while the other two used only RAP without any RAS

Table 2.3. JMF for District 1 - Optimum binder content of 5.4%

	Bin No.1 Grade # 4	Bin No.2 W.C.F	Bin No.3 Cyclone Sand	Bin No.4 Grade # 6	Bin No.5 Grade # 6-	Bin No.6 Lime	Bin No.8 Fraction-ated RAP	Bin No.9 RAS	Final Gradation
Individual Bin, %	27.0	27.0	8.5	21.0	8.0	1.0	7.0% of Binder 4.9% of Tot. Agg. 5.0% of Tot. Mix	17.5% of Binder 2.6% of Tot. Agg. 3.0% of Tot. Mix	
Sieve Size	Cumulative Passing %								
0	100	100	100	100.0					
1/2"	100	100	100	100	100	100	100	100	100.0
3/8"	62.2	99.8	99.8	99.8	100	100	99.2	100	89.6
No. 4	8.7	97.6	99.2	22.3	58.4	100	70.5	99.8	53.5
No. 8	7	78.4	98.2	2.2	6.9	100	49.7	96.7	38.4
No. 30	5.1	38.1	96.7	1.6	3.8	100	33.5	72.9	25.1
No. 50	4.4	23.1	63.3	1.5	3.3	100	28.3	61.1	17.4
No. 200	1.7	4.2	18.3	0.9	1.6	100	12.3	15.2	5.5

Figure 2.4 illustrates the difference in the proportion of each bin for the different mixture designs developed for this study. For asphalt mixtures without RAP, the proportion of other bins was increased compared to the JMF and vice-versa for mixtures with 10% additional RAP. The individual bins were altered to minimize the difference in the final gradation for mixes, which can be observed in Figure 2.5

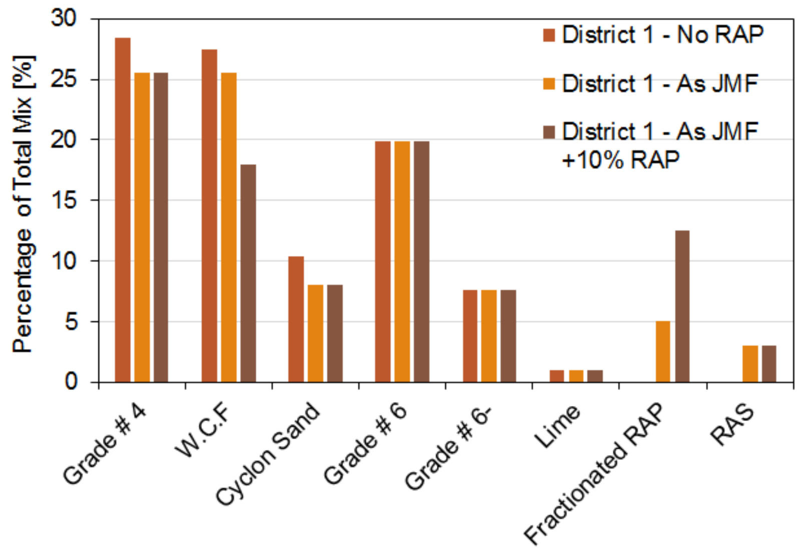

Figure 2.4. Differences in the proportion of each bin for different RAP mixes in District 1

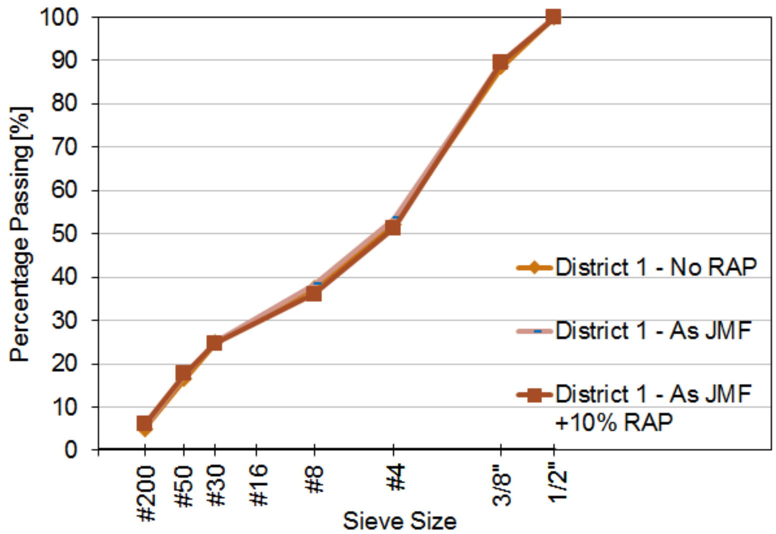

Figure 2.5. Differences in the final gradation for different mixes in District 1

The field mix was obtained at the time of construction for this specific mixture design (as JMF) and it was evaluated in as-is condition, representing short term aging, and after long term aging in the laboratory. Long term aging of field loose mixes was replicated by aging the loose material inside a conventional oven at 95 °C for 5 days. This is based on a previous study (Kim et al., 2018) that shows that the temperature and time selected replicate 8 years of field aging at 5 cm below the pavement surface on an average for most of the State of Texas.

Field core samples were obtained approximately 1.5 years after construction as shown in Figure 2.6.

Figure 2.6. Field core samples extracted in District 1

For this specific district, core samples were obtained between the wheel path.

2.2.2 District 2

District 2 used a PG76-28 as the specified binder and a PG70-28 as the substitute binder. The JMF was a Type D mix and individual bins included D-Rock, Shot Rock, Screening #4, Lime, Fine RAP, and Coarse RAP. The design process of the mixes for District 2 was exactly the same as the design process for District 1. The change in the amount of RAP was compensated for by changing other bins within the JMF. Table 2.4 shows the JMF for the District 2.

Table 2.4. JMF for District 2 - Optimum binder content of 6.3%

	Bin No.1 D' Rock	Bin No.2 Shot Rock	Bin No.3 Screen-ings #4	Bin No.4 Lime	Bin No.8 Fine RAP	Bin No.9 Coarse RAP	Final Gradation
Individual Bin, %	33.0	12.0	44.0	1.0	9.9% of Binder 5.0% of Tot. Agg. 5.2% of Tot. Mix	6.8% of Binder 5.0% of Tot. Agg. 5.0% of Tot. Mix	
Sieve Size	Cumulative Passing %						
3/4"	100	100	100	100	100	100	100.0
1/2"	99.5	99.5	100	100	100	89.7	99.3
3/8"	84.3	99.0	100	100	94.3	73.7	93.1
No. 4	19.7	60.5	92.7	100	76.8	36.8	61.2
No. 8	3.5	20.0	68.7	100	62.5	25.2	39.2
No. 30	1.3	3.6	31.8	100	34.4	16.9	18.4
No. 50	1.0	2.3	20.5	100	17.8	11.9	12.1
No. 200	0.5	1.3	8.3	100	11.0	3.0	5.7

The difference in the proportion of each bin for different RAP mixes can be observed in Figure 2.7. Also, individual bins were changed to minimize the difference in the final gradation for different mixes, which can be observed in Figure 2.8.

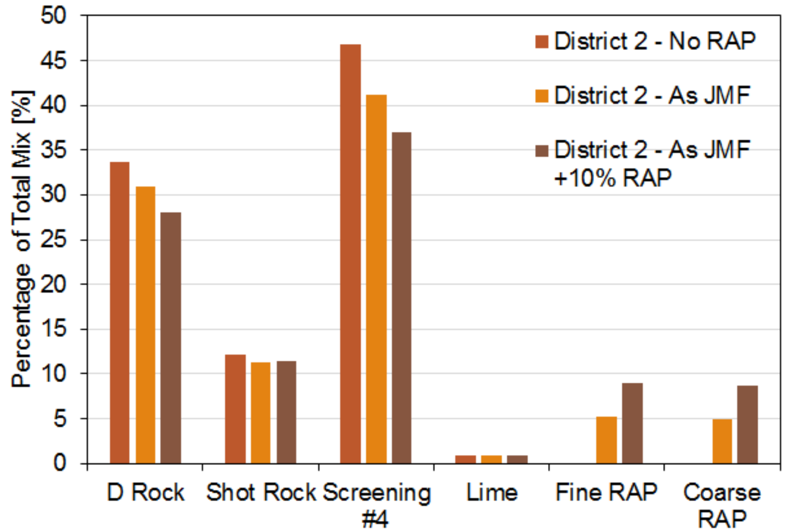

Figure 2.7. Differences in the proportion of each bin for different RAP mixes in District 2

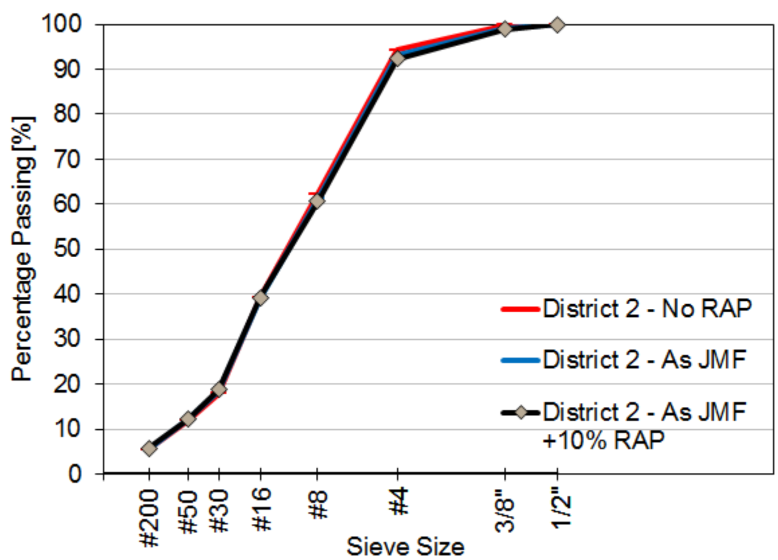

Figure 2.8. Differences in the final gradation for different mixes in District 2

Field mix was obtained at the time of construction for this specific mixture design (as

JMF) and it was evaluated in as-is condition, representing short term aging, and after long term aging in the laboratory. As before, long term aging of field loose mixes was replicated aging the loose material inside a conventional oven at 95 °C for 5 days.

Field core samples were obtained approximately 1.5 years after construction as shown in Figure 2.9.

Figure 2.9. Field core samples extracted in District 2

For this specific district, core samples were obtained between the wheel path.

2.2.3 District 3

District 3 used a PG70-22 as the specified binder and a PG64-22 as the substitute binder. The JMF was a Type D mix and individual bins included Grade #5, Screenings, Field Sand, and Fractionated RAP. The change in the amount of RAP was compensated for by changing other bins within the JMF. Table 2.5 shows the JMF for the District 3.

The difference in the proportion of each bin for different RAP mixes can be observed in Figure 2.10. Also, individual bins were changed to minimize the difference in the final gradation for different mixes, which can be observed in Figure 2.11.

Table 2.5. JMF for District 3 - Optimum binder content of 4.7%

	Bin No.1 Grade # 5	Bin No.2 Screenings	Bin No.3 Field Sand	Bin No.8 Fraction-ated RAP	Final Gradation
Individual Bin, %	42.0	30.0	10.0	4.7% of Binder 18.0% of Tot. Mix 18.0% of Tot. Agg.	
Sieve Size	Cumulative Passing %				
3/4"	100	100	100	100	100
1/2"	100	100	100	100	100
3/8"	98.5	100	99.8	92.5	98
No. 4	36.1	99.4	99.6	70	67.5
No. 8	4.1	79.1	99.1	51.5	44.6
No. 30	2.3	31.9	96.3	32.8	26.1
No. 50	2.2	22.2	67.7	23.9	18.7
No. 200	1.9	13.1	3.5	7.1	6.4

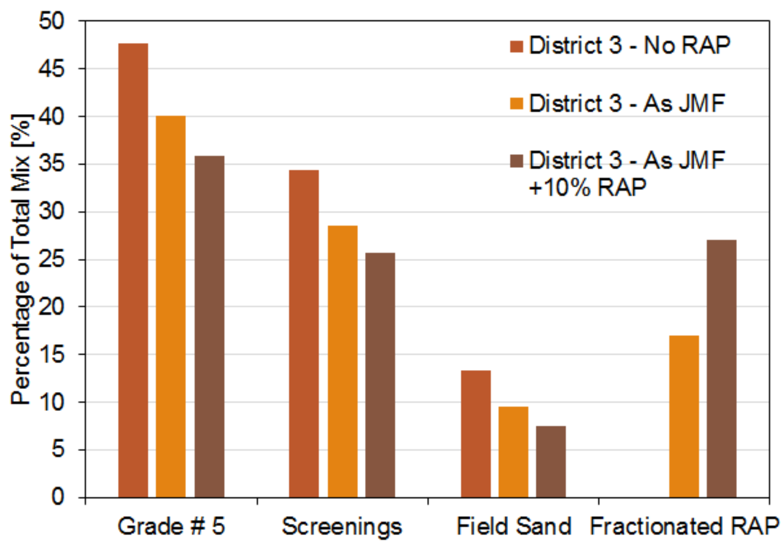

Figure 2.10. Differences in the proportion of each bin for different RAP mixes in District 3

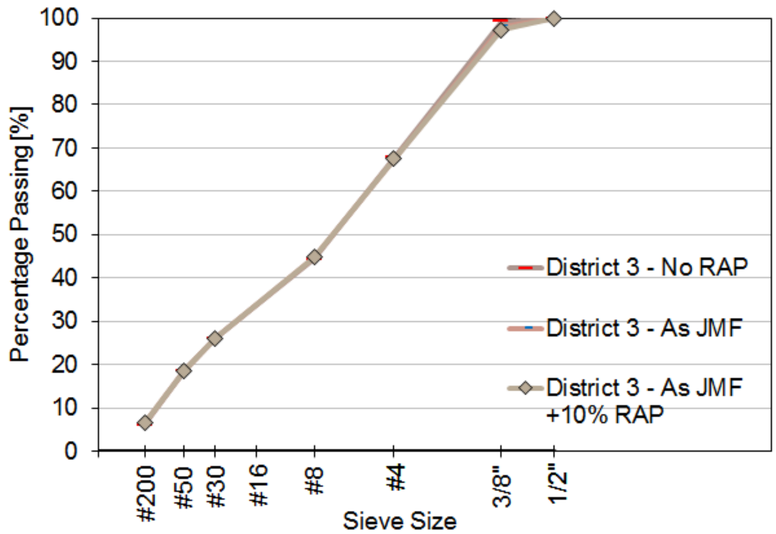

Figure 2.11. Differences in the final gradation for different mixes in District 3

Field mix was obtained at the time of construction for this specific mixture design (as JMF) and it was evaluated in as is condition to represent short term aged material.

Field core samples were obtained approximately 1.5 years after construction as shown in Figure 2.12.

Figure 2.12. Field core samples extracted in District 3

For this specific district, core samples were obtained between the wheel path.

2.2.4 District 4

District 4 used a PG76-22 as the specified binder and a PG70-22 as the substitute binder. The JMF was a Type SP D mix and individual bins included Sandstone, Gravel, Screenings, Field Sand, Sandstone Fine, Lime, Fractionated RAP, and RAS. Also, the quantity of RAS was kept constant as we increased the RBR for additional 10%, because the purpose of this study was to observe the effect of increasing RAP quantity. The change in the amount of RAP was compensated for by changing other bins within the JMF. Table 2.6 shows the JMF for the District 4.

Table 2.6. JMF for District 4 - Optimum binder content of 5.5%

	Bin No.1 Sandstone	Bin No.2 Gravel	Bin No.3 Screen-ings	Bin No.4 Field Sand	Bin No.5 Sandstone Fine	Bin No.6 Lime	Bin No.8 Fraction-ated RAP	Bin No.9 RAS	Final Gradation
Individual Bin, %	15	40	18	7.3	5	1	4.5% of Binder 11.0% of Tot. Mix 11.1% of Tot. Agg.	17.0% of Binder 3.0% of Tot. Mix 2.6% of Tot. Agg.	
Sieve Size	Cumulative Passing %								
3/4"	100	100	100	100	100	100	100	100	100
1/2"	100	100	100	100	100	100	100	100	100
3/8"	88	87	100	100	100	100	90.6	100	92
No. 4	34	41.3	100	99.4	100	100	67	100	62.9
No. 8	12	11	88	94.7	98	100	48.2	99	42.8
No. 16	8	3	61	87.2	89	100	37	82	31.4
No. 30	7	1	39	70.2	77	100	28.5	61	23.2
No. 50	6	1	21	24.7	66	100	21.7	53	15
No. 200	3	0.4	3.3	1.9	20	100	8.1	34.9	5.1

The difference in the proportion of each bin for different RAP mixes can be observed in Figure 2.13. Also, individual bins were changed to minimize the difference in the final gradation for different mixes, which can be observed in Figure 2.14.

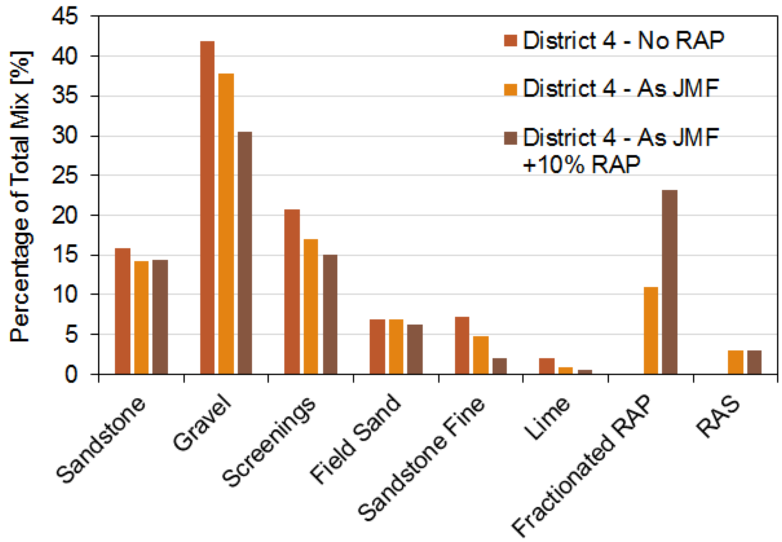

Figure 2.13. Differences in the proportion of each bin for different RAP mixes in District 4

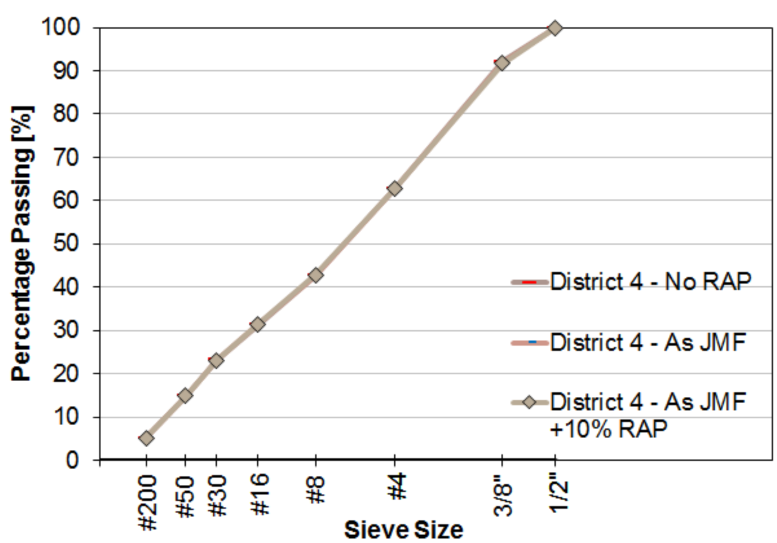

Figure 2.14. Differences in the final gradation for different mixes in District 4

Field mix was obtained at the time of construction for this specific mixture design (as

JMF) and it was evaluated in as is condition to represent short term aged material.

Field core samples were obtained approximately 1.5 years after construction as shown in Figure 2.15.

Figure 2.15. Field core samples extracted in District 4

For this specific district, core samples were obtained between the wheel path.

2.3 SUMMARY

In summary three different types of binders were analyzed using different RAP combinations with and without recycling or softening agents (31 binders in total), and ten different RAP stockpiles were used to characterize the low PG in order to determine the variability in the recovered binder. In addition, two different binders were used to evaluate the low PG using a constant RBR percentage of 30% from five of the different RAP stockpiles used in this study for laboratory evaluation as discussed in subsequent chapters.

CHAPTER 3. INFLUENCE OF RECYCLED AND SUBSTITUTE BINDER ON BINDER AND MIXTURE PERFORMANCE

3.1 INTRODUCTION AND MATERIALS USED

This chapter summarizes the work accomplished in Task 5 of this project, i.e. evaluation of binders and mixtures from field projects. Specifically, four different field sections were identified to represent different geographic and climatic regions across Texas. These sections were from the Pharr, Childress, Austin, and Atlanta districts. Details of the mix design and component materials are included in an earlier chapter of this report. The variations in the mix designs that were evaluated from each source are summarized here.

1. Laboratory mix prepared using the (job mix formula) JMF and the specified binder and without any RAP[1].
2. Laboratory mix prepared using the JMF and the substitute binder but without any RAP (this was intended to serve as a baseline for comparison).
3. Laboratory mix prepared using the JMF and the substitute binder and RAP (this would be the mix design that was ultimately used).
4. Laboratory mix prepared using the JMF and an additional 10% RAP after making appropriate adjustments to the aggregate gradation (details included in previous chapter).
5. Field mix obtained at the time of construction.
6. Field cores obtained approximately 1.5 years after construction.

Note that the loose plant mix is also representative of the condition of new cores in terms of material and mixture properties. Emphasis was placed on a more detailed evaluation of mixture performance.

For the originally specified binder, a binder sample was obtained from a producer that was most likely to supply the binder to the hot-mix plant in case binder substitution was not allowed. This allowed the closest representation of the scenario in which no substitution would be allowed. The substitute binder was sampled at the hot-mix plant during the production of the mix. In addition, a sample of the RAP was also obtained from the same batch or RAP stockpile that was being used at the hot-mix plant during mixture production. Finally, virgin aggregates in sufficient quantities were also obtained from the hot-mix

[1] In the context of this report RAP also includes RAS where applicable. Only two districts used a combination of RAP and RAS while the other two used only RAP

plant during mixture production. A portion of the RAP sample was used to extract and recover the asphalt binder. A sample of the originally specified asphalt binder and virgin aggregates were used to produce mix 1 (mix according to JMF with specified binder and no RAP). A sample of the substitute binder sampled from the hot-mix plan and virgin aggregates were used to produce mix 2 (mix according to JMF with substitute binder and no RAP). Finally, samples of the substitute binder, virgin aggregates, and RAP were used to produces mixes 3 and 4 (mix according to JMF with RAP and additional RAP). In all cases, the laboratory mixes were produced using the appropriate gradation and binder content and short-term aging of 2 hours at 160 °C. The mixes were compacted using a Superpave Gyratory Compactor (SGC) using the appropriate number of gyrations in order to achieve the specific air void content for mixture evaluation. Finally field mixes were obtained directly from the hot-mix plant or from the truck at the construction site (mix 5) and cores were obtained from the construction site. Details on the location and mix designs are provided in a previous chapter.

Note that for evaluation of binder properties, the binders corresponding to mixes 1 and 2 were available directly from source. For binders corresponding to mixes 3 and 4, a sample of the substitute binder was blended with the extracted RAP according to the proportions from the JMF using a high shear blender at the temperature of 160 °C for one hour at 2,400 rpm. For binders corresponding to mixes 5 and 6, the binder was extracted and recovered from the solution using ASTM (2009) and evaluated as is. For mix 6, it was not feasible to subdivide the core into multiple layers and generate adequate material for evaluation. Therefore, the binder from the cores were blended and evaluated as it is with multiple replicates.

3.2 BINDER PROPERTIES

Properties of the binder (with or without RAP) were evaluated for each of the aforementioned mixes. Parameters that were evaluated include rutting resistance, elastic recovery, intermediate temperature stiffness, cracking resistance, and thermal cracking resistance. All of them summarized as follows:

- Rutting resistance: True high temperature PG for the asphalt binder based on the $G^*/\sin\delta$ parameter for the unaged and RTFO (rolling thin film oven) aged binders, obtained by testing the binder at least three different temperatures following the specification AASHTO M320 (2017).
- Elastic recovery: The Multiple Stress Creep Recovery (MSCR) test was conducted

following AASHTO TP70 (2013) to measure the non-recoverable compliance and elastic recovery at 64 °C for the RTFO aged binder.

- Intermediate temperature stiffness and cracking resistance: The PG intermediate temperature parameter $G^* \sin \delta$ was measured for the long term or Pressure Aging Vessel (PAV) aged binder along with the Glover-Rowe (G-R) parameter. The G-R parameter was determined based on construction of a master curve from frequency sweep ranging from 15 to 0.02 Hz testing at 5, 15, and 25 °C in the DSR and interpolating to find the value of G-R at 15 °C and 0.005 rad/s to assess the ductility of the binder (Rowe et al., 2014). A higher G-R value indicates increased brittleness, a proposed G-R parameter value of 180 kPa corresponds to damage onset whereas a G-R value exceeding 450 kPa corresponds to significant cracking potential based on a study relating binder ductility to field block cracking and surface raveling by Anderson et al. (2011).
- Thermal cracking resistance: The PG parameters for low temperature cracking resistance were measured following AASHTO R49 (2009) using the PAV aged binders. The measurements were made at three different temperatures to obtain the true low grade based on both the stiffness (S) and m-value criteria. This information was also used to assess the ΔT_c parameter.

Figures 3.1 to 3.28 present the results for the binder characterization.

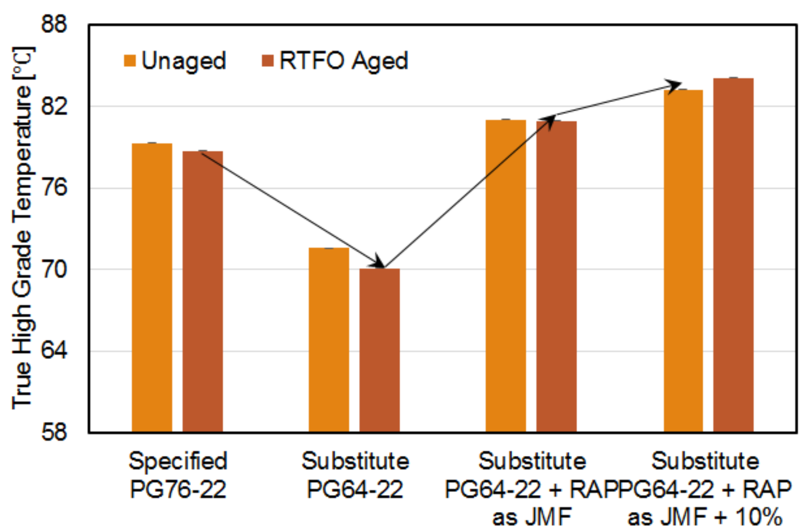

Figure 3.1. True high grade temperature for District 1

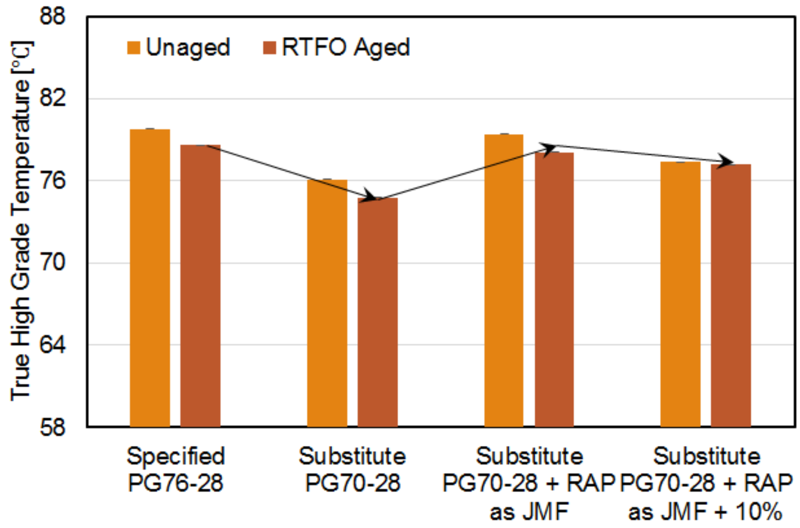

Figure 3.2. True high grade temperature for District 2

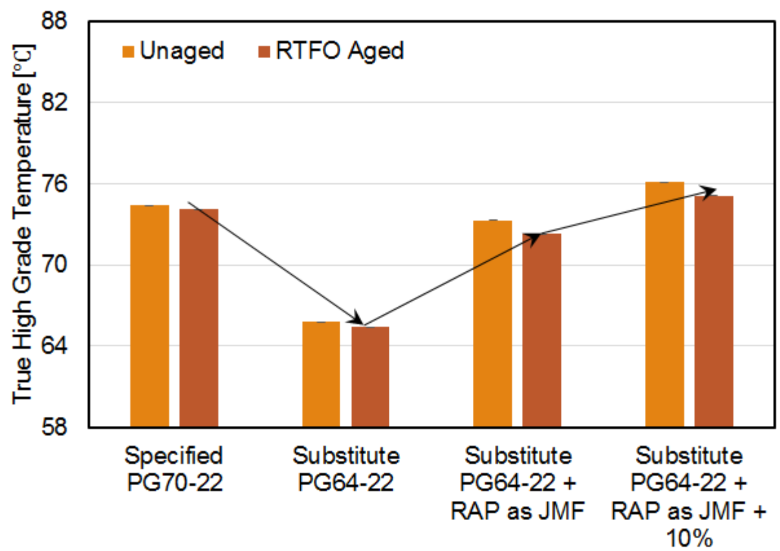

Figure 3.3. True high grade temperature for District 3

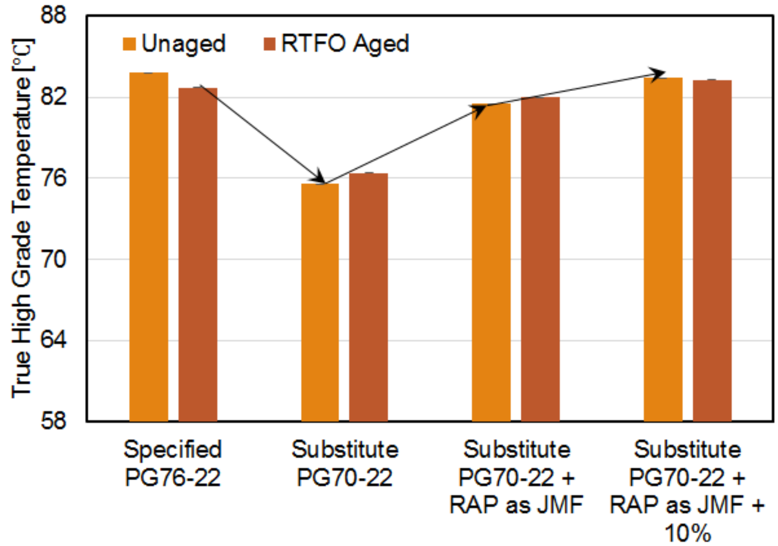

Figure 3.4. True high grade temperature for District 4

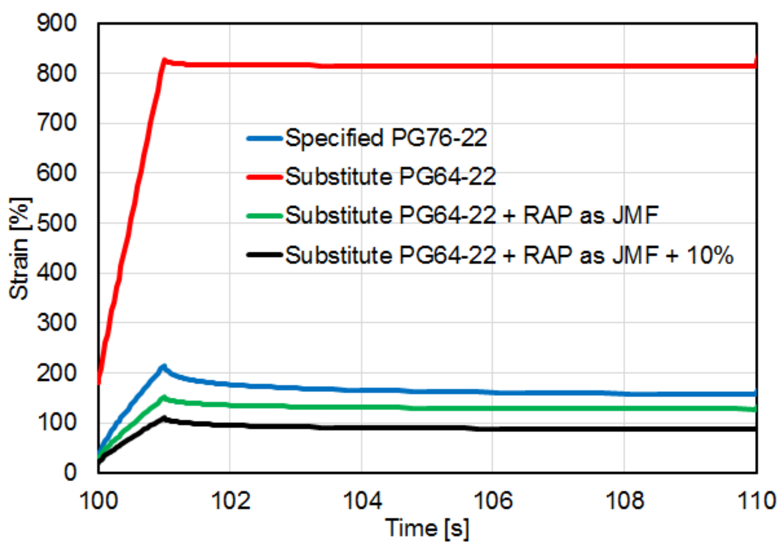

Figure 3.5. Elastic recovery at 3200 Pa and 64 °C for District 1 (only one cycle shown for clarity)

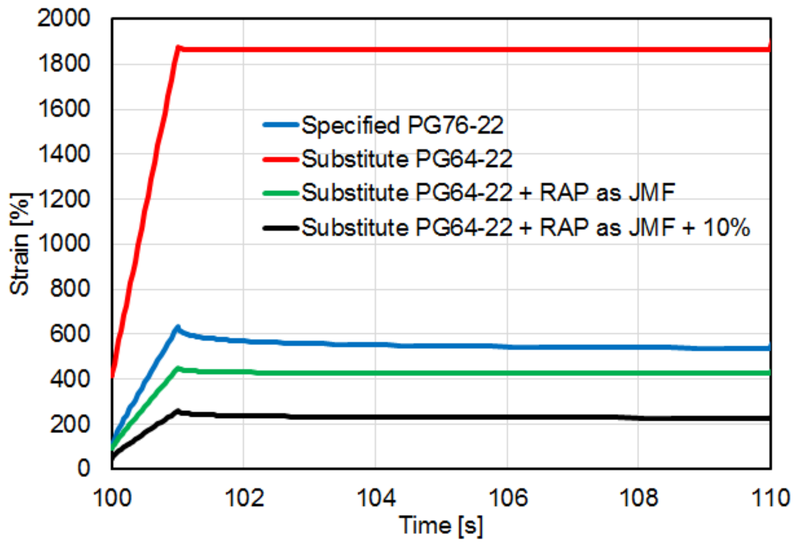

Figure 3.6. Elastic recovery at 3200 Pa and 70 °C for District 1 (only one cycle shown for clarity)

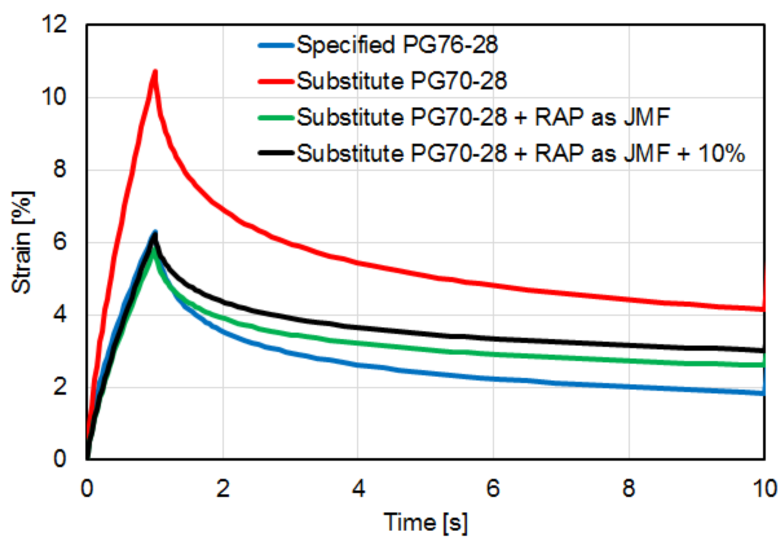

Figure 3.7. Elastic recovery at 3200 Pa and 64 °C for District 2 (only one cycle shown for clarity)

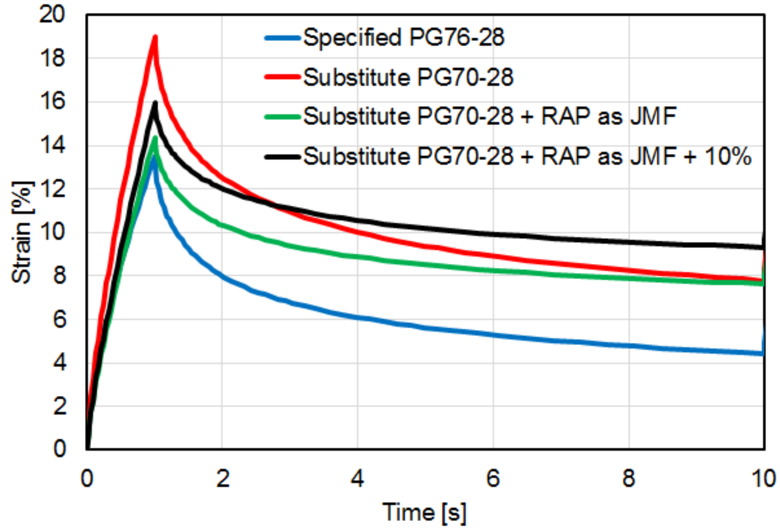

Figure 3.8. Elastic recovery at 3200 Pa and 70 °C for District 2 (only one cycle shown for clarity)

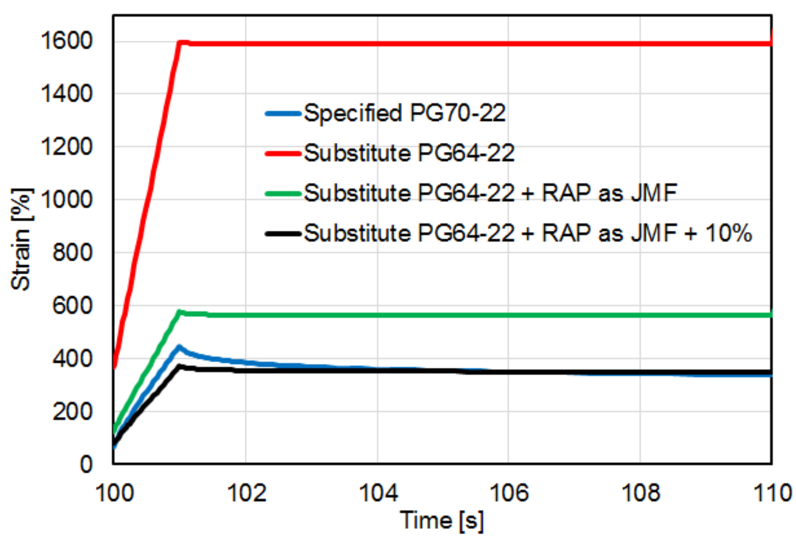

Figure 3.9. Elastic recovery at 3200 Pa and 64 °C for District 3 (only one cycle shown for clarity)

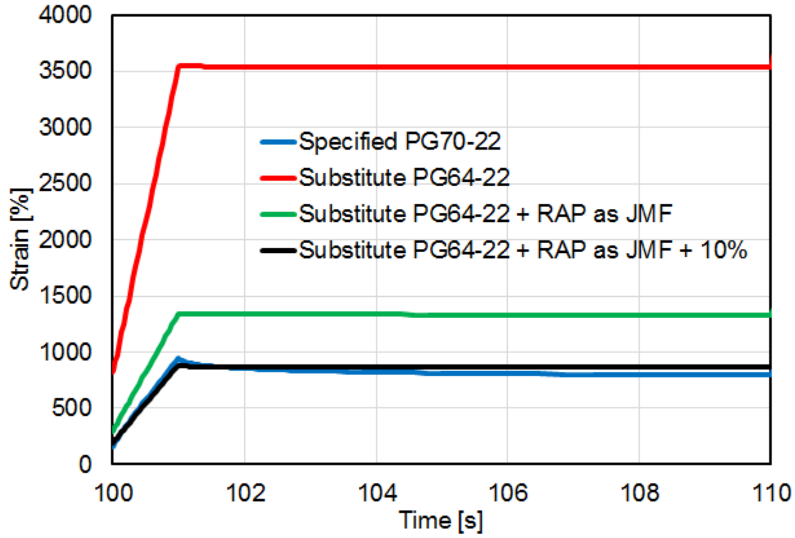

Figure 3.10. Elastic recovery at 3200 Pa and 70 °C for District 3 (only one cycle shown for clarity)

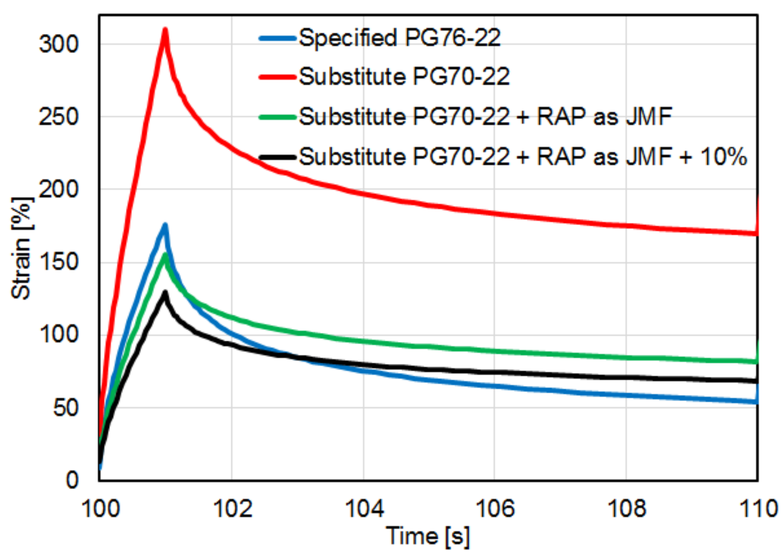

Figure 3.11. Elastic recovery at 3200 Pa and 64 °C for District 4 (only one cycle shown for clarity)

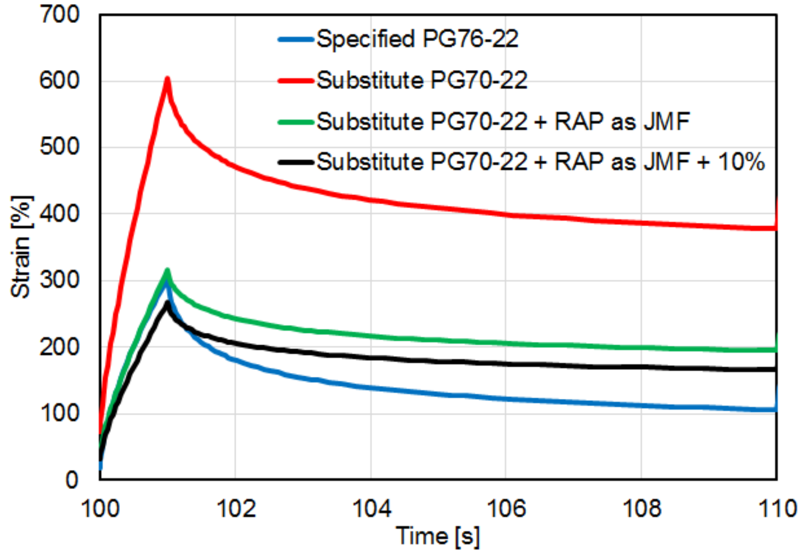

Figure 3.12. Elastic recovery at 3200 Pa and 70 °C for District 4 (only one cycle shown for clarity)

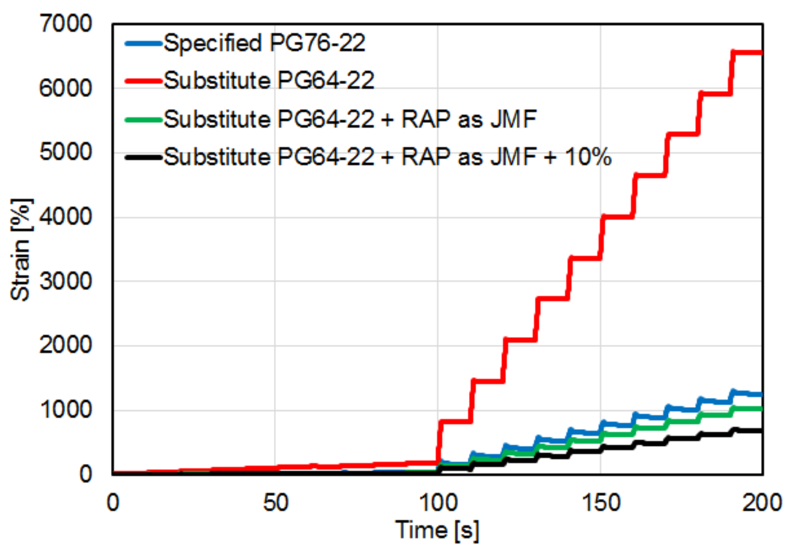

Figure 3.13. MSCR results for District 1 at 64 °C

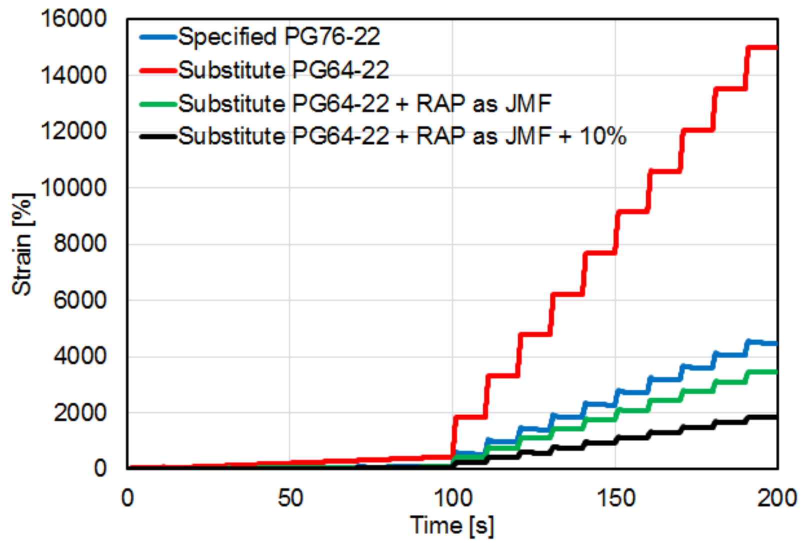

Figure 3.14. MSCR results for District 1 at 70 °C

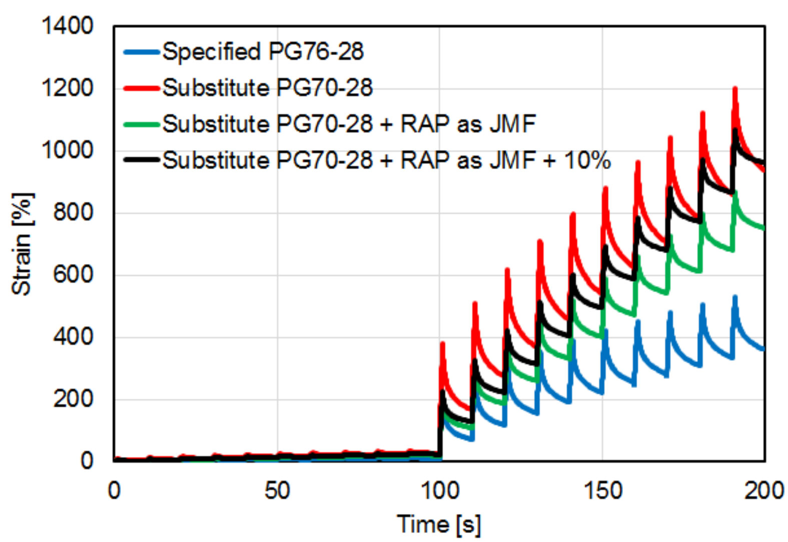

Figure 3.15. MSCR results for District 2 at 64 °C

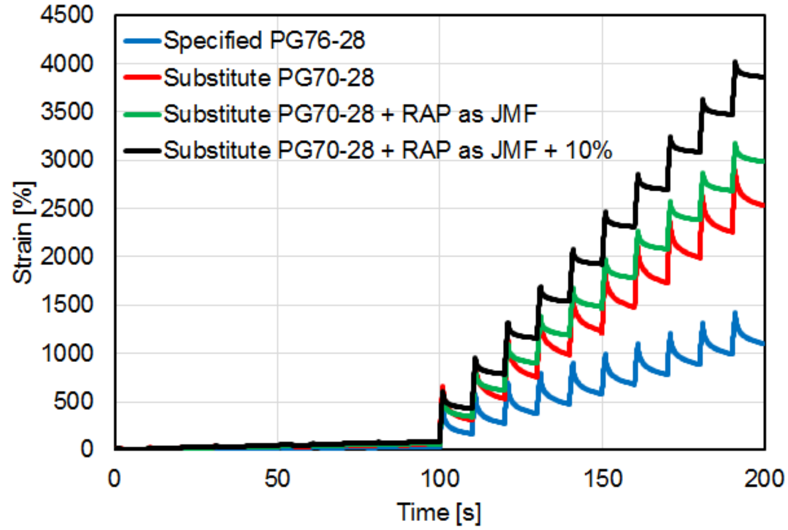

Figure 3.16. MSCR results for District 2 at 70 °C

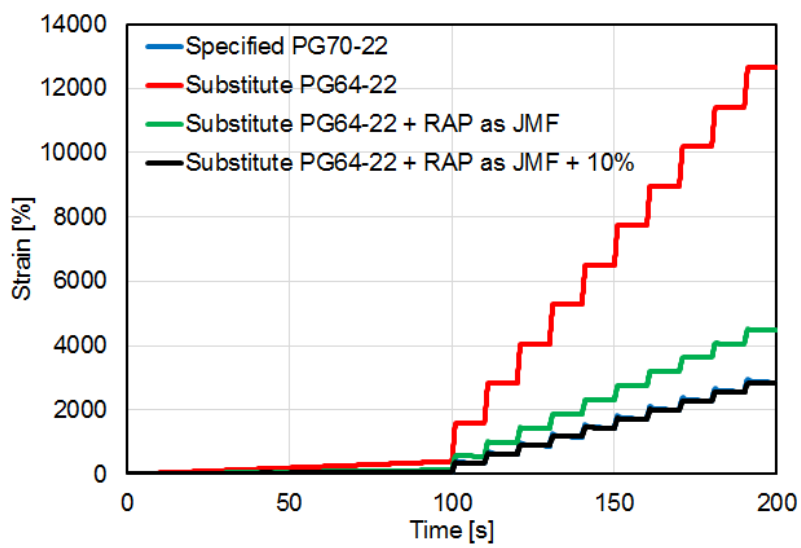

Figure 3.17. MSCR results for District 3 at 64 °C

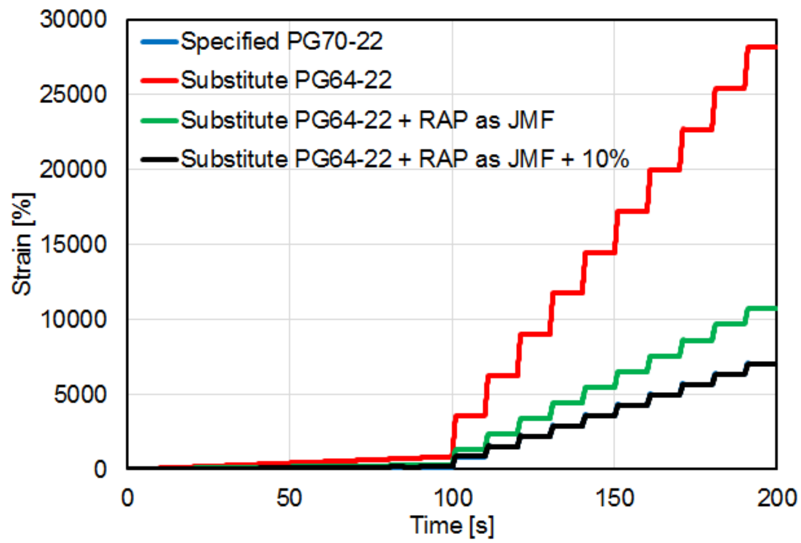

Figure 3.18. MSCR results for District 3 at 70 °C

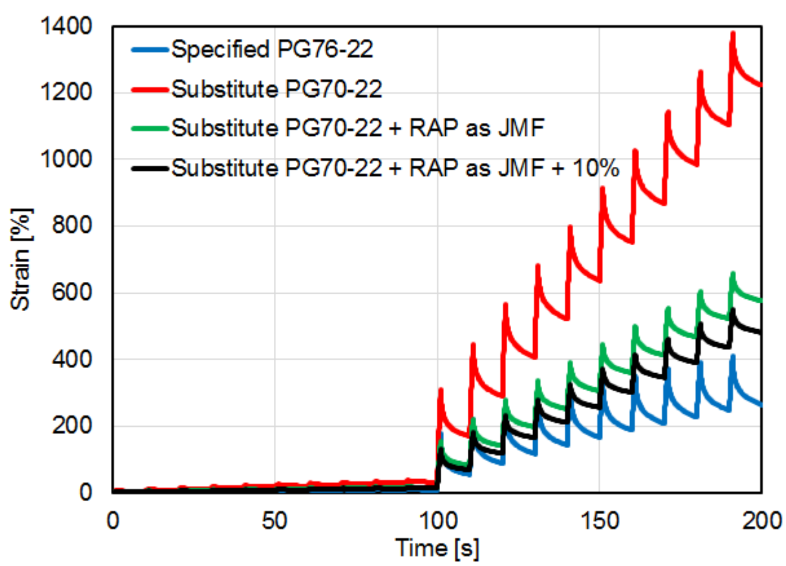

Figure 3.19. MSCR results for District 4 at 64 °C

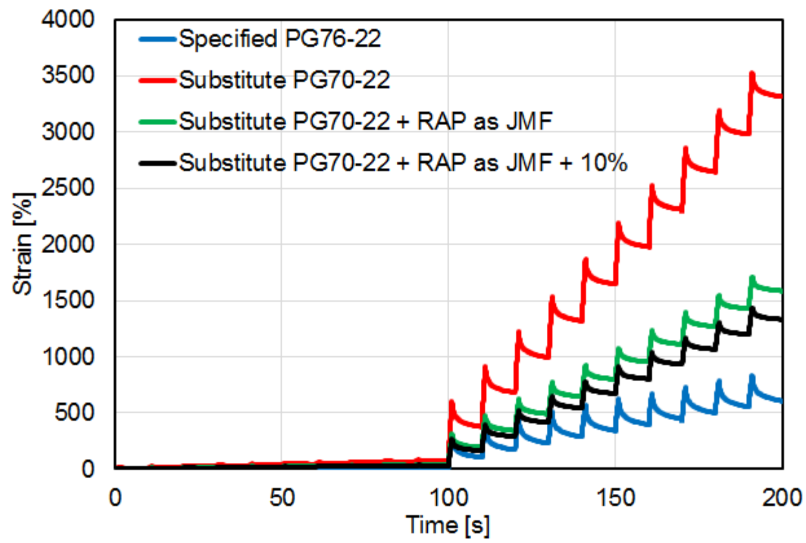

Figure 3.20. MSCR results for District 4 at 70 °C

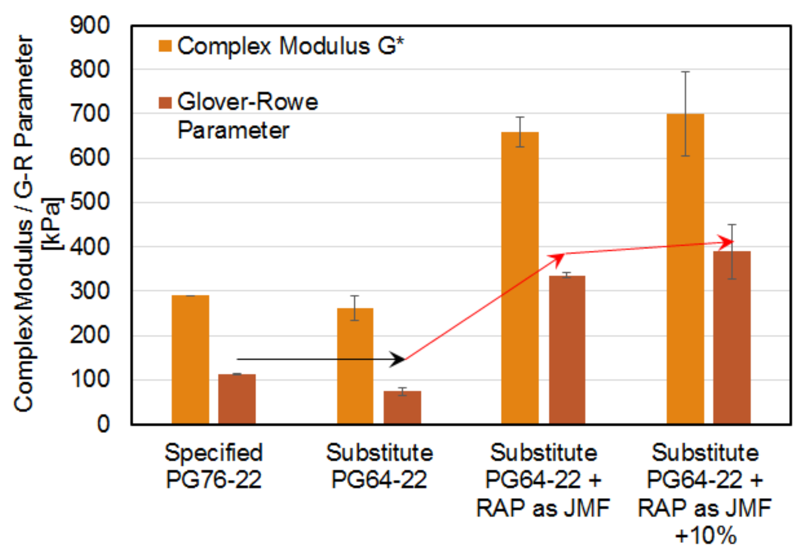

Figure 3.21. Complex modulus and Glover-Rowe results for District 1

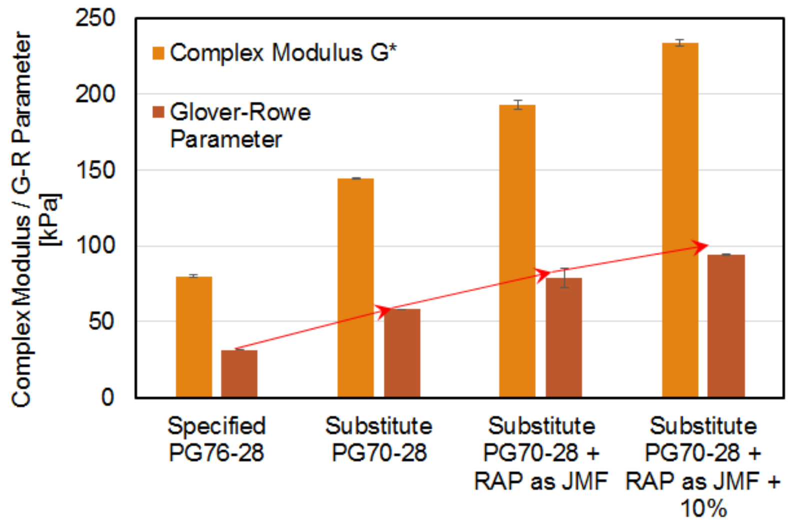

Figure 3.22. Complex modulus and Glover-Rowe results for District 2

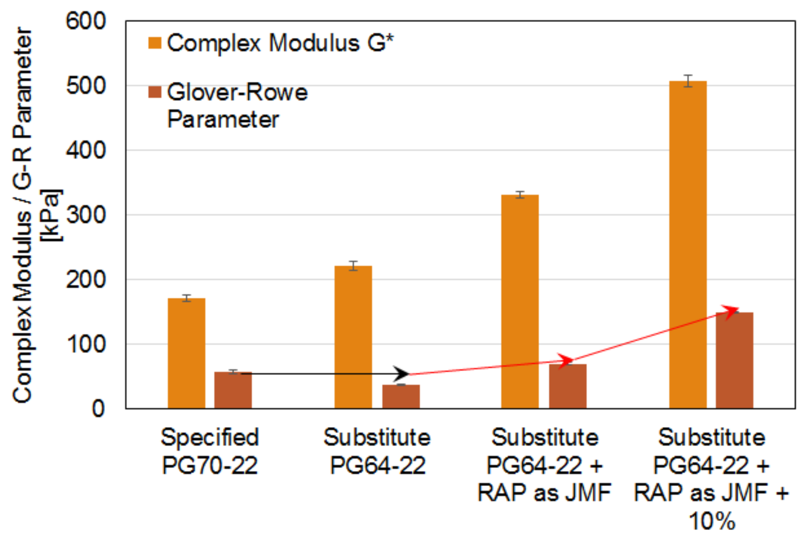

Figure 3.23. Complex modulus and Glover-Rowe results for District 3

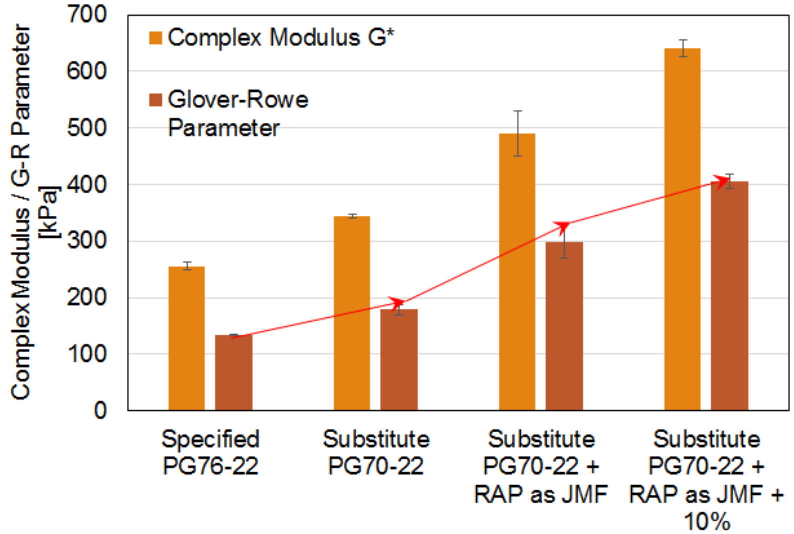

Figure 3.24. Complex modulus and Glover-Rowe results for District 4

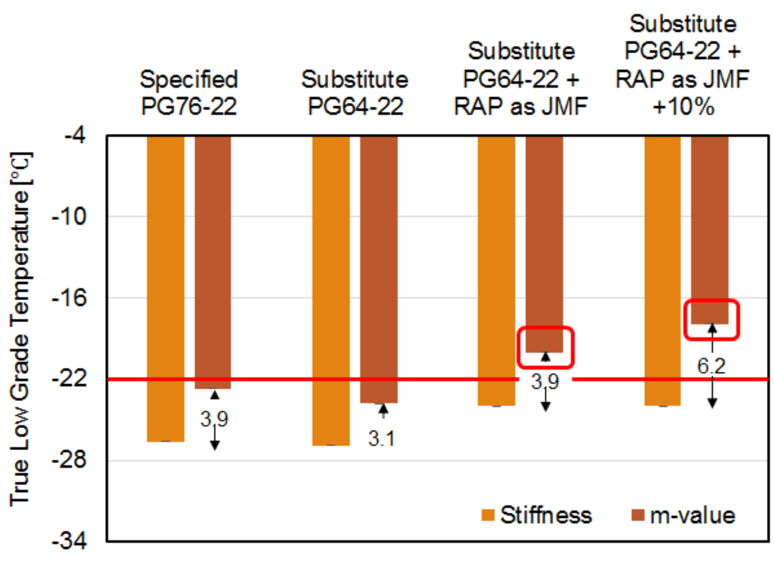

Figure 3.25. True low grade temperature for District 1

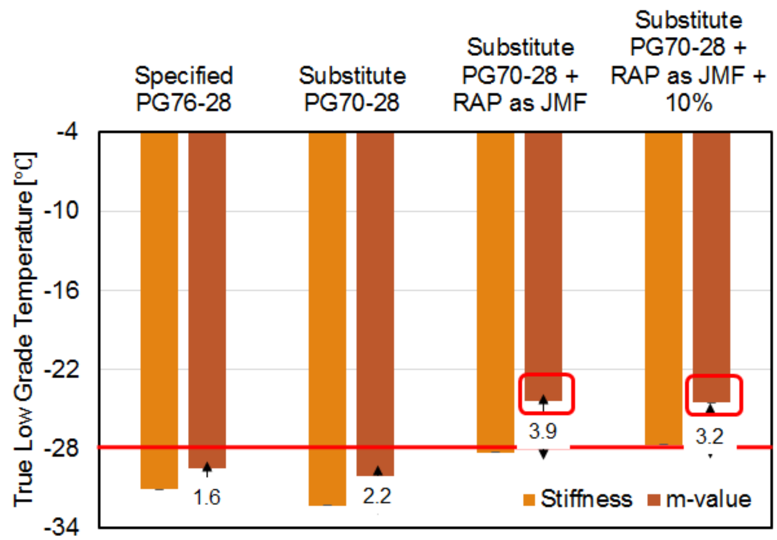

Figure 3.26. True low grade temperature for District 2

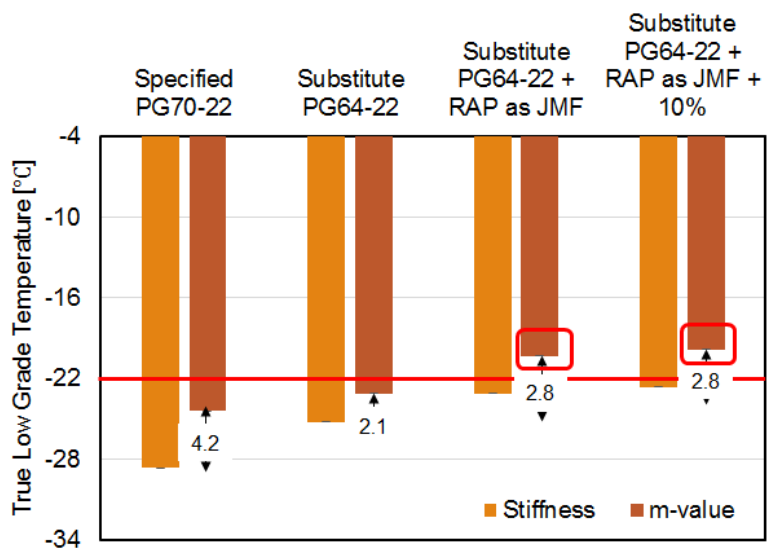

Figure 3.27. True low grade temperature for District 3

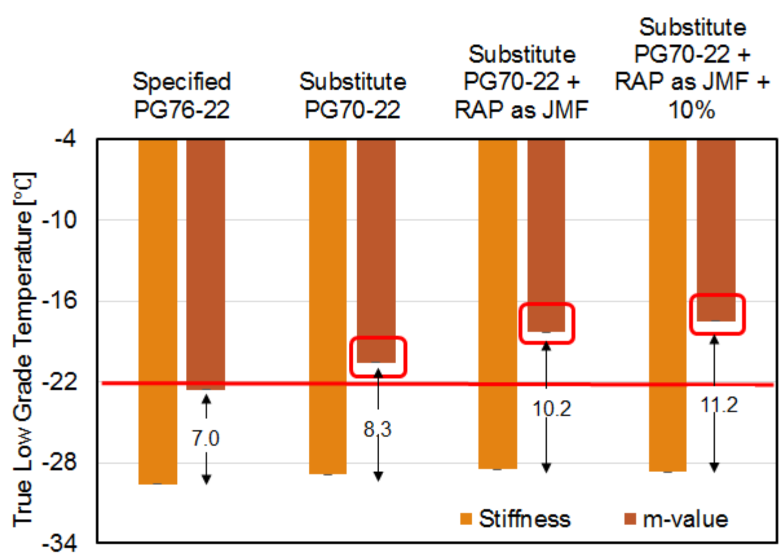

Figure 3.28. True low grade temperature for District 4

3.3 MIXTURE PROPERTIES

Properties of the mixture for each of the aforementioned mixes were evaluated. Specifically, the mixes were evaluated for their rutting resistance using the Hamburg Wheel Tracking Device (HWTD) and for their cracking resistance using the Overlay Test (OT) and Indirect Tensile Test (IDT). Figures 3.29 to 3.44 present the results for the mixture characterization.

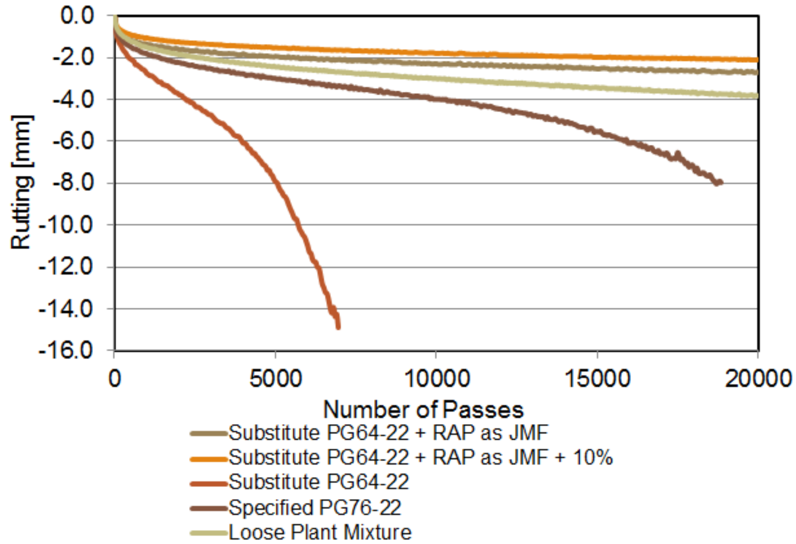

Figure 3.29. HWT results for District 1

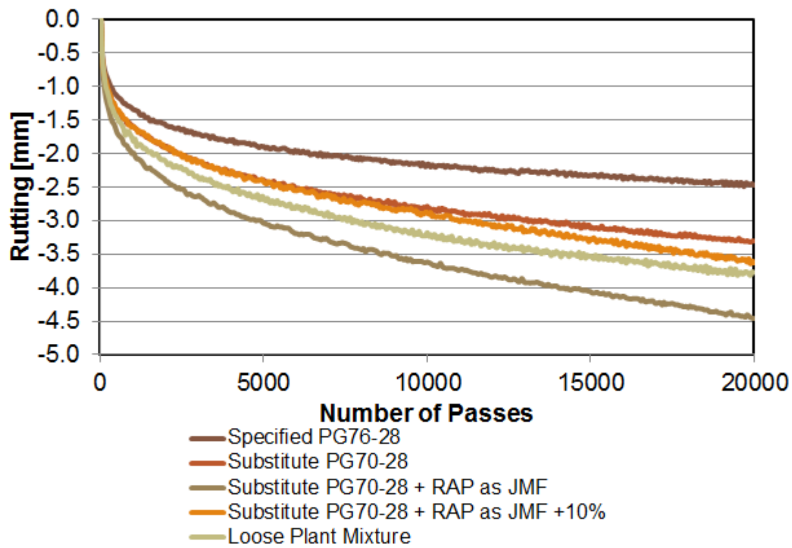

Figure 3.30. HWT results for District 2

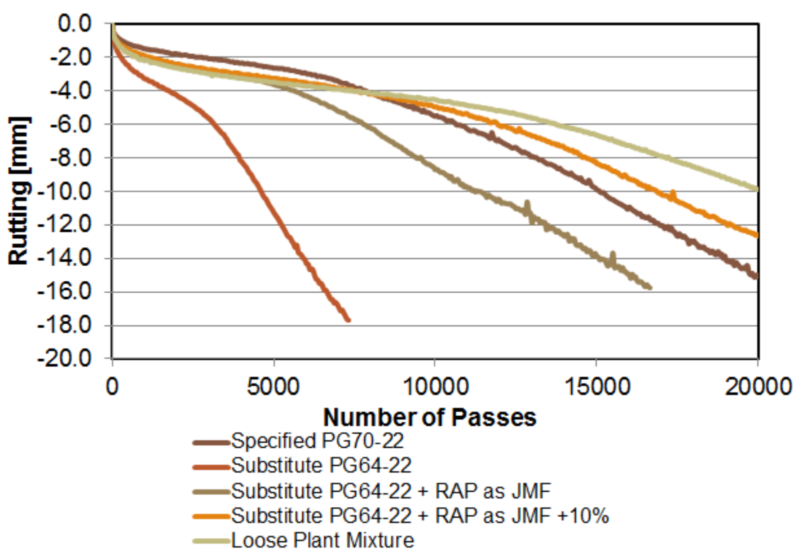

Figure 3.31. HWT results for District 3

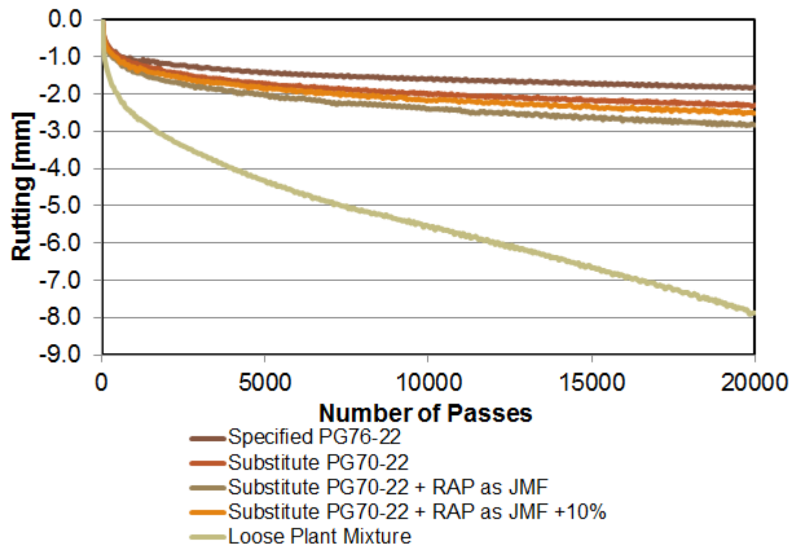

Figure 3.32. HWT results for District 4

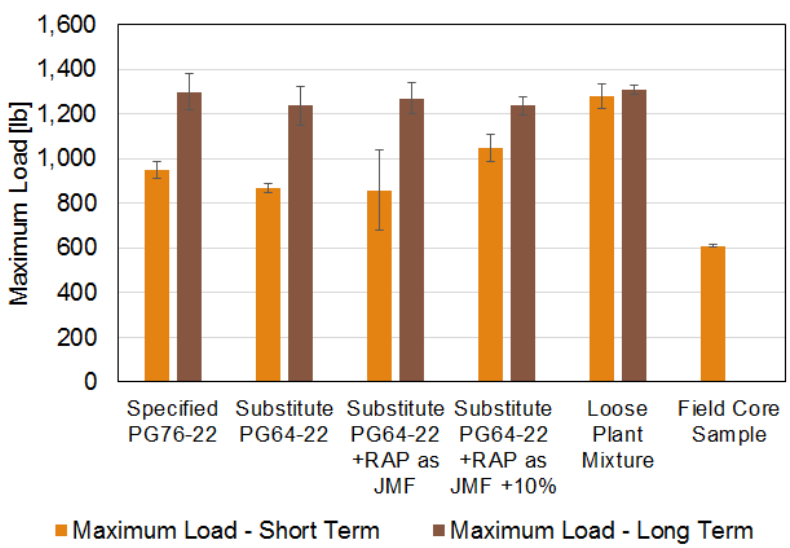

Figure 3.33. OT Maximum load for District 1

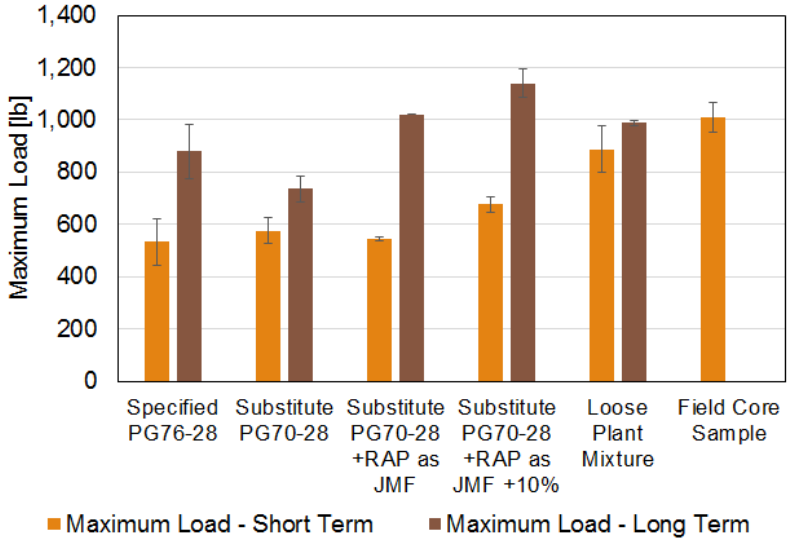

Figure 3.34. OT Maximum load for District 2

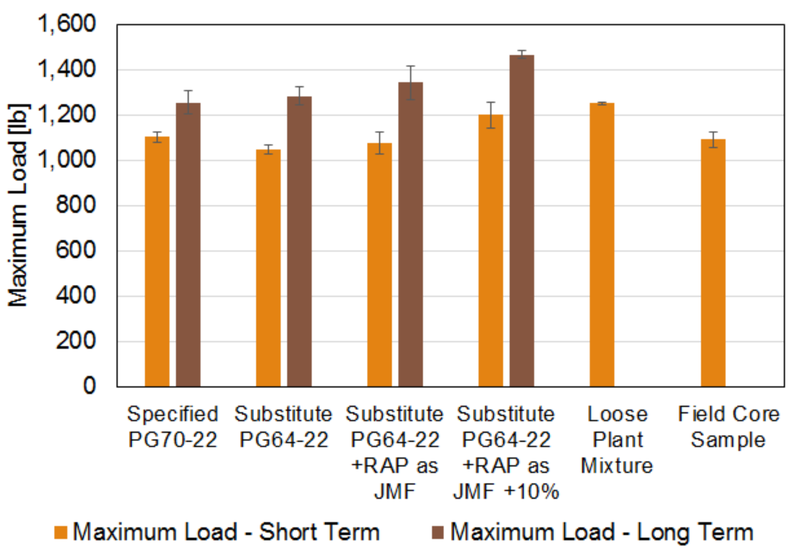

Figure 3.35. OT Maximum load for District 3

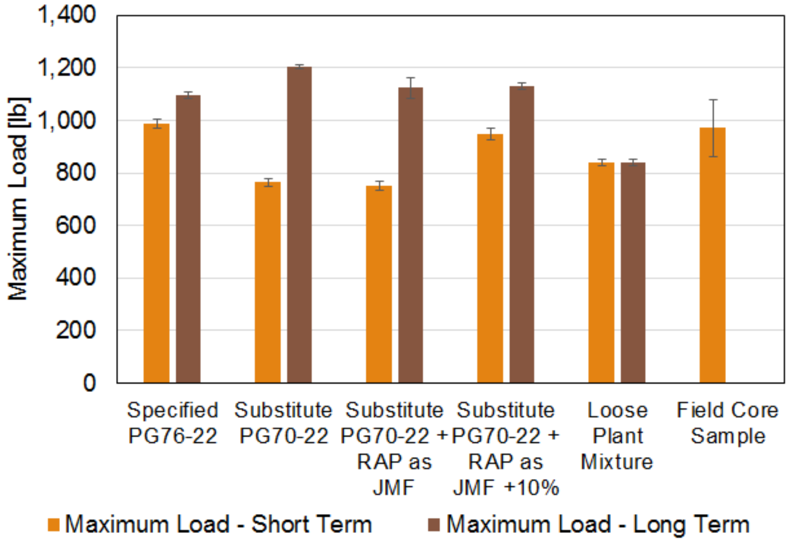

Figure 3.36. OT Maximum load for District 4

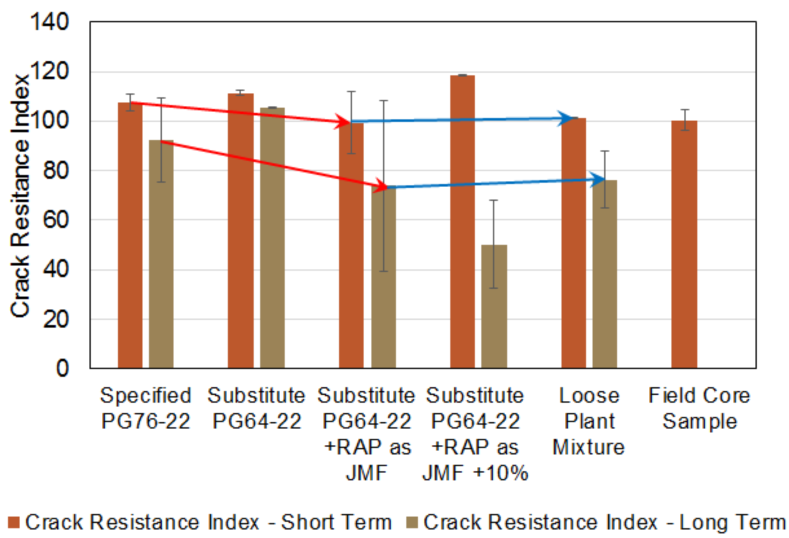

Figure 3.37. OT Crack resistance index for District 1

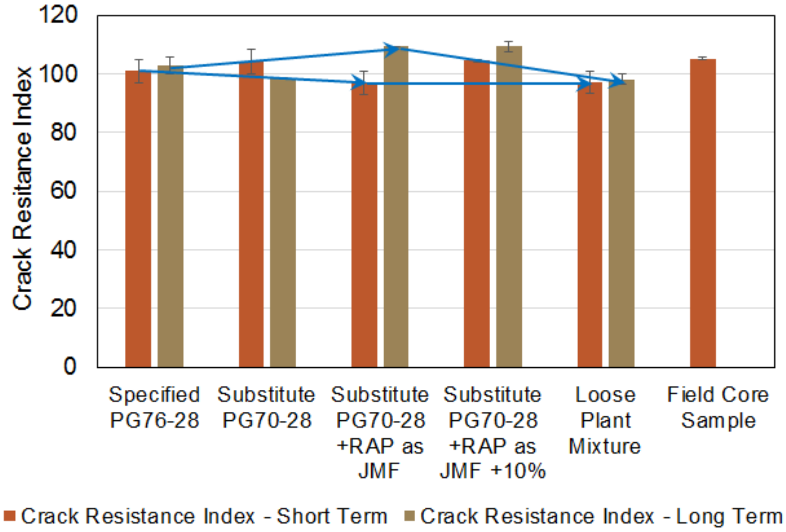

Figure 3.38. OT Crack resistance index for District 2

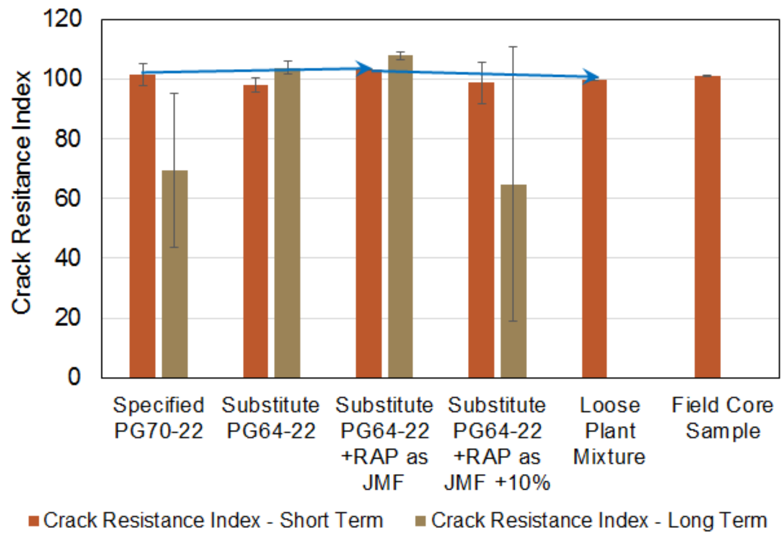

Figure 3.39. OT Crack resistance index for District 3

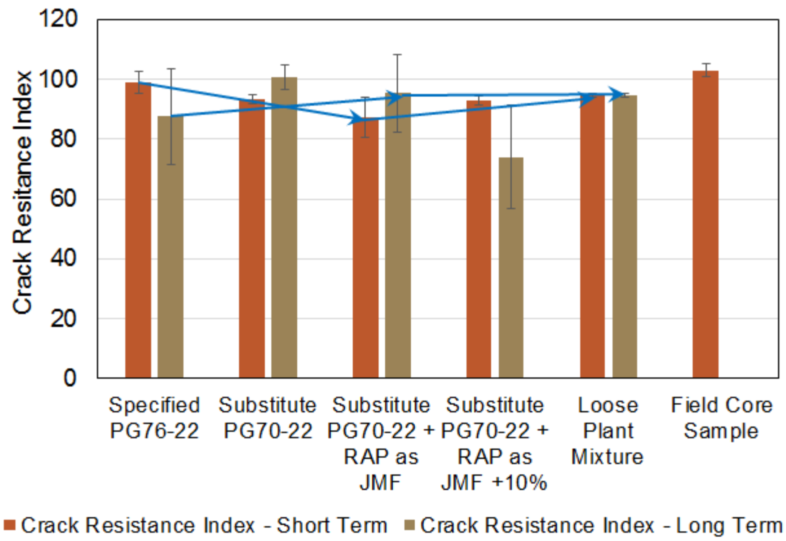

Figure 3.40. OT Crack resistance index for District 4

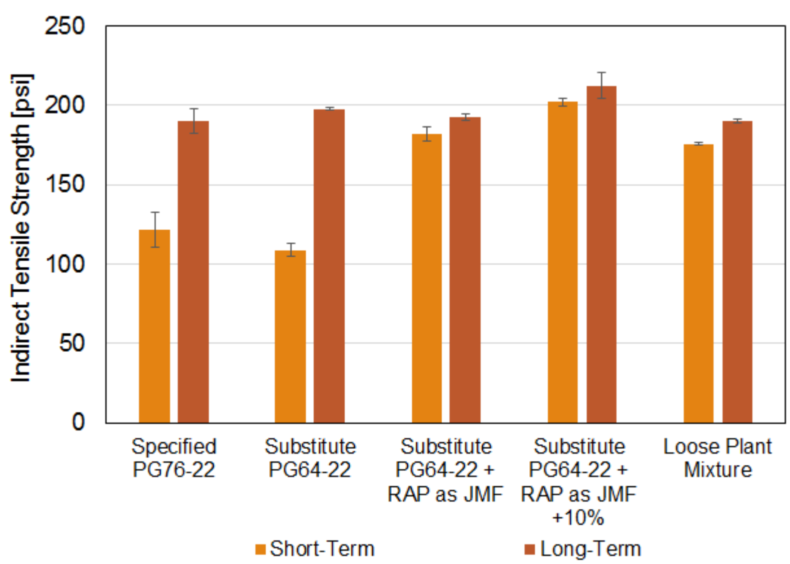

Figure 3.41. IDT Indirect tensile strength for District 1

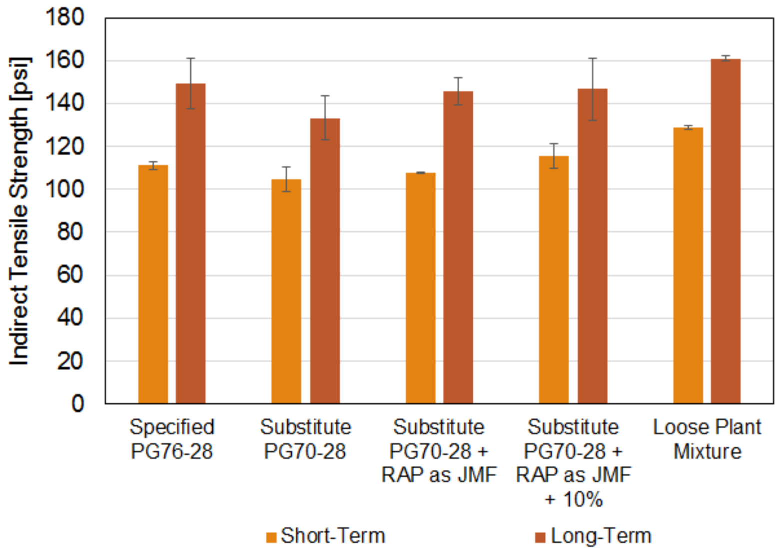

Figure 3.42. IDT Indirect tensile strength for District 2

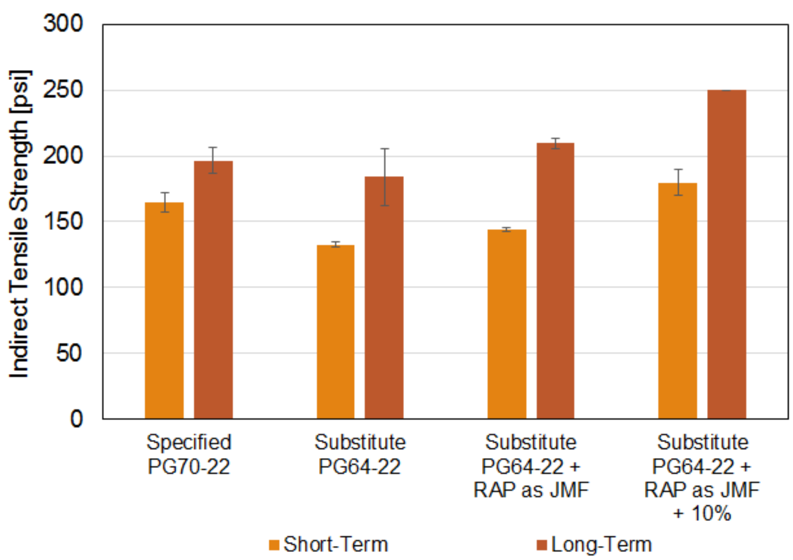

Figure 3.43. IDT Indirect tensile strength for District 3

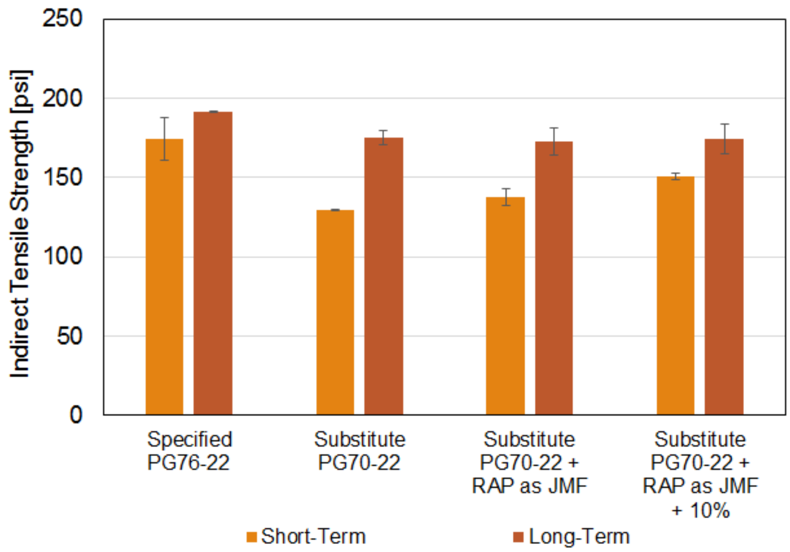

Figure 3.44. IDT Indirect tensile strength for District 4

3.4 SUMMARY OF RESULTS

Some of the key findings from this part of the study are as follows.

1. High temperature properties of the binder show that moving from specified to substitute binder (without RAP) reduces the high temperature stiffness and non-recoverable compliance. This is obvious and expected because no RAP is incorporated. Addition of RAP to the substitute binder then allows the mix to achieve a high temperature stiffness and non-recoverable compliance that is comparable to or better than the specified binder. This is a desirable and positive effect.
2. Elastic recovery of the substitute binder (without RAP) is generally lower than the elastic recovery of the specified binder. This is also obvious and expected in cases where the substitute binder is a PG64-22 since a PG64-22 binder does not have an elastic recovery requirement. Addition of RAP to a substitute binder that does not have any or low elastic recovery does not necessarily improve these characteristics of the virgin binder. The lack of elastic recovery associated with the use of a substitute binder (particularly when the substitute is a PG64-22) is generally associated with lower ductility and cracking resistance in the mix and it is not desirable.
3. Typically the substitute binder has the same low temperature properties as the specified binder. Therefore, the low temperature properties are similar when comparing the substitute to the specified binder without RAP. However, the addition of RAP to the substitute binder deteriorates the low temperature properties of the binder. In most cases a combination of the substitute binder with RAP raises the low temperature grade of the blend by one grade. The loss of low temperature grade can result in a binder with lower ductility and cause premature thermal cracking and it is also an indicator of reduced resistance to intermediate temperature fatigue cracking. This effect is also undesirable and can be offset by the use of a binder with one additional lower grade than required when using RAP and/or other recycling agents / additives.
4. The rutting performance of mixtures with the addition of RAP generally improves. In some cases, the rutting performance of mixes with the substitute binder and RAP may be lower than the rutting performance of the mix with the specified binder. Specifically, this was observed when the specified binder was a PG76-xx and the substitute binder was a PG70-xx. The reason for this counter-intuitive behavior was because although the PG70-xx binder by itself has a low rutting potential, this is because of its high elastic recovery and consequently low accumulated plastic strain.

However, the addition of RAP reduces the overall elastic recovery of the blend and thus increases the rutting potential. This behavior was consistent in both the HWTD results and the binder results using MSCR.

CHAPTER 4. EVALUATING THE IMPACT OF REJUVENATING AGENTS AND VARIABILITY IN RAP ON BINDER PROPERTIES

4.1 OPTIMAL RECYCLED BINDER RATIO DETERMINATION

This chapter summarizes the work accomplished in Task 4 of this project, i.e. laboratory evaluation of binder blends and recycling or softening agents that can potentially be used to improve the properties and performance of asphalt mixtures incorporating RAP. Furthermore, variability in the low temperature properties of RAP across the state of Texas was also evaluated as a part of this task.

4.2 LABORATORY EVALUATION OF BINDER BLENDS

The two common grades of asphalt binders used as a substitute are the PG70-22 and PG64-22 typically in lieu of the PG76-22 or PG70-22 grade binder, respectively. In cases where two grade drops are allowed, the PG64-22 binder may also be used in lieu of the PG70-22 binder. This section of the report examines the influence of RAP and recycling agents on the performance characteristics of the PG70-22 binder and the PG64-22 binder. One of the questions of interest for this research study was whether or not the addition of RAP compromises the elastic recovery of asphalt binders. Note that TxDOT specifications require a certain level of elastic recovery for the PG70-22 and PG76-22 binders but there is no requirement for the PG64-22 binder. The following subsections present the results from the evaluation of the aforementioned binders.

The following is a summary of the parameters that were evaluated for each binder:

- Rutting resistance: True high temperature PG for the asphalt binder based on the $G^*/\sin\delta$ parameter for the unaged and RTFO (rolling thin film oven) aged binders, obtained by testing the binder at least three different temperatures following the specification AASHTO M320 (2017).
- Elastic recovery: The Multiple Stress Creep Recovery (MSCR) test was conducted following AASHTO TP70 (2013) to measure the non-recoverable compliance and elastic recovery at 64 °C for the RTFO aged binder.
- Intermediate temperature stiffness and cracking resistance: The PG intermediate temperature parameter $G^*\sin\delta$ was measured for the long term or Pressure Aging Vessel (PAV) aged binder along with the Glover-Rowe (G-R) parameter. The G-R

parameter was determined based on construction of a master curve from frequency sweep ranging from 15 to 0.02 Hz testing at 5, 15, and 25 °C in the DSR and interpolating to find the value of G-R at 15 °C and 0.005 rad/s to assess the ductility of the binder (Rowe et al., 2014). A higher G-R value indicates increased brittleness, a proposed G-R parameter value of 180 kPa corresponds to damage onset whereas a G-R value exceeding 450 kPa corresponds to significant cracking potential based on a study relating binder ductility to field block cracking and surface raveling by Anderson et al. (2011).

- Thermal cracking resistance: The PG parameters for low temperature cracking resistance were measured following AASHTO R49 (2009) using the PAV aged binders. The measurements were made at three different temperatures to obtain the true low grade based on both the stiffness (S) and m-value criteria. This information was also used to assess the ΔT_c parameter.

4.2.1 PG70-22 Using Different Percentages of RAP and Types of Additives

For this part of the study, a PG70-22 binder was selected as the basis. Three different RAP ratios were used 20, 40 and 50%. Also, three different additives (recycling or softening agents referred to as A1, A2, A3, and the dosage rates used were: 2.0, 4.5, and 6.0%; respectively) were used in order to examine whether these agents facilitate the use of RAP with the modified binders.

Figure 4.1 shows the true high performance grade temperature results for all the configurations tested. Figures 4.2 and 4.3 present the MSCR results for PG70-22 binder at different percentages of RAP and types of additives. Figure 4.4 shows the complex modulus and Glover-Rowe parameter for all the configurations tested. Figure 4.5 shows the true low performance grade temperature results for all the configurations tested.

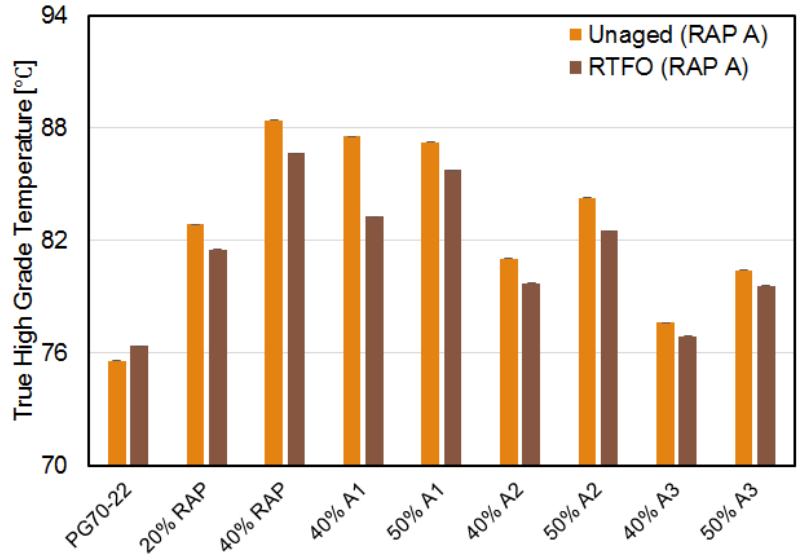

Figure 4.1. True high grade temperature for PG70-22 binder at different percentages of RAP and types of additives

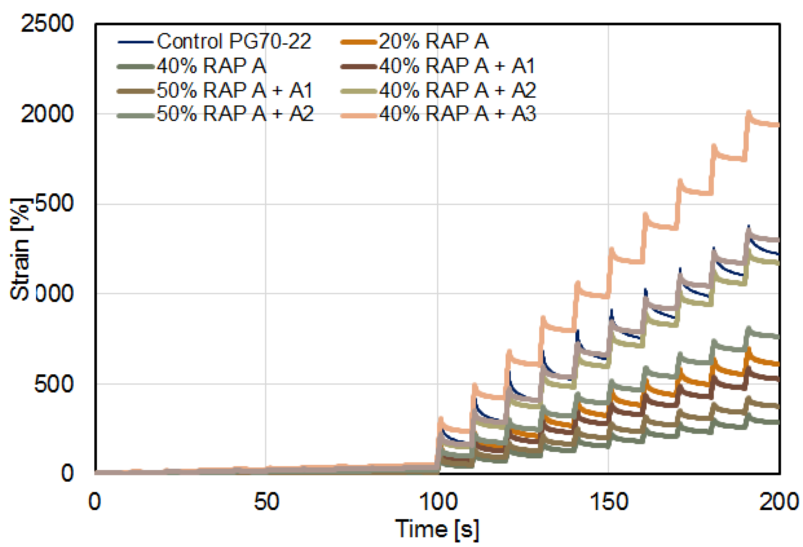

Figure 4.2. MSCR results at 64 °C for PG70-22 binder at different percentages of RAP and types of additives

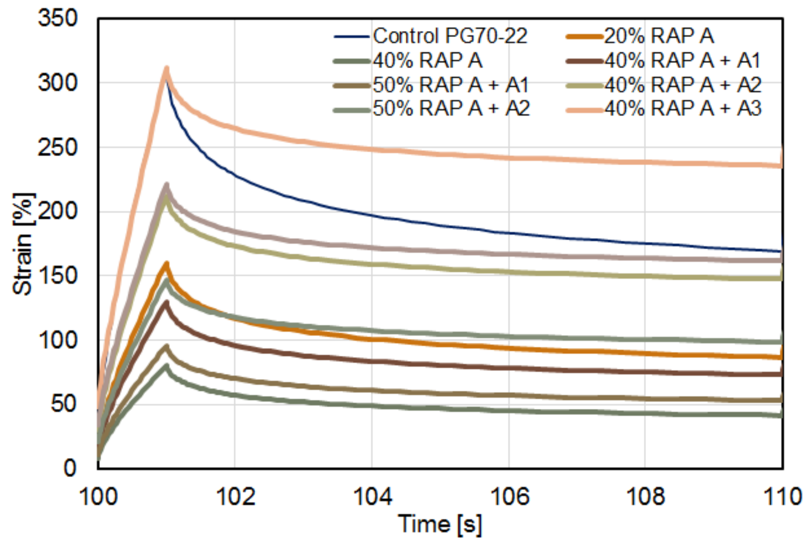

Figure 4.3. Elastic recovery at 3200 Pa and 64 °C for PG70-22 binder at different percentages of RAP and types of additives (only one cycle shown for clarity)

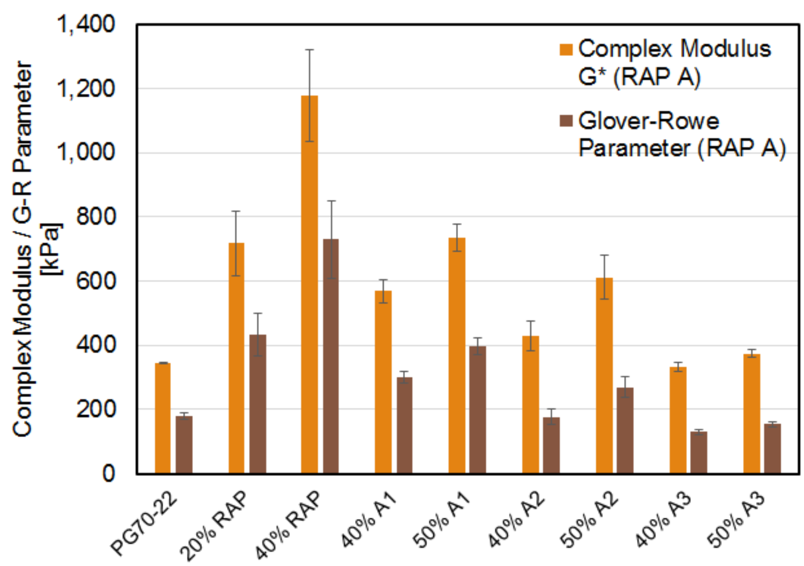

Figure 4.4. Complex modulus and Glover-Rowe results for PG70-22 binder at different percentages of RAP and types of additives

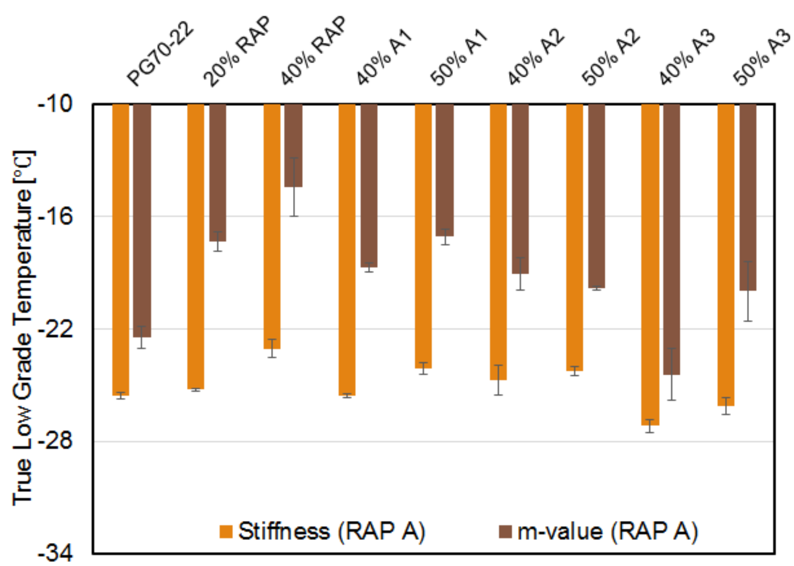

Figure 4.5. True low grade temperature for PG70-22 binder at different percentages of RAP and types of additives

Some of the key observations from these results are as follows.

1. As expected, addition of RAP increases the high temperature grade of the binder based on the $G^*/\sin\delta$ parameter and reduces the low temperature grade of the binder based on the S and $m-$ value parameters.
2. Addition of RAP also increases the value of the Glover-Rowe parameter, which indicates a reduced resistance to fatigue cracking.
3. Three different recycling agents were used with this binder. The effectiveness of each agent was different. In general, all agents reduced the rutting resistance based on both the MSCR and the $G^*/\sin\delta$ parameters, although some were more effective than others. However, it must be noted that when a substitute binder is being used, this reduction *may more than compensate for the expected increase in stiffness and rutting resistance due to a combination of the reduced high temperature grade and RAP/RAS*.
4. The additives also show a decrease in the Glover-Rowe parameter indicating an improvement in cracking resistance. As before, the effectiveness of each additive was different. These results must be interpreted with caution because the *efficacy of the G-R parameter for modified binders is not established.*
5. The additives also show an improvement in the low-temperature properties. In some additive-binder-RAP combinations, the low temperature properties are similar to that of the virgin binder with no RAP.
6. A final and very important observation was that the additives or recycling agents did not contribute to the elastic recovery of the binder-RAP-additive blend. In other words, although the additives helped recover the low-temperature grade of the binder after the addition of RAP, they did not necessarily help recover the elastic recovery of the virgin binder.

4.2.2 PG64-22 Using Different Percentages of RAP and Types of Additives

For this part of the study, a PG64-22 binder was selected as the basis. Three different RAP ratios were used 20, 40 and 50%. Also, three different additives (recycling or softening agents referred to as A1, A2 and A3) were used in order to examine whether these agents facilitate the use of RAP with the modified binders.

Figure 4.6 shows the true high performance grade temperature results for all the configurations tested. Figures 4.7 and 4.8 present the MSCR results for PG64-22 binder at different percentages of RAP and types of additives. Figure 4.9 shows the complex modulus and Glover-Rowe results for all the configurations tested. Figure 4.10 shows the true low performance grade temperature results for all the configurations tested.

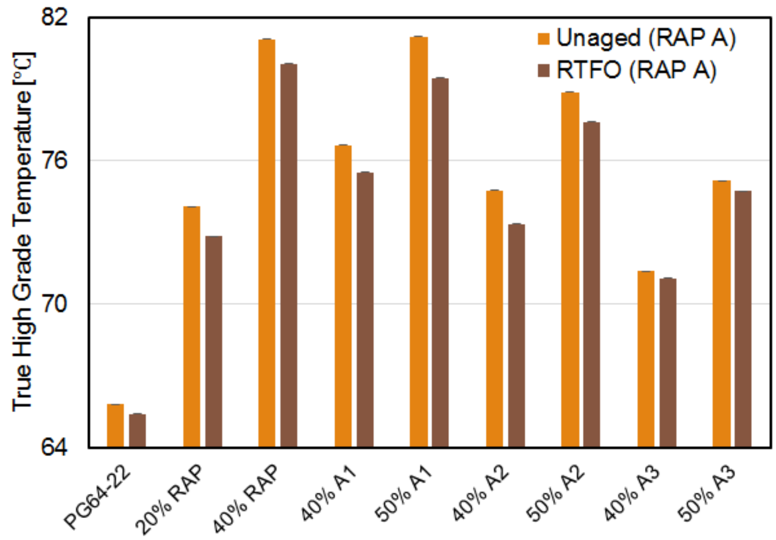

Figure 4.6. True high grade temperature for PG64-22 binder at different percentages of RAP and types of additives

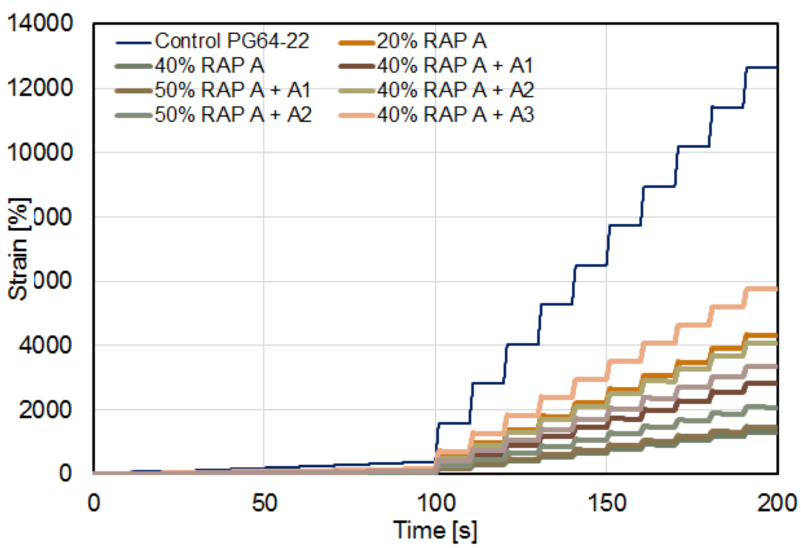

Figure 4.7. MSCR results at 64 °C for PG64-22 binder at different percentages of RAP and types of additives

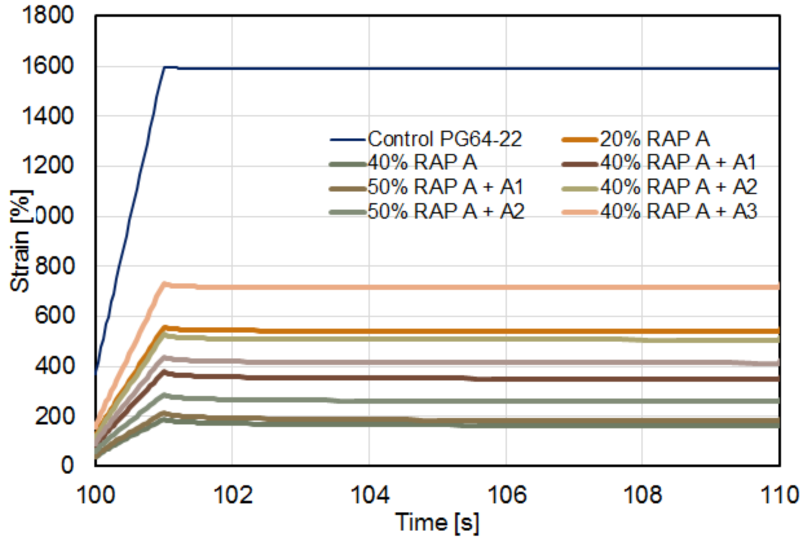

Figure 4.8. Elastic recovery at 3200 Pa and 64 °C for PG64-22 binder at different percentages of RAP and types of additives (only one cycle shown for clarity)

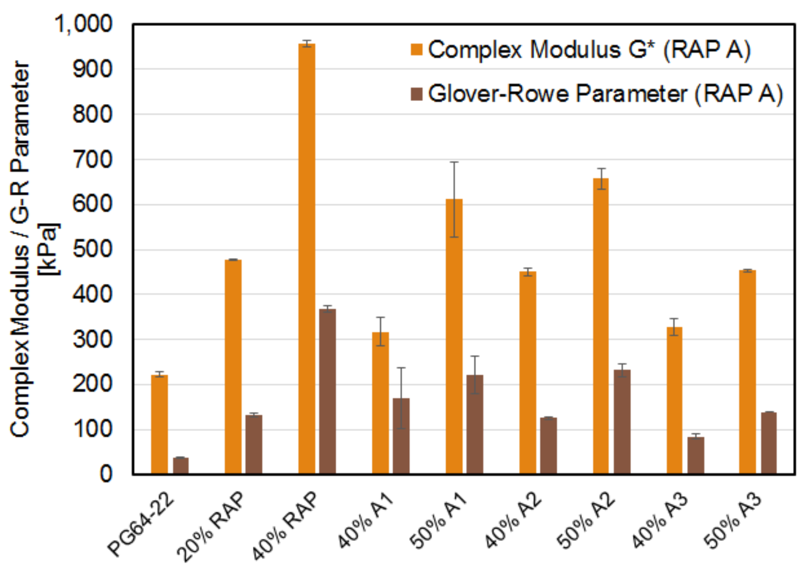

Figure 4.9. Complex modulus and Glover-Rowe results for PG64-22 binder at different percentages of RAP and types of additives

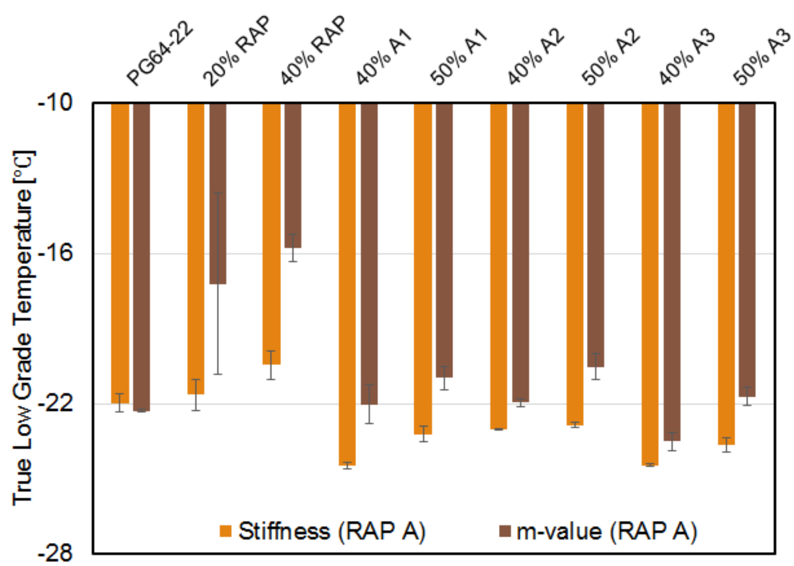

Figure 4.10. True low grade temperature for PG64-22 binder at different percentages of RAP and types of additives

The key observations with the PG64-22 binder were similar to those made using the PG 70-22 binder in the previous section. One notable exception to this was that the virgin PG64-22 did not demonstrate any substantial elastic recovery. As such there was no substantial elastic recovery that was observed in subsequent variations with the RAP and/or additives.

4.2.3 PG64-22 Using Two Different RAP Stockpiles and One Additive

The same PG64-22 binder, used before, was selected as the basis for this part of the study. The goal of the results presented in this subsection was to examine the influence of different types of RAP on the rheological and performance related properties of asphalt binder. Two different RAP stockpiles were used, referred to as RAP A and RAP B, at different percentages (20 and 40%), and one type of additive was used with the higher RAP ratio of 40%.

Figure 4.11 shows the true high performance grade temperature results for all the configurations tested. Figures 4.12 and 4.13 presents the MSCR results for PG64-22 binder using two different types of RAP and one additive. Figure 4.14 shows the complex modulus and Glover-Rowe results for all the configurations tested. Figure 4.15 shows the true low performance grade temperature results for all the configurations tested.

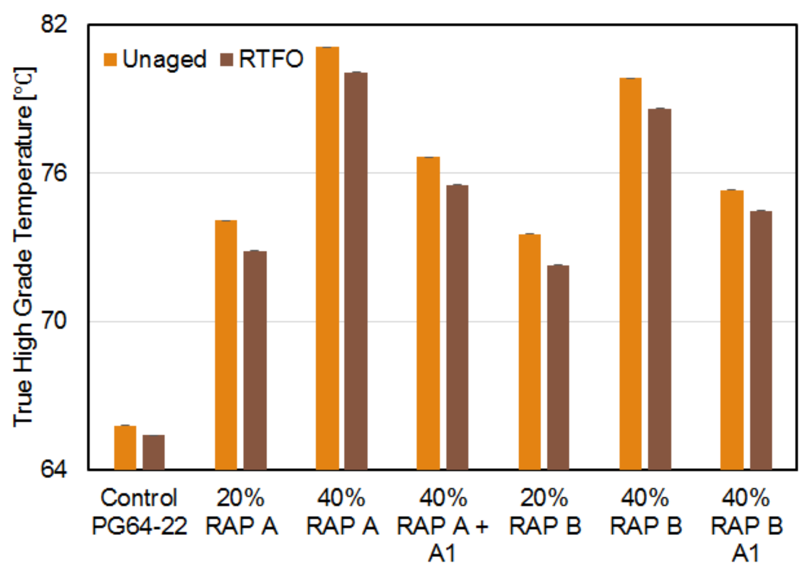

Figure 4.11. True high grade temperature for PG64-22 binder using two different types of RAP and one additive

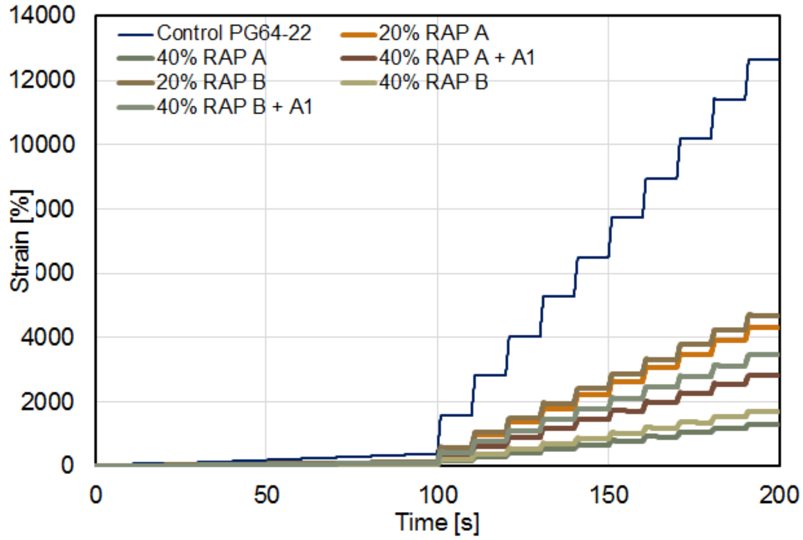

Figure 4.12. MSCR results at 64 °C for PG64-22 binder using two different types of RAP and one additive

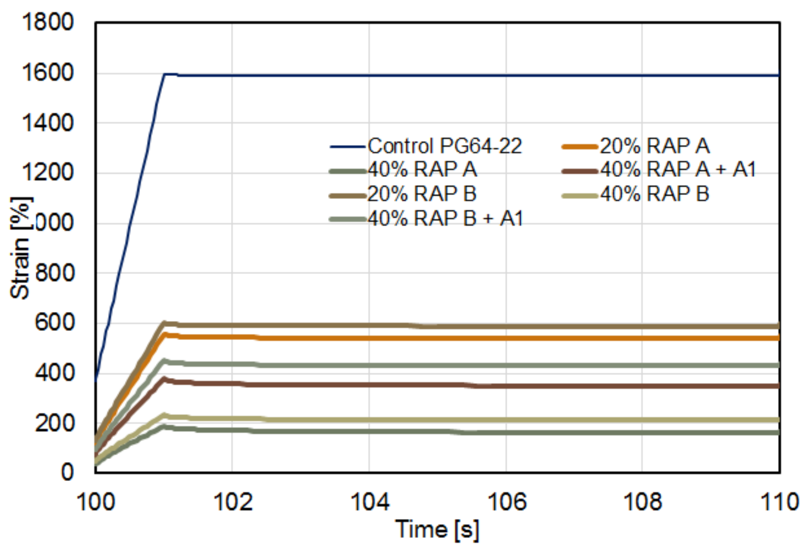

Figure 4.13. Elastic recovery at 3200 Pa and 64 °C for PG64-22 binder using two different types of RAP and one additive (only one cycle shown for clarity)

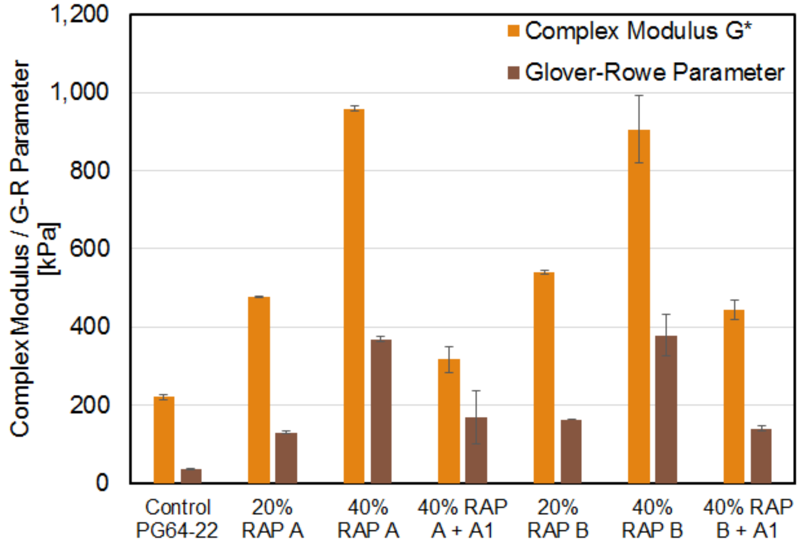

Figure 4.14. Complex modulus and Glover-Rowe results for PG64-22 binder using two different types of RAP and one additive

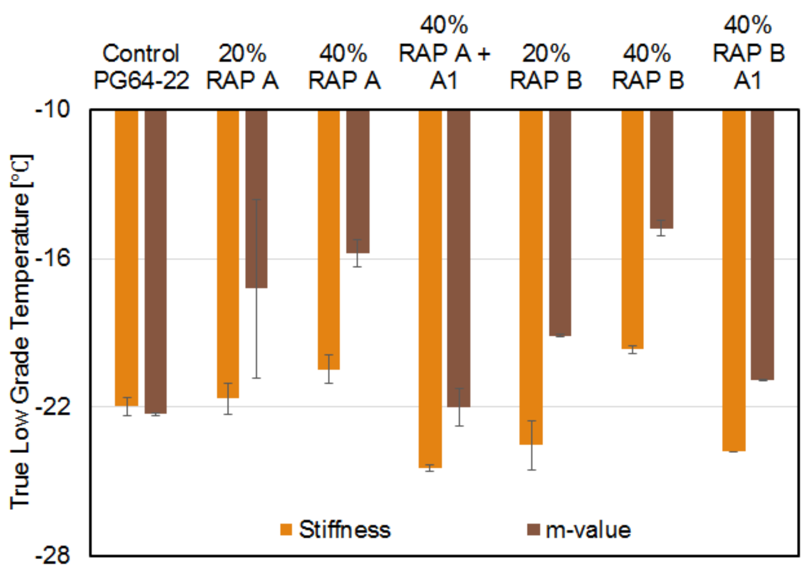

Figure 4.15. True low grade temperature for PG64-22 binder using two different types of RAP and one additive

Some of the key observations from these results are as follows.

1. The two different RAP stockpiles had a similar impact on the rheological and performance related characteristics of the asphalt binder in terms of high temperature rutting resistance based on MSCR and the $G^*/\sin\delta$ parameter, cracking resistance based on the G-R parameter, and low-temperature properties based on the S and $m-$value parameters. However, as demonstrated in the subsequent section, there is significant difference in the properties of RAP from one source to another, particularly when low-temperature properties are being examined, although these differences are not manifested in this specific pair.
2. Both additives had a similar impact on the binder-RAP-additive system in terms of rutting, cracking and low-temperature or thermal cracking resistance. As before, results from the G-R parameter must be interpreted with caution.

4.2.4 PG64-22 Using RAP and Two Different RAS Stockpiles with One Additive

The goal of this part of the study was to examine the influence of RAP and RAS. The same PG64-22 binder as before was used as the basis for this part of the study. Two different RAS stockpiles, referred to as RAS A and RAS B, were used together with one RAP stockpile at different percentages (20 and 40%), and one type of additive was used with the higher RAP ratio of 40%. A ratio of 1 to 1 was used when combining RAP and RAS binder. Note that this is generally on the higher side of typically allowed percentages. However, for example when adding 15% fractionated RAP and 5% RAS in a mix, it must also be noted that RAS has a much higher percentage of binder as compared to RAP. Therefore, in examining binder-RAP-RAS blends, a higher percentage of RAP and RAS is justified.

Figure 4.16 shows the true high performance grade temperature results for all the configurations tested. Figures 4.17 and 4.18 present the MSCR results for PG64-22 binder using two different types of RAS and one additive. Figure 4.19 shows the complex modulus and Glover-Rowe results for all the configurations tested. Figure 4.20 shows the true low performance grade temperature results for all the configurations tested.

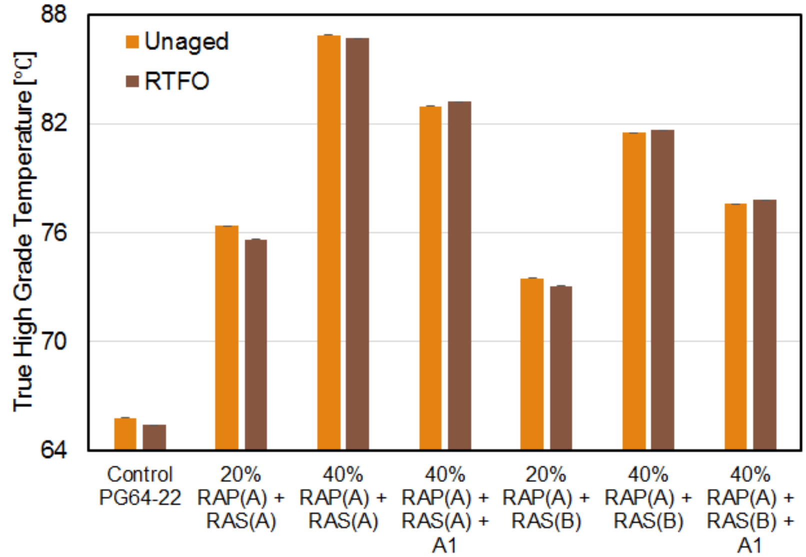

Figure 4.16. True high grade temperature for PG64-22 binder using two different types of RAS and one additive

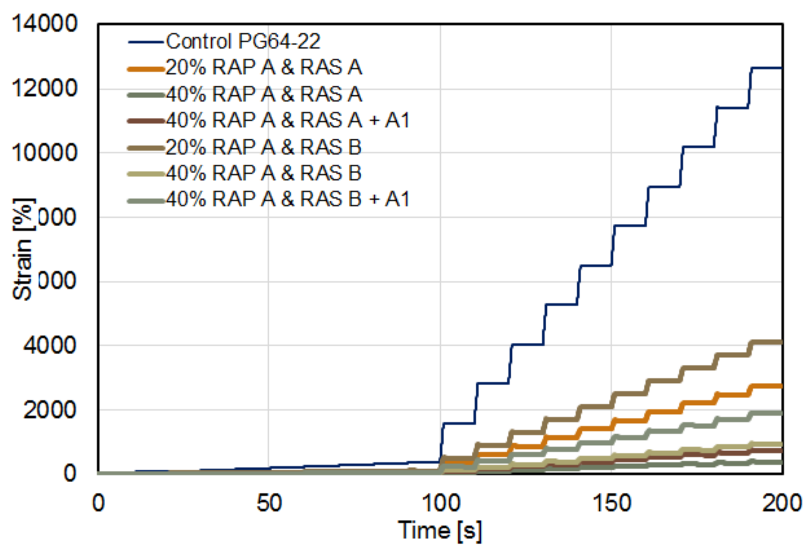

Figure 4.17. MSCR results at 64 °C for PG64-22 binder using two different types of RAS and one additive

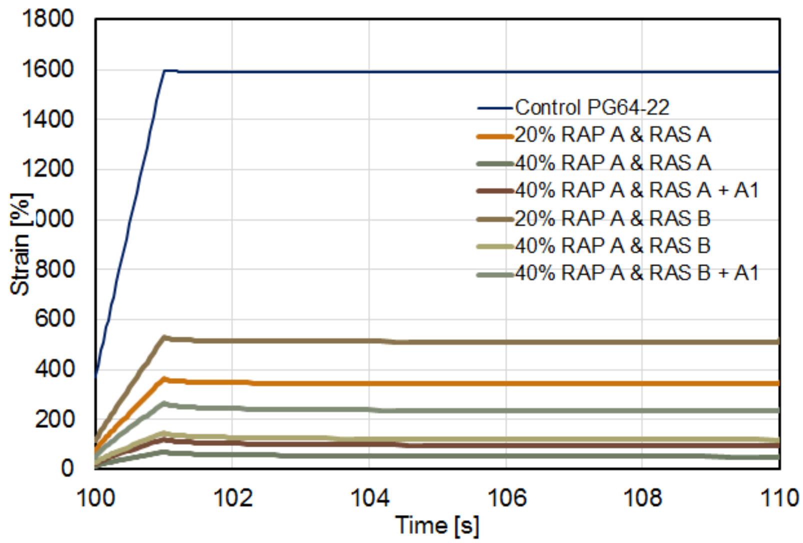

Figure 4.18. Elastic recovery at 3200 Pa and 64 °C for PG64-22 binder using two different types of RAS and one additive (only one cycle shown for clarity)

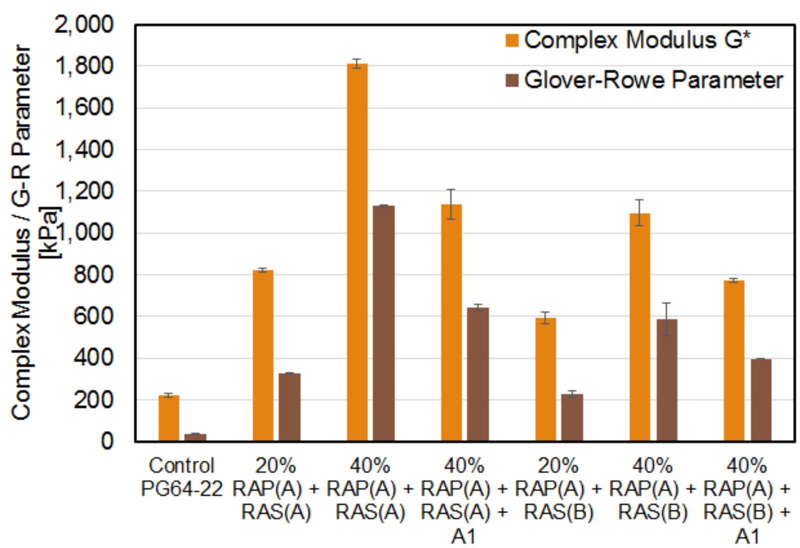

Figure 4.19. Complex modulus and Glover-Rowe results for PG64-22 binder using two different types of RAS and one additive

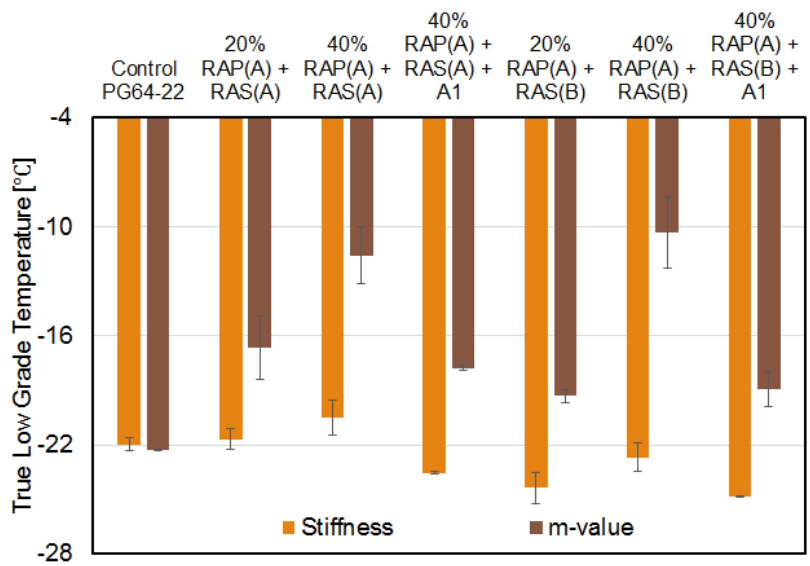

Figure 4.20. True low grade temperature for PG64-22 binder using two different types of RAS and one additive

One of the key findings from these results is that although the influence of RAP-RAS is the same as RAP, the magnitude of the impact by allowing RAS is much higher. Given that the RAS binder has much higher stiffness, this is not unexpected. For example, adding 40% RAP reduced the low temperature grade of the binder from -22 to -15 °C, whereas by using a combination of RAP and RAS the low temperature properties dropped to approximately -12 °C for one of the RAS sources and approximately -10 °C for the other RAS source. When only RAP was used, the additive was able to recover the low temperature grade to a large extent. However, the effectiveness of the agent or additive was reduced when using both RAP and RAS. Similarly, the G-R parameter for the base binder was close to 50 without any RAP. The use of 40% RAP increased this parameter to close to 380 and combining this with a recycling agent the G-R parameter could be reduced back to about 180. However, when a combination of RAP and RAS was used, the G-R parameter increased to 1,100 and even with the use of the additive the parameter did not reduce below 600.

4.2.5 Elastomer modified PG64-22 Using Two Different RAP Stockpiles and One Additive

As mentioned previously, there is currently no requirement for elastic recovery with the PG64-22 binder whereas there is a requirement for elastic recovery for the PG70-22 and PG76-22 binders. The goal of this part of the study was to examine the influence of RAP on the elastic recovery of the binders. In order to do so, a PG64-22P* binder was formulated in the laboratory using an elastomeric polymer. Two different RAP stockpiles were used, referred to as RAP A and RAP B, at different percentages (20 and 40%), and one type of additive was used with the higher RAP ratio of 40%.

Figure 4.21 shows the true high performance grade temperature results for all the configurations tested. Figures 4.22 and 4.23 present the MSCR results for PG64-22P* binder using two different types of RAP and one additive. Figure 4.24 shows the complex modulus and Glover-Rowe results for all the configurations tested. Figure 4.25 shows the true low performance grade temperature results for all the configurations tested.

Two key findings from this part of the work were as follows.

1. The use of RAP with or without additives typically compromised the elastic recovery of the binders.
2. The use of an elastomeric modified PG64-22P* was slightly more tolerant in terms of the G-R parameter when RAP was added compared to a PG64-22 binder without

any elastomer. This observation is based on a very limited binder set and therefore needs more scrutiny in the future.

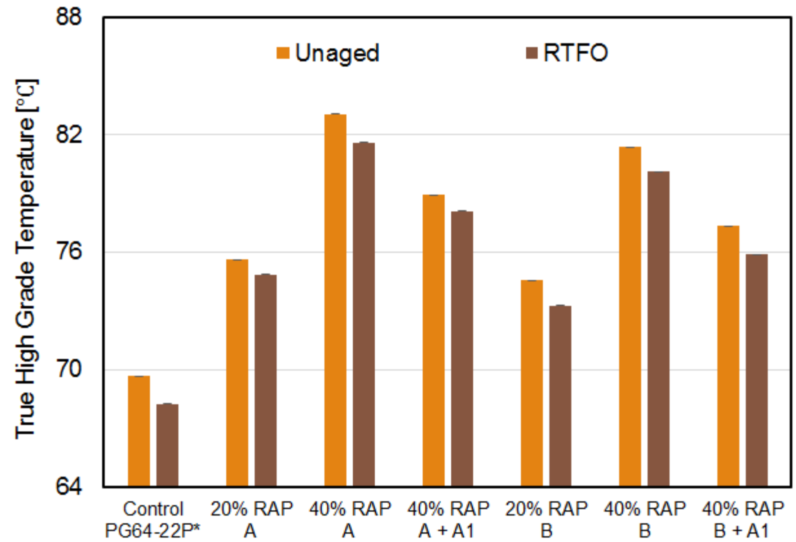

Figure 4.21. True high grade temperature for PG64-22P* binder using two different types of RAP and one additive

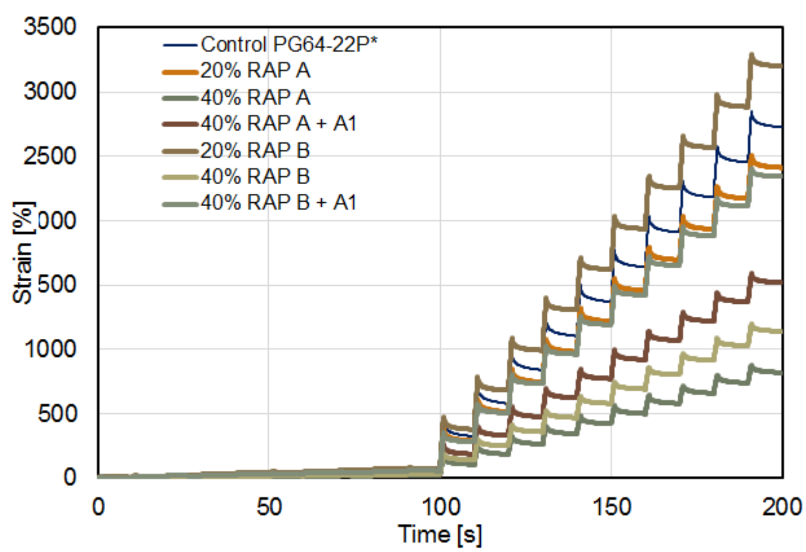

Figure 4.22. MSCR results at 64 °C for PG64-22P* binder using two different types of RAP and one additive

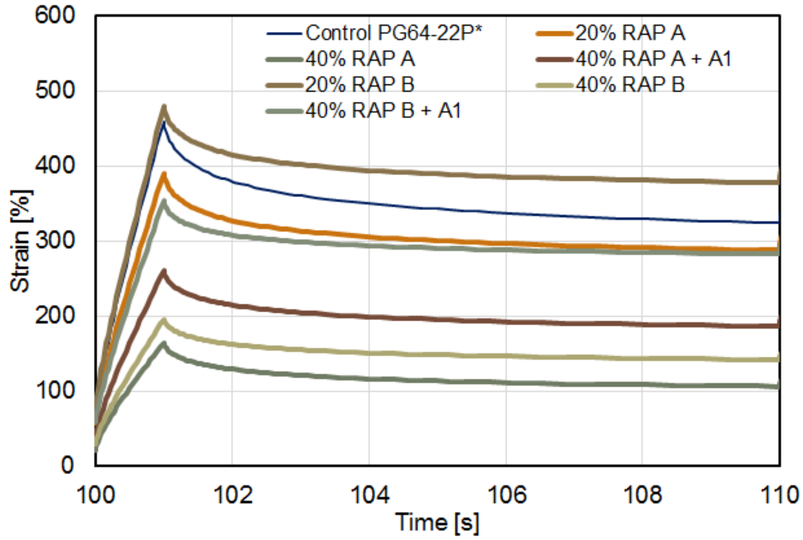

Figure 4.23. Elastic recovery at 3200 Pa and 64 °C for PG64-22P* binder using two different types of RAP and one additive (only one cycle shown for clarity)

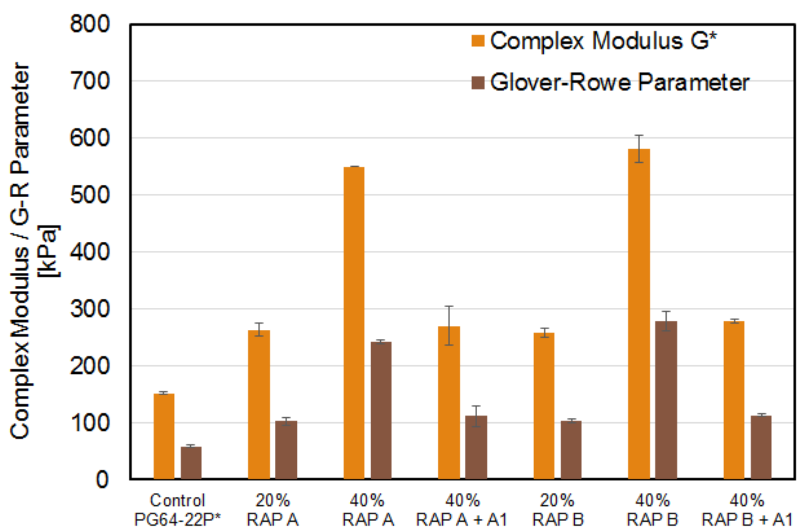

Figure 4.24. Complex modulus and Glover-Rowe results for PG64-22P* binder using two different types of RAP and one additive

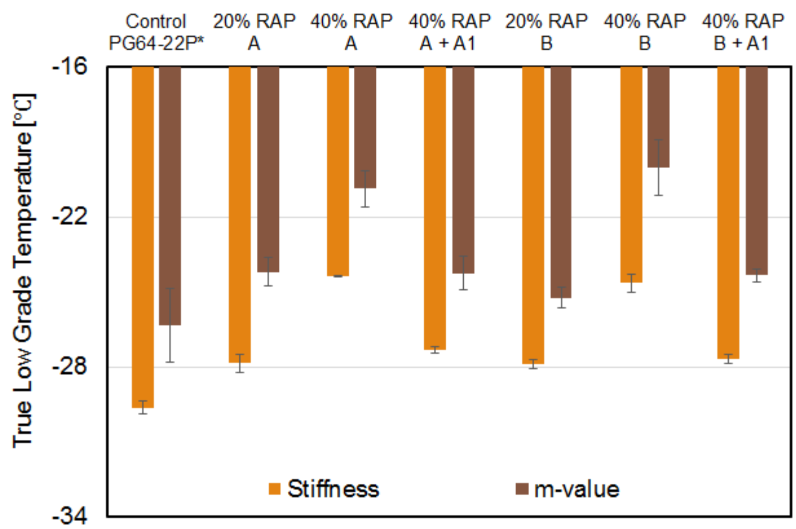

Figure 4.25. True low grade temperature for PG64-22P* binder using two different types of RAP and one additive

4.3 VARIABILITY IN RAP ACROSS THE STATE OF TEXAS

An earlier discussion with the Project Monitoring Committee with preliminary results prompted the need to examine the variability in the low temperature properties of RAP across the state in lieu of examining the mixture performance of a subset of binders with and without RAP. To this end, ten different RAP stockpiles were sampled from across the state and then used to characterize the low PG. This was done using a combination of micro-extraction and the DSR 4 mm plate geometry test, as described in the previous chapter.

Regular-extraction methods use different solvents such as toluene, trichloroethylene (TCE), toluene/ethanol, or N-propyl bromide (NPB), and methylene chloride for extraction. Some disadvantages of regular extraction processes include the excessive operator time, use of considerable amount of toxic solvents that are both costly to purchase and dispose, and increased exposure of the operator to these solvents. On the other hand, micro-extraction method can be used as an alternative, because it provides a test that requires significantly smaller operator time and it uses a small amount of toxic solvent thus addressing the main drawbacks associated with the regular-extraction method. A potential drawback of the micro-extraction method is that the sample recovered is very small and not adequate to conduct traditional tests such as the Bending Beam Rheometer (BBR) test. However, this shortcoming can be overcome by using a substitute test such as with the 4 mm DSR geometry.

The micro-extraction procedure that was used is summarized in the following steps:

(a) The loose mixture was first mixed and stirred with the solvent, i.e. toluene in this case. (Figure 4.26). Approximately 40 grams of RAP sample was used with 140 ml of toluene. The stirring was carried out for a duration of 12 hours using a magnetic stirrer in a vial sealed with a lid with a silicone septa. Prior to mixing, a syringe was used to draw out the air and vapors from the free space above the sample in the glass vial. This ensured that the availability of oxygen was minimized during the stirring and mixing thus minimizing the influence of oxidation.

(b) After stirring for 12 hours, the solution was filtered through a 1.0 μm disposable glass filter. (Figure 4.26).

(c) The solution extracted was then poured into a wide open mouthed glass container and evaporated in a vacuum oven to recover the binder. (Figure 4.27).

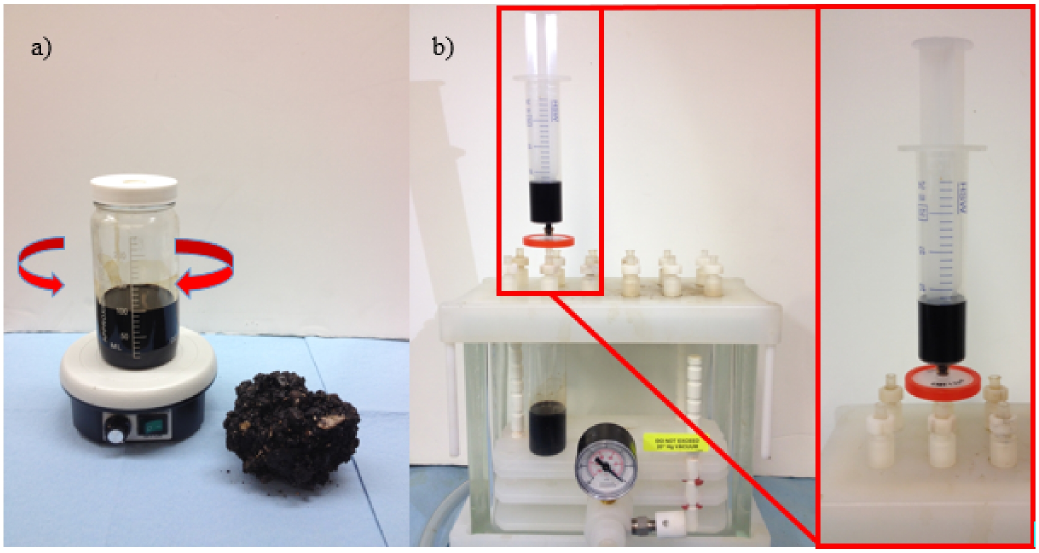

Figure 4.26. Micro-extraction procedure. a) Mixing and stirring the loose mixture with the solvent, and b) filtering the solution through a filter

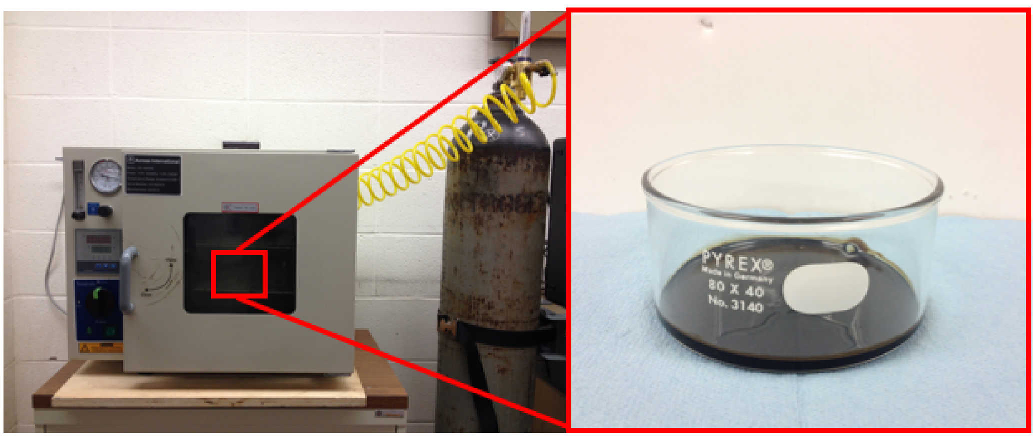

Figure 4.27. Micro-extraction procedure. Drying the solvent using a vacuum oven to obtain the extracted binder

4.3.1 Evaluation of ten RAP Stockpiles Across Texas

The objective of this exercise was to determine the variability in the recovered binder from different RAP stockpiles, as explained in the previous chapter.

Figure 4.28 shows the true low performance grade temperature results and the locations of the 10 different RAP stockpiles that were used in this study.

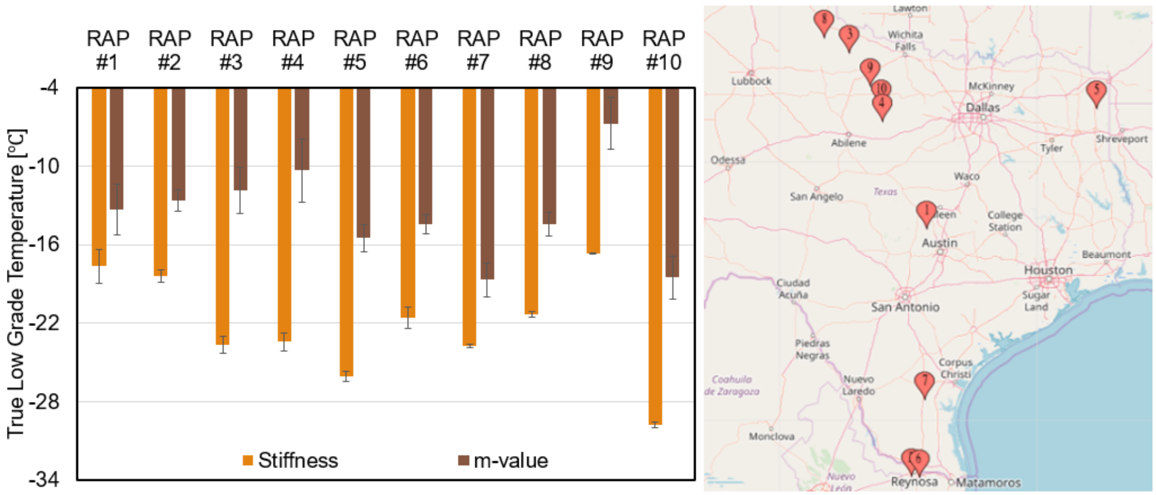

Figure 4.28. True low grade temperature and locations for ten different RAP stockpiles across the state of Texas

4.3.2 Evaluation of binder blends using five different RAP stockpiles

Two different binders (PG70-22 and PG64-22) were used to evaluate the low PG using a constant RBR percentage of 30% from five different RAP stockpiles after short term aging (RFTO) and long term aging (PAV).

Figure 4.29 shows the true low performance grade temperature results for the PG70-22 binder using a constant RBR percentage and also the results for the recovered binder of each RAP stockpile used.

Figure 4.30 shows the true low performance grade temperature results for the PG64-22 binder using a constant RBR percentage and also the results for the recovered binder of each RAP stockpile used.

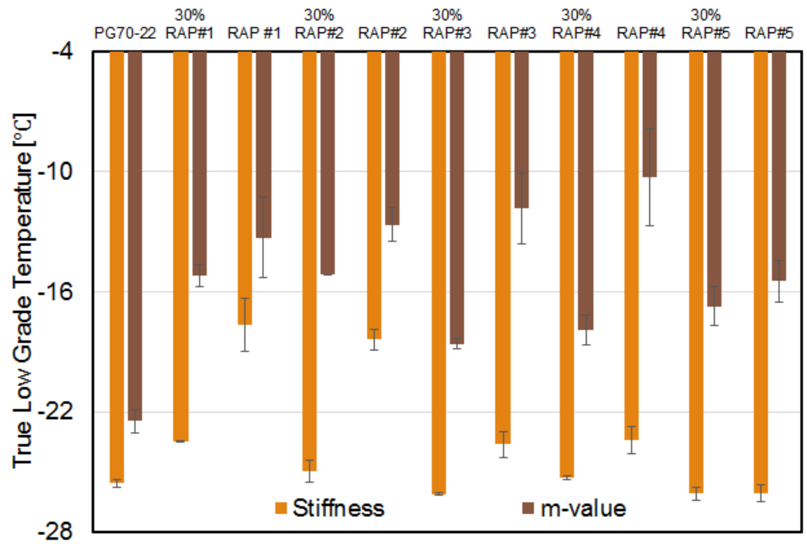

Figure 4.29. True low grade temperature for PG70-22 binder using five different types of RAP and true low grade temperature for each RAP stockpile

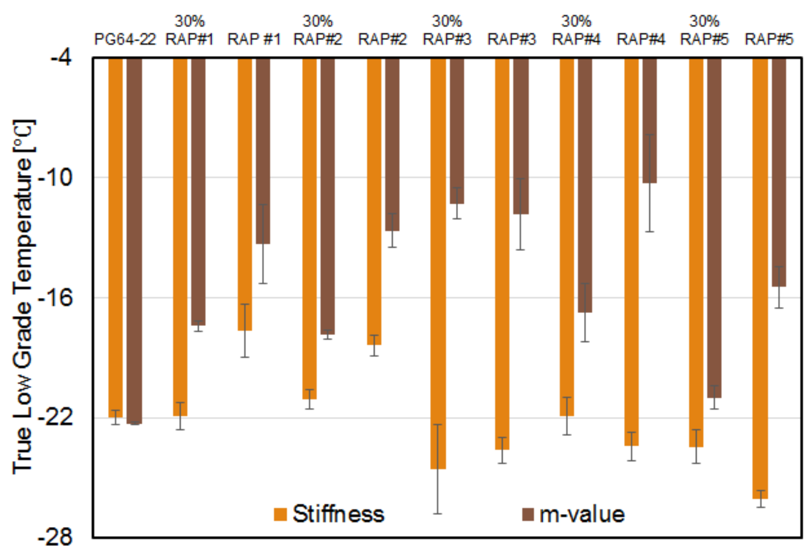

Figure 4.30. True low grade temperature for PG64-22 binder using five different types of RAP and true low grade temperature for each RAP stockpile

In summary, the results from this part of the task show that properties of RAP can vary significantly with source. In terms of the continuous grade, different RAP sources show a low temperature grade that varied from -18 °C to -6 °C. Interestingly, the RAP from the colder region of the state showed the highest low temperature grade of approximately -6

°C. These results demonstrate that not all RAP should be treated alike and consequently the determination of substitute binder grade, RAP content, and additives should be made on a case-by-case basis. Also, in almost all cases, the $m-$ value dictated the final grade of the binder-RAP blend and the grade of the RAP binder had a direct bearing on the grade of the blend.

4.4 SUMMARY OF RESULTS

To summarize, some of the key findings from this part of the study are as follows.

1. Addition of RAP increases the high temperature grade of the binder based on the $G^*/\sin\delta$ parameter and reduces the low temperature grade of the binder based on the S and $m-$ value parameters. Addition of RAP also increases the value of the Glover-Rowe parameter, which indicates a reduced resistance to fatigue cracking.
2. Three different recycling agents were used to evaluate their efficacy when using recycled binder. The effectiveness of each agent was different. In general, all agents reduced the rutting resistance based on both the MSCR and the $G^*/\sin\delta$ parameters and low-temperature properties of the binder based on the S and $m-$ value parameters, although some were more effective than others. However, it must be noted that when a substitute binder is being used, the reduction in stiffness and rutting resistance *may more than compensate for the expected increase in stiffness and rutting resistance due to a combination of the reduced high temperature grade and RAP/RAS*. The additives also show a decrease in the Glover-Rowe parameter indicating an improvement in cracking resistance. As before, the effectiveness of each additive was different. These results must be interpreted with caution because the *efficacy of the G-R parameter for modified binders is not established.*
3. *Recycling agents did not contribute to the elastic recovery of the binder-RAP-additive blend. In other words, although the additives helped recover the low-temperature grade of the binder after the addition of RAP, they did not necessarily help recover the elastic recovery of the virgin binder.*
4. Broadly, the influence of RAP-RAS is the same as RAP. However, *the magnitude of the impact by allowing RAS is much higher*. Given that the RAS binder has much higher stiffness, this is not unexpected. For example, RAP resulted in a 7 °C increase in the low-temperature properties whereas this number increased to 12 °C when same percent of RAP-RAS combination was used. Further, recycling agents (with the same concentration and type) were able to better recover the low temperature grade with

only RAP as compared to RAP-RAS. Finally, the G-R cracking parameter was also more adversely affected when a RAP-RAS combination was used in lieu of just RAP.

5. Low temperature properties of RAP can vary significantly from one source to another and this range was approximately two grade equivalents in a sample of ten different sources of RAP. These results demonstrate that not all RAP should be treated alike and consequently the determination of substitute binder grade, RAP content, and additives should be made on a case-by-case basis.

CHAPTER 5. IMPACT OF PRODUCTION PARAMETERS AND REJUVENATING AGENTS ON PERFORMANCE OF MIXTURES WITH RAP

5.1 INTRODUCTION AND MATERIALS USED

This chapter summarizes the work accomplished in Task 6 of this project, i.e. evaluation of agents that can potentially be used to improve the properties and performance of asphalt mixtures incorporating RAP.

For this part of the project one mix design was selected as a control. The mix design was a Type D and the aggregates were sourced from Spicewood, Texas quarry. Figure 5.1 shows the aggregate gradation.

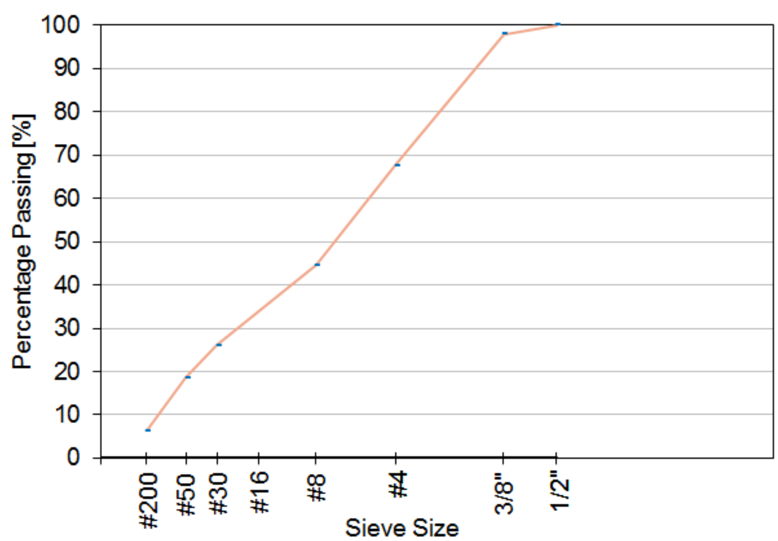

Figure 5.1. Aggregate gradation for the control mix

Two different additives were used to examine the effect of agents used to facilitate the use of RAP. These additives were a commercial rejuvenator and a particulate additive referred to as Additive 1 and Additive 2. Binder properties were evaluated using Additive 1 and mixture properties were evaluated using both additives. This was done to avoid confounding effect of particulate material in the binder.

5.2 BINDER PROPERTIES

Figures 5.2 to 5.4 present the influence of the additive on binder properties.

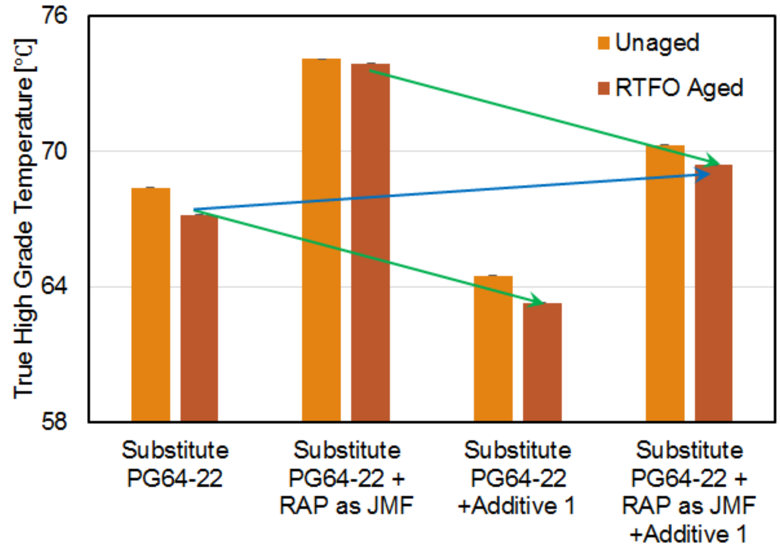

Figure 5.2. True high grade temperature of controls to enhance blending

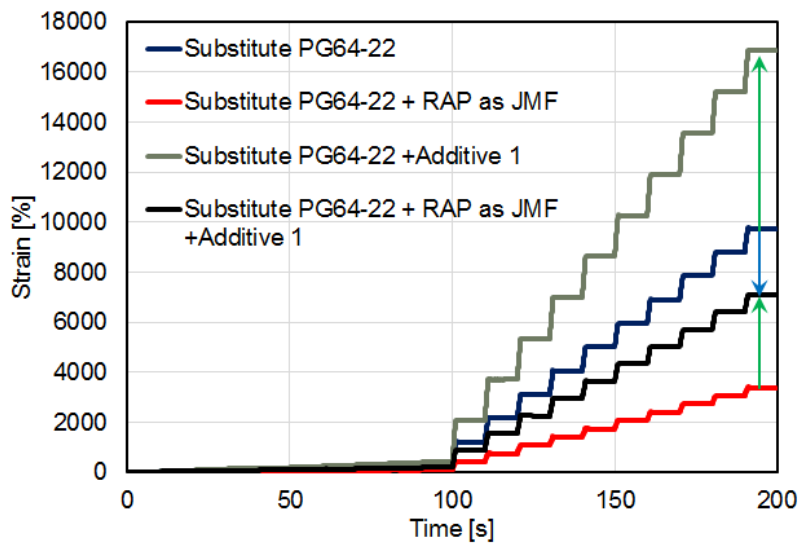

Figure 5.3. MSCR results of controls to enhance blending

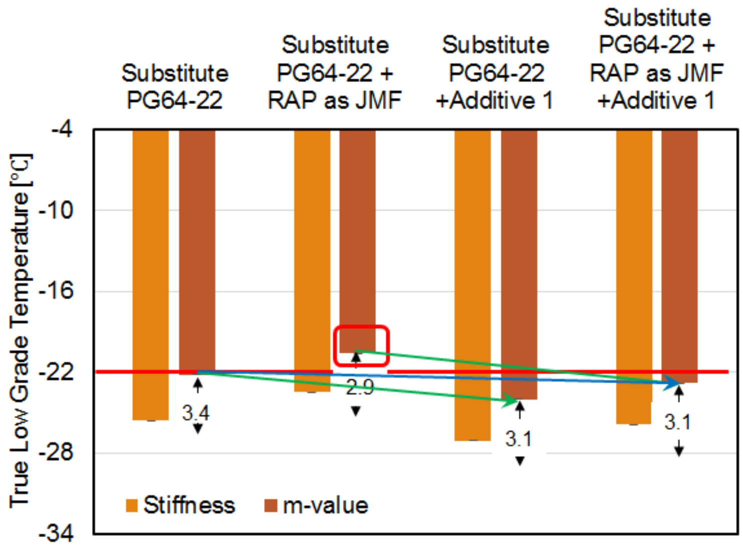

Figure 5.4. True low grade temperature of controls to enhance blending

5.3 MIXTURE PROPERTIES

Mixture properties were evaluated using Additive 1 and Additive 2.

For Additive 1, two variations were evaluated. In the first variation, the additive was added to the binder, using a high shear mixer at the temperature of 160°C for one hour at 2,400 rpm, and the modified was then used with the mix.

In the second variation, the additive was applied to the RAP material to maximize its effectiveness. The first variation is referred to as pre-blended and the second variation is referred to as pre-treated.

For Additive 2, which was particulate, only the pre-treated option was feasible.

Figures 5.5 to 5.7 show results from mixture testing.

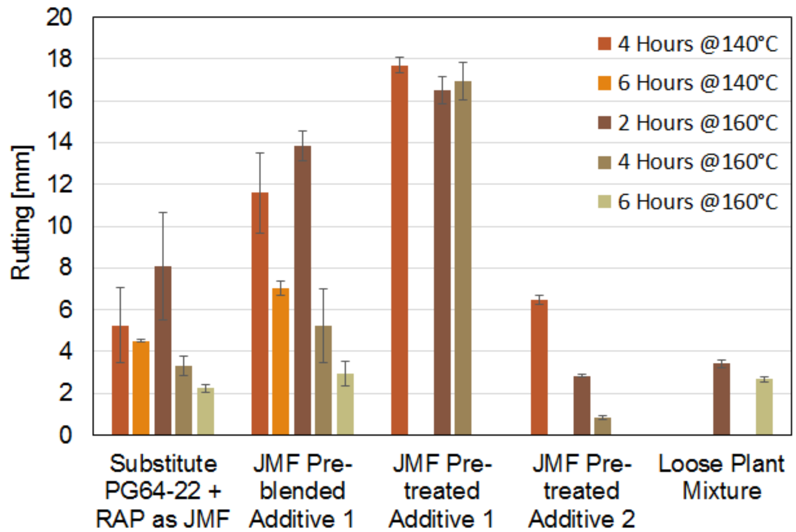

Figure 5.5. HWT Rutting of controls to enhance blending at different short term aging

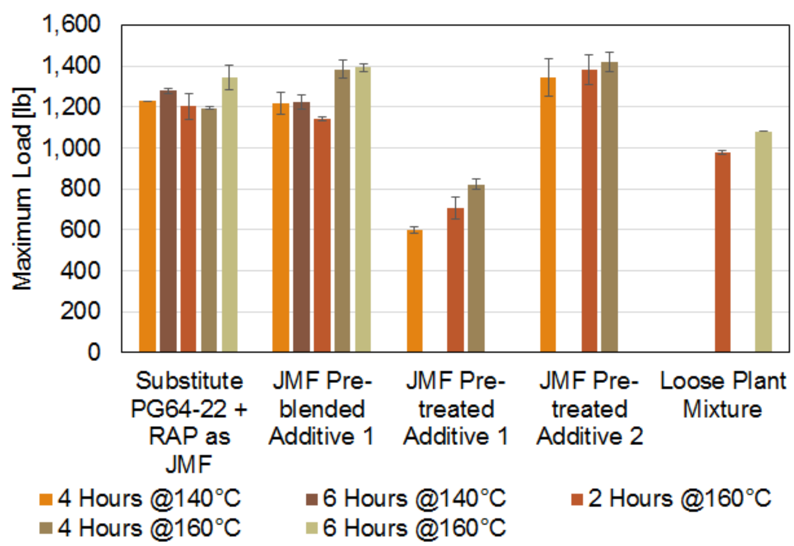

Figure 5.6. OT Maximum load of controls to enhance blending at different short term aging

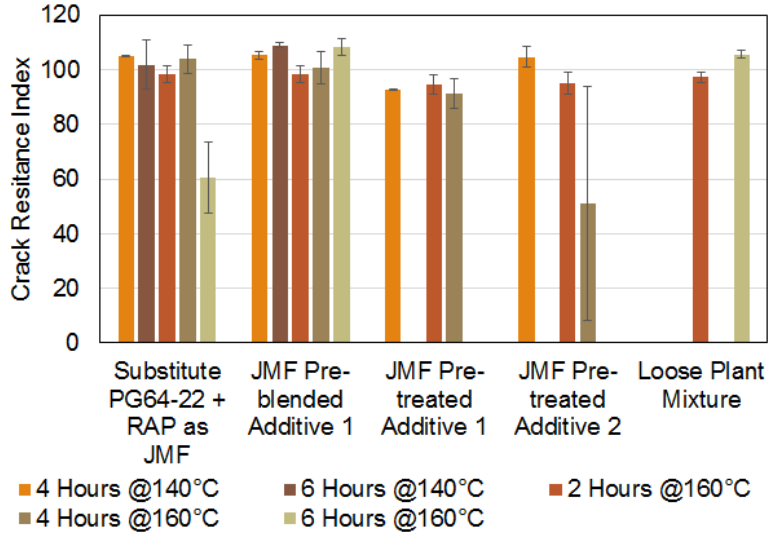

Figure 5.7. OT Crack resistance index of controls to enhance blending at different short term aging

SUMMARY OF RESULTS

Some of the key findings from this part of the study are as follows.

One of the key findings from these results is that the additives typically tend to soften the binder when used without RAP. Particularly, the low temperature properties of the binder with RAP and rejuvenator were very similar to the specified binder without the RAP.

This effect is then offset by the addition of RAP. Notwithstanding aging durations, it appears that additives must be carefully evaluated and used for mixture production with RAP.

CHAPTER 6. SUMMARY AND CONCLUSIONS

6.1 OVERVIEW

The main goals of this study were to:

1. address the allowable substitute binder, and the maximum ratio of recycled binder to total binder to be used without compromising the durability of the mix as currently prescribed in Table 5 in Specification 2014 Items 340, 341, and 344 TxDOT (2004). This table allows for binder substitution regardless of the percentage of RAP, which is different from the general trend of using the same grade up to typically 20% RAP, and in many instances the grade lowering is restricted to only the higher grade and not the lower grade.
2. examine the influence of recycled and substitute binder on binder and mixture performance using different grades of virgin binder and percentages of RAP,
3. examine the influence of different types of RAP on the rheological and performance related properties of asphalt binder, and
4. evaluate agents or additives that can potentially be used to improve the properties and performance of asphalt mixtures incorporating RAP.

In order to achieve the aforementioned goals, the performance of binders and mixtures were evaluated using systematically controlled materials prepared in the laboratory as well as materials sampled from the field. In the case of laboratory evaluation, two different types of binders that are typically recommended for asphalt pavement construction were selected as control binders (PG76-22, and PG70-22). In addition, three different types of binders were selected as substitute binders (PG70-22, PG64-22, and PG64-22* which is a polymer modified binder specifically formulated in the lab to have good elastic recovery). Binder recovered from two RAP stockpiles and two RAS stockpiles were used to create blends with different percentages of RAP, or RAP and RAS, to study the influence of RAP or RAS inclusion in binders. Also, three different additives (recycling or softening agents) were used in order to enhance the properties of the RAP modified binders.

In the case of field evaluation, four different field sections were identified from different geographic and climatic regions across Texas. The different mixture combinations or variations that were evaluated for each of the four mix designs were:

1. laboratory mix prepared using the job mix formula (JMF) and the specified binder and without any RAP (this is the baseline case with specified binder and no RAP),

2. JMF using the substitute binder without any RAP inclusion (this is the extreme case where the binder was substituted but no RAP was included to compensate for the substitution),
3. JMF using the substitute binder and RAP (this represents the as-built case), and
4. JMF with an additional 10% RAP and appropriate adjustments for aggregate gradation (this explores the possibility of using additional RAP in mixes).

Also, field mixes were obtained at the time of construction and field cores were obtained approximately 1 to 1.5 years after construction. In the case of binder testing, parameters that were evaluated include rutting resistance, elastic recovery, intermediate temperature stiffness, cracking resistance, and thermal cracking resistance. In the case of mixture testing, rutting resistance was evaluated using the Hamburg Wheel Tracking Device (HWTD) and cracking resistance was evaluated using the Overlay Test (OT) and Indirect Tensile Test (IDT).

6.2 SUMMARY OF KEY FINDINGS

Some of the key findings from this study are summarized below:

1. The current (2014) specification Items 340, 341, and 344 (i) may result in the substitution of a polymer modified binder with a binder that has little or no polymer (elastomer), (ii) does not account for the influence of recycling agents, and (iii) does not address the potential differences in the quality of binders from different sources of RAP or recycled asphalt shingles (RAS).
2. High temperature properties of the binder show that substituting a softer or lower high temperature grade binder for the specified binder (without RAP) results in a reduced the high temperature stiffness, non-recoverable compliance, and consequently a reduced resistance to rutting. This is expected because no RAP is incorporated. Addition of RAP to the substitute binder compensates for the lower high temperature grade binder and allows the mix to achieve a high temperature stiffness, non-recoverable compliance, and rutting resistance that is comparable to or better than the specified binder without RAP. This is a desirable and positive effect.
3. Elastic recovery of the substitute binder (without RAP) is generally lower than the elastic recovery of the specified binder. This is also expected in cases where the substitute binder is a PG64-22 since a PG64-22 binder does not have an elastic recovery requirement in the current specifications. Addition of RAP to a substitute binder that does not have any or low elastic recovery does not improve these characteristics of

the virgin binder. The lack of elastic recovery associated with the use of a substitute binder (particularly when the substitute is a PG64-22) is generally associated with lower ductility and cracking resistance in the mix and it is not desirable.

4. Typically, the substitute binder has the same low temperature properties as the specified binder. Therefore, the low temperature properties are similar when comparing the substitute to the specified binder without RAP. However, the addition of RAP to the substitute binder deteriorates the low temperature properties of the binder. In most cases, a combination of the substitute binder with RAP raises the low temperature grade of the blend by one grade. The loss of low temperature grade can result in a binder with lower ductility and cause premature thermal cracking and it is also an indicator of reduced resistance to intermediate temperature fatigue cracking. This effect is also undesirable and can be offset by the use of a binder with one additional lower grade than required when using RAP and/or other recycling agents/additives.
5. Typically, the rutting performance of mixtures improves with the addition of RAP. However, in some cases, the rutting performance of mixes with a lower grade substitute binder and RAP may be slightly lower than the rutting performance of the mix with the specified binder and without RAP. Specifically, this was observed when the specified binder was a PG76-xx and the substitute binder was a PG70-xx. The reason for this counter-intuitive behavior was because the PG70-xx binder by itself has a low rutting potential. However, the addition of RAP reduces the overall elastic recovery of the blend and thus increases the rutting potential. This behavior was consistent in both the HWTD results for the mixtures and the binder results using MSCR.
6. Addition of RAP increases the high temperature grade of the binder based on the $G^*/\sin\delta$ parameter and reduces the low temperature grade of the binder based on the S and $m-$value parameters. Addition of RAP also increases the value of the Glover-Rowe (G-R) parameter, which indicates a reduced resistance to fatigue cracking.
7. Three different recycling agents were used to evaluate their efficacy when using recycled binder. The effectiveness of each agent was different. In general, all agents reduced the rutting resistance based on both the MSCR and the $G^*/\sin\delta$ parameters and improved the low-temperature properties of the binder based on the S and $m-$value parameters, although some were more effective than others. However, it must be noted that when a substitute binder is being used, the reduction in stiffness and rutting resistance *may more than compensate for the expected increase in stiffness and rutting resistance due to a combination of the reduced high temperature*

grade of the substitute binder and RAP/RAS. The additives also show a decrease in the Glover-Rowe parameter indicating an improvement in cracking resistance. As before, the effectiveness of each additive was different. These results must be interpreted with caution because the *efficacy of the G-R parameter for modified binders is not established.*

8. *Recycling agents did not contribute to the elastic recovery of the binder-RAP-additive blend. In other words, although the additives helped recover the low-temperature grade of the binder after the addition of RAP, they did not help recover the elastic recovery of the virgin binder.*
9. Broadly, the influence of RAP-RAS is the same as RAP. However, *the magnitude of the impact by allowing RAS is much higher*. Given that the RAS binder has much higher stiffness, this is not unexpected. For example, RAP resulted in a 7 °C increase in the low-temperature properties whereas this number increased to 12 °C when similar recycled binder content was used. Further, recycling agents (for a given concentration and type) were able to better recover the low temperature grade when RAP was used as compared to when both RAP and RAS were being used together. Finally, the G-R cracking parameter was also more adversely affected when a combination of RAP and RAS were used compared to just the use of RAP without any RAS.
10. Low temperature properties of RAP can vary significantly from one source to another and this range was approximately two grade equivalents in a sample of ten different sources of RAP across Texas. These results demonstrate that not all RAP should be treated alike and consequently the determination of substitute binder grade, RAP content, and additives should be made on a case-by-case basis.

6.3 SUMMARY OF RECOMMENDATIONS

6.3.1 Recommendations that may be implemented immediately

Based on the findings from this study the following may be considered for further implementation in the near future:

1. Two grade drops in the high temperature performance grade should be avoided when using a substitute binder. Lower high temperature grade of binders also have lower requirements for elastic recovery. The implicit impact of allowing the high temperature grade of the substitute binder two grades below the specified binder is that the resulting blending of the RAP and virgin binder typically results in lower or no elastic

recovery and overall performance in terms of rutting and cracking resistance.

2. The addition of RAP compromises the low PG of the binder. One way to mitigate this effect is to use a substitute binder that has one grade lower than required (e.g. if the specified binder is PG76-22 then, the substitute binder is recommended as PG70-28). A second way to mitigate this would be to use an additive (rejuvenating agent). Rejuvenating agents must be allowed for use only after examining their efficacy with RAP and the virgin binder using binder and/or mixture tests. In other words, mixture performance must be evaluated after incorporating proposed rejuvenators and RAP during the mixture design approval stage instead of approving a mix with virgin binder and allowing a substitution later.
3. The addition of RAP and RAS together substantially changes the performance grade of the blend, particularly in terms of cracking resistance, and must be used very cautiously. The magnitude of the impact of allowing RAS is much higher compared to RAP due to the fact that RAS binder has much higher stiffness compared to binder from typical RAP samples. Typically, intermediate and low temperature performance are more severely and adversely affected when a RAP-RAS combination was used in lieu of just RAP. The use of RAP-RAS must be verified using both binder and mixture performance tests.

6.3.2 Recommendations that may be implemented in the near future

Furthermore, the following may also be considered for implementation in the future:

1. Properties of the binder from different RAP stockpiles must be measured and evaluated on a regular basis. This information must also be incorporated in the job mix formula (JMF) and SiteManager database to develop historical data that can be used to enhance the responsible use of RAP in the future.
2. Additives such as recycling or softening agents are effective at restoring binder properties and enhancing the properties of the RAP modified binders. However, the efficacy of such agents depends on type of additive, virgin binder, and type of RAP. These interactions must also be measured and documented on a project by project basis.
3. This project also developed and demonstrated the use of a micro-extraction procedure to extract and recover small amounts of binder from a RAP stockpile and evaluate these binder samples using the 4 mm diameter parallel plate geometry test with the DSR. This procedure requires significantly less resources compared to conventional

methods and can be used on a routine basis to extract and characterize properties of the binder from a RAP stockpile as well the effectiveness of different rejuvenating agents.

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