Crumb Rubber Modified Crack Sealants to Improve Performance

by

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ABSTRACT

Crack sealing is considered one of the least expensive and cost effective maintenance activity used on pavements. In some cases, crack sealing suffers from premature failure due to various material, environmental, and construction issues. A survey that was conducted as part of this study showed that the highest sealant failure year occurring on the second year. Therefore, any attempt to increase the sealants' service life by addressing and improving the sealant properties and their resistance to failure will benefit the effectiveness of this treatment.

The goal behind this study was to evaluate the potential improvement in performance of hot applied sealant material commonly used in the Phoenix area, and evaluate the performance of using a neat binder modified with crumb rubber (at 5 and 10% by weight of binder) as a low-grade sealing material. The sealants was also modified with crumb rubber at 2.5, and 5% by weight fo the sealant. Six ASTM tests were conducted for the comparison. These tests are the Standard Penetration Test (SPT) and Cone Penetration Test (CPT), Resilience Test, Softening Point Test, Brookfield Viscometer Test, and Dynamic Shear Rheometer (DSR).

The results showed that adding only crumb rubber to a neat binder for its potential use as a crack sealant is inadequate to meet the specifications expected for sealants. However, the modification of the sealant with crumb rubber showed some benefits, such as increased elasticity and decreased temperature susceptibility. A crumb rubber content of 2.5% by weight of the sealant was recommended.

DEDICATION

I would like to dedicate this thesis to my mother Sharifah AlKhalifah and my father Saleh Thuwaini, who have provided me with unconditional love and support throughout my life. I am grateful to have you in my life.

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Chapter 1 Introduction

1.1 Background

Crack sealing is considered one of the least expensive and cost effective preventative maintenance procedures used on pavements [1]. The main goal from applying a crack sealant is to minimize any water infiltrations that cause additional distress and deterioration in or around the crack area. Such deterioration may also contribute to asphalt stripping and base moisture failure. Additionally, infiltrations may also cause spalling and potholes. In some instances, crack sealing is thought to provide a more uniform ride helping to maintain the integrity of the pavement before placing an overlay, and possibly by mitigating reflection cracking of non-working or heavily deteriorated cracks.

Numerous reports are found in the literature to support the crack sealing effectiveness claim. For example, a study was completed by the Ohio Department of Transportation (ODOT) in association with the University of Cincinnati (UC) in 2011 to evaluate the effectiveness of the preventative crack sealing program [2]. The evaluation was conducted on 700 one-mile long sections. The study results showed that crack sealing is capable of extending the service life of a pavement up to 3.6 years.

On the other hand, the main issue with crack sealing is the premature failure due to various material, environmental, and construction causes. Most sealant manufacturer label their product’s service life between 5 and 7 years. Various agencies showed otherwise with a lower effective average life span of 1 to 3 years [3]. In fact, a survey that was conducted as part of this study showed that the highest sealant failure year occurring on the second year. Therefore, any attempt to increase the sealants’ service life by addressing and improving the sealant properties and their resistance to failure will benefit the effectiveness of this treatment.

1.2 Study Objective

The main objective of this study was to evaluate the potential improvement in performance of hot applied sealant material and neat asphalt binders using crumb rubber. Better understanding of the effect of crumb rubber in terms of additional elasticity and better rheology in binders was the basis for the attempt of using them, possibly, as one alternative composition for sealing purposes.

1.3 Scope of Work

In order to achieve the study objective a plan was proposed and implemented in this work. First, an extensive literature review of the crack sealants failure modes and their causes were investigated. Each cause was addressed separately with the latest knowledge and approach to minimize its effect. Second, a series of American Standards of Testing Materials (ASTM) laboratory tests were identified and introduced to describe the evaluation process of various sealant and binders properties. Third, a crumb rubber source was introduced to a PG64-22 neat binder for the potential use of the crumb rubber modified binder as a sealant. In addition, a commonly used sealant in Phoenix, Arizona was also subjected to laboratory testing in original form and using different crumb rubber contents for potential improved properties. Finally, a comparison was conducted between the modified PG64-22 binder and Sealant to evaluate the best benefit added value for crack sealant performance.

1.4 Organization of Thesis

This thesis is divided into six chapters. The first chapter showed the background information about the importance of crack sealing, study objective and scope of work. The second chapter provides extensive literature review about hot applied sealant material composition, various forces and failure modes experienced by a sealant, current crack sealant construction practices, and a review of the current ASTM laboratory tests used to evaluate sealants. The third chapter includes information and results from an agency survey conducted on various aspects of crack sealing experience. The fourth chapter provides detailed information about the experimental program and the results. The fifth chapter presents data analysis that is organized in the form of three phases: starting with crumb rubber modified PG64-22 binder, Sealant testing results with and without crumb rubber modification, and a final comparison with statistical analyses. The sixth chapter includes conclusions and recommendations of this study.

Chapter 2 Literature Review

2.1 Sealants Types

There are two major types of crack sealants used on asphalt pavements: cold applied and hot applied sealants. Most agencies use the hot applied sealants due to their better performance and longevity [4]. Cold applied sealants are lower in initial costs and can be used in conditions where hot applied sealant cannot be installed; such as in high humidity or when the crack is moist or damp [4]. In addition, cold applied sealants are considered safer since curing is done by water evaporation and does not require any heating [4]. With respect to the life cycle costs, hot applied/poured sealants proved to be more cost effective than cold poured sealants in areas where both can be used. This is mainly due to the longer service life outweighing the cost gap between the two types of sealants [5]. In this study, the focus will be on the hot applied sealants since they are predominantly used in the Phoenix area.

2.2 Hot applied crack sealant physical composition

Hot applied crack sealants are made from two main components similar to asphalt binders used in Hot Mix Asphalt (HMA) pavements. The first component is the asphalt cement from refined crude oil. Since crude oil chemical composition, purity, and refining process may vary from one source to another, the resulting asphalt cement also varies in properties accordingly. Therefore, in the process of creating the optimum crack sealant, it is crucial to compare between base asphalt cement in term of physical properties and cost effectiveness. Currently, the refining phase technologies are considered mature and will not likely change. On the other hand, various new specifications are pushing the refining industry to reevaluate the refining process to produce high quality asphalt cement [6].

The second component is the solid and liquid formulations added to the base asphalt cement to alter its properties to more desirable ranges. These formulations are referred to as additives. Examples of these additives are oils, rubber, plastic, and antioxidants. For hot applied crack sealants the common desirable properties are rheology and elasticity. Therefore, one or more of these additives are mixed at different percentages to achieve the intended properties levels. Practically, most manufacturers use life cycle cost analysis to determine the quantity and type of each component to come up with a customized sealant that fit any agency networks' needs and budget.

Within the asphalt pavement industry, binders and sealants are mostly categorized under the same group since they are made from the same two main components. In fact, many of the ASTM tests used to evaluate binders are also used for sealants. The distinction between both is the numerical values of the same properties that serve their purpose in the pavement. For instance, crack sealant are known to have lower modulus of elasticity, compared to binders, which allow them to stretch up to ten times their original length while coping with crack movements [7].

2.3 Cracks categorization and dimensions

Crack sealing or filling are considered one of the most commonly used crack treatment to minimize the deterioration of any pavement surface. Due to the various causes of cracking, once the evaluation assures that a crack is a functional distress, crack sealing or filling become attractive options due to their costs effectiveness. In addition, these crack treatments are mainly used on pavements in good conditions since they are preventative / proactive treatments that will not resolve mix or design issues. For instance, the same cost effectiveness study mentioned earlier and conducted by ODOT, the maximum performance gains from crack sealing is on pavements with a Pavement Condition Index (PCI) ranging from 66 to 80 [2]. Additionally, one of the study final recommendations was to start sealing cracks in pavements before reaching a PCI of 80.

The difference between crack sealing and filling is the amount of movement the crack experience. The suggested amount of horizontal movement differentiating between the two crack treatments is 2.5mm based on the Standard Highway Research Program (SHRP) H-348 study [8]. As a result, crack sealing is used for higher movements (more than 2.5mm) and cracking filling for lower movements (lower than 2.5mm). Since this report revolves around hot applied sealants, the focus will be concentrated on crack sealing activity only.

Before applying any seal, all cracks should be cleaned and air blown using high-pressure air blasting equipment to remove any moisture, dust, and loose particles. When applying any seal, it is preferred to do so in moderate temperatures of fall and spring to avoid the extreme expansion or contraction in cold and hot temperatures. Additionally, achieving the recommended seal placing temperature is crucial to avoid any seal properties alteration or placing difficulties such as interface bonding. A more detailed construction guide for the best current practices will be presented later in this literature review section.

The width of the crack also plays a role in selecting the appropriate treatment. For cracks widths smaller than 5mm, crack treatments are not used due to the practical difficulties in the application in the field [4]. For such tight cracks, surface treatments such as scrub seal and slurry seal are commonly used to minimize future deterioration. Crack sealing and filling are used for crack widths of 5mm to 19mm and 5mm to 25mm respectively [8]. In some rare cases in asphalt pavements, for cracks wider than 10 mm, a bond backer rod made from polyethylene foam is placed in the crack before applying the seal [9]. This backer rod should be non-absorptive, flexible, and compatible with the sealant material. In addition, it should be 25% larger in diameter than the crack width [9].

2.4 Crack sealant governing forces

When a crack is exposed to various forces it mostly transfer them into movements that could be measured. Cracks experience two types of movements, which are horizontal and vertical. Horizontal movements occur due to thermal expansion and contraction as a result of temperature fluctuations. Meanwhile, vertical movements occur due to traffic loading. Due to the crack movements in both axis, loads on the pavement are transferred onto the sealant. Based on past pavement maintenance experience there are five main modes of failure hot applied sealant experience:

- Adhesion failure
- Cohesion failure
- Settlement failure
- Pullout of material failure
- Spalls or secondary crack around the sealed crack

Since crack sealants are viscoelastic materials in nature, they tend to experience and relax the imposed load. If the build up stress in the sealant is higher than the relaxed stress, the differential will cause either an adhesive or cohesive failure [8]. Adhesive failure occurs when the sealant detach from the crack walls or bottom creating an area for infiltrations [10]. Cohesive failure occurs when the sealant breaks into separate parts within its body [10]. Other factors such as sealant weathering can enhance adhesion/cohesive failure modes by lowering the sealant ability to respond to external forces applied from the pavement. Settlement failure is when the sealant settles in the crack due to gravity by the decrease in viscosity at elevated temperatures. Settlement often occurs in wider cracks. Therefore, a backer rod is placed as a support in addition to being a filler.

Since a common construction method is to create an over band for the sealant, pullout and tracking are common issues for newly applied sealants. If the sealant was not fully cured car tires could fully remove the sealant while going over them [11]. Spalling occurs when further deterioration is observed at the crack edges mainly caused from poor construction practices. Some causes of spalling are improper crack cutting prior to applying the sealant and overheating crack edges using the hot air blaster [10]. In addition, the asphalt mix strength around the crack is crucial to avoid any secondary cracking resulting from excessive loading around the existing sealed crack.

Several studies have been conducted to identify the most common failure mode experienced throughout the United States. For example, a study conducted by D.R. Johnson et al. evaluated four test sections with different crack sealant material and difference construction procedures at one, six and 12 month periods [12]. Results showed that adhesion and cohesion low integrity was the leading cause of failure while excluding the effect of construction practices.

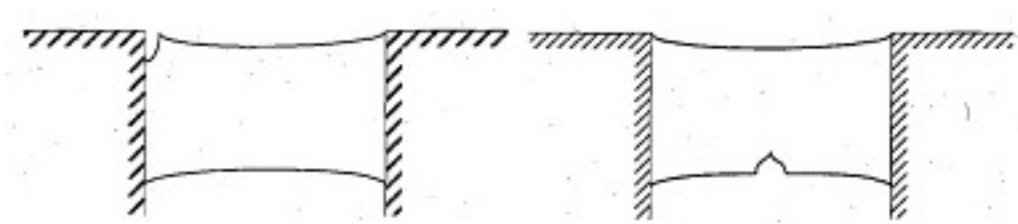

Figure 2-1: (a) Adhesive Failure and (b) Cohesive Failure [9]

Even when an adequate crack sealant is chosen, it is crucial to apply the sealant following the best construction practices. The same failure modes can occur when overseeing any of the crack preparation and installation procedures. These procedures will be discussed more in the following sections. For instance, not monitoring the hot air blaster temperature during drying might cause the crack edges to overheat and age. Therefore, weaken the crack edges causing spalling. Additional information about sealant failure modes related to construction practices are presented in the following construction practices Section 2.8.

2.5 Standard Laboratory Tests

In order to evaluate whether a suitable hot applied sealant for any sealing application meets specifications. a standardize testing approach is used by several organizations including ASTM. ASTM D6690 and D5329 are the codes for performance testing and evaluation of hot applied crack sealants. They include a number of laboratory standard tests to numerically differentiate between different types of sealants performance levels. This list of standard tests is used by both the sealant manufacturer to show the sealant properties are met, and by the user agency for sample verification / quality assurance purposes before full application. According to ASTM D6690 standards there are four main classification groups separating all hot applied sealants. These classifications range from Type 1 through Type 4, which are based on climate. Based on empirical practices, the hot applied sealants used in the Phoenix area optimally lie within Type 1 sealants, which are capable of maintaining an effective seal in moderate climates. Additionally, ASTM D5329 contains several standard tests that also can be used for hot applied sealants.

2.5.1 Specimen Conditioning and Heating Standards (D5167)

Before conducting any laboratory tests, the atmospheric conditions must comply with the standards of 23 +/- 2 °C and 50% relative humidity +/- 5% concluded from E171. The sealant should be placed in the same atmospheric conditions for 24 hours before melting or heating. In order to achieve high level of consistency, laboratory equipment should comply with all the ASTM standards in the test method. For laboratory melting, D5167 provided several typical melting units, which comply with the stated standards. These melting units should be under an exhaust hood to disperse emissions.

2.5.2 Standard Penetration Test (D5)

The Standard Penetration Test (SPT) is an ASTM standard test for most bituminous materials to measure consistency (see Figure 2-2). Consistency is important because it provides an insight of the construction practicality when using the tested material. Based on ASTM D6690, SPT is not considered one of the governing design tests for crack sealants. The rationale behind excluding this test is the chance of providing misleading results due to effect of specimen testing location. Since the test uses a needle it is adequate for homogenous sealants that do not contain any visible particles such as rubber. Nevertheless, several studies have shown the benefits of conducting the Standard Penetration Test on sealants for its use in the viscosity temperature susceptibility analysis. SPT results are converted to equivalent viscosity values through regression models. ASTM D5 will be used as reference for this test.

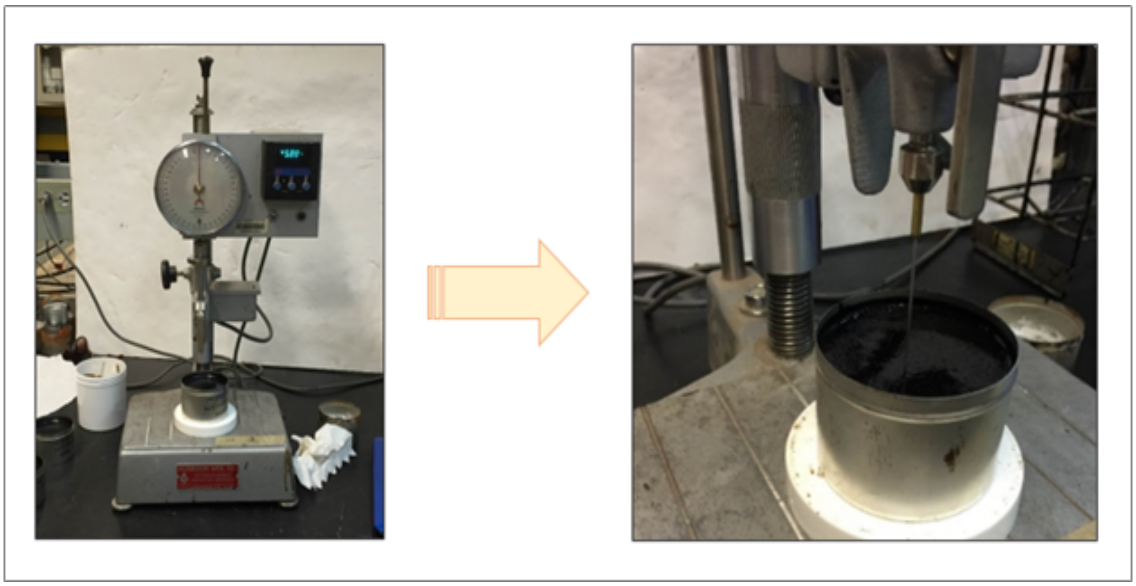

Figure 2-2: Penetrometer Device with a Needle Tool Attached to it

2.5.3 Cone Penetration Test (D5329)

The Cone Penetration Test (CPT) is an ASTM standard test specified for sealants to measure consistency and hardness/softness of a sealant. CPT is identical to SPT in the testing method. What differentiates CPT is the cone shaped penetration tool to account for visible solid additives instead of a needle in SPT, as shown in Figure 2-3. Consistency is an indicator of the degree of sealant resistance to flow. Therefore, consistency can be a measure of the sealants' installation practicality. CPT will provide a view of the sealants properties at moderate temperature. Higher penetration values indicate a softer sealant while lower values indicate a more viscous and stiff sealant. The rationale behind including the CPT in a testing program is to account for the difference in the resulted sealant texture or measure a modification benefit such as adding crumb rubber; in case of the SPT, test results may show inconsistencies. In addition, some studies showed interest in investigating whether there is a significant difference or correlation between SPT and CPT.

Regarding past studies addressing CPT, a one year performance evaluation by David E. Erickson compared between four different types of sealants based on performance in an area in eastern Washington. These sealants were CRF, Flex-A-Fill, Roadsaver 221, and a sand slurry mixture designed by Washington State Department of Transportation (WSDOT). Different cracks were categorized based on size. Out of the four sealants, the best sealant was the Roadsaver 221 manufactured by Crafco, which used emulsified asphalt cement. The Roadsaver 221 was the least to de-bond and split. Regarding the ASTM specification, the Roadsaver CPT value was 110, which is over the maximum ASTM CPT limit of 90. Therefore, revision of the penetration requirements was recommended since it seems to be beneficial to have higher values for areas that experience extreme temperature cycles [13].

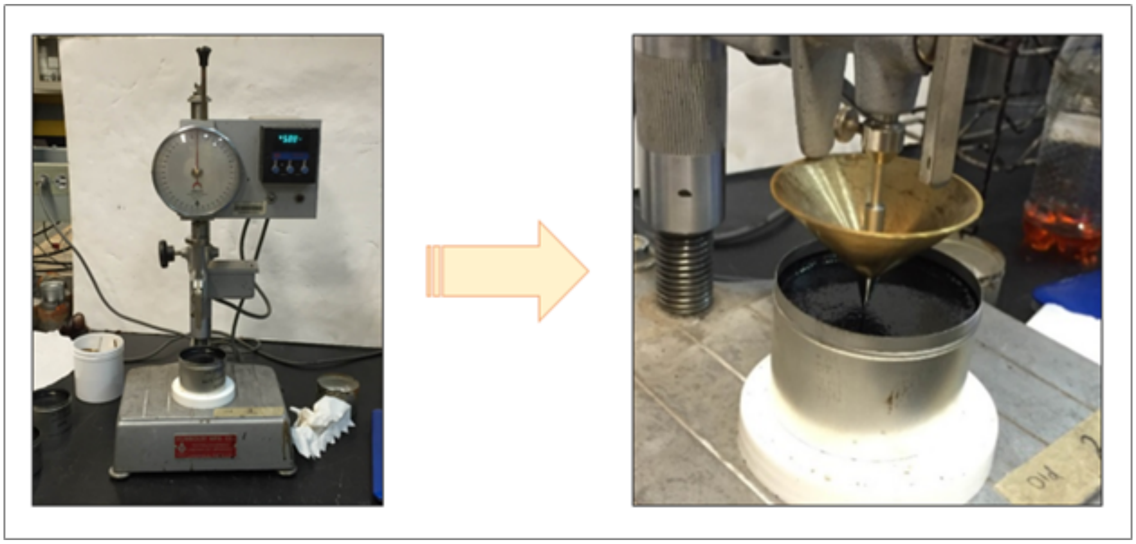

Figure 2-3: Penetrometer Device with a Cone Tool Attached to it

2.5.4 Resilience Test (D5329)

This test provides an insight on the elastic and strength property of the sealant in which it measures the rebound of the ball needle after applying specific force for a specific time (Figure 2-4). It is important to characterize the elasticity of a sealant because throughout the different seasons the sealant expand and shrink due to temperature differential. Therefore, it is important for the sealant to counter the stress and strain forces efficiently without showing any deficiencies. According the ASTM 6690, there is only a minimum value of 60% for Types 2 through 4 and no limit for Type 1. Up to this point, there is not an upper limit for the resilience value for sealant of any type. The choice is seen subjective and based on past experience.

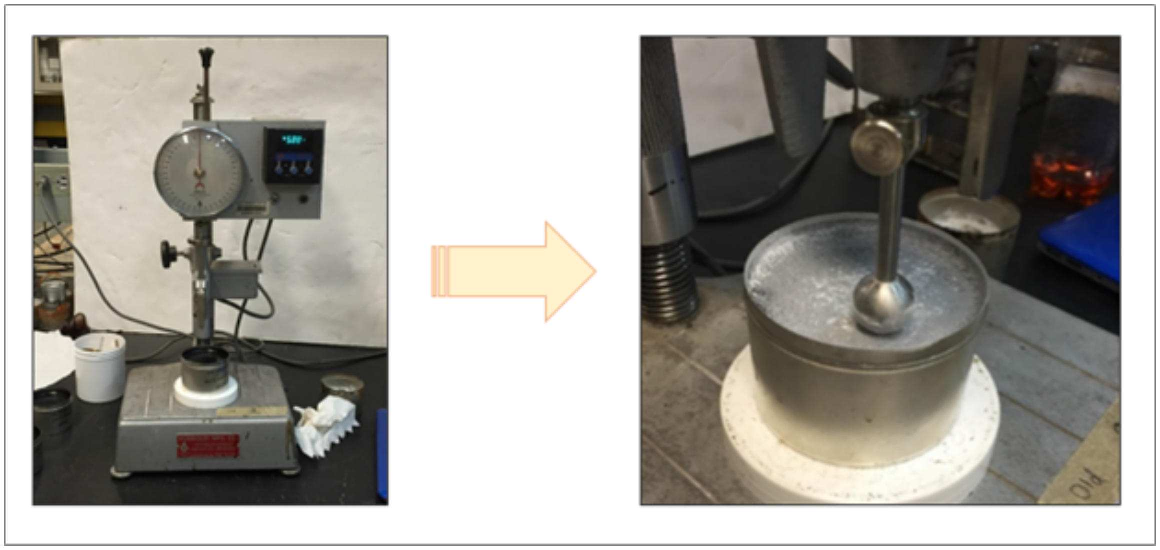

Figure 2-4: Penetrometer Device with a Recovery Ball Tool Attached to it

2.5.5 Softening Point Test (D36)

Softening Point test, also called Ring and Ball test is considered one of the ASTM governing tests for sealants focusing on the climate parameters. The significance of conducting the softening point test is to identify the temperature where the sealant alters its behavior from viscous to softer and less viscous. The higher the softening point temperature the less sensitive the sealant will be towards temperature. This test will indicate the tendency of the sealant to flow in or out of the crack at any given temperature. Therefore, this test sheds light on the high temperature properties of the crack sealant. In addition, it provides information about the likelihood of sealant tracking or settling when the sealant temperature is at its peak after application. According to D6690, the minimum softening point temperature for all sealant classification types is 176°F (Figure 2-5). The specification was left without a maximum temperature because the higher the softening point temperature the less temperature reactive will it be. On the other hand, industry practices show that a trade off occurs in higher manufacturing costs and crucial properties such as viscosity.

Regarding other studies about softening point temperature effect, a task group from Caltrans developed a crack sealing standard special provision in 2009 to modify the minimum required values. The proposal was to raise the minimum temperature for hot climates regions from 176°F to 208°F to better reflect the newer types of sealants used [14]. As of the latest revised standard specification dated in 2015, Caltrans still require sealants to comply with the ASTM D6690 without any test values modifications [15].

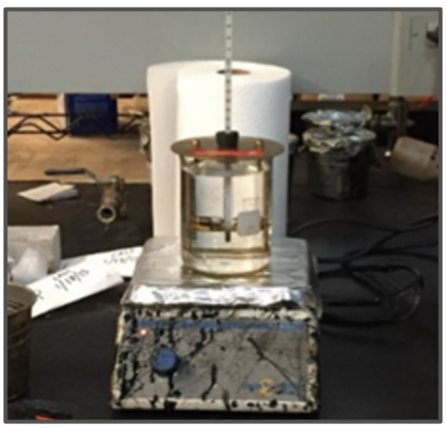

Figure 2-5: Softening Point Becker on a Hot plate

2.5.6 Brookfield Viscometer Test (D4402)

This test is an ASTM standard for all bituminous materials to measure the viscosity at elevated temperatures (Figure 2-6) . The goal behind the test is to measure the viscosity susceptibility to temperature for binder/sealant design and construction purposes. According to ASTM 6690 and 5329, the Brookfield Viscometer Test is not a parameter in measuring a sealant performance since many of the sealants contain additives that will oppose the homogeneous and newtonian assumptions required to run this test. Similar to the SPT, this assumption could be argued since past research have shown benefits from conducting this test on sealants in understanding the behavior of the sealants at various temperatures by creating the temperature/viscosity susceptibility graphs.

Figure 2-6: Brookfield Device placing a spindle in the tube heat chamber

2.5.7 Dynamic Shear Rheometer Test (D7175)

The Dynamic Shear Rheometer (DSR) test provides information about the flow and deformation properties by measuring the stiffness and relaxation (Figure 2-7) . The test mimics the effect of various traffic levels and maximum temperatures on the asphalt binder. DSR is mostly used to evaluate asphalt binders and not sealants because the ASTM procedure is limited to any material containing particles with a maximum dimensions of 250 nanometer. On the other hand, benefits might be gained in conducting the DSR test in measuring the effect of rubber on stiffness from the complex modulus and phase angle developments. Regarding previous studies showing the effect of crumb rubber in binders using DSR, a study conducted in 2012 by Nuha Mashaan and Mohamed

Karim from the University of Malaya showed that crumb rubber content and blending temperature have significant effect on modified binders properties. On the other hand, blending time showed an insignificant effect [17].

Figure 2-7: Dynamic Shear Rheometer Device

2.6 Crumb Rubber

According to the Arizona Department of Transportation (ADOT) Standard Specifications for Road and Bridge Construction, the crumb rubber used for roadway materials should be free of wire and any contaminating material, with a specific weight of 1.15 +/- 0.05. Additionally, the crumb rubber source should be derived from tire materials from automobiles and trucks owned and operated in the United State [16]. Several other states allow for the use of other sources of rubber, but since this study is addressing the Phoenix area needs, the ADOT standard will be followed.

Regarding the rubber gradation, there are two main types of gradations (A and B) used in all asphalt pavement applications. Type B crumb rubber is considered finer than Type A based on sieve gradation. Table 2-1 shows the gradation of Type B crumb rubber.

The mid path of Type B gradation is commonly used for sealant rubber doses since its finer rubber and faster to melt and react with the sealant during mixing. Furthermore, industry practices have noticed that finer crumb rubber gradation is resulting in better adhesive capabilities [18].

Table 2-1: Type B Crumb Rubber Gradation

Sieve Size (Mesh)	Sieve Size (mm)	Type B Percent Passing
No. 10	2	100
No. 16	1.19	65-100
No. 30	0.595	20-100
No. 50	0.297	0-45
No. 200	0.074	0-5

2.7 Current Test Limits

In order to differentiate between various sealant material properties a set of test limits need to be placed. These limits also serve as a quality control check for desired properties. There are three main sources of limits that can be used as a base; these are from ASTM, ADOT, and the manufacturer's. One sealant in particular referred to as Sealant PF is one of interest and was used in this study.

Regarding ASTM tests limits, D6690 contains the acceptable limits for some of the tests conducted in this study. The ASTM D6690 limits are divided into four sealant categories based on climatic region. For the Phoenix area the sealants used are placed in the warm climate category, which is represented with Type 1 limits.

Table 2-2: Type 1 ASTM D6690 Limits

ASTM D6690	Type 1 Limits
Standard Penetration Test	-
Cone Penetration Test	90 Max.
Resilience Test	-
Softening Point Test	176 °F / 80 °C Min.
Brookfield Viscometer Test	-
Dynamic Shear Rheometer	-

According to the ADOT Standard Specification for Road and Bridge Construction, limits was set for rubberized sealant use. The ADOT specification contains tighter limits than the ASTM limits, again which is considered to be more customized for the Phoenix area [16].

Table 2-3: 2008 ADOT Rubberized Sealant Limits

ADOT	Type 1 Limits
Standard Penetration Test	10 to 25
Cone Penetration Test	-
Resilience Test	-
Softening Point Test	210 °F / 99 °C Min.
Brookfield Viscometer Test	7500 cp Max. at 400 °F
Dynamic Shear Rheometer	-

In addition to the previous limits, the manufacturer of Sealant PF provided a set of recommended limits based on their experience. These limits can be seen in Table 2-4.

Table 2-4: Sealant PF manufacturer recommended limits

Sealant PF	Limits
Standard Penetration Test	-
Cone Penetration Test	20 to 40
Resilience Test	30% Min.
Softening Point Test	210 °F / 99 °C Min.
Brookfield Viscometer Test	10000 cp Max. at 400 °F
Dynamic Shear Rheometer	-

2.8 Crack Sealing Construction Practices

In order to minimize any failure risks associated with crack sealant installation, the following step-by-step guideline will address the latest proper installation practices:

2.8.1 Crack Sealant Pre-Installation:

To maximize the benefits of any crack sealant implementation, an identification process must be established to determine whether or not applying a sealant is the optimum solution to prolong the service life of any pavement. There are two main causes of any surface cracks; structural deficiencies and functional deficiencies. Cracks caused by structural deficiencies such as fatigue cracking should not be treated with crack sealant as the main treatment since crack sealants serve a different goal. Their primary purpose is to block the infiltration of solids and liquids into lower layers of any pavement structure. As a result, sealing a crack with an efficient amount of sealant at a timely manner will help slow the overall deterioration rate caused by restricting vertical and horizontal movement (solids), and moisture damage (liquids).

On the other hand, cracks caused by functional deficiencies can be treated using crack sealants. Based on the available treatments options in the market, cracking sealant is considered one of the top desirable options. Several studies have shown the cost effectiveness of using crack sealant to prolong the service life of any pavement when constructed accurately [12]. Within all functional cracks there are two main subgroups, which are working cracks and non-working cracks. The difference between both subgroups is the amount of movement in the vertical and/or horizontal direction. Working cracks experience movement of 2.5mm or more while non-working cracks experience movements up to 2.5 mm [10]. The importance in differentiating between both subgroups is in whether to fill or seal the crack and sealant material selection for better field performance.

2.8.2 Crack Routing

One of the main failure modes experienced by many agencies causing premature failure when applying sealants is adhesive failure. It occurs as a result of improper installation causing weak bond between the sealant and the surrounding crack walls by the effect of temperature fluctuation and traffic loading. In order to address this issue, crack routing using either a diamond saw or rotary impact router is used to increase the surface area of the crack to allow for more sealant to be used for higher bonding area (Figure 2-8). Slightly different results can be achieved using either of the cutting equipment. For example, diamond saw tend to create smooth walls which increases the surface area while the rotary impact router is more maneuverable.

The crack cutting operation is done by creating an uninformed rectangular reservoir aligned as close as possible to the center of the crack without effecting the surrounding pavement. In fact, studies have shown that the success changes of a crack sealant operation can increase to 40% by cutting the crack prior to applying the sealant [13].

Figure 2-8: Typical Routing Equipment [10]

2.8.3 Crack Cleaning and Drying

After the completion of the cutting operation, it is crucial to clean the cuts to remove any dust and loose fragments caused by routing. Several methods can be used for crack cleaning such as automated air blasting and automated/manual wire brushing. Due to the desire to minimize the labor effort, air blasting is favored over wire brushing (Figure 2-9). For effective air blasting performance, a minimum air pressure should be 100 psi with air flow of 2.5 ft^3/s [10]. Crack cleaning should not be mixed up with crack drying. Based on the surrounding climate, hot air blasting is often used for cracks to simultaneously clean and warm up crack edges to enhance bonding associated with the crack edges. The heat lance in the hot air blaster should produce 2500 °F with a velocity of 1970 ft/s [10]. Meanwhile, extra caution should be taken since overheating can cause hardening of the asphalt binder and weakening of the crack edges.

Figure 2-9: Snapshot of Crack Cleaning Using Air blaster [6]

2.8.4 Sealant Preparation

One crucial aspect in the sealant installation process is following the manufacturer preparation guidelines to achieve the best sealant performance during and after installation. These guidelines range from the sealants' minimum placement temperature, recommended limits of the pavement temperature, prolong heating guidelines, and recommended moisture conditions. It is important to do so since not achieving these guidelines will most likely alter the sealant properties and introduce additional installation complications. For example, under heating the sealant may not allow the material to flow correctly in the crack and cause improper bonding. Additionally, applying the sealant in mild weather of spring or fall can be beneficial since the crack width will be moderate compared to its relative extremes in the summer or winter. There might be other guidelines that could be stated with the sealant product description. It is crucial to follow all of them.

2.8.5 Sealant Placement

Throughout the pavement management industry, there are five practiced configurations used to apply the sealant correctly based on the crack shape, crew equipment and experience. After numerous years of trial and error, several of the configurations are more favorable since they help enhancing the sealant performance. These configurations are as follows (Figure 2-10):

- Reservoir and Overband
- Shallow Reservoir and Overband
- Reservoir and Recessed
- Reservoir and Flush
- Reservoir and Flush (with Backer Rod)

As discussed previously, a reservoir is created in the crack routing process to create enough room for the sealant to be applied. A flush is when a sealant is applied starting from the bottom of the crack and following its shape until it reach either the reservoir or the pavement surface. An overband is when the sealant is applied above a reservoir and the surface surrounding the crack to increase the cohesive and adhesive bonding between the sealant within itself and the crack edges. As a result, a combination of “Reservoir and Overband” and “Reservoir and Flush” was often practiced by many agencies.

A serious disadvantage of overbands is pullout failure where the risk of the sealant peeling off with time when traffic overrun it is high. Therefore, overband is becoming a less desired practice compared to the other configurations. In addition, even sealants in reservoir were recessed slightly below the surface level to prevent plow and traffic damage. Additionally, in some cracks a foam backer rod is placed to block and control the shape of the above sealant. In order for the rod to perform well, the foam material should be non-absorptive, flexible, and compatible with the sealant material. Typically, the backer rod is cylindrically shaped with a diameter 25% larger than the width of the crack [11].

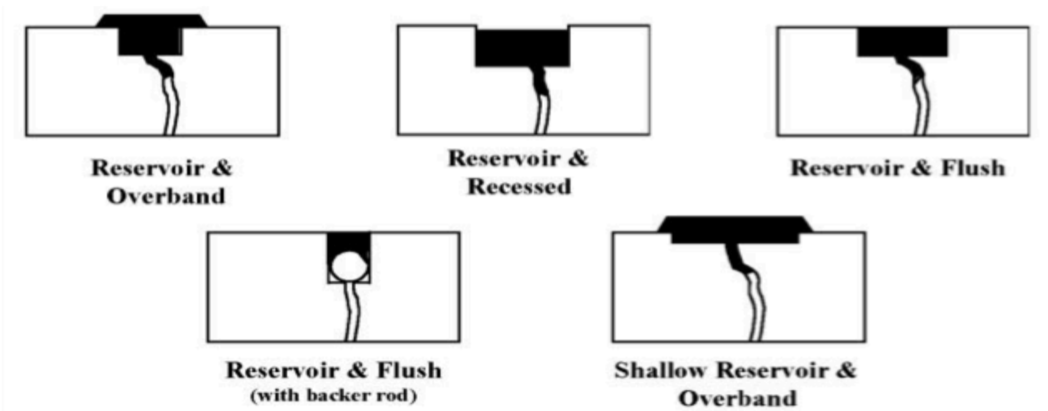

Figure 2-10: Standard Crack Sealing Configurations [8]

Therefore, the best-practiced configuration will mainly depend on the size of the crack. For new small cracks, a new proposed combination of Flush and Recessed should be the optimum method for better performance. For well-developed cracks, Flush and Recessed should be the optimum method for better performance. A typical reservoir shape widths are 12.5 - 40mm, and 12.5 - 20 mm deep. With a backer rod, the previous measurement will be slightly increased to account for the rod size.

Extra care should be taken when applying the sealant. The sealing operation should start from the bottom of the crack moving upwards to avoid leaving any entrapped air. The operation should be conducted in a continuous motion at a steady state. Continuous periodic temperature inspection should be conducted to maintain a low margin of error.

2.8.6 Blotting

Since it is difficult to keep traffic off freshly sealed cracks a technique called blotting is used extensively. Blotting is a technique used to preserve the sealed crack during the curing process by applying a material over the sealed crack to protect it from pullout under traffic (Figure 2-11). Examples of blotting materials range are limestone, talcum powder, lime sand, and clean sand.

Figure 2-11: Blotting By Pouring Clean Sand Over Sealed Crack [10]

2.9 Additional Studies

A study in 2014 by Carter et al. evaluated the thermoelastic properties of bituminous crack sealing of asphalt pavements. Findings of that study show that the overband configurations are considered optimum based on laboratory testing using the Thermal Stress Restrained Specimen Test (TSRST). In addition, field studies showed that traffic have a significant effect on the performance of the sealed surface [19].

A report in 2007 by Al-Qadi from the Illinois Center for Transportation showed that the standard Bending Beam Rheometer (BBR) test developed during the Strategic Highway Research Program (SHRP) is inappropriate to be used for crack sealant due to most sealants exceeding the deflection limits within seconds even at low temperatures. Therefore, the study introduced several modifications to the BBR test such as doubling the thickness of the tested specimen and referred to it as Crack Sealant Bending Beam Rheometer (CSBBR), which overcame excessive deflection during testing [20].

In addition, another report by Al-Qadi from the Illinois Center for Transportation showed the potential of introducing a reliable standard test for hot applied sealant using the Brookfield Viscometer Test. The report focused on the precision and bias of the test by conducting the test in seven laboratories. Results showed that for the polymer and crumb rubber modified sealants, the coefficient of variation within and between laboratories was between 2% and 6%, which is acceptable by ASTM standards [21].

Chapter 3 Crack Sealant Use and Performance Survey

3.1 Introduction

In the interest of collecting customized information regarding hot-applied crack sealants failure modes, a survey was distributed to number of asphalt pavement maintenance and preservation industry around the United States, but with the majority responding being from the southwest. The purpose was to compile information about crack sealants general performance and failure type from agency users' point of view. The survey questions were as follows:

1. Type of agency responding?
2. The responding geographic location?
3. How important is crack sealing within the agency's pavement preservation program?
4. Does your agency route the cracks before applying the sealant?
5. What is the average service life of crack sealants in years?
6. Rank the following crack sealant failure modes in terms of occurrence:
    a) Adhesive Failure (sealant separating from the walls)
    b) Cohesive Failure (failure within the sealant)
    c) Settlement Failure
    d) Pullout Failure
    e) Spalls or Secondary Cracking

Forty two people/agencies responded to the survey. A scoring rank approach was used from 1 to 5 describing the least important/occurrence and most important/occurrence respectively. The results of the survey can be seen graphically below in addition to a screenshot of the survey in Appendix A.

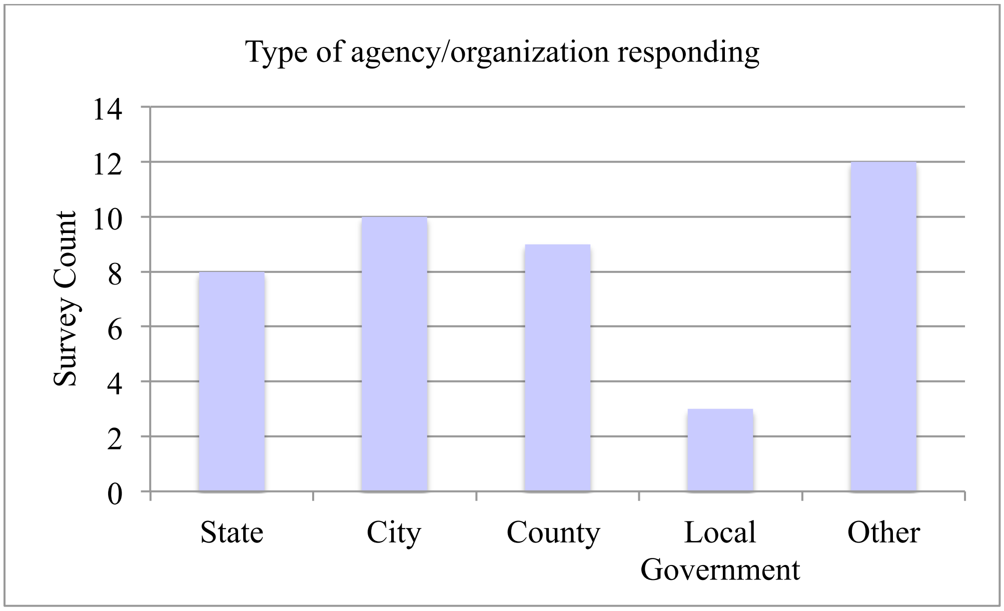

Figure 3-1 Graphical Representation of First Survey Question Answers

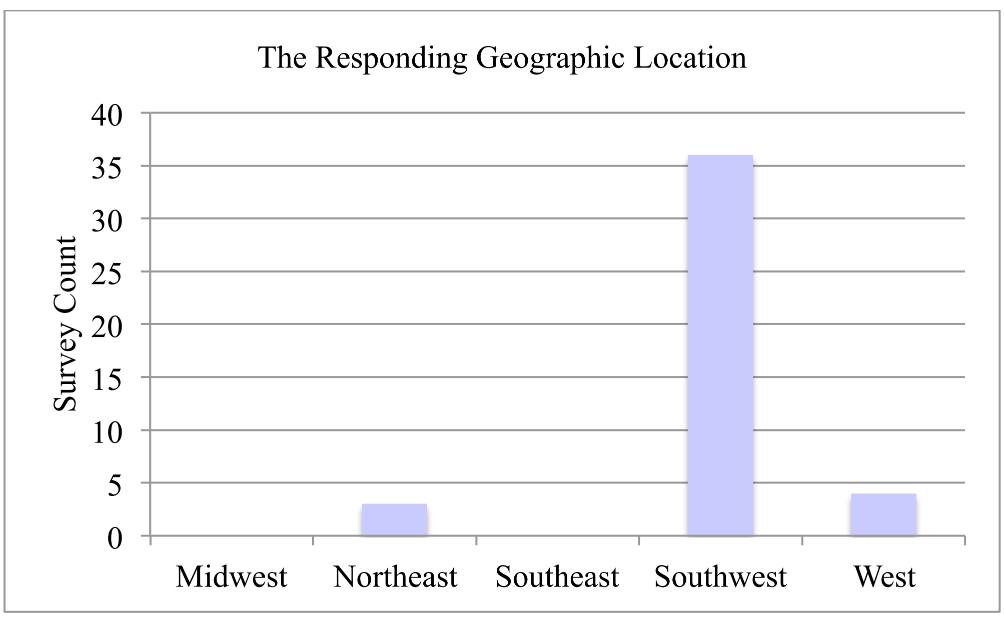

Figure 3-2 Graphical Representation of Second Survey Question Answers

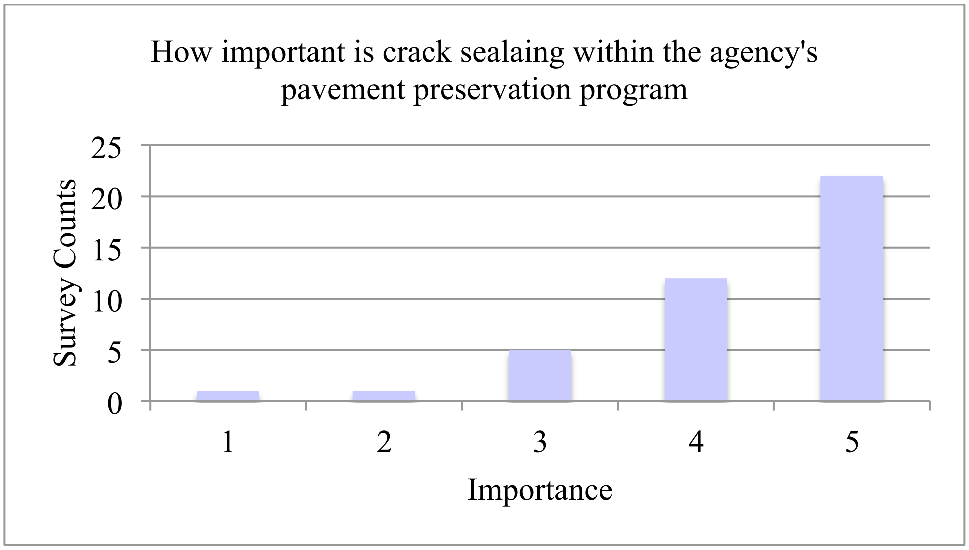

Figure 3-3: Graphical Representation of Third Survey Question Answers

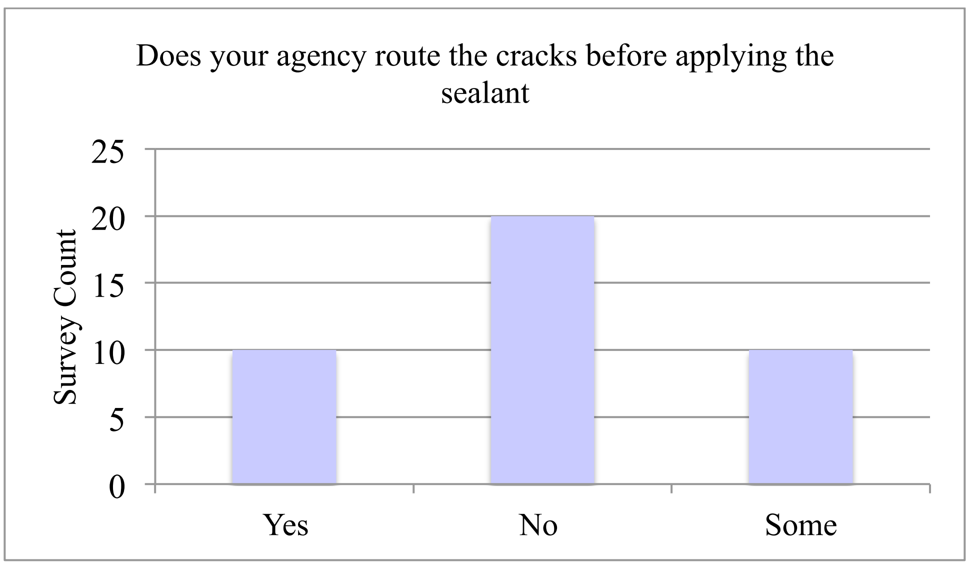

Figure 3-4: Graphical Representation of Fourth Survey Question Answers

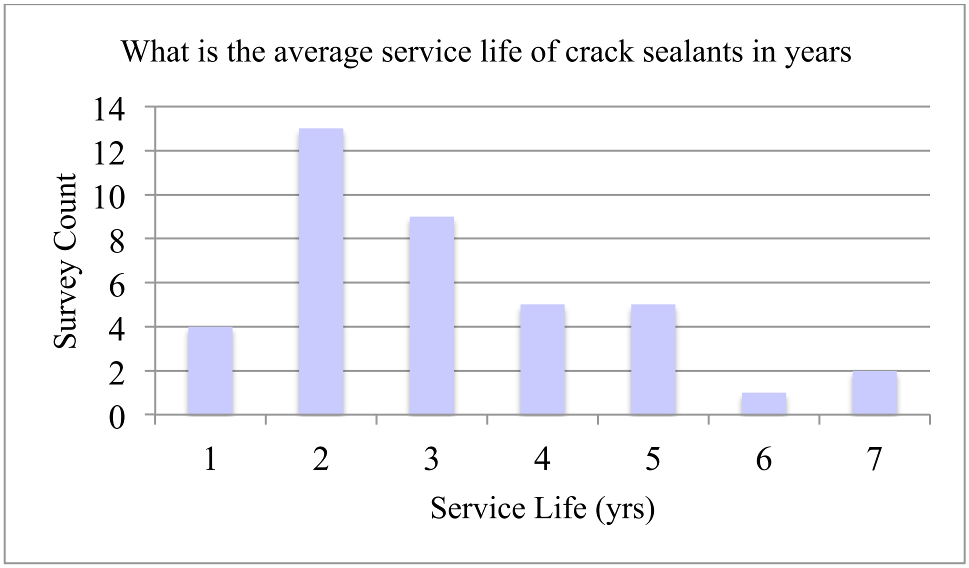

Figure 3-5: Graphical Representation of Fifth Survey Question Answers

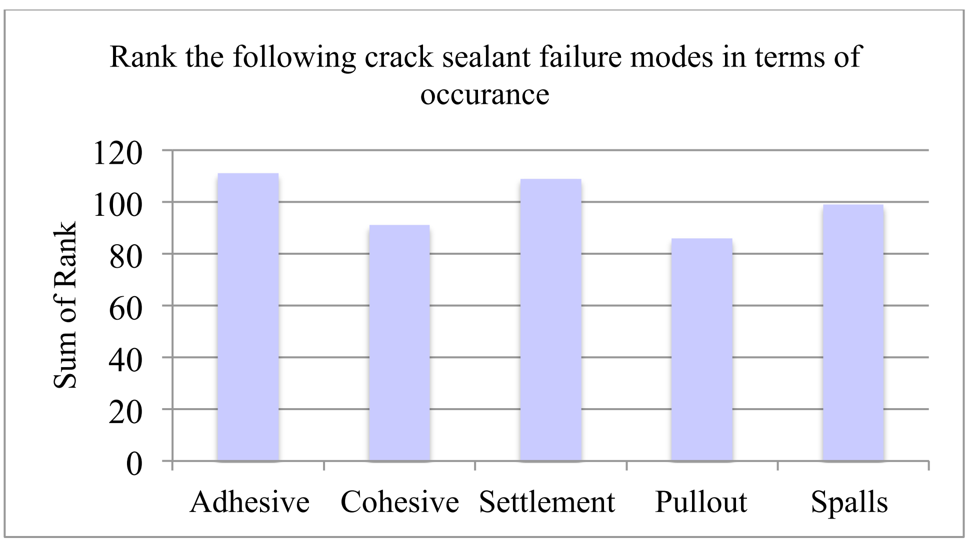

Figure 3-6: Graphical Representation of Sixth Survey Question Answers

As can be seen from the previous results and figures, the types of agencies responded to the survey mostly ranged between local, county, and state agencies located in the southwest region of the United States. Results show agencies considering crack sealing very important as a preventative treatment due to similar reasons that were discussed in the literature review section. As an insight to the construction practices of various agencies, results show that the majority of surveyed agencies do not route cracks before applying a sealant, which drastically affect the performance of sealant negatively. Additional information about the benefits of routing cracks and other construction practices can be seen in section 2.8.2.

Regarding the service life of sealants, survey data agrees with the claim that most sealant fail after one to three years; while recording the highest count in the survey in the second year. In addition, survey data show that all failure modes are recorded at a similar rate without any significant distinction of one type over the other. Therefore, balancing between all failure modes when modifying a sealant will be crucial to avoid any unintended consequences. For this study the focus will be on addressing the cohesive and settlement failure modes through an experimental program that will be discussed in details in the following chapter. Note, an attempt to correlate the estimated service life of a sealant was made to the type of agency responding to identify whether the current properties limits have an impact on the sealant performance. The results of this correlation was insignificant showing no sign between both questions.

Chapter 4 Experimental Program and Test Results

4.1 Experimental Method

For this study, the test selection process was through identifying ASTM standard test that could be related to sealant properties possibly indicative of failure modes discussed previously. The ASTM tests selection addressed mainly cohesive and settlement limitation in addition to pumping and handling limits. Other sealant failure modes were addressed through construction practices discussed in the preparation/installation section in the literature review. Since the study revolves around crack sealants in the Phoenix area, the focus was on moderate and high temperature tests. Regarding failure modes that occur due to poor construction practices, the preparation and installation guide was used as a reference. Below, Table 4-1 and Table 4-2 show a summary of the sealants failure modes with the chosen ASTM test to address them. Note that, as discussed previously, not all failure modes were addressed in this study.

Table 4-1: Sealants Failure Modes with Chosen ASTM Tests

Failure Mode	**Chosen ASTM Test/Focus**
Adhesive	Preparation/Installation Practices
Cohesive	Cone Penetration Test Brookfield Rheometer Test Dynamic Shear Rheometer Resilience Test
Settlement	Softening Point Brookfield Rheometer Test
Pullout	Preparation/Installation Practices
Spalls or Secondary Cracking	Preparation/Installation Practices

Table 4-2: Sealant Installation Practicality and Chosen ASTM Tests

Installation Practicality	Chosen ASTM Test/Focus
Pumping Difficulty	Brookfield Rheometer Test

Additionally, all tests complied with the specimen conditioning and heating standards specified in Practice D5167 discussed in section 2.5.1. Since the performance of the sealant is significantly governed by many factors such as construction practices and not only the sealant properties themselves, many studies have tried modifying these tests to account for such changes or factors. However in this study, the tests followed the ASTM standards without any changes in order to make the results comparable to possible future follow up testing and standards correlations.

4.2 Laboratory Tests

The experimental plan was to conduct three sets of tests on a neat PG64-22 binder and Sealant PF at unaged and aged conditions. The aged condition followed the Rolling Thin Film Oven (RTFO) process. The two products were also modified by the addition of two crumb rubber dosages of 5% and 10% for the PG64-22 binder, and 2.5% and 5% for the Sealant PF. As described previously, the tests were as follows:

- Standard Penetration Test (SPT)
- Cone Penetration Test (CPT)
- Resilience Test
- Brookfield Viscometer Test
- Dynamic Shear Rheometer (DSR)

Due to the amount of material required and time needed to obtain aged samples, SPT, CPT, and the resilience test were only conducted for the unaged samples. The penetration and resilience tests would provide more information about the samples, but would not serve as a comparison between aged and unaged conditions. The temperature viscosity relationship were still analyzed for both aging conditions using the softening point and rotational viscometer test results. Similarly, DSR tests were conducted for both aging conditions.

4.3 Crumb Rubber

The mid-range of ADOT's Type B crumb rubber gradation was used for the addition of rubber dosages. Type B was chosen because finer rubber is faster to blend and react with the sealant during mixing. The methodology of adding the crumb rubber involved three cycles of 15 minutes of mixing and rest periods. Each cycle consisted of 5 minutes of continuous mixing on a hot plate following 10 minutes rest period in an oven at 135°C for the binder and 185°C for the sealant. The mixing shaft/blade rotation speed was held constant at 600 RPM. Regarding the rubber dosage, all percentages were calculated based on final material weight. A sample calculation can be seen below.

X = Binder/Sealant Weight

Y = Crumb Rubber Weight

T = Total Weight

P = Crumb Rubber Percentage

$$T = X + Y$$

$$T = X + P*T$$

$$T = X/(1 - P)$$

4.4 Experiments Schedule Summary

Experiment Phases:

1. Neat Binder (Sealant PF/ PG64-22 Binder) (Control)
2. Rubber Dosage #1: (Sealant PF) (2.5% Rubber)
3. Rubber Dosage #2: (Sealant PF/ PG64-22 Binder) (5% Rubber)
4. Rubber Dosage #2: (PG64-22 Binder) (10% Rubber)

For each previous experiment phase the following experiment plan was conducted:

a. Unaged Testing

i. Standard Penetration Test

ii. Cone Penetration Test

iii. Resilience Test

iv. Softening Point Test

v. Brookfield Viscometer

vi. DSR Testing

b. RTFO Testing

i. Softening Point Test

ii. Brookfield Viscometer

iii. DSR Testing

Figure 4-1 shows a flow chart of the experimental program.

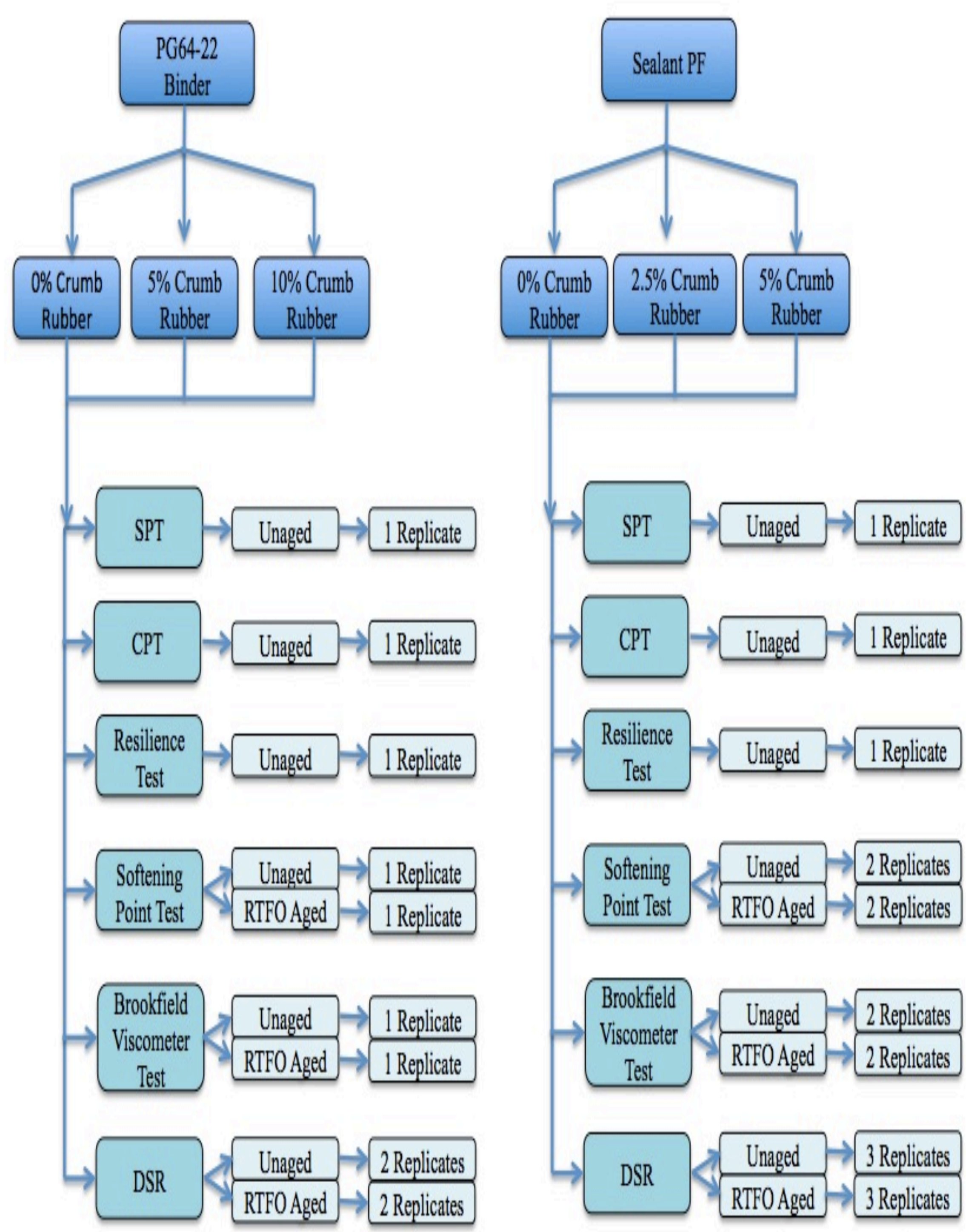

Figure 4-1: Flow Chart of the Experiment Summary Schedule

4.5 Test Results

The following subsections will present the test results for all materials and each test.

4.5.1 Standard Penetration Test

Five readings were obtained for each material and rubber content. As mentioned earlier, due to the extensive amount of material needed for RTFO aging, testing was only done for the unaged condition. Table 4-3 shows the SPT test results. The penetration values decreased with the increase of rubber content for both tested materials. The coefficient of variation (CV) percentages were within the same range, and they were below 5%. This shows that the tests were had high degree of repeatability.

Table 4-3: Standard Penetration Test Results Data

		Penetration Readings (0.1mm)							
	Rubber Content	1	2	3	4	5	**AVG**	**SD**	**CV (%)**
Unaged PG64-22 Binder	0%	55	57	60	60	56	**58**	**2.30**	**4.00**
	5%	50	50	51	54	52	**51**	**1.67**	**3.26**
	10%	43	45	44.5	46	44	**45**	**1.12**	**2.51**
Unaged Sealant PF	0%	38	39	38	40	38	**39**	**0.89**	**2.32**
	2.5%	36	35	33	36	34	**35**	**1.30**	**3.75**
	5%	31	32	30	33	30	**31**	**1.30**	**4.18**

4.5.2 Cone Penetration Test

Five readings were conducted for each material and rubber content. The test results are shown in Table 3-3. Similar to the SPT, penetration values decreased with the increase of rubber content in both tested materials. The CV percentages were within the same range below 5%. The results are considered to be precise and repeatable.

Table 4-4: Cone Penetration Test Results Data

	Rubber Content	Penetration Readings (0.1mm) 1	2	3	4	5	AVG	SD	CV (%)
Unaged PG64-22 Binder	0%	61	64	65	65	64	**64**	**1.64**	**2.58**
	5%	54	54	54	55	54	**54**	**0.45**	**0.83**
	10%	51	49	46	45	46	**47**	**2.51**	**5.30**
Unaged Sealant PF	0%	40	41	39	42	41	**41**	**1.14**	**2.81**
	2.5%	28	28	30	28	31	**29**	**1.41**	**4.88**
	5%	25	24	23	24	26	**24**	**1.14**	**4.67**

4.5.3 Resilience Test

Similar to the SPT and CPT tests, four readings were conducted for each material and rubber content. The results are shown in Table 4-5. Due to the rubber elastic properties, the results showed an increase in resilience values with the increase in rubber content. The CV percentages were mostly within the same range below 10% besides the PG64-22 5% rubber content with a CV of 18%. The reason for the relatively higher CV percentage is due to the low value / range recorded, in addition to the low number of readings. Overall, the data in Table 4-5 are considered to be satisfactory.

Table 4-5: Resilience Test Results Data

	Rubber Content	Resilience Readings (%) 1	2	3	4	AVG	SD	CV (%)
Unaged PG64-22 Binder	0%	0	0	0	0	**0**	**0**	**0**
	5%	2	3	3	3	**3**	**0.50**	**18.18**
	10%	6	6	6.5	7	**6**	**0.48**	**7.51**
Unaged Sealant PF	0%	34	35	32	33	**34**	**1.29**	**3.85**
	2.5%	40	39	39	39	**39**	**0.50**	**1.27**
	5%	46	43	43	43	**44**	**1.50**	**3.43**

4.5.4 Softening Point Test

One replicate was conducted for the PG64-22 binder; whereas, two replicates were conducted for the Sealant PF. The test results are shown in Table 4-6. According to ASTM standard, valid softening point temperatures can differ a maximum of one degree between the left and right ring. Therefore, all the presented data in Table 4-6 meet that criteria and is considered valid. The results also showed that softening point temperatures increased with the increase in rubber content. The CV percentages were within the same range below 2%. These test results are considered precise and repeatable.

Table 4-6: Softening Point Test Result Data

		Replicates (°C)						
	Sample	Left Ring	Right Ring	Left Ring	Right Ring	**AVG**	**SD**	**CV (%)**
PG 64-22 Binder	0% Unaged	47	48	-	-	**47.5**	**0.71**	**1.49**
	0% RTFO Aged	55	56	-	-	**55.5**	**0.71**	**1.27**
	5% Unaged	49	49	-	-	**49**	**0**	**0**
	5% RTFO Aged	57	57	-	-	**57**	**0**	**0**
	10% Unaged	50	50	-	-	**50**	**0**	**0**
	10% RTFO Aged	59	60	-	-	**59.5**	**0.71**	**1.19**
Sealant PF	0% Unaged	82	82	83	83	**82.5**	**0.58**	**0.70**
	0% RTFO Aged	89	90	90	90	**89.75**	**0.50**	**0.56**
	2.5% Unaged	82	82	84	84	**83**	**1.16**	**1.39**
	2.5% RTFO Aged	92.5	93	93	93	**92.875**	**0.25**	**0.27**
	5% Unaged	90	90	90	90	**90**	**0**	**0**
	5% RTFO Aged	94	94	93	93	**93.5**	**0.58**	**0.62**

4.5.5 Brookfield Viscometer Test

The Brookfield viscosity test results for the PG64-22 binder are shown in Tables 4-7 and 4-8. The results show that an increase in the rubber content causes an increase in viscosity at every tested temperature. The CV percentages were within the same range below 5% for both aging conditions. Note that in Table4-7 the binders with rubber contents had slightly higher standard deviation and CV percentages at the lower test temperatures, most likely due to the presence of the crumb rubble particles. Overall, the test results are considered precise and repeatable.

Table 4-7: Brookfield Viscometer Test Results Data for Unaged PG64-22 Binder

		0% Readings (cP)					
PG64-22 Binder Unaged	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	275	459.3	457.4	459.3	**459**	**1.10**	**0.24**
	300	251.2	251.2	249.3	**251**	**1.10**	**0.44**
	325	145.3	144.1	142.9	**144**	**1.20**	**0.83**
	350	89	89	88.3	**89**	**0.40**	**0.46**
	375	56.2	58.2	58.9	**58**	**1.40**	**2.43**
		5% Readings (cP)					
	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	275	568.4	524.6	519.1	**537**	**27.02**	**5.03**
	300	288.7	286.8	283.1	**286**	**2.85**	**1.00**
	325	159.3	159.3	158	**159**	**0.75**	**0.47**
	350	99.4	98.4	97.5	**98**	**0.95**	**0.97**
	375	60.6	60.9	60.6	**61**	**0.17**	**0.29**
		10% Readings (cP)					
	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	275	585.8	574.1	569.4	**576**	**8.45**	**1.47**
	300	314	309.3	304.6	**309**	**4.70**	**1.52**
	325	179.3	179.3	179.3	**179**	**0**	**0**
	350	117.2	117.2	116.2	**117**	**0.58**	**0.49**
	375	82.3	81.7	78.3	**81**	**2.16**	**2.67**

Table 4-8: Brookfield Viscometer Test Results Data for RTFO Aged PG64-22 Binder

		0% Readings (cP)					
PG64-22 Binder RTFO Aged	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	275	431.2	428.8	433.5	**431**	**2.35**	**0.55**
	300	184.3	181.2	182.8	**183**	**1.55**	**0.850**
	325	92.8	92.8	92.8	**93**	**0**	**0**
	350	52.4	51.3	51.8	**52**	**0.55**	**1.06**
	375	18.7	18.7	19.7	**19**	**0.58**	**3.03**
		5% Readings (cP)					
	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	275	695.6	693.6	691.3	**694**	**2.15**	**0.31**
	300	344.5	346.8	342.1	**344**	**2.35**	**0.68**
	325	195.3	196.8	198.4	**197**	**1.55**	**0.79**
	350	110.4	111.4	115.6	**112**	**2.76**	**2.45**
	375	70.3	69.6	71	**70**	**0.70**	**1.00**
		10% Readings (cP)					
	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	275	1250	1243	1237	**1243**	**6.51**	**0.52**
	300	581.1	577.4	573.6	**577**	**3.75**	**0.65**
	325	321.4	321.4	318.7	**321**	**1.56**	**0.49**
	350	192.1	190.6	189	**191**	**1.55**	**0.81**
	375	121.2	120	120	**120**	**0.69**	**0.58**

Similar to PG64-22 binder results, the test results presented in Tables 4-9 and 4-10 for the Sealant PF show an increase in viscosity with an increase in rubber. Note that the initial testing temperature was also elevated from 275°F to 325°F to account for the Sealant PF stiffness that causes measurements issues at lower temperature. Based on the low CV percentages in Table 4-9 and Table 4-10, the data are also considered repeatable and precise.

Table 4-9: Brookfield Viscometer Test Results Data for Unaged Sealant PF

		0% Readings (cP) Replicate 1					
Sealant PF Unaged	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	325	8951	9232	9376	**9186**	**216.15**	**2.35**
	350	5749	5718	5811	**5759**	**47.35**	**0.82**
	375	4068	4012	4105	**4062**	**46.82**	**1.15**
		0% Readings (cP) Replicate 2					
	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	325	8623	8295	8155	**8358**	**240.21**	**2.87**
	350	5952	5764	5811	**5842**	**97.84**	**1.67**
	375	3960	3890	3913	**3921**	**35.68**	**0.91**
		2.5% Readings (cP) Replicate 1					
	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	325	12935	12419	12888	**12747**	**285.31**	**2.24**
	350	9654	8670	9420	**9248**	**514.05**	**5.56**
	375	6499	6217	6311	**6342**	**143.59**	**2.26**
		2.5% Readings (cP) Replicate 2					
	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	325	13310	13731	13050	**13364**	**343.66**	**2.57**
	350	10545	10451	9748	**10248**	**435.56**	**4.25**
	375	6874	7061	6745	**6893**	**158.88**	**2.31**
		5% Readings (cP) Replicate 1					
	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	325	26619	26807	26619	**26682**	**108.54**	**0.41**
	350	11762	11810	12138	**11903**	**204.64**	**1.72**
	375	8764	8998	9082	**8948**	**164.79**	**1.84**
		5% Readings (cP) Replicate 2					
	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	325	21558	22214	22589	**22120**	**521.84**	**2.36**
	350	16495	17059	16955	**16836**	**300.14**	**1.78**
	375	13122	12841	13310	**13091**	**236.03**	**1.80**

Table 4-10: Brookfield Viscometer Test Results Data for RTFO Aged Sealant PF

Sealant PF RTFO Aged		0% Readings (cP) Replicate 1					
	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	325	11623	10779	11341	**11248**	**429.67**	**3.82**
	350	6030	6435	6217	**6227**	**202.70**	**3.26**
	375	4054	4077	4101	**4077**	**23.50**	**0.58**
		0% Readings (cP) Replicate 2					
	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	325	10170	10732	10685	**10529**	**311.79**	**2.96**
	350	6905	6842	7092	**6946**	**130.02**	**1.87**
	375	4851	4874	4827	**4851**	**23.50**	**0.48**
		2.5% Readings (cP) Replicate 1					
	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	325	22308	20808	21370	**21495**	**757.81**	**3.53**
	350	11060	11951	11623	**11545**	**450.64**	**3.90**
	375	8951	8623	9042	**8872**	**220.39**	**2.48**
		2.5% Readings (cP) Replicate 2					
	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	325	21464	20621	20714	**20933**	**462.20**	**2.21**
	350	11201	10732	10826	**10920**	**248.13**	**2.27**
	375	8295	9045	8342	**8561**	**420.10**	**4.91**
		5% Readings (cP) Replicate 1					
	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	325	31306	31184	30556	**31015**	**402.44**	**1.30**
	350	16778	16403	16540	**16574**	**189.75**	**1.14**
	375	13497	13403	13122	**13341**	**195.12**	**1.46**
		5% Readings (cP) Replicate 2					
	Temp, ºF	1	2	3	**AVG**	**SD**	**CV (%)**
	325	34617	34861	34680	**34719**	**126.67**	**0.36**
	350	22542	22870	22401	**22604**	**240.63**	**1.06**
	375	15094	15278	14997	**15123**	**142.73**	**0.94**

4.5.6 Dynamic Shear Rheometer Test

Two replicates were conducted for both the PG64-22 binder and Sealant PF at unaged and RTFO aged conditions. The test results are shown in Tables 4-11 and 4-12. Regarding the RTFO aged PG64-22 10% rubber content sample, several trials were conducted for the second replicate, but the samples kept on failing after running the test. Therefore, no results were reported in Table 4-11 for the second replicate.

The results in Table 4-11 show that an increase in the rubber content causes an increase in complex modulus at every tested temperature. On the other hand, the phase angle decrease with the increase in rubber content. As one would expect, the complex modulus CV percentages were higher and increased with an increase in rubber content. The trend for the phase angle CV percentages also showed an increasing trend with the increase in rubber content, but the percentages were much lower.

Three replicates were successfully conducted for all unaged and RTFO aged Sealant PF samples as shown in Table 4-12. A third replicate was added due to the high variability found between the first two replicates. The test results in Table 4-12 show that an increase in the rubber content causes decease in complex modulus at every tested temperature at the unaged condition. RTFO aged condition results showed the opposite and followed the trends recorded in Table 4-11. Regarding the phase angles, similar to Table 4-11 results, an increase in rubber content caused a decrease in phase angle for both aging conditions.

Based on the CV percentages in Table 4-12, the complex modulus data variability is relatively very high compared to other conducted tests reaching up to 83% indicating issues with the data. The high variability might be caused by the equipment limitation of testing a material such as a sealant with a combination of unknown additives and crumb rubber. On the other hand, phase angle CV percentages showed to be within the same range below 10%. Therefore, any conclusions on Sealant PF based solely on the DSR data should be carefully evaluated.

Table 4-11: Dynamic Shear Rheometer Results Data for PG64-22 Binder

	Sample	Temp (°C)	Replicate 1		Replicate 2		AVG		SD		CV (%)	
			G* (Pa)	δ (degree)	G* (Pa)	δ (degree)	G* (Pa)	δ (degree)	G*	δ	G*	δ
PG64-22 Binder	0% Unaged	58	2587	85.4	3030	83.8	**2808**	**84.6**	**313**	**1.1**	**11.2**	**1.3**
		64	1173	86.8	1296	85.8	**1235**	**86.3**	**87**	**0.7**	**7.0**	**0.8**
		70	556	88.3	603	87.4	**580**	**87.9**	**33**	**0.6**	**5.7**	**0.7**
	0% RTFO AGED	58	7951	80.0	6962	78.8	**7457**	**79.4**	**699**	**0.8**	**9.4**	**1.1**
		64	3408	82.8	2883	81.5	**3146**	**82.2**	**371**	**0.9**	**11.8**	**1.1**
		70	1551	85.3	1235	84.2	**1393**	**84.8**	**223**	**0.8**	**16.0**	**0.9**
		76	723	86.7	554	86.2	**638**	**86.5**	**120**	**0.4**	**18.8**	**0.4**
	5% Unaged	58	2611	84.8	3587	82.8	**3099**	**83.8**	**690**	**1.4**	**22.3**	**1.7**
		64	1311	86.5	1487	85.3	**1399**	**85.9**	**125**	**0.8**	**8.9**	**1.0**
		70	617	87.7	674	86.8	**645**	**87.3**	**40**	**0.6**	**6.2**	**0.7**
	5% RTFO AGED	58	13602	73.1	14413	73.6	**14008**	**73.4**	**573**	**0.4**	**4.1**	**0.5**
		64	6215	74.8	6336	76.9	**6275**	**75.9**	**86**	**1.5**	**1.4**	**2.0**
		70	2923	75.5	2878	80.5	**2900**	**78.0**	**32**	**3.5**	**1.1**	**4.5**
		76	1458	73.9	1349	82.9	**1404**	**78.4**	**77**	**6.4**	**5.5**	**8.1**
		82	802	69.4	642	84.5	**722**	**77.0**	**113**	**10.7**	**15.7**	**13.9**
	10% Unaged	58	4526	81.7	8636	78.4	**6581**	**80.1**	**2906**	**2.3**	**44.2**	**2.9**
		64	2066	84.6	3879	81.0	**2972**	**82.8**	**1281**	**2.5**	**43.1**	**3.1**
		70	986	86.0	1987	83.2	**1487**	**84.6**	**708**	**2.0**	**47.6**	**2.3**
		76	1100	87.0	990	84.9	**1045**	**86.0**	**78**	**1.5**	**7.5**	**1.7**
	10% RTFO AGED	58	16459	64.7	-	-	**16459**	**64.7**	-	-	-	-
		64	9961	67.3	-	-	**9961**	**67.3**	-	-	-	-
		70	7497	64.4	-	-	**7497**	**64.4**	-	-	-	-
		76	4091	64.1	-	-	**4091**	**64.1**	-	-	-	-
		82	2350	62.1	-	-	**2350**	**62.1**	-	-	-	-
		88	1487	58.6	-	-	**1487**	**58.6**	-	-	-	-

Table 4-12: Dynamic Shear Rheometer Results Data for Sealant PF

	Sample	Temp (°C)	Replicate 1		Replicate 2		Replicate 3		Average		SD		CV (%)	
			G* (Pa)	δ (degree)	G* (Pa)	δ (degree)	G* (Pa)	δ (degree)	G* (Pa)	δ (degree)	G*	δ	G*	δ
Sealant PF	0% Unaged	64	8441	61.1	19688	60.6	19054	61.5	**15728**	**61.1**	**6318**	**0.5**	**40.2**	**0.7**
		70	6421	64.4	11519	63.2	10886	64.6	**9609**	**64.1**	**2779**	**0.8**	**28.9**	**1.2**
		76	4715	68.6	6781	66.5	6297	68	**5931**	**67.7**	**1081**	**1.1**	**18.2**	**1.6**
		82	3484	68.2	4053	68.6	3686	70.3	**3741**	**69**	**288**	**1.1**	**7.7**	**1.6**
		88	2558	69.4	2483	70.8	2194	72.1	**2412**	**70.8**	**192**	**1.4**	**8.0**	**1.9**
	0% RTFO Aged	64	10662	49	19307	48.9	10098	49.7	**13356**	**49.2**	**5162**	**0.4**	**38.6**	**0.9**
		70	6721	50.2	14421	49.9	6264	51.4	**9135**	**50.5**	**4583**	**0.8**	**50.2**	**1.6**
		76	4280	51.4	11945	52.4	3930	53.6	**6718**	**52.5**	**4530**	**1.1**	**67.4**	**2.1**
		82	2779	52.9	7664	56.3	2488	55.4	**4310**	**54.9**	**2908**	**1.8**	**67.5**	**3.2**
		88	1854	54.7	4883	59.5	1587	57.4	**2775**	**57.2**	**1831**	**2.4**	**66.0**	**4.2**
	2.5% Unaged	64	7843	54.8	21026	52.2	8171	54.4	**12347**	**53.8**	**7518**	**1.4**	**60.9**	**2.6**
		70	4645	58.4	17803	53.7	4891	57	**9113**	**56.4**	**7527**	**2.4**	**82.6**	**4.3**
		76	2773	61.2	10840	57.1	2970	59.8	**5528**	**59.4**	**4602**	**2.1**	**83.2**	**3.5**
		82	1686	63.4	6604	60.4	1830	62.1	**3374**	**62**	**2799**	**1.5**	**83.0**	**2.4**
		88	1048	65.8	4115	61.9	1140	63.8	**2101**	**63.8**	**1745**	**2.0**	**83.0**	**3.1**
	2.5% RTFO Aged	64	14198	44.6	10166	42.3	19950	45.6	**14771**	**44.2**	**4917**	**1.7**	**33.3**	**3.8**
		70	9250	45.3	6648	43.2	12644	46.6	**9514**	**45**	**3007**	**1.7**	**31.6**	**3.8**
		76	6079	46.8	4409	43.8	8176	48.7	**6221**	**46.4**	**1888**	**2.5**	**30.3**	**5.3**
		82	4025	49.3	3667	49.8	5279	51.1	**4324**	**50.1**	**846**	**0.9**	**19.6**	**1.9**
		88	2655	51.2	2524	50.6	3423	53.5	**2868**	**51.8**	**486**	**1.5**	**16.9**	**3.0**
	5% Unaged	64	12087	51.2	10807	54	8835	53.2	**10576**	**52.8**	**1638**	**1.4**	**15.5**	**2.7**
		70	7502	53.6	6745	57.9	5368	55.9	**6538**	**55.8**	**1082**	**2.2**	**16.5**	**3.9**
		76	4662	55.9	4116	59.7	3232	58.2	**4003**	**57.9**	**722**	**1.9**	**18.0**	**3.3**
		82	2962	58.7	3688	61	2060	60.1	**2903**	**59.9**	**816**	**1.2**	**28.1**	**1.9**
		88	1899	60.9	2754	64.5	1334	62.4	**1996**	**62.6**	**715**	**1.8**	**35.8**	**2.9**
	5% RTFO Aged	64	24745	39.9	18163	41.3	14667	39	**19192**	**40.1**	**5117**	**1.2**	**26.7**	**2.9**
		70	16593	40.7	12236	41.7	10004	39.8	**12944**	**40.7**	**3351**	**1.0**	**25.9**	**2.3**
		76	11330	42.3	8332	43	6758	41	**8807**	**42.1**	**2323**	**1.0**	**26.4**	**2.4**
		82	12219	45	5683	44.5	4511	43.9	**7471**	**44.5**	**4153**	**0.6**	**55.6**	**1.2**
		88	12416	53.7	3788	48.1	3164	44.7	**6456**	**48.8**	**5171**	**4.5**	**80.1**	**9.3**

Chapter 5 Data Analysis

5.1 Analysis Structure and Existing Limits

The experimental data and results from Chapter 4 are presented in this chapter with the aim of achieving a better understanding of the trends observed and determine best performing sealant using crumb rubber as an additive or modifier. The analyses are presented in phases. The first phase is a comparison between the PG64-22 binder results with the two crumb rubber dosages and the commonly used sealant in the Phoenix area, which is referred to as Sealant PF. The goal behind this first comparison is to document and analyze the ability of neat binder with crumb rubber modification to possibly be applied as a sealant. The second phase is a comparison between the base Sealant PF also modified with two predetermined crumb rubber dosages. The goal behind this comparison is to evaluate the potential performance of the existing sealant with some additional modification such as adding crumb rubber. The third phase is a final comparison between the PG64-22 binder with rubber dosages and Sealant PF with rubber dosages to document and analyze the magnitude and effect of property changes, if any. Each phase is broken down into three main steps or stages , which aligns with the conducted tests. The first stage is the penetration and recovery testing analysis. The second stage is the viscosity testing analysis. The third stage is the DSR testing analysis.

Regarding the current test limits for sealant evaluation, the three sets of limits documented in the literature review are also shown below for convenience. Note that the limits shown in the tables below are chosen based on the tests conducted in this study. Therefore, other test limits for each set do exist, but not included.

Table 5-1: Type 1 ASTM D6690 Limits

ASTM D6690	Type 1 Limits
Standard Penetration Test	-
Cone Penetration Test	90 Max.
Resilience Test	-
Softening Point Test	176 °F / 80 °C Min.
Brookfield Viscometer Test	-
Dynamic Shear Rheometer	-

Table 5-2: 2008 ADOT Rubberized Sealant Limits

ADOT	Limits
Standard Penetration Test	10 to 25
Cone Penetration Test	-
Resilience Test	-
Softening Point Test	210 °F / 99 °C Min.
Brookfield Viscometer Test	7500 cp Max. at 400 °F
Dynamic Shear Rheometer	-

Table 5-3: Sealant PF manufacturer recommended limits

Sealant PF	Limits
Standard Penetration Test	-
Cone Penetration Test	20 to 40
Resilience Test	30% Min.
Softening Point Test	210 °F / 99 °C Min.
Brookfield Viscometer Test	10000 cp Max. at 400 °F
Dynamic Shear Rheometer	-

5.2 Phase One: PG64-22 Binder Evaluation

5.2.1 Stage One: Penetration and Recovery Tests

As discussed previously, Phase 1 comparison will be between the PG64-22 binder with crumb rubber dosages and Sealant PF. The crumb rubber dosages was 0%, 5% and 10% based on binder weight. The first stage will be addressing the penetration and recovery tests, which are the SPT, CPT, and Resilience Test respectively.

SPT is a standard ASTM test that measures the softness/hardness of a binder to provide an indication of the installation practicality and the ability to resist permanent deformation. The results of the SPT is used mainly for the viscosity-temperature susceptibility analysis, which will be discussed later on in the analysis. SPT is not commonly used, like the CPT, due to its limitation discussed in the literature review, but some benefits can be gained from it to increase the overall knowledge.

According to Figure 5-1, penetration measurements decreased with the increase in rubber content. The cause of the decrease it that during crumb rubber mixing the binder reacts causing the rubber particles to swell and absorb a portion of the oils within the binder leading it to become more stiff. Note that even with the addition of 10% crumb rubber to PG64-22 binder the penetration results did not reach the Sealant PF penetration value. According to Table 5-2, ADOT penetration limit is between 10 and 25, which was not achieved by any of the tested binders including the Sealant PF.

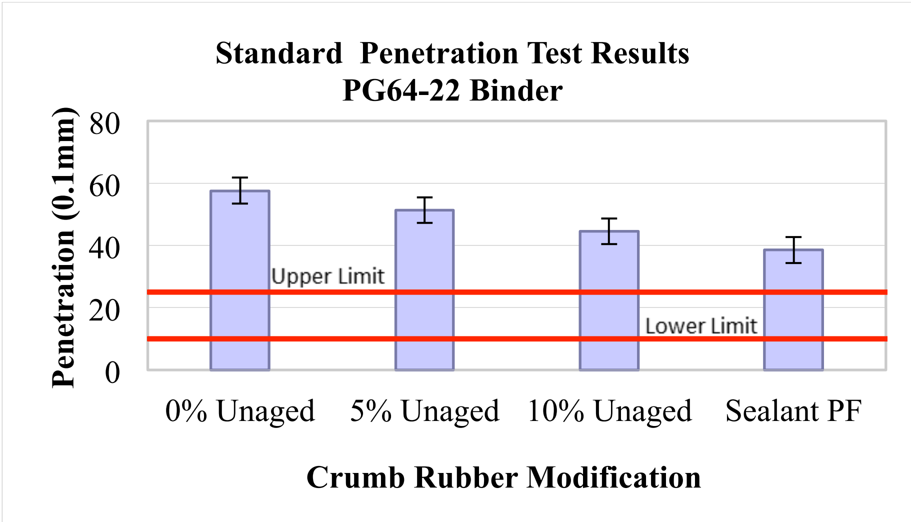

Figure 5-1: SPT Binder Results Graph

CPT is a standard ASTM test specified for sealants to measure the softness/hardness of a sealant for the same reasons as the SPT. The advantages of the CPT over SPT can be seen in the literature review. According to Figure 5-2, with the increase in crumb rubber content, cone penetration measurements decreased similar to the SPT results. This decrease in measured values indicates a better ability to resist permanent deformation due to increased stiffness.

With the addition of 10% crumb rubber to PG64-22 binder the cone penetration results did not reach the Sealant PF value. Meanwhile, the difficulty in handling the binder with increasing rubber content increased linearly which was noticed especially for the 10% crumb rubber. Therefore, other additives must be added to the modified PG64-22 binder to obtain a relatively low SPT and CPT values. According to Table 5-1, all tested binders including Sealant PF passed the ADOT limit of a maximum value of 90. According to Table 5-3, all tested binders besides Sealant PF did not meet Sealant PF manufacturer range of 20 to 40. Sealant PF barely passed with an average cone penetration value of 40.

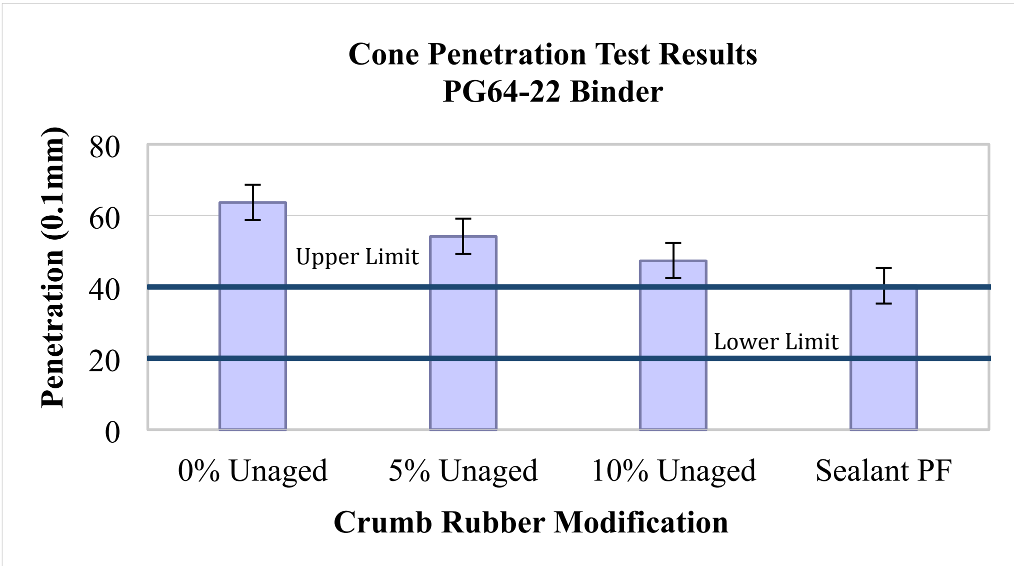

Figure 5-2: CPT Binder Results Graph

The Resilience Test is a standard ASTM test specified for sealant to measure the rebound and recovery ability after loading. This test indicates the amount of elasticity in a sealant to counter any deformation occurring within the sealant body. According to Figure 5-3, with increase in rubber content the rebound percentage increase simultaneously while still being significantly less than Sealant PF. This increase in resilience will cause higher elastic recovery leading to better cohesive performance. This shows that crumb rubber does increase resilience, but not as high as the rate which other unknown additives in Sealant PF did. As stated previously, increase in crumb rubber content causes increase in material handling difficulties, which was seen more in the 10% crumb rubber binder samples. Therefore, the gained resilience properties using crumb rubber should be weighted against handling capabilities. Based on Table 5-3, the resilience limit set by the Sealant PF manufacturer is a minimum of 30%. Therefore, all binders, except Sealant PF, failed to pass the limit. Meanwhile, Sealant PF barely passed with an average resilience percentage of 34%.

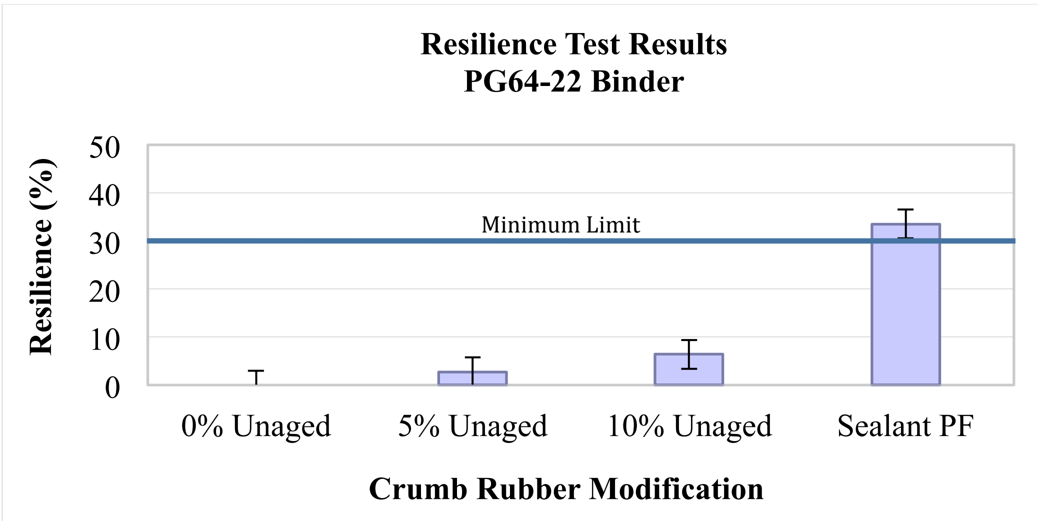

Figure 5-3: Resilience Test Binder Results Graph

5.2.2 Stage Two: Rheological Tests

The second stage of phase one is about testing analysis including the Softening Point Test and the Brookfield Rotational Viscometer Test. The main focus in the second stage is about the temperature-viscosity susceptibility analysis that links several of the conducted tests together.

Softening Point Test is a standard ASTM test for all bituminous materials to measure the temperature in which the material behavior changes from more viscous solid to less viscous flowable material. This test indicates the flow resistance capabilities of a sealant in terms of temperatures that is directly correlated to settlement failure mode and tracking. Two aging conditions, which are unaged and RTFO aged were tested for softening point to analyze any potential property change between the two conditions. Note that the main assumption for RTFO aging is that it will simulate sealant aging after a period of time closer to the end of the sealant service life. According to Figure 5-4, a slight increase in softening point temperature was documented with the increase in crumb rubber content. Due to the possible rubber binder reaction during mixing, the binder becomes stiffer. Regarding RTFO samples, aging caused the loss of oil and volatiles, which reflected in an increase in softening point temperature compared to the unaged condition. Similar trend was also documented for the RTFO samples with the increase in crumb rubber content.

In addition, it could be noticed that Sealant PF in both conditions has significantly higher softening point temperatures compared to PG64-22 binder with crumb rubber additives. This shows that other unknown additives in Sealant PF played a role in increasing the softening point temperature without giving up flexibility leading to higher resistance to settlement, which was clear in the 10% crumb rubber binder. Based on Table 5-1, all binders in both conditions, except Sealant PF, failed to pass the ASTM limit for softening point of 80 °C. On the other hand, ADOT and Sealant PF manufacturer limits in Table 5-2 and Table 5-3 were not met by any of the binders in both conditions including Sealant PF. The limit is 99 °C for the softening point temperature.

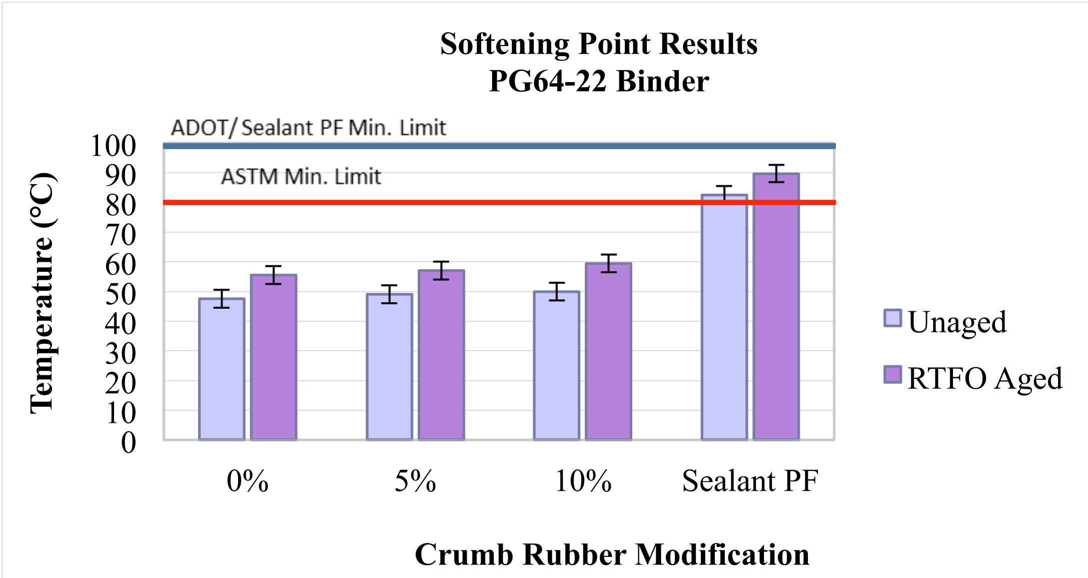

Figure 5-4: Softening Point Test Binder Results Graph

Brookfield Rotational Viscometer Test is an ASTM test for all bituminous material to measure viscosity or resistance to flow and provide information about the rheological behavior of the tested material. For sealants, this test is commonly used to generate a temperature versus viscosity graph to analyze and compare sealants' viscosities at moderate and elevated temperatures. In simple terms, the smaller the viscosity-temperature slope the better performing the sealant is. Performance improves since the sealant will be more resilient against failures caused and/or contributed by undesired flow at elevated temperatures such as settlement and cohesive failure. Another analysis approach is to compare viscosity threshold values at moderate temperatures. Both low and high initial viscosity can post issues in all phases of the sealant service life including installation. All the plots and tables leading to the figures below (Figures 5-5 and 5-6) can be seen in Appendix B.

According to Figure 5-5, all PG64-22 unaged binders with various crumb rubber modification roughly have an identical threshold viscosity value at moderate temperatures with various slopes. Note that the positive change in slope between the three crumb rubber modified binders are not identical. The benefit gained from the first 5% crumb rubber is higher than the 10% while still being above the 5%. Since all binders' viscosity threshold values are roughly identical, a comparison at moderate temperatures cannot be achieved. Sealant PF had a similar viscosity threshold value compared to PG64-22 binders but with a different slope. Sealant PF slope is significantly smaller than all the tested binders showing better cohesive and settlement performance.

According to Figure 5-6, PG64-22 RTFO aged binders with higher crumb rubber modification show a shift in threshold viscosity value at moderate temperatures with various slopes. This was due to the relative higher increase in softening point with the increase in crumb rubber content. Note that the positive change in slope between the three crumb rubber modified binders are not identical. In contrast to Figure 5-5, benefits gained from the first 5% crumb rubber is lower than the 10%. Sealant PF have a shift in viscosity threshold value compared to PG64-22 binders and with a different slope. Sealant PF slope is significantly lower than all the tested binders showing better performance. The closest slope to Sealant PF was the 10% PG64-22 binder in the RTFO aged condition.

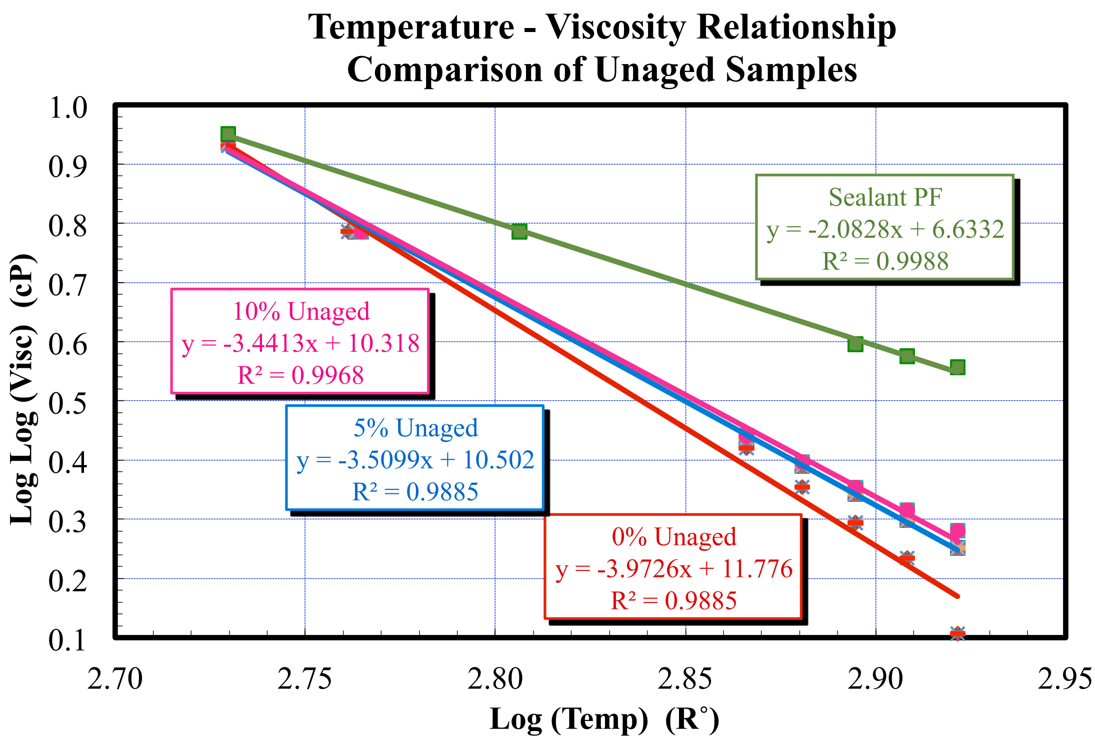

Figure 5-5: Temperature –Viscosity Relationship Comparison of Unaged Binder Samples

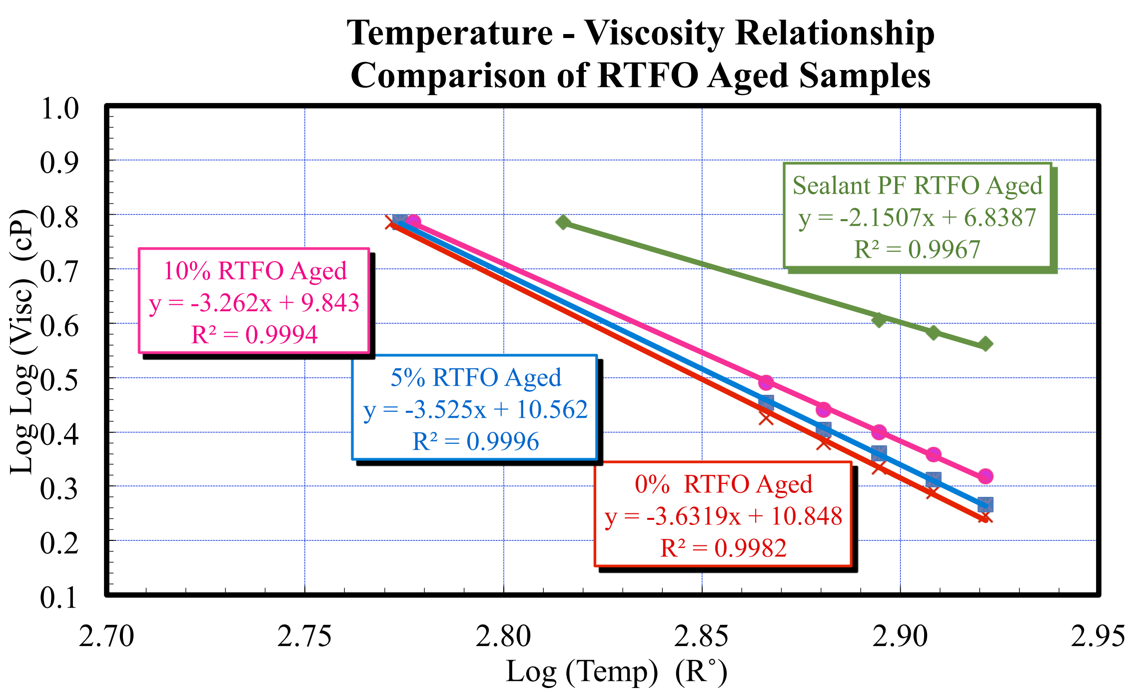

Figure 5-6: Temperature –Viscosity Relationship Comparison of RTFO Aged Binder Samples

Based on Table 5-2, ADOT limit for viscosity is a maximum of 7500 cp at 400 °F. This limit is used to avoid using sealants that are difficult to pump and handle during installation. Comparing between ADOT and Sealant PF manufacturer limits, the ADOT limit is considered more difficult to achieve. Therefore, for analysis purposes the ADOT limit will be used. Using extrapolation, LogLog(visc) at 400 °F of all binders including Sealant PF can be seen below in Table 5-4 for unaged and RTFO aged conditions. Results show that all binders including Sealant PF passed the ADOT limit, meaning that all binders are within acceptable handling and pumping limits.

Table 5-4: LogLog Viscosity Values of All Binders at 400 °F

	LogLog(visc) at 400 °F
ADOT Limit	0.5883
0% Unaged	0.1188
0% RTFO Aged	0.1906
5% Unaged	0.203
5% RTFO Aged	0.2186
10% Unaged	0.2198
10% RTFO Aged	0.2712
Sealant PF Unaged	0.5216
Sealant PF RTFO Aged	0.5278

5.2.3 Stage Three: Dynamic Shear Rheometer Test

The third stage of phase 1 will be about the Dynamic Shear Rheometer Test. The main focus in third stage is to analyze the relationship between the complex modulus and phase angle of the tested materials. In addition, to further differentiate between sealant deformations in terms of recoverable and elastic properties.

The Dynamic Shear Rheometer is a standard ASTM test for all bituminous materials to measure shear modulus and phase angle to determine the viscoelastic properties of the material. This test is important because it provides indication of the sealant resistance to deformation and criteria of the upper temperature performance range of the sealant. Therefore, it focuses on the underlying cohesive properties that will cause the sealant to maintain shape and bonding. Regarding the desired shear modulus, the higher the shear modulus the more desirable the sealant is due to the increase in stiffness and resistance to deformation. On the other hand, the desired phase angle tends to be the lowest since it represents a higher elastic recovery to any experienced deformation.

Figures 5-7 through 5-10 show the complex modulus and phase angle for each binder and rubber dosage in the unaged and RTFO aged condition. According to Figure 5-7 and Figure 5-8, all binder / rubber dosages had lower complex modulus values relative to Sealant PF indicating less resistance to deformation under the same stress. RTFO binder samples showed an increase in complex modulus compared to the unaged samples, especially for the 10% binder, probably due to extensive oil volitization. Regarding Figures 5-9 and Figure 5-10, the phase angle for all binders are higher than Sealant PF indicating that any deformation will tend not to be recovered compared to same deformation occurring in Sealant PF.

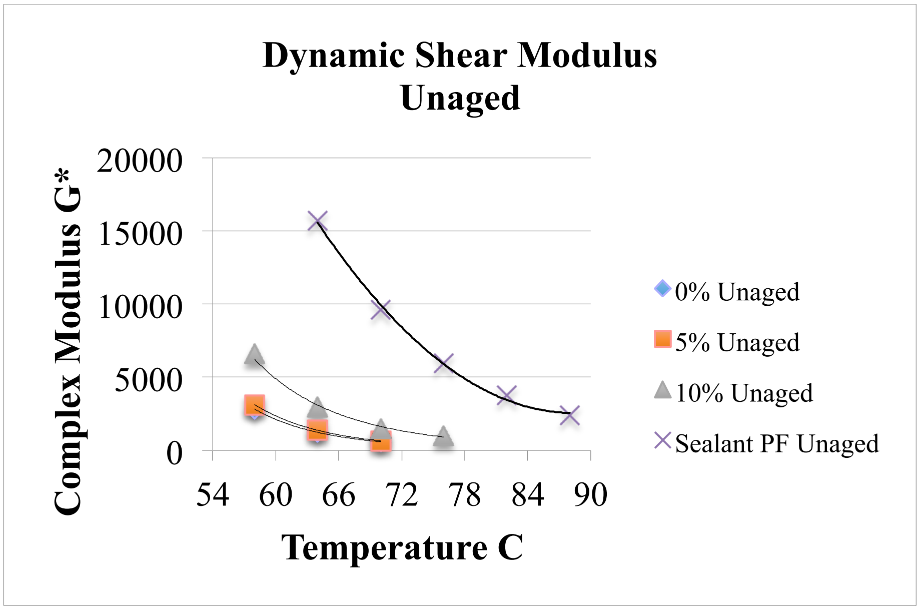

Figure 5-7: Complex Modulus Unaged Binder Results Graph

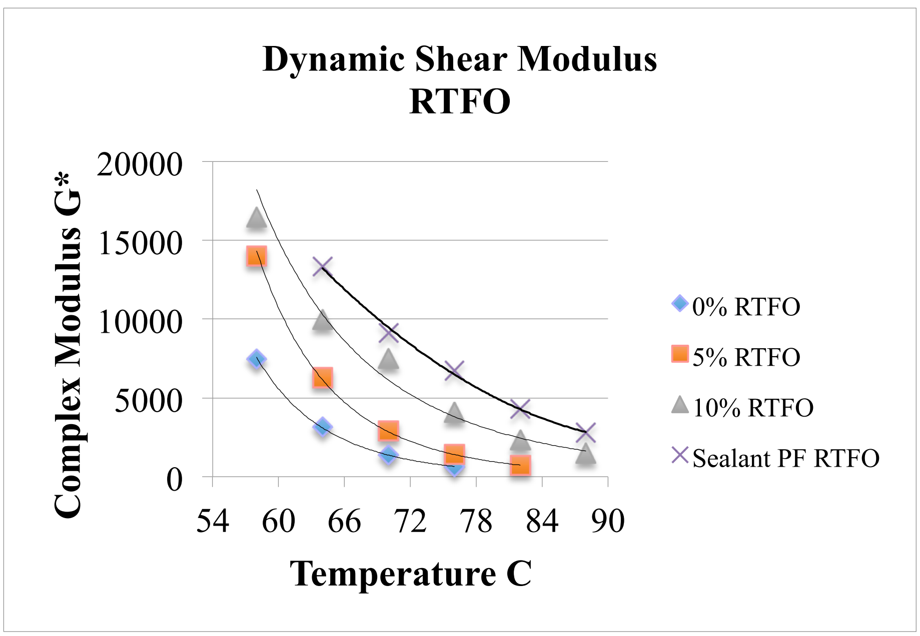

Figure 5-8: Complex Modulus RTFO Aged Binder Results Graph

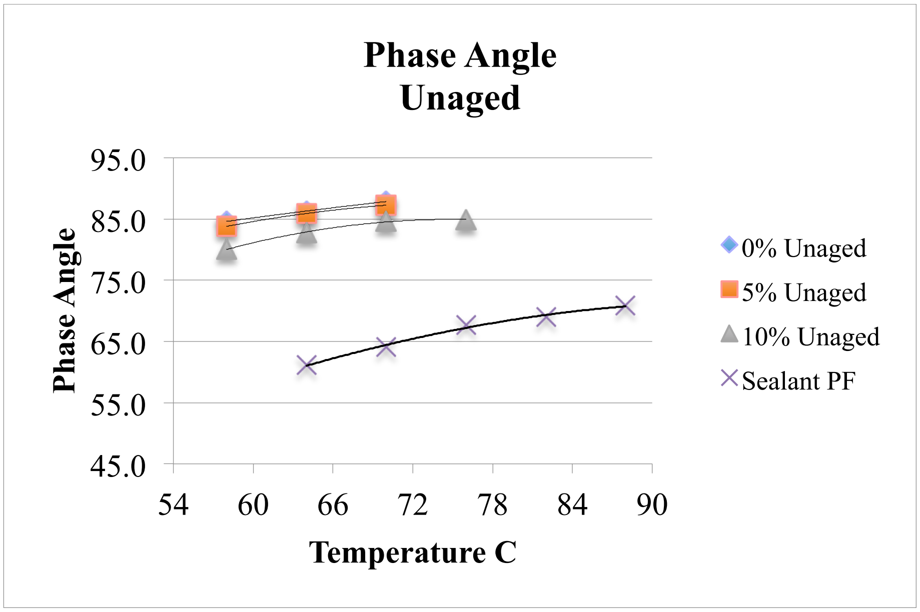

Figure 5-9: Phase Angle Unaged Binder Results Graph

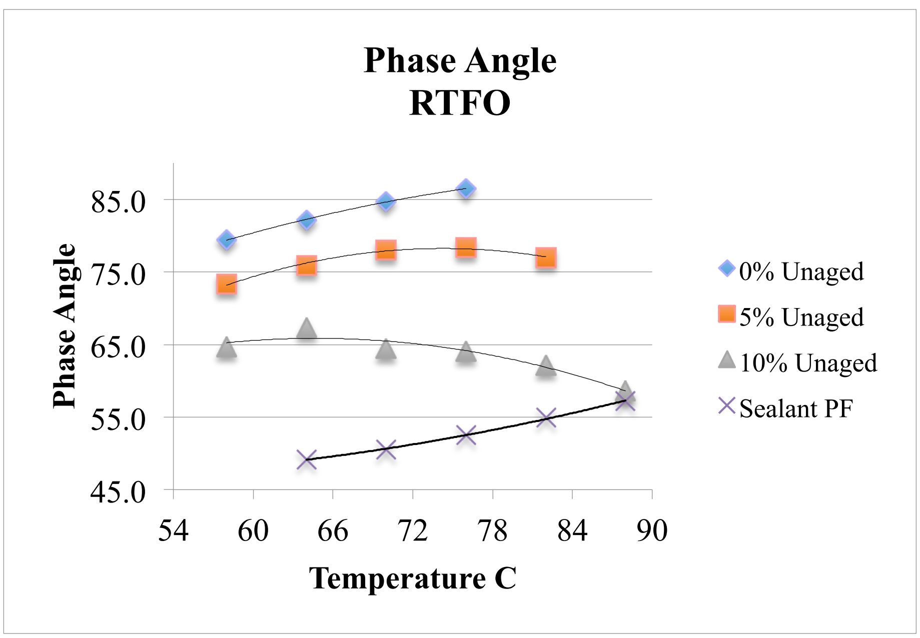

Figure 5-10: Phase Angle RTFO Aged Binder Results Graph

5.3 Phase Two: Sealant PF Evaluation

5.3.1 Stage One: Penetration and Recovery Tests

Phase 2 comparisons is about Sealant PF and crumb rubber dosages added to Sealant PF. The crumb rubber dosages is 2.5% and 5% by sealant weight. Similar to Phase 1, the first stage in Phase 2 will be about the penetration and recovery tests, which will be SPT, CPT, and Resilience Test.

According to Figure 5-11, SPT values decreased with the increase in crumb rubber content indicating a stiffer sealant. Based on the final values, ADOT penetration range of 10 to 25 was still not met when adding 5% crumb rubber to Sealant PF. Similar to the PG64-22 10% crumb rubber, Sealant PF with 5% crumb rubber showed similar difficulty in handling.

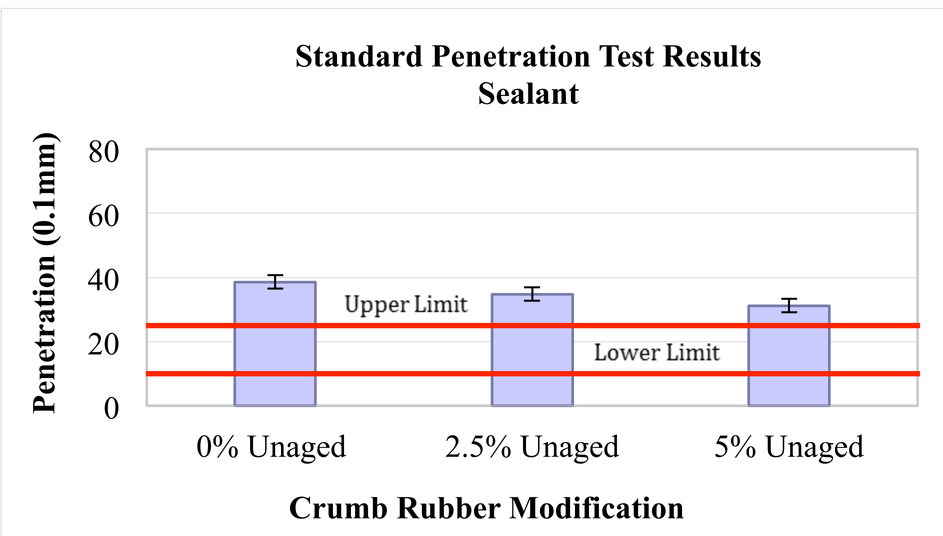

Figure 5-11: SPT Sealant PF Results Graph

According to Figure 5-12, CPT values decreased with the increase in crumb rubber content similar to SPT results. Based on Table 5-1, ASTM limit of maximum of 90 was met by all sealants. Based on Table 5-3, Sealant PF manufacture range of 20 to 40 was also met by all sealants. Note that the 5% Sealant PF is approaching the lower limit of 20, which indicates that additional rubber will potentially cause penetration value to decrease lower than the limit.

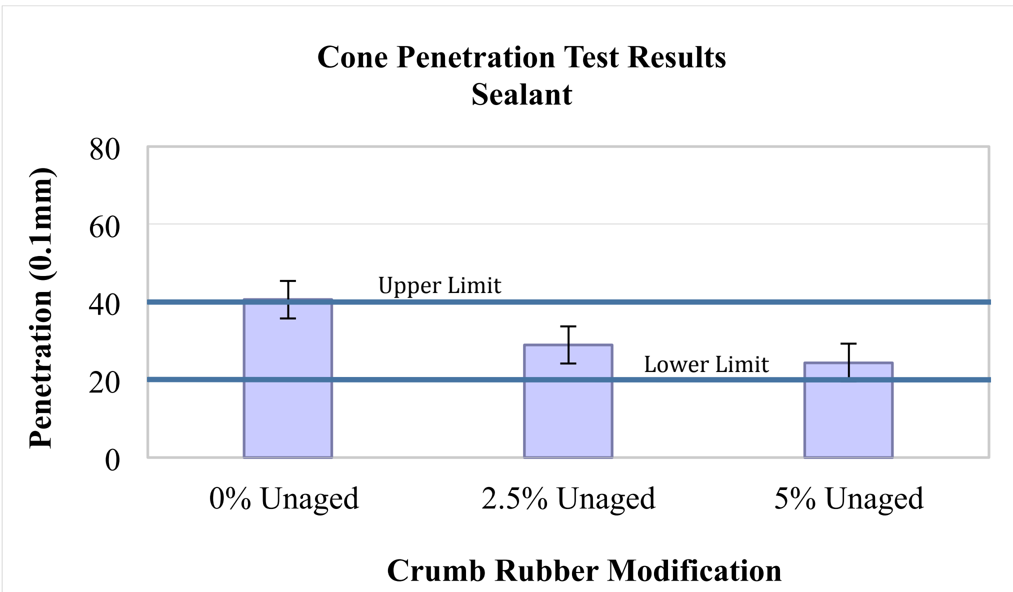

Figure 5-12: CPT Sealant PF Results Graph

According to Figure 5-13, resilience values increased with the increase in crumb rubber content similar to binder PG64-22. This increase in resilience will cause higher elastic recovery leading to better cohesive performance and other desirable properties such as pushing solids out of a crack with a greater force. Based on Table 5-3, the resilience limit set by the Sealant PF manufacturer is a minimum of 30%. Therefore, all sealants passed the limit.

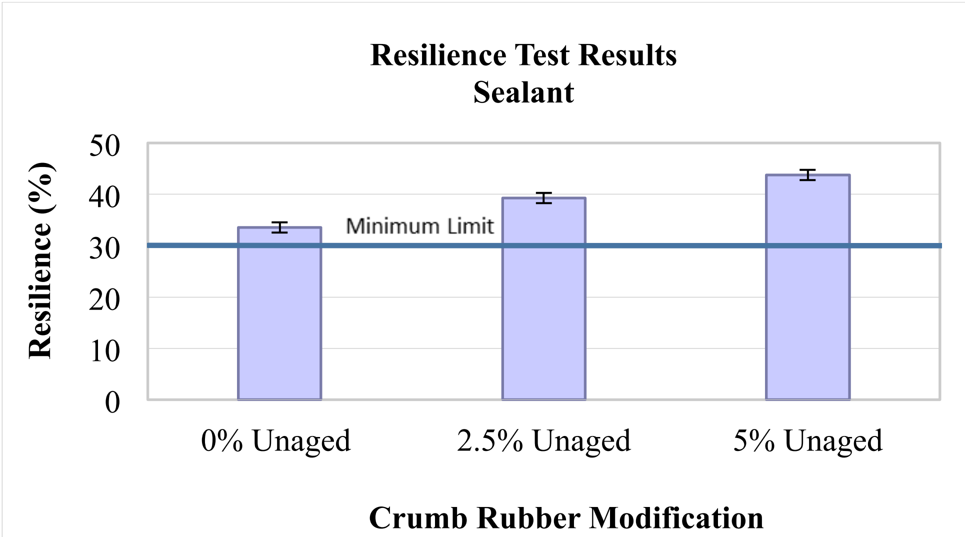

Figure 5-13: Resilience Test Sealant PF Results Graph

5.3.2 Stage Two: Rheological Tests

Similar to Phase 1 testing, two sealants conditions were tested which were unaged and RTFO aged. According to Figure 5-14, a slight increase in softening point temperature is observed with the increase in crumb rubber content, which was expected. Regarding RTFO samples, an increase in softening point temperature is observed compared to the unaged condition. Similar trend was also observed for the RTFO samples with the increase in crumb rubber content. Based on Table 5-1, all sealant passed ASTM limit of 80 °C minimum. On the other hand, ADOT and Sealant PF manufacturer limit in Table 5-2 and Table 5-3 were not met by any of the sealants in both conditions. The limit is 99 °C for softening point temperature.

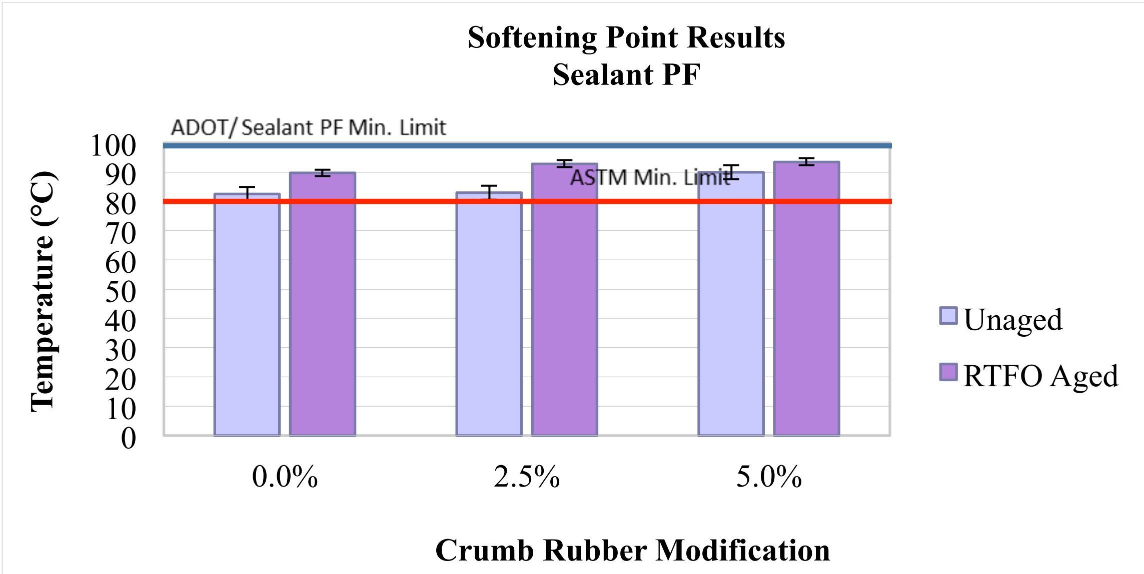

Figure 5-14: Softening Point Test Sealant PF Results Graph

Figures 5-15 and Figure 5-16 show the final viscosity-temperature relationship graph for all sealants in the unaged and RTFO conditions. According to Figure 5-15, all sealants with various crumb rubber modification roughly have an identical threshold viscosity value at moderate temperatures with various slopes. Note that the positive change in slope between the three crumb rubber modified binders are not identical. The benefit gained from the first 2.5% crumb rubber is similar to the second 2.5% showing improvements in the cohesive and settlement resistance properties. According to Figure 5-16, Sealant PF with crumb rubber modification show a shift in viscosity value with various slopes. This was due to the decrease in penetration values with the increase in crumb rubber content. Note that the positive change in slope between the three crumb rubber modified binders are not identical.

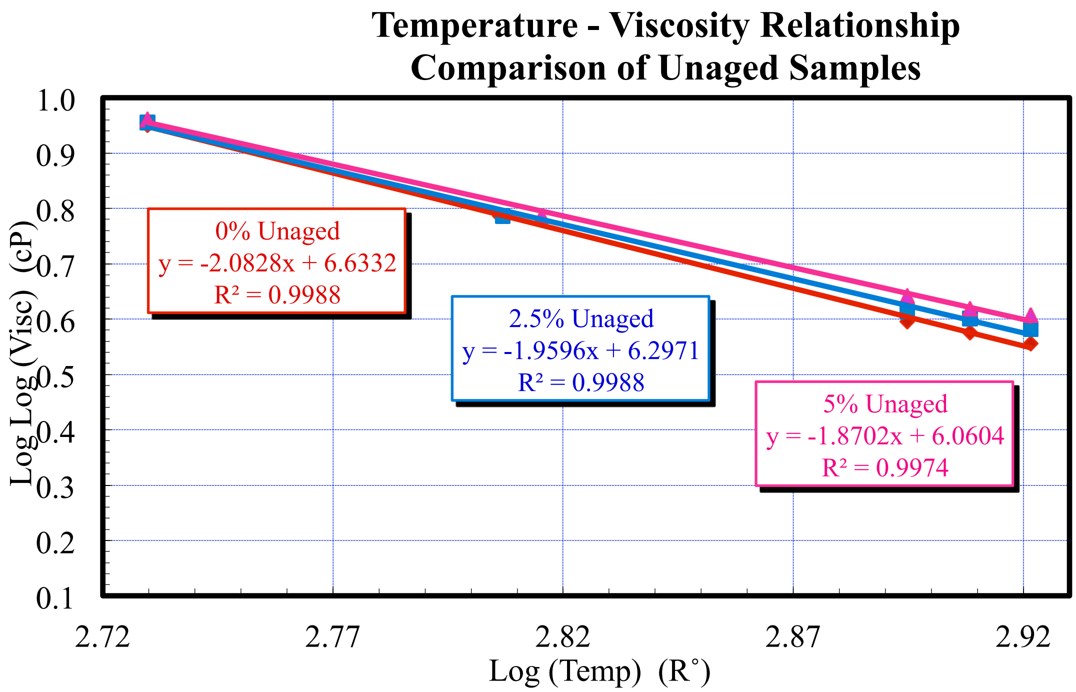

Figure 5-15: Temperature – Viscosity Relationship Comparison of Unaged Sealant PF Samples

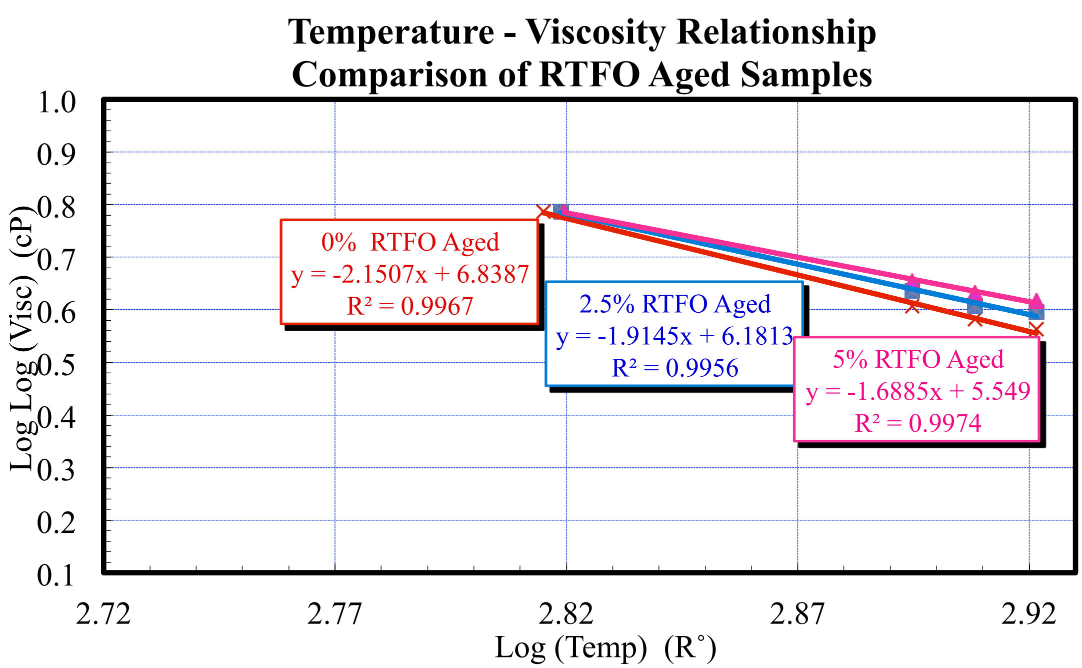

Figure 5-16: Temperature – Viscosity Relationship Comparison of RTFO Aged Sealant PF Samples

Based on Table 5-2, ADOT limit for viscosity is a maximum of 7500 cp at 400 °F. Using extrapolation, LogLog(visc) at 400 °F of all sealants can be seen below in Table 5-5. Results show that all Sealant PF crumb rubber dosages passed the ADOT limit except the 5% RTFO aged samples. Note that the Sealant PF 5% unaged was the closest to the limit indicating a higher potential risk for pumping and handling issues.

Table 5-5: LogLog Viscosity Values of all Sealant PF at 400°F

	LogLog(visc) at 400 °F
ADOT Limit	0.5883
0% Unaged	0.52161
0% RTFO Aged	0.52781
2.5% Unaged	0.54691
2.5% RTFO Aged	0.56351
5% Unaged	0.57259
5% RTFO Aged	0.59117

5.3.3 Stage Three: Dynamic Shear Rheometer Tests

As mentioned before, the third stage of phase 2 is about the Dynamic Shear Rheometer Test. The main focus in the third stage is to analyze the relationship between the complex modulus and phase angle of the tested Sealant PF material.

Figures 5-17 through Figure 5-20 show the complex modulus and phase angle for each Sealant PF rubber dosage in the unaged and RTFO aged condition. Several unexpected trends could be noticed, which may question the validity of the test on sealants. In Figure 5-17, with the increase in rubber content the complex modulus decreased at every temperature for the unaged samples. The opposite can be seen in Figure 5-18 for the RTFO samples with the exception of neat Sealant PF to 2.5% crumb rubber Sealant PF. Regarding phase angles in Figures 5-19 and 5-20, with the increase in rubber content the phase angle decreases for the unaged and RTFO conditions. In comparison to the binder phase angle results, Sealant PF with rubber content up to 5% preformed more elastic in recovering deformation by having lower phase angle values at all temperatures.

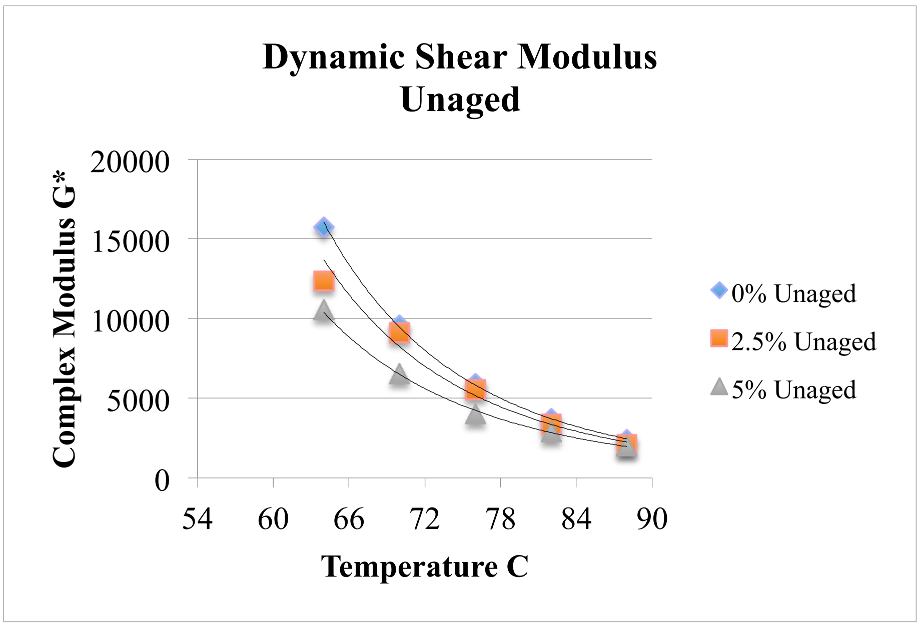

Figure 5-17: Complex Modulus Unaged Sealant PF Results Graph

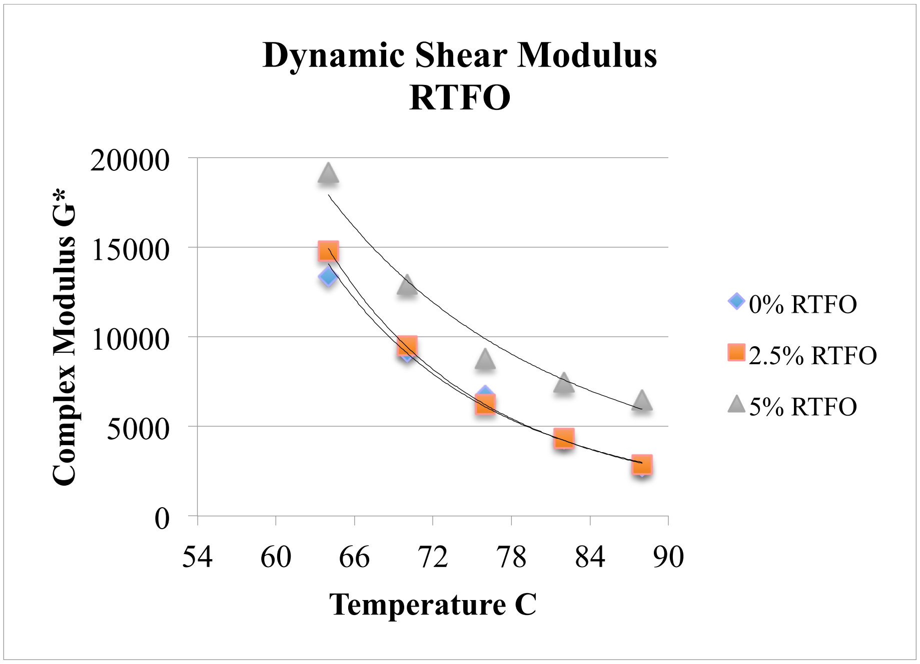

Figure 5-18: Complex Modulus RTFO Aged Sealant PF Results Graph

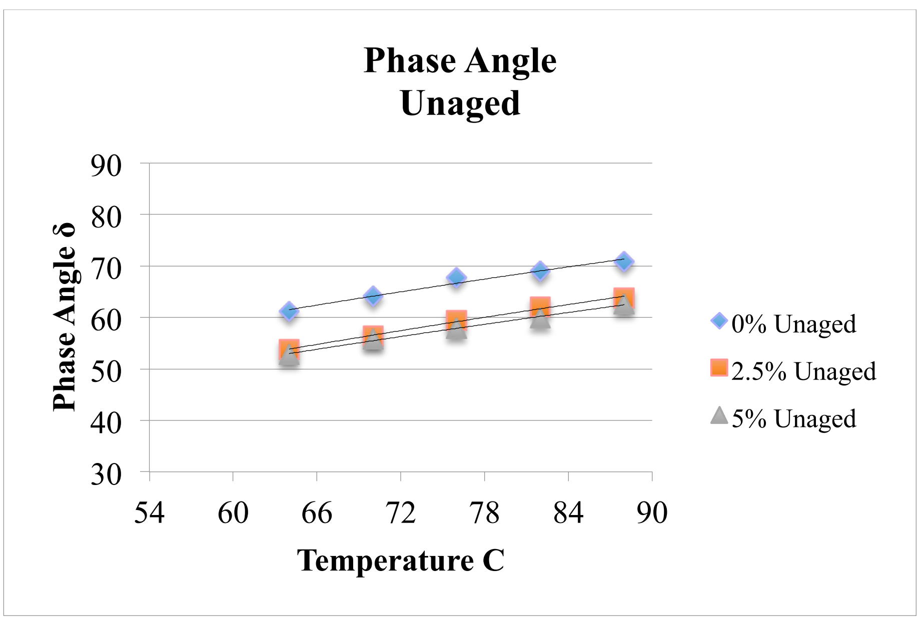

Figure 5-19: Phase Angle Unaged Sealant PF Results Graph

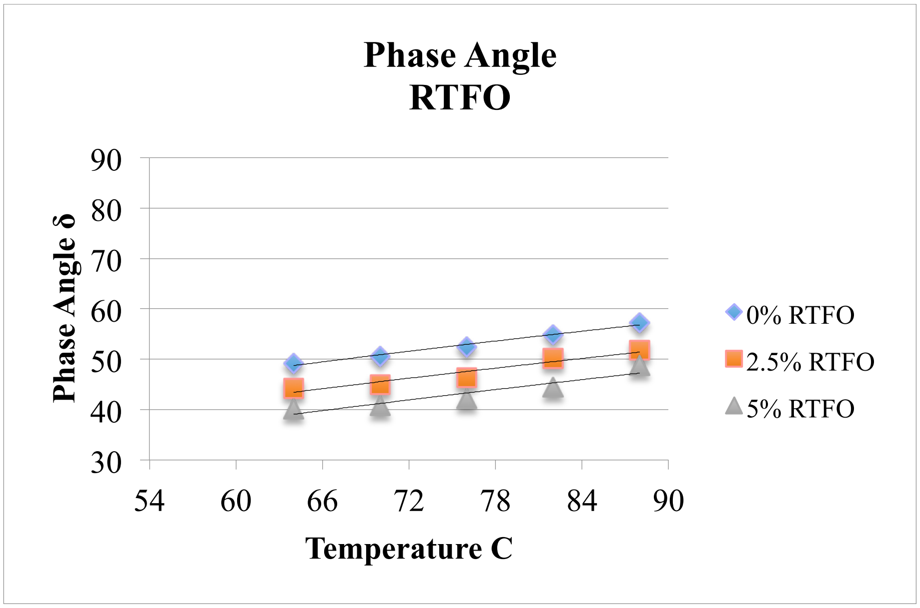

Figure 5-20: Phase Angle RTFO Aged Sealant PF Results Graph

5.4 Phase Three: Statistical Comparison

5.4.1 Stage One: Penetration and Recovery Tests

As discussed previously, Phase 3 includes statistical analyses of the results to establish any correlations, if any, and determine if the differences among the groups and modification process is significant. Analysis of Variance (ANOVA) tests were conducted on the test results to document the statistical significance of adding crumb rubber to binders or sealants.

According to Table 5-6 most of the penetration percent changes with the addition of crumb rubber increments were within the same range. Using the recorded measurements for both tests a correlation graph shown in Figure 5-21 was generated between SPT and CPT data. As expected, the SPT and CPT test results are very well correlated.

Table 5-6: SPT and CPT Results Percentage Change

	Sample	SPT	SPT % Change	CPT	Cone % Change
PG64-22 Binder	0% Binder	58	-	64	-
	5% Binder	51	-11	54	-15
	10% Binder	45	-23	47	-26
Sealant PF	0% Sealant	39	-	41	-
	2.5% Sealant	35	-10	29	-29
	5% Sealant	31	-19	24	-40

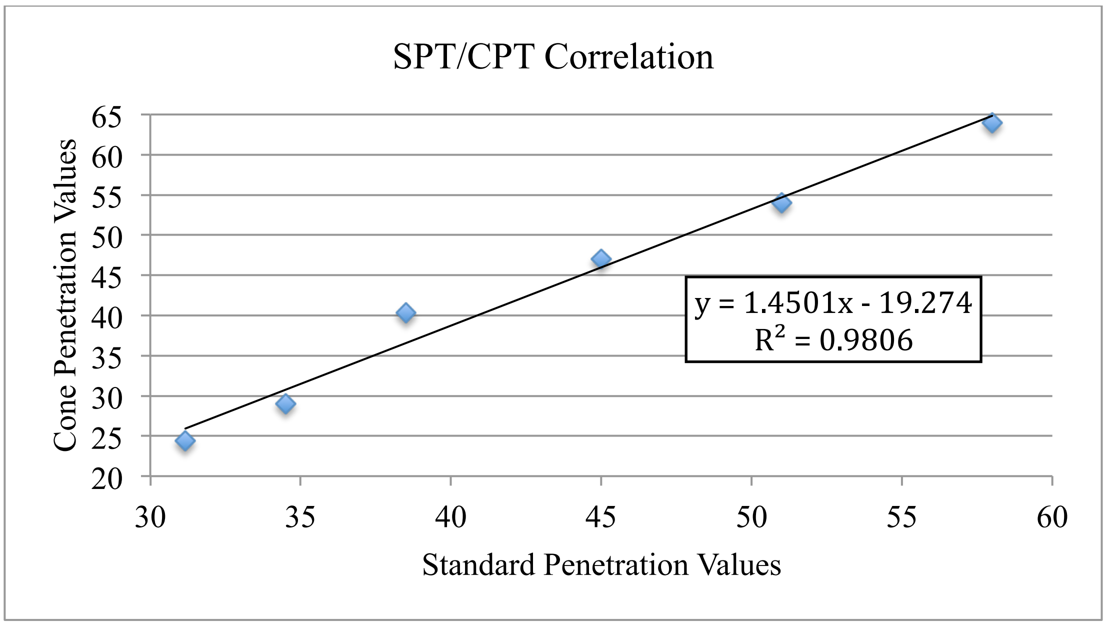

Figure 5-21: SPT/CPT Correlation Graph

A similar table was generated for the Resilience Test accounting for percent changes with the addition of crumb rubber. Based on Table 5-7, a trend could not be achieved for the binders. On the other hand, the sealant percent change was within the same range.

Table 5-7: Resilience Test Results Percentage Change

	Sample	Resilience	% Change
PG64-22 Binder	0% Binder	0	-
	5% Binder	3	-
	10% Binder	6	100
Sealant PF	0% Sealant	34	-
	2.5% Sealant	39	15
	5% Sealant	44	13

For each of the penetration and resilience recovery tests, ANOVA test of significance was generated and the results are included in Appendix C. A summary of the results can be seen in Table 5-8. The ANOVA tests were conducted on the PG 64-22 binder results as well as Sealant PF at the unaged condition. Based on the results, the addition of crumb rubber is statistically significant for both cases; this is simply concluded by verifying the P-value approaching zero in every case.

Table 5-8: Penetration and resilience recovery tests ANOVA test summary

			SPT	CPT	Resilience Test
PG64-22	Unaged	0%	Significant	Significant	Significant
		5%			
		10%			
Sealant PF	Unaged	0%	Significant	Significant	Significant
		2.5%			
		5%			

5.4.2 Stage Two: Rheological Tests

The second stage of Phase 3 was to examine the results for the Softening Point Test and the Brookfield Rotational Viscometer Test. Table 5-9 show the percentage change in softening point temperature for the PG64-22 and Sealant PF samples. Based on these results, a clear trend could not be achieved between the crumb rubber contents or aging conditions.

Table 5-9: Softening Point Test Results Percentage Change

	Sample	Softening Point % Change
PG64-22 Binder	0% Unaged	-
	5% Unaged	3
	10% Unaged	5
PG64-22 Binder	0% RTFO Aged	-
	5% RTFO Aged	3
	10% RTFO Aged	7
Sealant PF	0% Unaged	-
	2.5% Unaged	1
	5% Unaged	9
Sealant PF	0% RTFO Aged	-
	2.5% RTFO Aged	3
	5% RTFO Aged	4

In Table 5-10, a similar percentage change table was generated for the viscosity – temperature slope values for each sample. A noticeable trend in the Brookfield Test results is that the unaged samples slope drop from the first rubber dosage is always higher than the second dosage. On the other hand, the RTFO samples showed no trends.

Table 5-10: Viscosity – Temperature Susceptibility Graph Slope Results Percentage Change

	Sample	% Change of Slope (VTSi)
PG64-22 Binder	0% Unaged	-
	5% Unaged	-12
	10% Unaged	-13
PG64-22 Binder	0% RTFO Aged	-
	5% RTFO Aged	-3
	10% RTFO Aged	-10
Sealant PF	0% Unaged	-
	2.5% Unaged	-6
	5% Unaged	-10
Sealant PF	0% RTFO Aged	-
	2.5% RTFO Aged	-11
	5% RTFO Aged	-21

ANOVA have been run on the viscosity results for the three highest tested temperatures and for each crumb rubber modification/aging condition combination. The results are summarized in Table 5-11. Results show that crumb rubber modification had a significant effect on viscosity at every tested temperature and aging condition for both materials. Those results are found to be similar to the penetration and resilience recovery ANOVA summary results in Table 5-8.

Table 5-11: ANOVA test of Brookfield Viscometer Test at three temperatures

			325 °F	350 °F	375 °F
PG64-22	Unaged	0%	Significant	Significant	Significant
		5%			
		10%			
	RTFO Aged	0%	Significant	Significant	Significant
		5%			
		10%			
Sealant PF	Unaged	0%	Significant	Significant	Significant
		2.5%			
		5%			
	RTFO Aged	0%	Significant	Significant	Significant
		2.5%			
		5%			

5.4.3 Stage Three: Dynamic Shear Rheometer Test

The third stage of phase 3 is about Dynamic Shear Rheometer Test. According to Table 5-12, PG64-22 binder with crumb rubber additives was tested in the unaged and RTFO conditions. PG64-22 binder with no crumb rubber additives complied with the labeled temperature performance limit of 64 °C. With the increase in crumb rubber content the shear modulus increased and phase angle decreased simultaneously leading the G*/sin(Δ) to increase. An increase in G*/sin(Δ) indicates an improvement in the upper temperature performance range. Since RTFO aging exposes the bituminous material to additional oil volitization, it becomes stiffer, which reflect on the complex modulus positively and phase angle negatively. When adding 10% crumb rubber, an increase in one temperature increment was achieved for the unaged (70 °C) and three temperature increments for RTFO aged (82 °C). Comparison between the binder results and Sealant PF show that adding 10% crumb rubber in both conditions was not enough to reach an upper temperature performance limit of 88 °C.

According to Table 5-13, Sealant PF achieved a performance grade temperature of 88 °C without any crumb rubber modification. With the increase in temperature, a decrease in $G^*/(\sin(\Delta))$ was observed similar to Table 5-12. On the other hand, for the unaged samples an increase in crumb rubber content caused a decrease in $G^*/(\sin(\Delta))$ at each temperature increment.

The cause for this unexpected trend could potentially be due to several reasons. First, the sealant material is rather stiff in its original condition. Adding a softer material in the form of crumb rubber may have made the final composite sealant less stiff, which reflected in the complex modulus measurements. Another possibility would be the high variability of the test results, which was documented by the high coefficient of variance values; this might have shifted the results to come up with misleading data. Another possibility is the limitation or the capability of using the DSR equipment, which may have contributed to erroneous reading, especially when testing sealants with unknown components in addition to the crumb rubber content. On the other hand, for the RTFO samples, the same trend seen in Table 5-13 was seen with a noticeable increase in 5% crumb rubber $G^*/(\sin(\Delta))$ at the upper temperatures of 82 °C up to 88 °C.

Table 5-12: Dynamic Shear Rheometer Performance Grading for PG64-22 Binder

		Dynamic Shear Rheometer Grading Parameter	
Sample	Temp (°C)	G*/(Sin(Δ)) (kPa)	G*/SinΔ 1 kPa Limit (PG Upper Grade)
0% Unaged	58	2.8	64.0
	64	1.2	
	70	0.6	
5% Unaged	58	3.1	64.0
	64	1.4	
	70	0.6	
10% Unaged	58	6.7	70.0
	64	3.0	
	70	1.5	
	76	1.0	
0% RTFO AGED	58	7.6	64.0
	64	3.2	
	70	1.4	
	76	0.6	
5% RTFO AGED	58	14.6	70.0
	64	6.5	
	70	3.0	
	76	1.4	
	82	0.7	
10% RTFO AGED	58	18.2	82.0
	64	10.8	
	70	8.3	
	76	4.5	
	82	2.7	
	88	1.7	

Table 5-13: Dynamic Shear Rheometer Performance Grading for Sealant PF

		Dynamic Shear Rheometer Grading Parameter	
Sample	**Temp (°C)**	**G*/(Sin(Δ)) (kPa)**	**G*/SinΔ 1 kPa Limit (PG Upper Grade)**
0% Unaged	64	17.97	88
	70	10.68	
	76	6.41	
	82	4.01	
	88	2.55	
2.5% Unaged	64	15.30	88
	70	10.94	
	76	6.42	
	82	3.82	
	88	2.34	
5% Unaged	64	13.28	88
	70	7.90	
	76	4.73	
	82	3.36	
	88	2.25	
0% RTFO Aged	64	17.64	88
	70	11.84	
	76	8.47	
	82	5.27	
	88	3.30	
2.5% RTFO Aged	64	21.19	88
	70	13.45	
	76	8.59	
	82	5.64	
	88	3.65	
5% RTFO Aaged	64	29.80	88
	70	19.85	
	76	13.14	
	82	10.66	
	88	8.58	

Chapter 6 Summary, Conclusions and Recommendations

6.1 Summary and Conclusions

In this study, one objective was to investigate the potential of using Crumb rubber as an effective additive to improve the current material properties of the hot-applied sealants. In addition, another objective was to investigate the addition of crumb rubber to a neat PG64-22 binder for its potential use as a low-grade crack sealant. The tests used for this evaluation followed ASTM standards. Several of the tests were specific for crack sealants such as the Cone Penetrometer Test (CPT) and Resilience Test. Other tests such as the Standard Penetration Test (SPT), Softening Point, Brookfield Viscometer, and the Dynamic Shear Rheometer (DSR) were also included as they are binder tests potentially used to evaluate sealants.

The conclusions stated in this section follow the analysis section in chapter 5. First, adding only crumb rubber (up to 10%) to a neat binder for its potential use as a crack sealant is inadequate. This is based on all the conducted tests where the addition of 10% crumb rubber did not achieve the expected limits as shown by Sealant PF. For instance, the elastic properties gained from adding crumb rubber reflected by the Resilience Test values were significantly lower for the highest crumb rubber modified binder. This could also be seen in the Temperature – Viscosity Susceptibility graphs where the slope of Sealant PF was significantly less than any of the modified binders. Additionally, the DSR complex modulus and phase angle results for the Sealant PF were better than the binder with the highest crumb rubber dosage. It is also noted that the 10% crumb rubber modified binder was only getting closer to the performance of Sealant PF in the DSR RTFO complex modulus measurement. Meanwhile, the RTFO phase angle graph in Figure 5-10 is still higher at all temperatures indicating that the deformations are less elastic. Therefore, a better approach along this notion is to include crumb rubber along with a group of other additives that increases the stiffness as a primary purpose and provide elastic properties as a secondary feature.

In regards to modifying hot applied sealants by adding crumb rubber, it was shown to be beneficial in improving various desired properties. Additional crumb rubber in sealants was shown to increase elasticity through improvement in resilience values and decreasing viscosity susceptibility to temperature. Based on the crumb rubber dosages added to Sealant PF, the optimum rubber content is chosen to be 2.5% by weight of the sealant. The reason behind this decision is that Sealant PF with 5% crumb rubber was considered to be excessive amount of rubber, which reflected negatively in several crucial ways. For instance, in Table 5-5 the closest samples to the ADOT Brookfield limit of 7500 cp at 400 ^{o}F was the Sealant PF with 5% crumb rubber. In addition, the RTFO sample exceeded the specified limit and was the only failed sample. This showed that Sealant PF with 5% crumb rubber will be difficult to handle and pump.

Regarding the conducted tests, penetration and the resilience recovery tests results showed to have high repeatability as indicated by the statistical summaries. A very good correlation was found between the SPT and CPT test results. The Brookfield Viscometer Test showed to be beneficial in generating useful data that were used in the viscosity – temperature susceptibility graphs. The DSR showed issues in repeatability with the increase in rubber content and the amount of additives in the case of Sealant PF. This could be seen in the DSR results data of Sealant PF modified with 2.5% and 5% crumb rubber in Table 5-13 and the discussion presented in section 5.4.3. It could be caused by crumb rubber segregation or equipment limitations.

6.2 Future Works

Based on the experience gained from this study efforts, test results and analysis, the following is recommended as a future work activities:

1. Evaluate the use of other additives such as latex, with and without crumb rubber, to both neat binders and sealants to document and analyze their interaction and effect on laboratory performance tests.

2. Conduct laboratory tests that are directly correlated to adhesive failure such as the Bond Test to evaluate sealant bond strength to the surrounding crack walls.

3. Develop finite element analysis and/or use simulation models to analyze the vertical and horizontal forces excreted within and around the crack to model sealants mechanistically.

4. Conduct an evaluation comparing RTFO aged sealant to aged sealants at various time periods from a controlled field installation to determine the degree of aging RTFO induces on a sealant.

5. Continue to build on the conducted agency survey by focusing on different climatic locations, and additional questions to provide an overall view of sealants' failure modes and practices in every region in the United States.

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APPENDIX A

CRACK SEALANT USE AND PERFORMANCE SURVEY

Survey Questions:

1. Type of agency responding?
2. The responding geographic location?
3. How important is crack sealing within the agency's pavement preservation program?
4. Does your agency rout the cracks before applying the sealant?
5. What is the average service life of crack sealants in years?
6. Rank crack sealant failure modes in terms of occurrence?
   a) Adhesive Failure (sealant separating from the walls)
   b) Cohesive Failure (failure within the sealant)
   c) Settlement Failure
   d) Pullout Failure
   e) Spalls or Secondary Cracking

Survey Results:

Count	Q1	Q2	Q3					Q4	Q5	Q6
			a	b	c	d	e			
1	Other	2	2	4	3	1	1	4	Southwest	No
2	Other	2	2	4	3	1	1	4	Southwest	No
3	Local Gov.	5	3	1	3	1	3	5	West	No
4	Other	6	1	5	1	1	3	2	Southwest	Some
5	Local Gov.	4	-	-	-	-	-	5	Southwest	Some
6	Other	2	3	2	3	2	2	3	Southwest	Yes
7	State	5	4	3	4	2	1	4	Southwest	Some
8	State	2	4	2	2	2	3	4	Southwest	Some
9	State	1	4	2	3	4	2	4	Southwest	No
10	City	3	1	1	3	1	4	5	Southwest	No
11	Other	-	-	-	-	-	-	-	Southwest	-

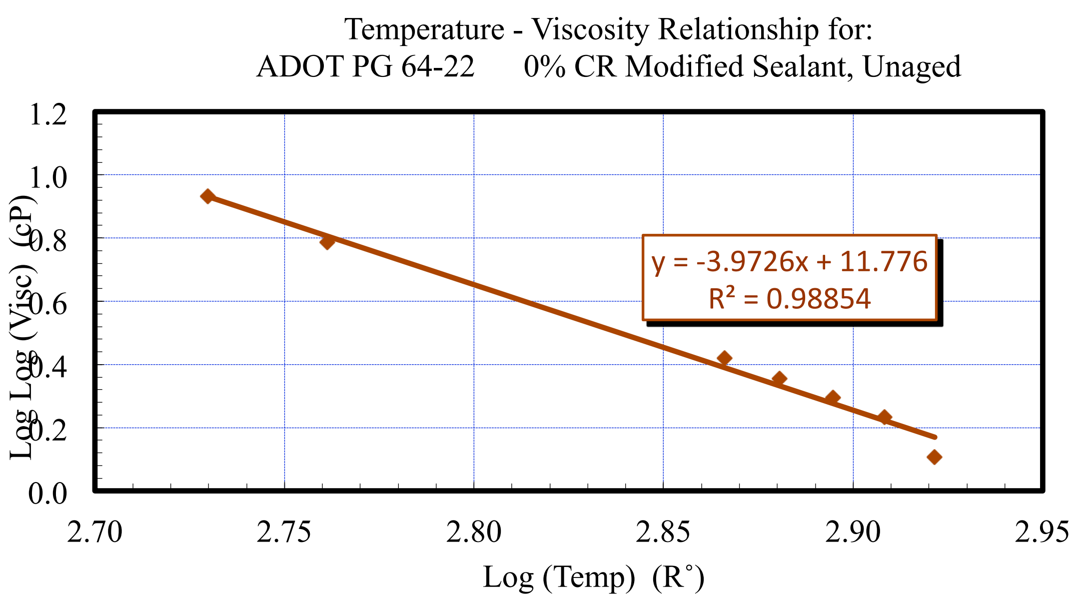
12	City	4	3	2	2	4	3	5	West	Some
13	Local Gov.	2	5	2	5	2	2	3	Southwest	Yes
14	Other	1	4	3	5	5	2	5	Southwest	Yes
15	City	4	1	1	2	2	3	5	Southwest	No
16	City	5	4	4	4	2	4	3	Southwest	No
17	Other	-	4	1	1	3	2	5	Southwest	Some
18	County	1	2	1	1	1	1	5	Southwest	No
19	State	3	3	3	5	1	1	5	Northeast	No
20	County	5	3	3	3	2	2	5	West	No
21	County	2	5	3	3	5	5	1	Southwest	Some
22	City	7	1	1	2	1	5	3	Southwest	No
23	County	7	2	1	1	1	1	5	Southwest	No
24	County	2	3	2	4	2	2	4	Southwest	No
25	County	2	2	3	2	3	3	4	Southeast	Yes
26	City	2	3	2	2	2	3	5	Southwest	No
27	State	2	2	2	3	4	1	5	Southwest	Yes
28	State	3	3	1	2	3	5	5	Northeast	No
29	Other	2	2	4	4	2	2	5	Southwest	No
30	Other	3	3	1	2	1	1	5	Southwest	Some
31	Other	2	3	1	1	1	2	4	Southwest	Yes
32	County	3	3	3	3	3	5	4	Southwest	No
33	State	1	4	2	4	4	4	4	Southwest	Yes
34	Other	2	3	2	2	3	3	3	Southwest	-
35	State	3	2	2	2	2	1	4	Southeast	Yes
36	City	4	2	4	2	1	4	5	Southwest	Yes
37	Other	3	1	1	1	1	1	5	West	No
38	City	3	3	1	5	2	2	4	Southwest	No
39	City	-	1	1	4	1	3	5	Southwest	No
40	County	3	3	3	3	3	3	5	Southwest	Yes
41	County	4	3	2	2	1	2	5	Southeast	Some
42	City	5	4	5	2	3	1	5	Southwest	Some

APPENDIX B

VISCOSITY – TEMPERATURE SUSCEPTIBILITY GRAPHS AND TABLES

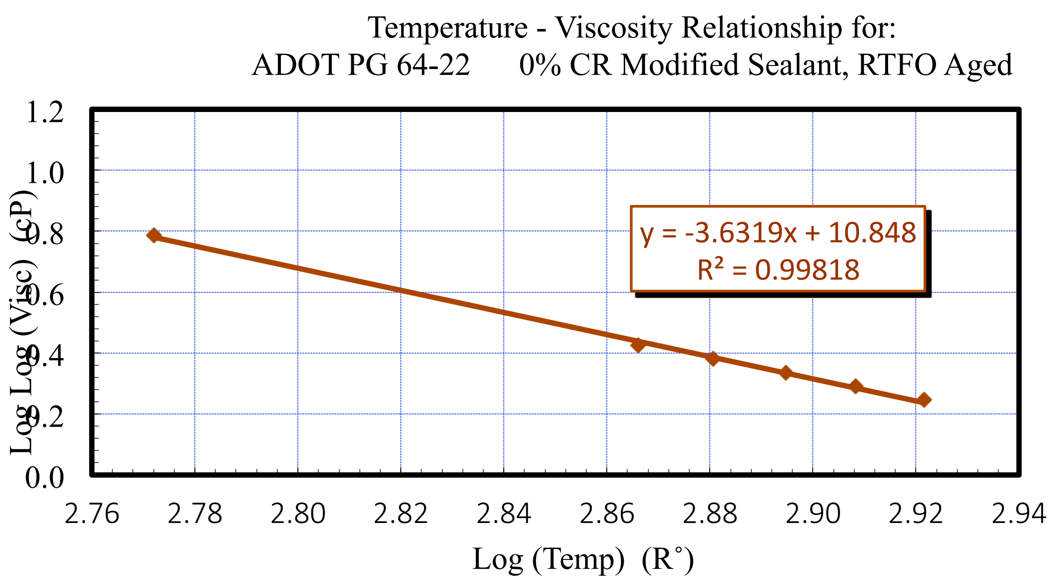
PG64-22 Binder 0% Crumb Rubber (Unaged)

Test	Temp (C)	Temp (F)	Temp (R)	Log Temp (R)	SPT (.1mm)	Vis. (Poise)	Vis. (cP)	Log Log Visc (cP)
SPT	25.0	77	536.7	2.73	*57.60*	3.4E+06	3.4E+08	0.931
Softening Point	47.5	117.5	577.2	2.76	---	13000	1.3E+06	0.786
Brookfield	135.0	275	734.7	2.87	---	---	*4.3E+02*	0.421
Brookfield	148.9	300	759.7	2.88	---	---	*1.8E+02*	0.354
Brookfield	162.8	325	784.7	2.89	---	---	*9.3E+01*	0.294
Brookfield	176.7	350	809.7	2.91	---	---	*5.2E+01*	0.234
Brookfield	190.6	375	834.7	2.92	---	---	*1.9E+01*	0.107



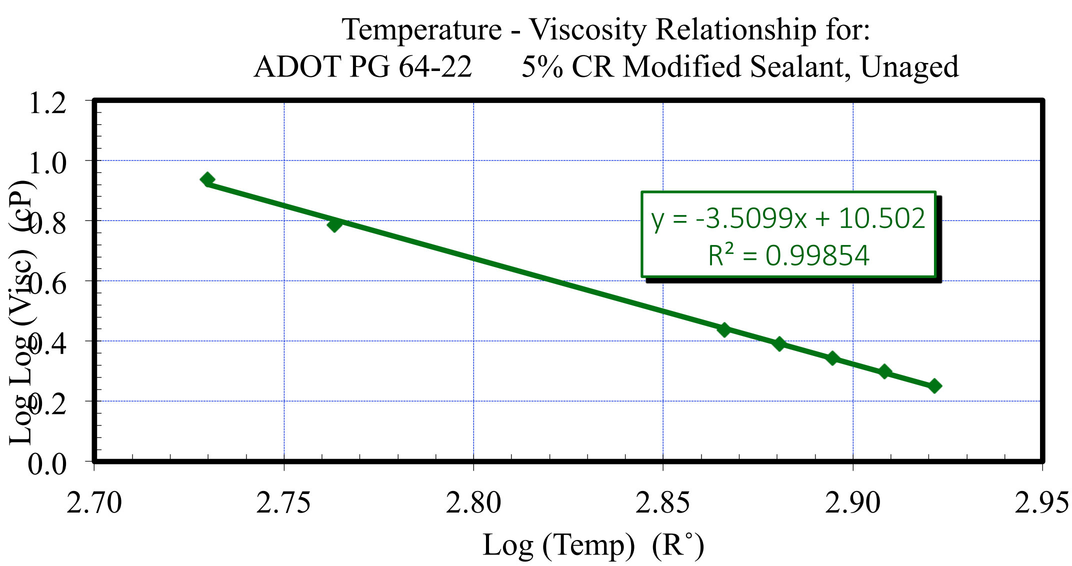
PG64-22 Binder 0% Crumb Rubber (RTFO Aged)

Test	Temp (C)	Temp (F)	Temp (R)	Log Temp (R)	SPT (.1mm)	Vis. (Poise)	Vis. (cP)	Log Log Visc (cP)
SPT	25.0	77	536.7	2.73				
Softening Point	55.5	131.9	591.6	2.77	---	13000	1.3E+06	0.786
Brookfield	135.0	275	734.7	2.87	---	---	*4.6E+02*	0.425
Brookfield	148.9	300	759.7	2.88	---	---	*2.5E+02*	0.380
Brookfield	162.8	325	784.7	2.89	---	---	*1.4E+02*	0.334
Brookfield	176.7	350	809.7	2.91	---	---	*8.9E+01*	0.290
Brookfield	190.6	375	834.7	2.92	---	---	*5.8E+01*	0.246



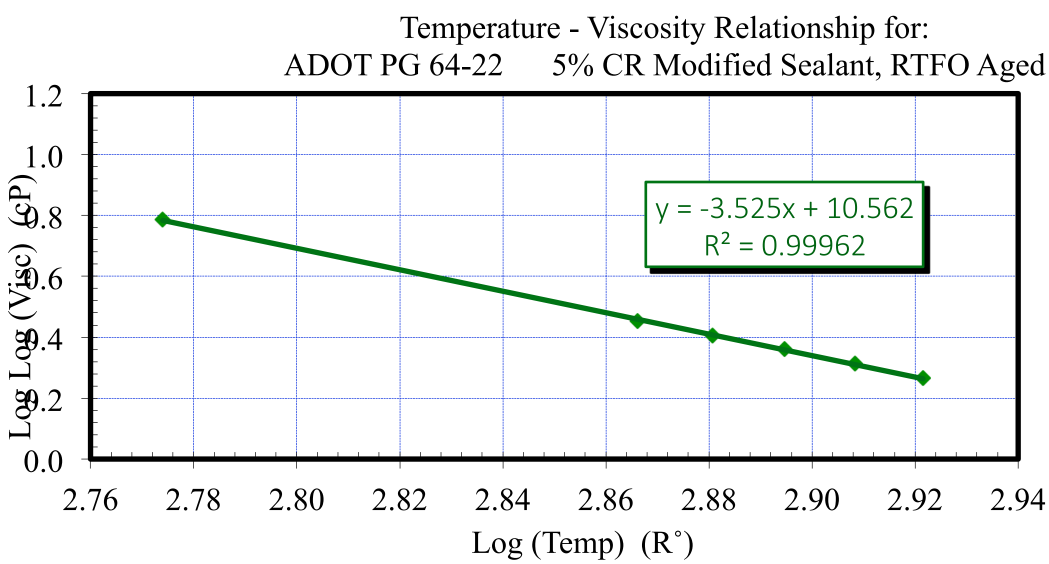
PG64-22 Binder 5% Crumb Rubber (Unaged)

Test	**Temp (C)**	**Temp (F)**	**Temp (R)**	**Log Temp (R)**	**SPT .1mm**	**Vis. (Poise)**	**Vis. (cP)**	**Log Log Visc (cP)**
SPT	25.0	77	536.7	2.73	*51.40*	4.4E+06	4.4E+08	0.937
Softening Point	49.0	120.2	579.9	2.76	---	13000	1.3E+06	0.786
Brookfield	135.0	275	734.7	2.87			*5.4E+02*	0.436
Brookfield	148.9	300	759.7	2.88	---	---	*2.9E+02*	0.390
Brookfield	162.8	325	784.7	2.89	---	---	*1.6E+02*	0.343
Brookfield	176.7	350	809.7	2.91	---	---	*9.8E+01*	0.300
Brookfield	190.6	375	834.7	2.92	---	---	*6.1E+01*	0.251



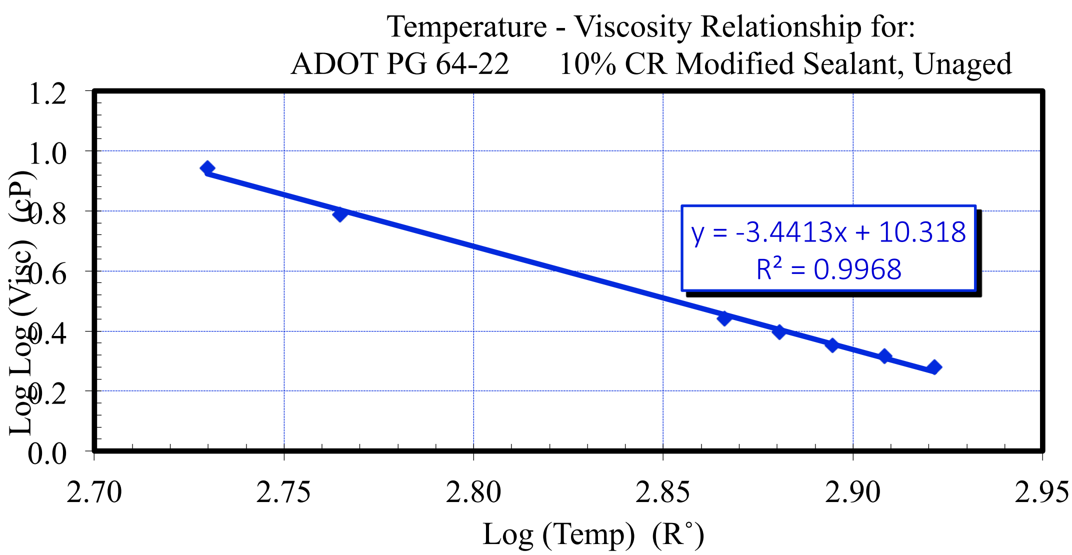
PG64-22 Binder 5% Crumb Rubber (RTFO Aged)

Test	Temp (C)	Temp (F)	Temp (R)	Log Temp (R)	SPT (.1mm)	Vis. (Poise)	Vis. (cP)	Log Log Visc (cP)
SPT	25.0	77	536.7	2.73				
Softening Point	57.0	134.6	594.3	2.77	---	13000	1.3E+06	0.786
Brookfield	135.0	275	734.7	2.87			*6.9E+02*	0.453
Brookfield	148.9	300	759.7	2.88	---	---	*3.4E+02*	0.404
Brookfield	162.8	325	784.7	2.89	---	---	*1.9E+02*	0.361
Brookfield	176.7	350	809.7	2.91	---	---	*1.1E+02*	0.312
Brookfield	190.6	375	834.7	2.92	---	---	*7.0E+01*	0.266



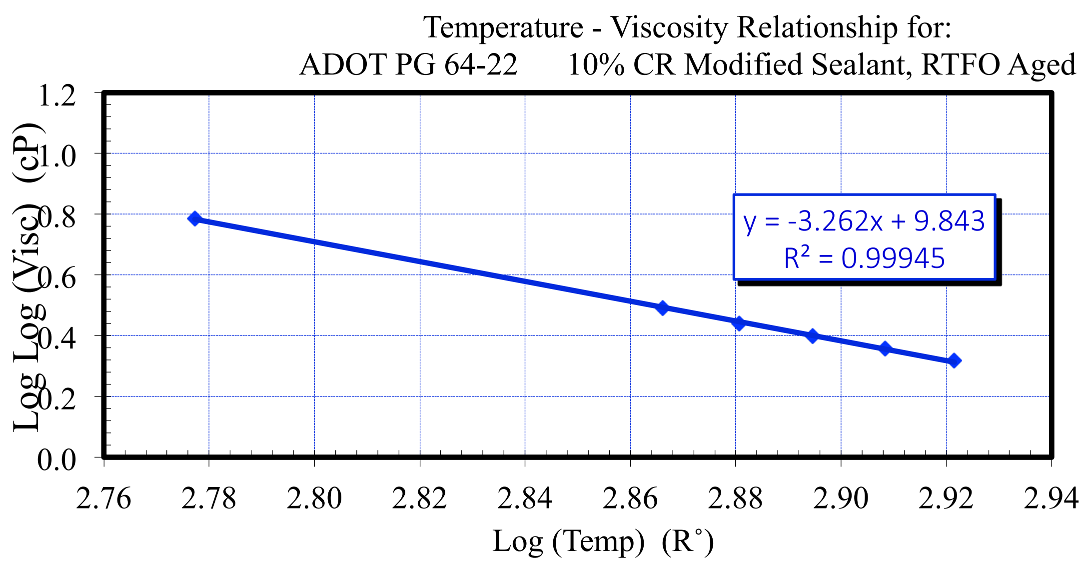
PG64-22 Binder 10% Crumb Rubber (Unaged)

Test	**Temp (C)**	**Temp (F)**	**Temp (R)**	**Log Temp (R)**	**SPT (.1mm)**	**Vis. (Poise)**	**Vis. (cP)**	**Log Log Visc (cP)**
SPT	25.0	77	536.7	2.73	*44.50*	6.1E+06	6.1E+08	0.944
Softening Point	50.0	122	581.7	2.76	---	13000	1.3E+06	0.786
Brookfield	135.0	275	734.7	2.87	---	---	*5.8E+02*	0.441
Brookfield	148.9	300	759.7	2.88	---	---	*3.1E+02*	0.396
Brookfield	162.8	325	784.7	2.89	---	---	*1.8E+02*	0.353
Brookfield	176.7	350	809.7	2.91	---	---	*1.2E+02*	0.315
Brookfield	190.6	375	834.7	2.92	---	---	*8.1E+01*	0.280



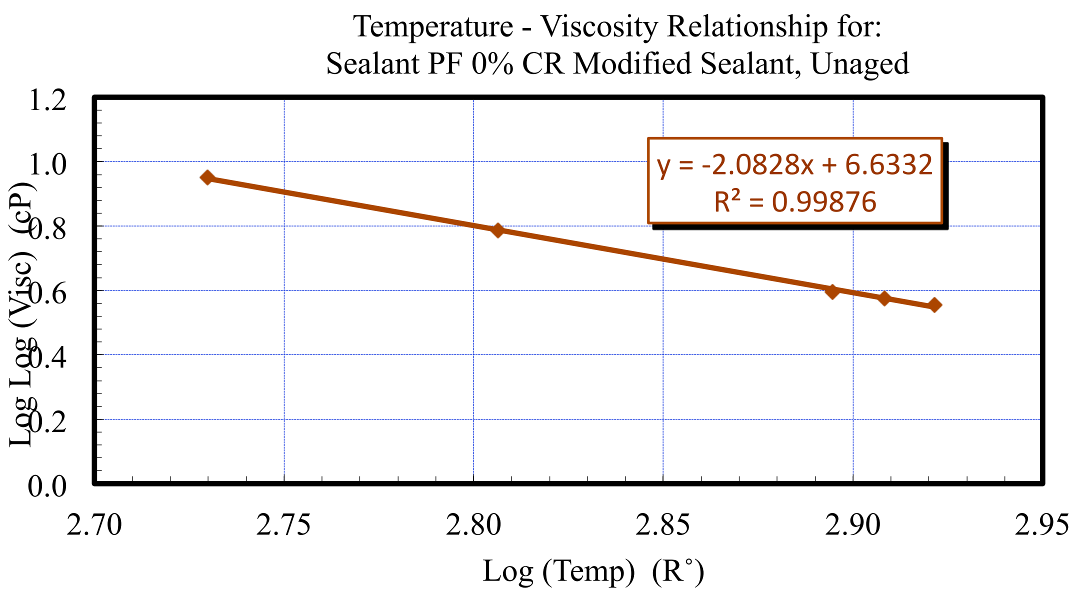
PG64-22 Binder 10% Crumb Rubber (RTFO Aged)

Test	Temp (C)	Temp (F)	Temp (R)	Log Temp (R)	SPT (.1mm)	Vis. (Poise)	Vis. (cP)	Log Log Visc (cP)
SPT	25.0	77	536.7	2.73				
Softening Point	59.5	139.1	598.8	2.78	---	13000	1.3E+06	0.786
Brookfield	135.0	275	734.7	2.87			*1.2E+03*	0.491
Brookfield	148.9	300	759.7	2.88	---	---	*5.8E+02*	0.441
Brookfield	162.8	325	784.7	2.89	---	---	*3.2E+02*	0.399
Brookfield	176.7	350	809.7	2.91	---	---	*1.9E+02*	0.358
Brookfield	190.6	375	834.7	2.92	---	---	*1.2E+02*	0.318



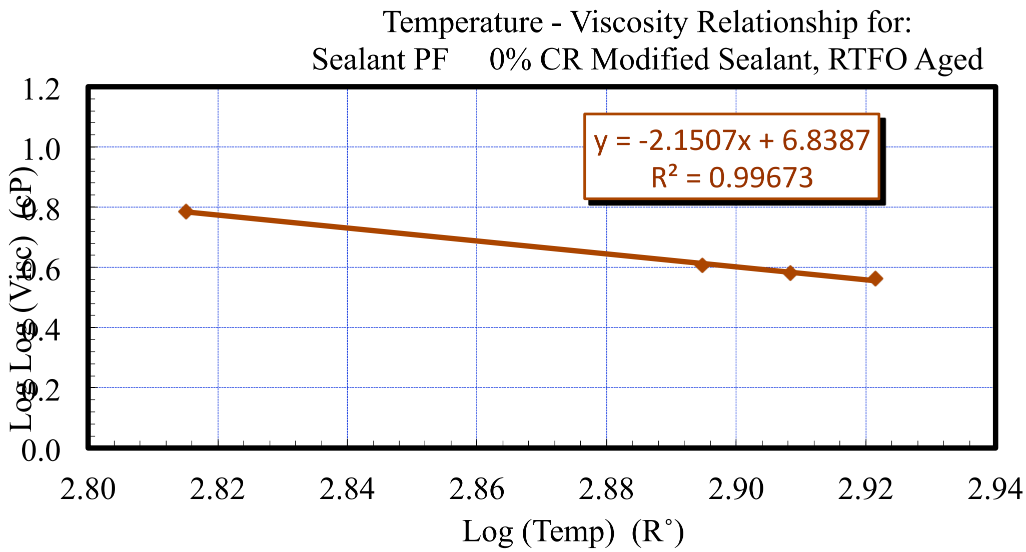
Sealant PF Binder 0% Crumb Rubber (Unaged)

Test	Temp (C)	Temp (F)	Temp (R)	Log Temp (R)	SPT (.1mm)	Vis. (Poise)	Vis. (cP)	Log Log Visc (cP)
SPT	25.0	77	536.7	2.73	*39.00*	8.2E+06	8.2E+08	0.950
Softening Point	82.5	180.5	640.2	2.81	---	13000	1.3E+06	0.786
Brookfield	162.8	325	784.7	2.89	---	---	*8.8E+03*	0.596
Brookfield	176.7	350	809.7	2.91	---	---	*5.8E+03*	0.576
Brookfield	190.6	375	834.7	2.92	---	---	*3.9E+03*	0.556



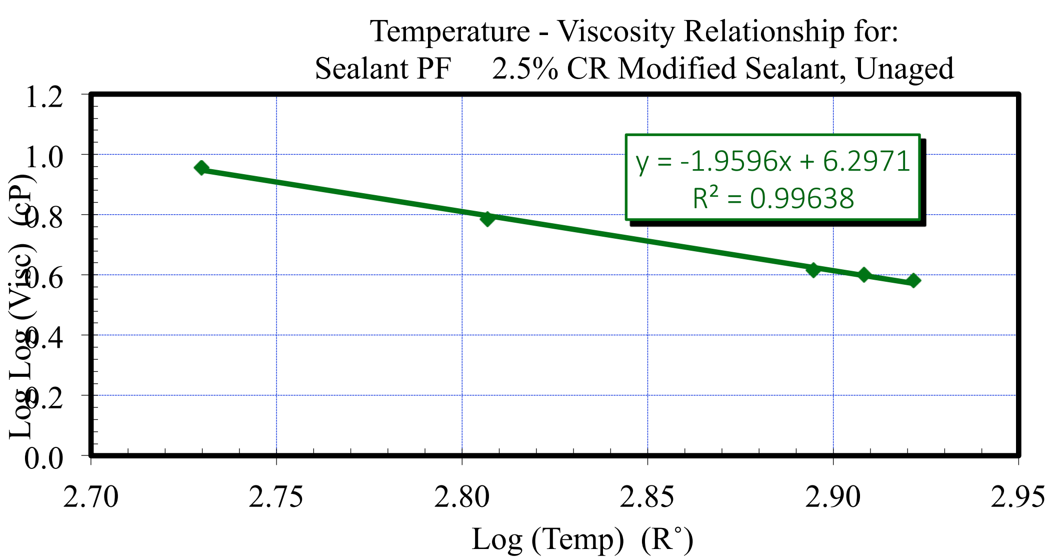
Sealant PF 0% Crumb Rubber (RTFO Aged)

Test	Temp (C)	Temp (F)	Temp (R)	Log Temp (R)	SPT (.1mm)	Vis. (Poise)	Vis. (cP)	Log Log Visc (cP)
SPT	25.0	77	536.7	2.73				
Softening Point	89.8	193.55	653.25	2.82	---	13000	1.3E+06	0.786
Brookfield	162.8	325	784.7	2.89	---	---	*1.1E+04*	0.606
Brookfield	176.7	350	809.7	2.91	---	---	*6.6E+03*	0.582
Brookfield	190.6	375	834.7	2.92	---	---	*4.5E+03*	0.562



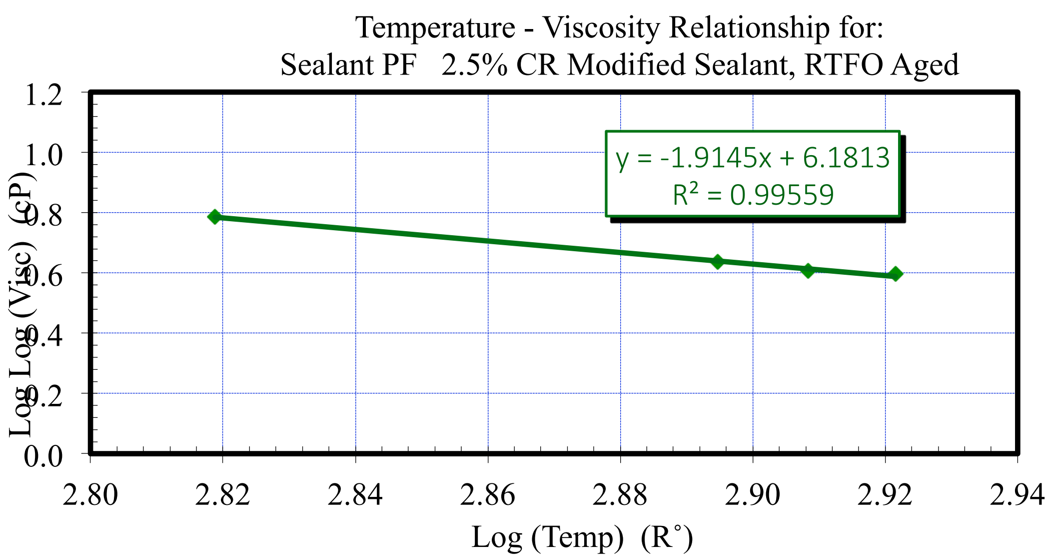
Sealant PF Binder 2.5% Crumb Rubber (Unaged)

Test	Temp (C)	Temp (F)	Temp (R)	Log Temp (R)	SPT .1mm	Vis. (Poise)	Vis. (cP)	Log Log Visc (cP)
SPT	25.0	77	536.7	2.73	*35.00*	1.1E+07	1.1E+09	0.955
Softening Point	83.0	181.4	641.1	2.81	---	13000	1.3E+06	0.786
Brookfield	162.8	325	784.7	2.89	---	---	*1.3E+04*	0.614
Brookfield	176.7	350	809.7	2.91	---	---	*9.7E+03*	0.601
Brookfield	190.6	375	834.7	2.92	---	---	*6.6E+03*	0.582



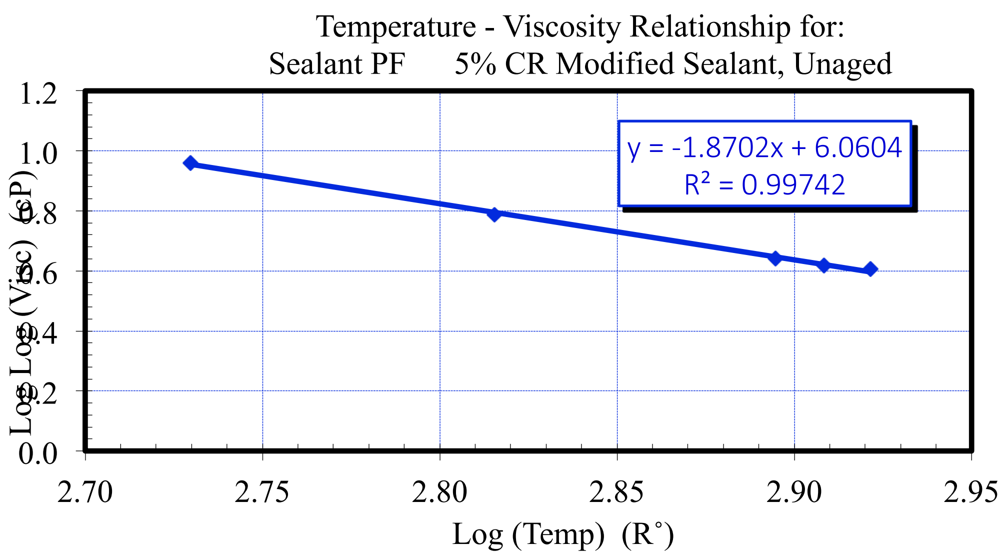
Sealant PF 2.5% Crumb Rubber (RTFO Aged)

Test	Temp (C)	Temp (F)	Temp (R)	Log Temp (R)	SPT (.1mm)	Vis. (Poise)	Vis. (cP)	Log Log Visc (cP)
SPT	25.0	77	536.7	2.73				
Softening Point	92.9	199.17	658.87	2.82	---	13000	1.3E+06	0.786
Brookfield	162.8	325	784.7	2.89	---	---	*2.1E+04*	0.636
Brookfield	176.7	350	809.7	2.91	---	---	*1.1E+04*	0.608
Brookfield	190.6	375	834.7	2.92	---	---	*8.7E+03*	0.596



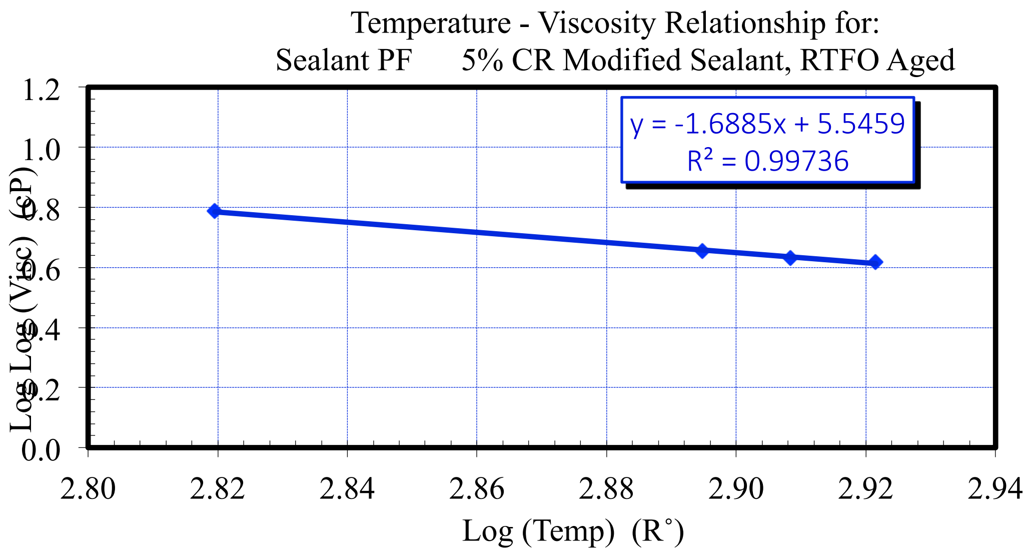
Sealant PF Binder 5% Crumb Rubber (Unaged)

Test	**Temp (C)**	**Temp (F)**	**Temp (R)**	**Log Temp (R)**	**SPT .1mm**	**Vis. (Poise)**	**Vis. (cP)**	**Log Log Visc (cP)**
SPT	25.0	77	536.7	2.73	*31*	1.4E+07	1.4E+09	0.961
Softening Point	90.0	194	653.7	2.82	---	13000	1.3E+06	0.786
Brookfield	162.8	325	784.7	2.89	---	---	*2.4E+04*	0.642
Brookfield	176.7	350	809.7	2.91	---	---	*1.4E+04*	0.619
Brookfield	190.6	375	834.7	2.92	---	---	*1.1E+04*	0.607



Sealant PF 5% Crumb Rubber (RTFO Aged)

Test	Temp (C)	Temp (F)	Temp (R)	Log Temp (R)	SPT .1mm	Vis. (Poise)	Vis. (cP)	Log Log Visc (cP)
SPT	25.0	77	536.7	2.73				
Softening Point	93.5	200.3	660	2.82	---	13000	1.30E+06	0.786
Brookfield	162.8	325	784.7	2.89	---	---	*3.26E+04*	0.655
Brookfield	176.7	350	809.7	2.91	---	---	*1.95E+04*	0.632
Brookfield	190.6	375	834.7	2.92	---	---	*1.41E+04*	0.618



APPENDIX C

ANOVA TESTS FOR PENETRATION AND RECOVERY TESTS

ANOVA test of SPT for PG64-22 Binder

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
0	5	288	57.6	5.3
0.05	5	257	51.4	2.8
0.1	5	222.5	44.5	1.25

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	429.4333	2	214.7167	68.89305	2.64E-07	3.885294
Within Groups	37.4	12	3.116667			
Total	466.8333	14				

ANOVA test of SPT for Sealant PF

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
0	5	193	38.6	0.8
0.025	5	174	34.8	1.7
0.05	5	156	31.2	1.7

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	136.9333	2	68.46667	48.90476	1.7E-06	3.885294
Within Groups	16.8	12	1.4			
Total	153.7333	14				

ANOVA test of CPT for PG64-22 Binder

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
0	5	318.5	63.7	2.7
0.05	5	271	54.2	0.2
0.1	5	237	47.4	6.3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	670.3	2	335.15	109.288	1.99E-08	3.885294
Within Groups	36.8	12	3.066667			
Total	707.1	14				

ANOVA test of CPT for Sealant PF

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
0	5	203	40.6	1.3
0.025	5	145	29	2
0.05	5	122	24.4	1.3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	696.9333	2	348.4667	227.2609	2.9E-10	3.885294
Within Groups	18.4	12	1.533333			
Total	715.3333	14				

ANOVA test of Resilience Test for PG64-22 Binder

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
0	4	0	0	0
0.05	4	11	2.75	0.25
0.1	4	25.5	6.375	0.229167

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	81.79167	2	40.89583	256.0435	1.17E-08	4.256495
Within Groups	1.4375	9	0.159722			
Total	83.22917	11				

ANOVA test of Resilience Test for Sealant PF

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
0	4	134	33.5	1.666667
0.025	4	157	39.25	0.25
0.05	4	175	43.75	2.25

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	211.1667	2	105.5833	76.02	2.31E-06	4.256495
Within Groups	12.5	9	1.388889			
Total	223.6667	11				