Innovative Modification and Testing of Asphalt Crack Sealants

by

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ABSTRACT

Asphalt crack sealants are essential for preserving the integrity of asphalt pavements. They act as a barrier against water infiltration, a primary cause of base erosion and structural failure. However, these sealants are susceptible to degradation from traffic wear, weathering, and thermal stresses. This degradation manifests in multiple failure modes, including loss of cohesion, adhesion, and settlement. Being one of the most cost-effective pavement maintenance techniques, its market size is expected to be worth about $1.1 billion by 2028, with a 56% market share in North America alone. With extreme climatic events, sealants will have a tendency to fail more often. Therefore, this research effort investigated the incorporation of various modifiers into asphalt crack sealants and fillers to enhance their performance and durability, to perform beyond their designed life. Four different modifiers were selected and tested using a specific laboratory testing protocol targeting the failure modes observed in the field and ultimately leading to extended pavement lifespans and reduced maintenance expenditures. Furthermore, a novel test procedure to measure the coefficient of expansion and contraction of control and modified sealants was developed and calibrated as part of this study. These modifiers included an aerogel modified bituminous material, a pre-activated crumb rubber material, a recycled aerogel composite, and synthetic fibers.

The testing program included durability and strength testing such as bonding strength, shear thinning, toughness, and tenacity; and thermal behavior testing such as expansion and contraction, thermal conductivity, and specific heat capacity. The coated aerogel modifier provided better toughness, tenacity, and bonding properties with improved thermal properties. The pre-activated crumb rubber reduced the effect of aging,

whereas fibers showed promising results across most parameters. As for the recycled aerogel composite, thermal susceptibility was slightly improved, in addition to low temperature behavior for the filling material.

Finally, a multiple decision-making criteria method was adopted to rank the best modifier for each material for parking lots and roadways followed by a life cycle cost analysis. A survey was conducted to rate the importance of each factor affecting performance, based on the integration of both quantitative and qualitative criteria, thereby accommodating diverse decision contexts and preferences.

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CHAPTER 1

1 INTRODUCTION

1.1. Problem Statement

Asphalt Crack Sealants are mainly composed of a mixture of materials that will form a resilient and adhesive compound. They are designed to effectively seal joints and cracks in pavements against moisture infiltration and foreign material throughout repeated cycles of expansion and contraction with temperature changes. These materials mainly consist of rubberized asphalt cement that is a liquid when heated and solid when cooled. Crack sealants are one of the inexpensive pavement maintenance techniques and typically last from 3 to 5 years. Researchers have widely demonstrated the cost-effectiveness of crack sealants (Cuelho et al., 2003). They are used on early-stage longitudinal cracks, transverse cracks, reflection cracks and block cracks. Sealants are produced to keep their shape and harden through chemical and physical processes to withstand crack movements and weathering (E. Fini et al., 2007).

The global market size for crack sealing and filling was estimated to be worth $861.9 million dollars in 2022 and is forecast to reach $1090.5 million by 2028 at a compound annual growth rate of 4% for the period of 2022 to 2028. In this market, North America occupies the main market share of 54%, followed by the Asia-Pacific region with a share of 26% (*Crack Sealing and Crack Filling Market Size, Report 2031*, n.d.). The key factor driving the growth of the crack sealing and filling industry and market share is the growing demand of product in the highway and arterial roads, which are the biggest segment of the market, followed by parking lots, airports, and residential streets.

However, these materials may fail due to different circumstances in the field. During the installation, if the viscosity of the sealant is too high, it may not be able to fill the crack properly without overflowing and affecting the bonding between the pavement's interface and the material itself. On the other hand, if the viscosity is too low, it will flow out of the crack (Al-Qadi, Fini, et al., 2006). Other failure types happen at high service temperatures where it may fail due to tire pullout from the crack, known as tracking (P. Collins et al., 2008). Studies have shown that bituminous sealants applied to cracked pavements sometimes fail due to deformation under the action of shear stresses and high temperatures (Masson et al., 2007). At low temperatures, the crack's width will increase due to the contraction mechanism which will lead to either a cohesive or adhesive failure. The sealant becomes brittle due to physical hardening while it is being subjected to loading (Al-Qadi, Yang, et al., 2006).

To obtain a successful and cost-effective crack sealing performance, the mechanical and rheological properties of the material must be closely controlled: viscosity, stiffness, bonding strength, and shear thinning. Therefore, crack sealants are selected based on a series of conventional tests developed by the American Association of State Highway and Transportation Officials (AASHTO) and the American Society of Testing Materials (ASTM) International (ASTM D5329, 2020a; ASTM D6690, 2021).

Given those reasons and growing market opportunities, there is a need to improve the performance of the crack sealants in the field and increase their service life. This study investigated untraditional and novel modifiers that could potentially improve the performance of sealants; it also proposes new parameters and evaluation techniques that could provide insight into their performance in the field. Those properties take into consideration the material's behavior with respect to different climates and applications, such as toughness and tenacity, moisture susceptibility and thermal properties.

1.2. Research Objectives

The main objective of this study is to recommend and execute a laboratory test protocol to better evaluate the hot asphalt crack sealant behavior in different climates and conditions, mainly temperature cycling, for both unaged and aged conditions. The testing includes high and low temperature settings, to reflect different performance conditions in the field. This experimental work was achieved by examining different modifiers and two different sealant types to identify potential improvements in performance as well as increased durability under different conditions.

The recommended testing protocol tackles two different aspects to enhance the crack sealing durability: performance testing, which relies on the rheological and strength properties of the material, and thermal properties measurement and behavior identification. Those two testing phases address the different failure modes experienced by the asphalt crack sealants under different climatic conditions; it will also identify the behaviors of the modified sealants compared to the conventional material.

Within the framework of the main objective, a secondary objective of this study focuses on material characterization; specifically, to study the effect of loading rates and temperatures on the performance of sealants. In particular, the toughness and tenacity testing procedure developed for asphalt binders is of interest (ASTM D5801, 2024). As asphalt crack sealants are temperature susceptible, studying the behavior at low, intermediate, and high temperatures is crucial for material and behavior characterization.

Regarding the thermal properties, understanding the effect of temperature exposure and cycling on the sealant is also of equal importance to strength performance. One important material property resulting from temperature fluctuation is the expansion and contraction mechanisms of crack sealants. The author is not aware of any specific test being used for crack sealants or fillers. Therefore, a novel expansion and contraction test protocol was developed as part of this study as a third objective. In terms of sealant modification, better flexibility, expansion, and contraction considerations as well as reduced thermal susceptibility will be targeted with different modifier types and contents.

1.3. Scope of Work

The research scope of work is presented in this section. **Figure 1** represents a flowchart summarizing the overall research outline of the study. The scope includes the following:

- Conduct literature review.
- Identify the typical failure modes of asphalt crack sealants.
- Understand the different test procedures already available for crack sealants.
- Design and conduct a testing protocol tackling both rheological and thermal performance of the sealants.
- Determine the different effect on performance of modifiers on two types of asphalt crack sealants. These modifiers include: aerogel modified bituminous material “aMBx”; it is aerogel based and potentially has the capability to reduce thermal susceptibility of the sealants and enhance its adhesive properties; a Pre-activated Crumb Rubber (PCR) to provide additional flexibility and strength; a Recycled aerogel Composite (RaC), which included both crumb rubber and aerogel, for

possible thermal resistance and added flexible behavior; and the fourth modifier comprised a blend of copolymer polypropylene, polyethylene terephthalate and spandex Synthetic Fibers (SF) for improved flexibility and crack movement accommodation.. Again, each of those modifiers targeted potential improvement of specific properties such as thermal insulation, elasticity, and improved high temperature performance.

- Identify the best mixing procedure, optimum dosage content and improvements obtained from the different modifiers.
- Design a novel laboratory test procedure measuring the coefficient of thermal expansion and contraction of sealants and fillers and use it in the experimental program.
- Assess material behavior at different loading rates and temperatures using the toughness and tenacity testing procedures. This could provide indication and recommendations on the best performance under different conditions for the material (i.e., best temperature at optimum pull out rate).
- Recommend the best sealant modification according to the different applications, locations, and climate.
- Analyze the cost breakdown of each modifier and sealing activity to support the recommendation.

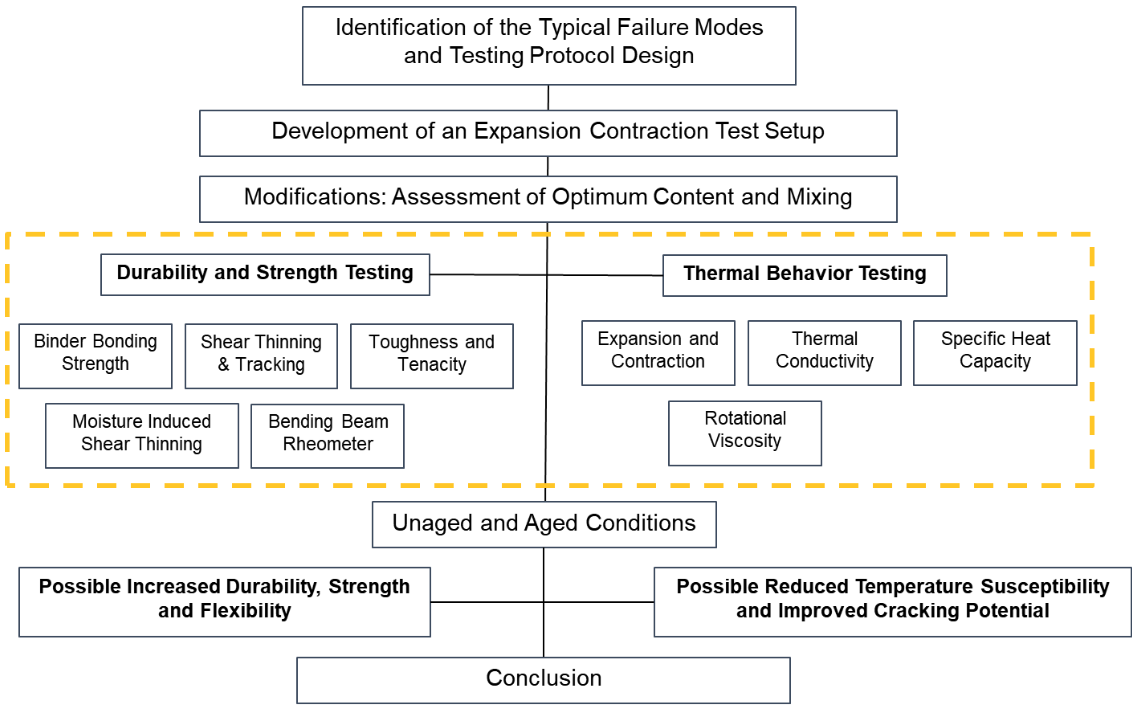


Figure 1- Research Methodology and Experimental Program

1.4. Report Organization

This dissertation is divided into 11 chapters. Chapter 1, the introduction, includes the problem statement, research objectives and the outline of the scope of work. Chapter 2 includes the literature review and theoretical background with respect to asphalt crack sealant applications in the field, standard procedures, and specifications as well as recent studies conducted relevant to the project. It also includes an in-depth analysis of the parameters of interest that are affecting the performance and durability of the materials in the field. Those parameters will be used in the future assessment of the performance of the material. Furthermore, it explains the different techniques implemented to improve the material's performance, as well as a wide description of the modifiers that are used in this study in the efforts of modifying the asphalt crack sealants to increase their durability. Chapter 3 shows the experimental plan, as well as the suggested tests performed on both unmodified and modified sealant for different aging levels. Furthermore, this section summarizes the modification techniques as well as the testing protocol suggested to assess the durability and performance of the materials. Chapter 4 of this study shows the development of a new test procedure to measure the linear expansion and contraction coefficient of bituminous materials. This section includes the developed procedure as well as the geometry analysis of the samples to be tested and the calibration curves for further sample testing. As for Chapter 5, it includes a material characterization analysis based on measured toughness and tenacity parameters of asphalt crack sealants. The behavior of the material will be analyzed based on different temperatures and pulling rates to identify its characteristics under different settings. Chapter 6, 7, 8 and 9 include the assessment and results obtained from the sealant modification testing using aMBx, RaC, PCR and SF respectively. The potential improvement of the suggested modifiers will be evaluated, and an optimum modifier content will be recommended. As for Chapter 10, it includes the multi-criteria decision-making analysis, where the results obtained from the laboratory testing will determine the ranking for all modified material. A Life Cycle Cost Analysis was also developed as part of this chapter based on the results obtained from the multi-criteria decision-making method. Finally, Chapter 11 consist of the summary, conclusions and recommendations based on this study.

CHAPTER 2

2 LITERATURE REVIEW

2.1. Hot-Poured Asphalt Crack Sealant Composition

Crack sealing is one of the least expensive maintenance techniques used to prevent moisture infiltration into pavements. This material is produced in such a way that it keeps its shape when applied and hardens through chemical and physical processes (Al-Qadi et al., 2017). Crack sealants are resilient compounds capable of effectively sealing cracks and form a viscoelastic rubber-like material sustaining expansion and contraction with respect to the crack movement. To achieve a cost-effective crack sealing activity and appropriate, many factors should be considered such as proper installation, and mechanical and rheological properties of the sealant depending on the climate. In general, sealants are composed of bitumen, fillers, and styrene-butadiene (SB) copolymer. The fillers can be typically ground tire rubber, calcium carbonate, fibers, or mineral fines. As for the SB copolymer, it consists of blocks of polystyrene (PS) and polybutadiene (PB) (Al-Qadi et al., 2007). As different manufacturers have their own recipe to produce hot-poured asphalt crack sealants, the chemical composition depends on the different contents of the main components. For this reason, it is important to test multiple types of sealants with different compositions to be able to identify which one is most suitable for the desired application. Furthermore, variations in rheological properties could be due to the different sources of the components, notably the bitumen. Some manufacturers also add modifiers to the original composition, depending on the use. Polymer modified asphalt emulsion, asphalt binder, fiberized asphalt, and rubberized asphalt are also among the products used in crack sealing. In other words, crack sealants used in parking lots are going to be different than the ones used on residential roads in terms of composition, as the ones in parking lots are larger areas with much higher sun exposure.

Nowadays, various types of crack sealants are available and are chosen based on a series of specifications and temperature settings. The specific properties of a particular crack sealant will depend on its composition and the type of polymer used, as well as the specific requirements of the application and the conditions the pavement will be subjected to. Choosing the right crack sealant requires careful consideration of these factors, as well as a thorough understanding of the benefits and limitations of different types of sealants.

2.2. Different Types of Sealants and Applications

Preventive maintenance is characterized by the ability to preserve the pavement and increase its service life. Cracks on the surface of the pavement will allow the infiltration of debris, water, and incompressible materials, leading to a premature deterioration of the pavement. Crack sealants, when properly executed, can prevent the infiltration of such materials, and increase the life span of the pavement anywhere from 6 months to 4 years. According to the Texas Department of Transportation (TxDOT), cracks having a width greater than 1.5mm need to be sealed 6 to 12 months before applying any seal coat or overlay to minimize the potential of bleeding of the sealant into the subsequent surface layers (Yildirim, 2006). It is also important to select the right type of crack sealant for the desired applications under specific conditions. Crack sealing activities are not recommended for either fatigue or alligator cracking, as they do not add to the structural capacity of the pavement.

There are several types of asphalt crack sealants, including hot-applied and cold-applied sealants. Furthermore, it is important to note the two types of crack repair: crack sealing and crack filling. Usually, crack sealing refers to the activity of routing cracks and placing material within the routed channel, whereas crack filling refers to the placement of the material in an unrouted channel (Yildirim, 2006). Crack routing involves cutting through the crack to provide a uniform and rectangular reservoir for the material upon placement. It will allow better adhesion of the material to the pavement, with smooth and uniform edges.

Hot-applied sealants are heated to a liquid state and applied to the crack using a special applicator. They typically consist of a mixture of asphalt and rubber or plastic polymers and are used in larger cracks and joints.

Cold-applied sealants are applied as a solid or semi-solid material, without the need for heating. They typically consist of a rubber or plastic material and are used in smaller cracks and joints. As asphalt crack sealants are composed of asphalt binders, also referred to as Bitumen, aging and weathering are another major contributor to the overall performance of this maintenance technique.

2.3. Crack Sealing Activity Considerations

2.3.1. Factors Affecting Sealing Activities

Various factors should be taken into consideration before applying crack sealants. The ambient temperatures where the material is to be applied play a big role: sealing is generally done in winter seasons, where cracks are contracted and are open (between 7^{o}C and 20^{o}C). In addition, during the sealing procedures, all safety precautions must be taken with respect to the handling of the material and equipment. As crack sealants are typically installed at temperatures greater than equal to 180°C depending on the manufacturer's recommendations, special caution must be exercised. Another safety action must be taken concerns traffic control, where traffic control devices should be installed in work areas.

2.3.2. Crack Sealing Equipment

Crack sealing operations require a wide range of equipment for both crack and sealant preparation. This includes the sealant installation and finishing.

2.3.2.1. Crack Preparation Equipment

- Airblaster or leaf blower: air blasting is a method of cleaning cracks using a high-pressure air compressor placed on a truck with hoses and wands. This method is effective at removing dust and debris, but it is not effective in drying the crack channel. Air blasting may also be performed with leaf blowers, but most states do not allow it due to a lack of air velocity and poor cleaning results associated with it.
- Air lance: hot air blasting is a method of cleaning cracks using air that is heated to a minimum of 1,370°C. This method is effective at removing dirt and debris and creates a dry and hot crack surface for a sealant to bond to. A hot surface will likely create a better bond for the sealant by activating the binder in the pavement itself. However, caution must be used as it is possible to burn the asphalt concrete pavement with a lance. For this reason, an open flame torch should never be used for this procedure.
- Sandblaster: it is a highly effective way of removing debris and loosened fragments from the channel of a crack. This procedure leaves a smooth and textured surface

that is ideal for the sealant to bond to. Sandblasting consists of a compressed air unit, sandblaster machine, hoses, and a wand. One pass of the sandblaster should be made on each side of a routed reservoir. A second pass with an air compressor is typically necessary to clean any debris that was left during the sand blast. However, due to the number of passes needed, sand blasting requires a great deal of equipment, is labor-intensive, and time-consuming.

- Wire Brush: power-driven wire brushes are used in conjunction with some form of compressed air to clean cracks. This combination effectively removes debris from the crack but fails to remove loose pieces of the asphalt. Wire brushes are available with and without blowers. Some contractors have had success modifying pavement saws to fit wire brushes in place of the saw blade.
- Routing Machine (router): crack routing is performed by a worker using a router or saw unit mounted onto a cart. The operator uses his/her eyes and best judgment to follow the path of the crack with the routing or sawing machine. It was noted that although a saw with a 150-200 mm diameter diamond blade can follow the meanders of cracks well, the high cutting rate of an impact router creates smoother reservoir walls with a higher percentage of aggregate area for the sealant to bond to. Most companies require that employees operating routing equipment wear some type of respirator mask. The most modern routing machines have air and dust control systems built into them.

2.3.2.2. Sealant Preparation Equipment

- Melter: hot pour sealant is heated in a double-walled heating tank that uses a heat transfer oil, such that no flames come into direct contact with the tank holding the sealant. The Federal Highway Administration (FHWA) recommends that the Melter should allow an operator to regulate the sealant temperature up to 220°C (428°F). The ideal heated temperature of each sealant material is typically specified on the package label. Upon being heated, the materials will transform from a solid state to a liquid state. Some melters have a recirculation feature, which is important to prevent temperature stratification within the tank and maintain a proper temperature for the sealant being laid into cracks.

- Distribution Hose: A Melter truck has various distribution hoses connected to the back of it. The sealant flows through these hoses in order to be applied into cracks. A distribution hose may have a precision tip or may be equipped with a squeegee type nozzle that shapes the material in addition to applying it into the crack. A metal distributor may also be used to level off the poured sealant if no squeegee is present.
- Blotter Applier: the use of paper blotter material is to prevent fresh sealant material from sticking to passing vehicle tires. However, it is common practice to use a release agent such as soapy water to prevent the sealant from sticking to vehicle tires.
- Applicator: using an applicator is essential to pour sealants into the cracks or the routs efficiently, ensuring that the material is filling the crack.
- Squeegee: the use of a squeegee is for leveling and finishing and to provide a band extension on the sides of the crack.

2.3.3. Installation Methods

Before placing sealants, a clean dry crack is recommended to ensure the proper bonding between the pavement surface and the material. This step is called crack cleaning and is a crucial step to ensure proper installation as one of the most common failure modes is adhesive failure. To effectively clean the crack, the use of a high-pressure blasting device producing a jet stream of air is used to remove any impurities from the crack. The compressed air should have a minimum pressure of 690 kPa and a minimum blast flow of 4.3 m^3/min, free of moisture and oil. The second step involves drying the crack using a hot air lance, after which the material should be immediately placed (Crafco Inc, Installation Manual 2021).

In the case where crack routing is selected to seal large cracks, special consideration should be given to prevent the sealant from draining to the bottom of the crack. In this case, sand or backer rods are used in the cracks when appropriate. Blotting is also used when sealing large areas to maintain the skid resistance. It is referred to as the application of fine aggregate to the non-cured material to prevent tracking. The fine aggregate should be directly sprayed on the material to allow for proper adhesion and serve its purpose. Finally, all traffic should be reverted until the material has properly cured.

The proper installation method must be selected to ensure long-lasting crack sealing. The annual movement of the crack has an impact on the treatment method and amount of material needed. In other words, the width of the crack determines if routing is needed before sealing. In general, routing is recommended for narrow cracks, minimal edge deterioration and thermal and transverse cracks.

Clean-and-seal methods are used on all types of cracks and are the quickest and simplest method of sealing. It is recommended to clean and seal while the cracks are narrow during the spring and fall seasons when the temperatures are moderate. It is expected to perform for 3 years before signs of material pull-off appear from the side of the crack (Johnson, 2000).

As for Rout-and-seal, it is used on transverse cracks and involves using a router along the length of the crack to create centered reservoir. Working cracks (generally transverse cracks) have vertical and horizontal movements with a width greater than 2.5 mm and are recommended for routing. They open in the winter and close in the summer due to thermal expansion and contraction of the surrounding pavement. With this method, special consideration should be given such as flush fill, fill and overband, reservoir and combination as seen in **Figure 2**. Furthermore, those cracks are associated with the expansion and contraction of the surrounding pavement, which typically develop in the transverse direction. The cracks open in winter as the pavement contracts, and close in summer as the pavement expands at higher temperatures. This method is recommended early in the pavement's life to be successful (Johnson, 2000).

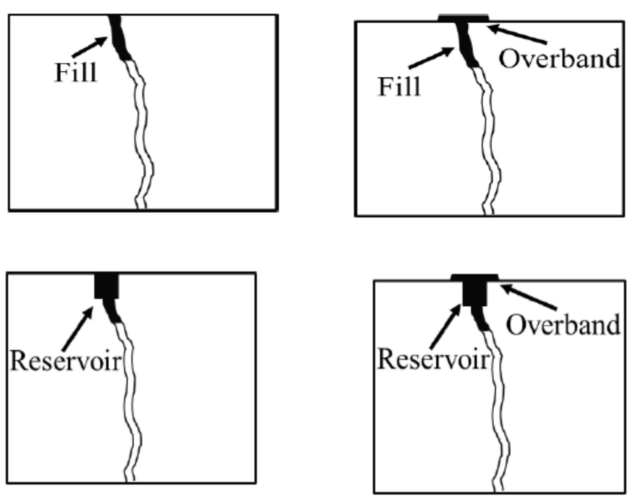


Figure 2- Routing Considerations for Crack Sealing using Reservoir or a Combination of Reservoir and Overband (Yildirim, 2006)

Crack sealing activities may vary depending on the country. In general, for working cracks, crack sealing is preferred. As for crack filling, they are often used on non-working cracks. This type of crack normally develops in the longitudinal direction and does not undergo notable changes in width with the change of seasons, typically due to pavement fatigue failure within the wheel path, or at the lane joint because of the weak or less-dense asphalt. A summary table (**Table 1**) of the procedures mentioned above was suggested in the FHWA report TPF-5 (Al-Qadi et al., 2017) and is shown below:

Table 1- Considerations for Sealant Placement

Consideration	Clean and Seal	Rout and Seal
Type and Extent of Operation	No crack cutting, shorter duration of operation, used when traffic closure is of concern	Larger duration of operation due to routing, requires traffic closure
Traffic	Overband wear is not of concern, impact on the sealant is less severe	Overband wear and high tensile stresses are experienced directly above the crack edge leading to internal failure
Crack Characteristics	Overband configurations are more appropriate for cracks having a considerable amount of edge deterioration (>10% of crack length), the overband simultaneously fills and covers the deterioration segments in the same pass.	
Material Type	Material such as emulsion, asphalt cement, and silicone must be placed unexposed to traffic due to serious tracking or abrasion problems.	
Desired Performance	For long-term sealant performance, flush, reservoir, and overband configurations should be considered (combination configuration).	
Cost	Filling requires less material than reservoir, leading to lower costs	Combination requires more material than reservoir, leading to higher costs

Recent studies showed that using overband configurations had a significant effect on crack sealant performances for certain width. However, excess overband contributes to pavement noises and is easily picked up by traffic (Ozer et al., 2014). For sealing, a combination of reservoir and overband was shown to reduce the likelihood of sealant failure during the service life. If the material had a lower modulus, a recession would form after installation and cooling leading to a premature failure of the sealant. Therefore, it was recommended to rout and seal in two steps, while the sealant is injected into the reservoir up to 2/3 of its depth. Then, the remaining is filled with an overband application followed by blotting. Another study was conducted to evaluate the effect of different installation parameters, notably the rout geometry, crack treatment type (rout and seal vs. clean and seal), overbanding, installation temperature and the pavement condition prior to installation of the sealant. A total of 8 hot-poured crack sealants in 3 different test sites were monitored in colder climates for 2 consecutive years (Solanki et al., 2014). The results showed that after 2 years of installation, the smallest rout geometry yielded the best performance, whereas the clean and seal sections showed the poorest performance on the same test section. Furthermore, overbanding showed better performance of the sealant.

2.3.4. Crack Sealing Construction Season

Crack sealing construction seasons largely affects the amount of product that is to be poured into the cracks. Furthermore, sealing in spring compared to summer months will result in different performances due to the difference in crack widths at the time of installation. During summer months, sealing while the crack is partially closed will allow a minimal amount of material to be placed. In this case, if the material is placed flat with the surface during the summer, it will have to stretch as the pavement contracts during the winter season. If the crack over-expands during winter, the material will either fail in adhesive or cohesive failures. On the other hand, crack sealing is not recommended in the winter. If the material is flushed to the road surface during winter, the material would overhang outside the crack in the summer. This will lead to material loss and tracking with the passing of tires. In addition, it is to be noted that during winter, crack preparation activities are more challenging. **Figure 3** shows the best seasons to apply crack sealants

(Spring and Fall), and the movements of the material corresponding to the crack movements.

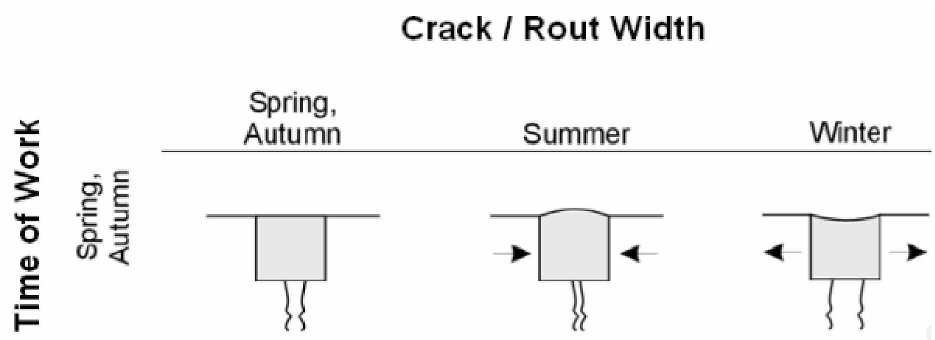


Figure 3- Crack Sealing Application Construction Seasons (Johnson, 2000)

The installation season is therefore recommended when the crack width is neither at its maximum or minimum, to allow for a reasonable expansion during the winter and maintain a minimal overhang during summer.

2.4. Failure Approaches

Over time, the sealant can harden, become brittle and crack, allowing water to penetrate the crack and cause further damage to the asphalt surface. In addition, some sealants can shrink and crack over time, especially in extreme weather conditions. As the sealant cools and dries, it can shrink and pull away from the sides of the crack, leading to cracking and failure. However, sealant failure can occur with issues related to application: improper preparation of the crack surface, incorrect sealing techniques, as well as using the wrong type of sealant can lead to failure. If the surface is not properly cleaned or if the sealant is not applied thick enough, it can fail to adhere to the surface, leading to cracking and separation.

The performance of the sealants depends in part on the size, shape, and cleanliness of the crack for optimized performance. An adequate bond between the material and the joint sidewalls is necessary, to prevent the sealant from pulling away from the joint face or being forced out of the joint during crack movements. The crack sealant undergoes specific stresses as the crack moves as per the following (Departments of the Army and the Air Force, 1993):

- Adhesive stresses: caused by the joint as it expands between the joint face and the sealant in tension. The sealant will separate from the side of the joint if the bond strength is too weak or the tensile stress created by the movement of the joint is too large.
- Cohesive stresses: caused by the tensile stresses within the material itself. The sealant will separate under stress if not sufficiently elastic or the interparticle bond within the material is too weak.
- Peeling stresses: caused by load concentrations at the edge of the contact between the sealant and the joint face. The sealant peels from the face of the joint leading to a loss of bond. This is also caused by excessive movement of the joint.
- Tensile stresses between the material and the face of the reservoir: caused by improper cleaning of the crack or joint, or when the concrete is deteriorated or damaged during joint preparation. The sealant will pull the weaker material apart with joint opening.
- Compressive stresses when the joint or crack closes: caused by contraction of the joint pushing the sealant above the surface of the pavement. This will cause

tire tracking of the sealing material, or a complete pull out of the sealant from the reservoir.

It is very important to ensure that the selected sealant material can maintain its elastic properties and withstand any crack movement. The stresses experienced by the poured sealant into a crack are shown in **Figure 4**.

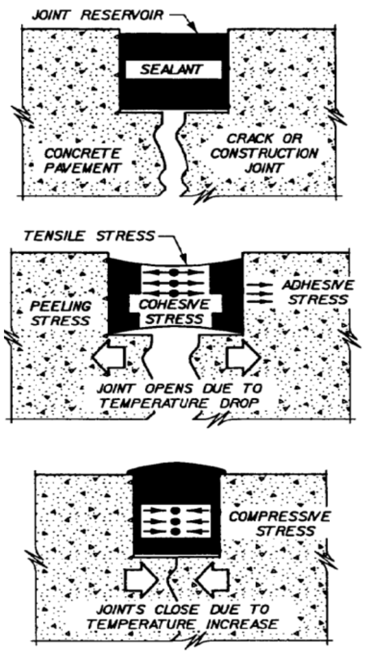


Figure 4- Stress Development in Asphalt Crack Sealants (Departments of the Army and the Air Force, 1993)

As the sealing material is subjected to crack or joint movements, it experiences a certain stress distribution that will limit its performance:

- A sealant in compression transmitting forces to the joint face will act similar to springs, known as the web stress of a seal. When the joint becomes too narrow, the compression stresses will cause the material, or in this case the webs, to lose their elasticity. As a result, the webs won’t be able to transmit the required forces to the joint face when it opens: the sealant will either fall at the bottom of the joint or is pulled out when the joint reopens.

- An improper web design can create a vertical stress to the web. This leads to the sealant working itself out or deeper into the joint as movement occurs.

For the reasons mentioned above, a shape factor must be taken into consideration when implementing crack sealant. As the material is poured, the movement of the joint will cause the material to change its shape, but not its volume. The shape of the poured material is expressed in terms of a Depth to Width ratio, known as the shape factor. A smaller shape factor (small depth versus a large width) generates reduced internal strains, which in turn improves the elasticity of the sealant. To maintain an adequate bond strength as well as a reduction in the internal strains, a shape factor between 1 to 1.5 is recommended. The depth of the poured material can be controlled by using a backer rod material when the depth of the joint reservoir is deeper than the required depth to maintain the shape factor. The sealant is not to adhere to the backer rod, as it will be limiting its movement causing higher stresses into the material. The backer rod should be as soft as possible, while staying in its position to maintain the shape.

Sealant defects can result from excessive stress and a loss in bonding either between the joint face and the sealant, or within the material itself. For this reason, using sealants with better low temperature recovery and resistance to set at high temperature is ideal.

2.5. Current Standard Specifications

Currently, most agencies' preferred method of material selection is based on either ASTM International (ASTM D5329, 2020b; ASTM D6690, 2021) and/or AASHTO specifications. According to the ASTM D6690, asphalt crack sealants are categorized into four different groups based on their performance and locations where the material is to be applied. In particular, the asphalt crack sealants are separated into Type I, Type II, Type III, and Type IV. Those types are generated based on the penetration resistance, softening point, bonding strength, and asphalt compatibility of the materials. Furthermore, low modulus sealants belong to the ASTM Type II to IV and are preferred in wet-freeze locations, whereas high modulus materials are ASTM Types I to II and are preferred for dry-non freeze regions. If crack filling is the method of choice, a material with higher modulus is preferred for a similar climatic region. A systematic procedure was developed to select asphalt crack sealants, referred to as "Sealant Grade" (SG) based on environmental conditions (Al-Qadi et al., 2009).

The standards associated with this procedure are listed below:

- AASHTO M 338: Standard Specification for Performance-Graded Hot-Poured Asphalt Crack Sealant
- AASHTO TP 126: Standard Method of Test for Evaluation of the Tracking Resistance of Hot-Poured Asphalt Crack Sealant by Dynamic Shear Rheometer (DSR)
- AASHTO PP 85: Standard Practice for Grading or Verifying the Sealant Grade (SG) of a Hot-Poured Asphalt Crack Sealant
- AASHTO T 368: Standard Method of Test for Measuring Low-Temperature Flexural Creep Stiffness of Hot-Poured Asphalt Crack Sealant by Bending Beam Rheometer (BBR).
- AASHTO TP 85: Apparent Viscosity of Hot-Poured Asphalt Crack Sealant Using Rotational Viscometer.

- AASHTO TP 86: Accelerated Aging of Hot-Poured Asphalt Crack Sealants Using a Vacuum Oven.
- AASHTO TP 88: Evaluation of the Low-Temperature Tensile Property of Hot-Poured Asphalt Crack Sealants by Direct Tension Test.
- AASHTO TP 89: Measuring Adhesion of Hot-Poured Asphalt Crack Sealant Using Direct Adhesion Tester.
- AASHTO TP 90: Measuring Interfacial Fracture Energy of Hot-Poured Crack Sealant Using a Blister Test.
- ASTM D 6690: Standard Specification for Joint and Crack Sealants, Hot Applied, for Concrete and Asphalt Pavements.
- ASTM D 5329: Standard Test Methods for Sealants and Fillers, Hot-Applied, for Joints and Cracks in Asphalt Pavements and Portland Cement Concrete Pavements (PCC).
- ASTM D 5078: Standard Specification for Crack Filler, Hot-Applied, for Asphalt Concrete and Portland Cement Concrete Pavements.

Those tests are used to measure the mechanical and rheological properties of the asphalt cack sealants over a wide range of temperatures. In addition, similar to the asphalt binder's performance grade (PG), the SG of the sealant refers to the high and low service temperatures. Using the laboratory tests, a proper crack sealant could be selected based on its expected service temperature.

2.5.1. Federal Highway Administration Specifications

The FHWA has prepared a manual to be used by highway maintenance agencies and contracted firms summarizing good practices for asphalt concrete sealing and filling operations. The manual of practice is in the FHWA Report No. FHWA-RD-99-147 (K.L. Smith and A.R. Romine, 1999). The Strategic Highway Research Program (SHRP) H-106 maintenance experiment and the FHWA Long-Term Monitoring (LTM) of Pavement Maintenance Materials Test Sites project investigated both sealing and filling of cracks on asphalt pavement surfaces. The results of this project in five different locations in the United States and Canada were merged with standard highway agency procedures to provide this manual with the most up to date practices for asphalt crack treatments. This manual includes the availability and relative costs of materials with planning and constructing as well as monitoring the performance of crack treatments. A follow-up study sponsored by the FHWA was also included in the report where the treatments were evaluated annually throughout 1997. Long-term performance and cost-effectiveness information were analyzed by the continued monitoring and included in the manual. In summary, the manual includes primary considerations for selecting the right method and material for the job, as well as the right installation methods based on the presented conditions and a few considerations during construction. Those methods were adopted by the different state departments and adjusted according to the specific conditions of each state. The specific considerations for Arizona, as well as the city of Phoenix are detailed in the following sections.

2.5.2. Arizona Department of Transportation Specifications

The Arizona Department of Transportation (ADOT) has a specific construction manual where guidelines and standards related to asphalt crack sealing activities are provided. Those guidelines are found under Division IV, Surface Treatments and Pavements Section 402-6 for Joint and Crack Repair for Portland Cement Concrete Pavement Repairs, 404-3.30 for Bituminous Treatments on asphaltic concrete pavements and 404-3.40 for Joint Sealing on asphaltic concrete overlay.

In general, asphalt-rubber material is used for crack sealing purposes and a certificate of compliance must accompany the product before using it for a certain project. Furthermore, all cracks must be thoroughly cleaned to remove any incompressible materials by either routing or using high-pressure air. Grass or weeds growing within the crack must be marked and properly prepped with an approved liquid herbicide after cleaning. A polymer modified type III asphalt crack sealants shall be used, conforming to the specific requirements for each type (**Table 2**).

Table 2- ADOT Asphaltic Crack Sealants Specific Provisions, Division IV Section 404.30

Test	Test Method	Type I	Type II	Type III
Cone Penetration, at 77ºF	ASTM D 5329	50-80	35-55	20-40
Resilience at 77ºF	ASTM D 5329	30%	30%	30%
Softening Point, minimum	ASTM D 36	190ºF (87.7ºC)	200ºF (93.3ºC)	210ºF (98.8ºC)
Ductility at 77ºF, minimum	ASTM D 113	11.8'' or 30cm	11.8'' or 30cm	11.8'' or 30cm
Asphalt Compatibility	ASTM D 5329	Pass	Pass	Pass
Bitumen Content, minimum	ASTM D 4	60%	60%	60%
Tensile Adhesion, 1'' or 2.54cm thick, minimum	ASTM D 5329	500%	500%	400%

The heating and sampling should be done in compliance with ASTM D 5078, and the sealant should be capable of being melted and applied to cracks at temperatures below 400ºF (204.4ºC). In addition, the sealant, when heated, should penetrate the crack ¼'' (6.35 mm) or wider with an equipment capable of providing a continuous supply to complete the operation without delays. A proper blotter material should also be used, with a standard gradation conforming the Special Provisions under section 404CRKBT. As for the crack preparation, it should be cleaned to the bottom of the crack or to a depth of at least 1 ½'' (3.8cm). All cracks with an average opening between ¼ and ½'' should be routing to a depth of at least ¾'' and a width between 3/8'' and 5/8''. A detackifying solution may be used, with an approved water-based spray to reduce the sealant adhesiveness and the time required for opening the traffic. In general, cracks with a width greater than ¼'' are recommended to be cleaned, routed, and sealed.

2.5.3. City of Phoenix Specifications

Similarly, the City of Phoenix has standard specifications with regards to asphalt crack sealing activities. The material that should be used is a polymer modified asphalt rubber in sold form to seal both cracks and joints in asphalt and PCC pavements. The cracks or joints must have a minimum width of ¼’’ (6.35 mm) and maximum width of 1’’(2.54 cm) at the time of work. The City of Phoenix has more requirements for the materials to meet upon application. Those requirements are found under section 337 in the standard specification manual and are summarized in **Table 3** below. Furthermore, the material shall be heated according to ASTM D 5708 and be applied in the crack or joint uniformly from top to bottom and should be filled without the formation of air voids or entrapped air.

Table 3- City of Phoenix Standard Specifications for Asphalt Crack or Joint Sealing Activities Section 337

Test	Test Method	Type III
Cone Penetration, at 77ºF	ASTM D 5329	20-40
Resilience at 77ºF	ASTM D 5329	30%
Softening Point, minimum	ASTM D 36	210ºF (98.9ºC)
Ductility at 77ºF, minimum	ASTM D 113	11.8’’or 30cm
Flexibility, *Specimen bent 90º over a 1’’ (2.54cm) mandrel within 10 seconds	ASTM D 3111	Pass at 30ºF (-1ºC)
Flow at 140ºF, minimum	ASTM D 5329	1.18’’or 30cm
Brookfield Viscosity at 400ºF (204.4 ºC), maximum	ASTM D2669	100 Poise
Asphalt Compatibility	ASTM D 5329	Pass
Bitumen Content, minimum	ASTM D 4	60%
Tensile Adhesion, 1’’ (2.54 cm) thick, minimum	ASTM D 5329	400%
Maximum Heating Temperature	400ºF (204.4ºC)	
Minimum Heating Temperature	380ºF (193.3ºC)	

The City of Phoenix specifications also specify that the material should be overfilled, then leveled with a 3’’ (76.2mm) sealing disk or V-shaped squeegee to create a neat band extending by 1’’ (2.54cm) on each side of the crack, with a thickness no more than 1/8’’ (3mm). Furthermore, if the pavement being sealed will be overlaid by a Hot Mix Asphalt (HMA) layer within 6 months of the sealant application, the cracks must be cleaned, vacuumed, and routed with no overband and a ¼’’ (6.35mm) recession in the crack of the material.

On the other hand, while most cracks have less than 1/8’’ (3mm) movement over the year in Maricopa County, when a greater width is experienced, routing is recommended. Cutting should remove at least 1/8’’ (3mm) from each side and create vertical surfaces with well bonded aggregates. A typical application will yield to a crack or a joint with a ¾’’ (19mm) width and ¾’’ (19mm) depth.

As for vacuuming, the final cleaning should be done for a minimum of 1’’ depth. The vacuum shall have a high pressure of 90 psi (620 kPa) at least, directly attached to a vacuum unit to collect the dust and residue.

In case traffic is to be in contact with the hot poured sealant before it cures, a blotter or a specialized bond breaking material may be used to prevent tire tracking of the material. Finally, the polymer modified asphalt rubber should be placed when the pavement temperature exceeds 40^{o}F (4^{o}C) as lower temperature may cause a reduced adhesion due to the presence of ice or moisture. In such cases, a heat lance that puts no direct flame on the pavement should be used. Furthermore, the cracks must be ensured to be dry and free of ice and other contaminants.

2.6. Recent Studies

2.6.1. Possible Sealant Failures and Their Causes

Caltrans provided guidelines on the possible causes of sealant failures, as well as the type of failures observed in the field. Those are provided in the Maintenance Technical Advisory Guide Volume I for Flexible Pavement Preservation (California Department of Transportation, 2008). A poor sealant performance may be caused by the application of the material to either wet and/or dirty crack surfaces, poor material finishing, cold application of the material, insufficient amount, or simply due to the presence of rain and low temperatures during the crack sealing activity. The Caltrans Division of Maintenance have put together a troubleshooting guide for crack sealing and filling. The guide is summarized in **Table 4** below.

Table 4- Troubleshooting Guide for Sealing and Filling from the Maintenance Technical Advisory Guide Volume I for Flexible Pavement Preservation (California Department of Transportation, 2008)

	Problem		
	All Seals		
Cause	Tacky, Tracking	Cracking Quickly	Bumpy Surface
Sealant Not Cured	X		
Dirty Crack	X	X	
Insufficient Sanding	X		
Poor Finish	X	X	X
Sealant Too Cold		X	X
Sealant Too Hot	X		
Application Temperature Too High	X		X
Application Temperature Too Low		X	X
Sealant Degraded Due to Overheating	X	X	X
Cold Weather		X	
Hot Weather	X		X

Other sealant failures are mentioned due to improper material selection, poor workmanship, and application as well as lack of post-treatment. The failures modes include adhesion loss, where the sealant doesn't adhere to the edges of the crack; cohesion loss, where the material fails in tension by tearing; spalling, where the edges of the crack break away due to poor routing; pull-out, where the sealant is pulled out of the crack by car tires and finally pothole formation, where the crack is not properly sealed and allows water into the pavement leading to pumping and potholes.

2.6.2. Suggested Solutions for Observed Sealant Failures

Based on the troubleshooting guide mentioned above, suggested solutions to the common problems were summarized in **Table 5**.

Table 5- Suggested Solutions for Observed Sealant Failures from the Maintenance Technical Advisory Guide Volume I for Flexible Pavement Preservation (California Department of Transportation, 2008)

Problem	Solution
Tracking	Reduce the amount of material being applied
	For hot applied materials, allow to cool or use blotter
	Ensure the sealant/filler is appropriate for the weather in which it is being placed
Pick out of Sealer	Ensure cracks are clean and dry
	Increase application temperature
	Use correct sealant for climate
	Allow longer curing time before opening for traffic
Bumps	Ensure correct flush finish
	Have squeegee followed closely to the application
	Decrease the viscosity of the sealer
	Change the rubber of the squeegee
	Stop overbanding

2.6.3. Performance Measurement Suggestion

The treatment effectiveness relies on determining how much of the treatment has failed with respect of the total length of the treatment that was applied. (Federal Highway Administration, 1999). After multiple field inspections, the effectiveness of the crack sealant treatment over time was shown to be around 75 months. The percentage of failure assessing the performance measurement was calculated according to (Equation **1**:

$$\%Failure = 100 * \frac{L_f}{L_t} \qquad \textbf{(Equation 1)}$$

Where L_f is the total length of the failed segments and L_t is the total length of the treated cracks.

2.6.4. Field Performance Testing

A project was conducted by Al- Qadi et al. in 2017 (Yousefi, 2019) to attempt to match field performance to laboratory results. More than 200 cracks were evaluated and documented, for a percentage length of full and partial depths adhesive and cohesive failures. In addition, the percentage of length of overband wear, spalling, and stone intrusion were also recorded. Therefore, a performance index (PI) was defined as a function of percent full depth adhesive and cohesive loss (AC) and a percent of partial adhesive and cohesive loss (PAC) as shown in (Equation **2**, where PAC was multiplied by a factor of 0.5:

$$PI = 100 - (AC + PAC * 0.5) \qquad \textbf{(Equation 2)}$$

Different asphalt crack sealant types were evaluated in this project, from Type I to Type IV. It was observed that the most common failure mode was adhesive loss, during the winter season. Over a three-year period, the cracks were monitored and a series of performance indices with respect to time were developed for both clean-and-seal and rout-and-seal applications. After two to three winter seasons, the PI values were observed to drastically decrease. After the second winter, the result showed that the clean-and-seal application failed in all sections, whereas the rout-and-seal application was considered to have an acceptable performance.

Furthermore, two test sections were monitored with and without overband placement for the sealants. After two winters, the performance indexes were produced and compared. The overband usage was shown to be more efficient, and it outperformed the no-overband setup in most cases. However, no clear explanation was given for the reason behind those two instances.

An attempt to corelate field performance to laboratory testing was developed based on the observations from the field. A composite score approach combining ranking and correlation was used to develop a quantitative scale for assessing the level of performance acceptance. Based on the composite score, a strong or acceptable correlation was obtained between field performance and laboratory test parameters for field test sites. After confirming the correlation between field performance and lab results, the thresholds for test method were selected or fine-tuned (Yousefi, 2019).

Another case study was conducted in Michigan, where the effect of plow damage on clean-and-seal overbands was studied over a period of 3 years. In this case, the PI was measured as a percentage of the overband failure (OBF) caused by plow abrasion and tracking. Six hot-poured asphalt crack sealants of different types were studied. The results showed that the materials were not greatly damaged for the first year of analysis, but the PI was greatly reduced in the second year.

In 2011, Rajagopal ((Rajagopal & Infrastructure Management Group, 2011) performed a study with the Ohio Department of Transportation (ODOT) to determine the overall crack sealing performance by addressing a few questions with respect to the optimum timing for asphalt crack sealing treatments. In this study, 5 years of performance were analyzed for different types of pavements that underwent the same crack sealing processes. The results were analyzed based on the pavement type and Pavement Condition Index (PCI). It was shown that the clean-and-seal crack sealing provided the largest five-year condition gain in pavements with a PCI group of 66-80. It was also reported that crack sealing could extend the pavement service life by up to 3.6 years.

Other studies conducted in Ontario, Canada, evaluated the field performance of crack sealing focusing on the overall pavement condition. 37 sections were selected over different climatic regions, with different traffic levels and pavement ages where the pavement service life was assessed. Pavement performance curves in terms of PCI were compared over a 7-year monitoring period. The results showed that crack sealing did increase the pavement service life by an average of 2 years depending on traffic volume and original pavement condition (Tighe et al., 2003).

2.6.5. Cost Effectiveness of Crack Sealing Activities

As crack sealing activities are different from crack filling activities, the cost associated with each technique differs. According to Smith and Romine (Federal Highway Administration, 1999), crack sealing refers to the placement of specialized treatment materials into working cracks using unique configurations to prevent the intrusion of water and incompressible into the crack. As for crack filling, it refers to the placement of ordinary treatments into non-working cracks to reduce the infiltration of water and reinforce the adjacent pavement. As working cracks change in width constantly, the sealing activity requires higher quality materials and more detailed construction procedures and equipment which induce a greater cost.

Crack sealing activities increase pavement performance and extend its service life. By limiting the water intrusion, the risk of freeze/thaw damage by water expanding and contracting into a crack will be reduced (**Figure 5**). Furthermore, limiting incompressibles (**Figure 6**) into the crack will allow better movement of the pavement during warm weather, and reduce the compressive forces within the pavement. In other words, the pavement's life will be extended by restricting the crack's severities.

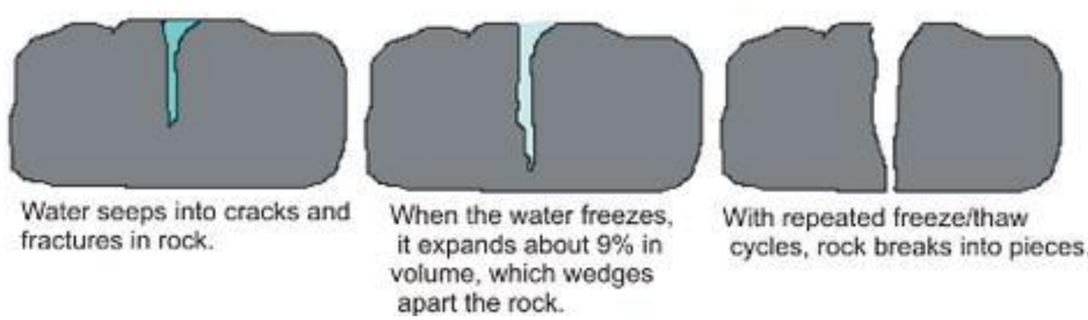


Figure 5- Effect of Freeze/Thaw Damages in Cracks (Julie Sandeen, CK-12 Foundation)

Figure 6- Intrusion of Incompressibles Damages in Cracks (For Construction Pros, 2017)

A cost-benefit study for a clean-and-seal application was conducted by Rajagopal in 2011 (Rajagopal & Infrastructure Management Group, 2011) by relating the performance gains of crack sealing on different pavement types with various PCI ranges. The study shows that the service life of pavements was extended by 1.85 years when treated with crack sealants. A Net Present Value (NPV) was derived from the service life extension with two different alternatives, either apply a crack seal and follow by a chip seal after a certain time or do nothing and apply the chip seal after a given number of years. The cost values were collected from ODOT's construction records for the years 2009 and 2010, where the cost per lane for crack sealing was reported to be $2,504 and the cost per lane for chip seal was recorded to be $10,565. It was concluded that crack sealing was mostly ineffective for roads with a Pavement Condition Rating (PCR) range of 66-80 but was effective for a PCR range of 60-70 for all types of pavements.

Another study by the Minnesota Department of Transportation (MnDOT) (Barman et al., 2019) showed the cost/benefit analysis of the effectiveness of different crack sealing techniques. This study showed the difference in cost and benefits between the clean-and-seal and rout-and-seal methods. As there are no specific guidelines for selecting the most cost-effective method based on the job, selecting the right method is largely affected by factors influencing the performance of the seals. In addition, a criterion to selecting the most appropriate crack sealing method based on the pavement type, condition, age and traffic volumes was developed. Furthermore, direct field performance data was collected at 35 different sites located throughout Minnesota by quantifying the Performance Index of the crack seals. The results showed that rout-and-seal was more commonly used in Minnesota, and that most failures occurred in adhesion during winters with wider crack spacings. It was also found that rout-and-seal methods had a service life of 4 years, compared to 3 years for the clean-and-seal. A life cycle cost analysis was conducted and showed that rout-and-seal was more efficient due to its longer service life. However, if short-term benefits are to be considered, clean-and-seal may be more cost effective. In general, the benefit to cost ratio was not considered to be significantly different, whereas more decision factors should be considered to establish the effectiveness of each method such as the ease of operation, the practitioner's opinion, and the traffic level. Finally, the clean-and-seal was found to be more appropriate for high severity cracks, sandy soil subgrades and low initial budget whereas the rout-and-seal was preferred for clayey and silty subgrades, irrespective of other variables.

2.6.6. Crack Sealing Costs

The cost of crack sealing may be impacted by the type of material, location of the project, as well as the equipment needed to perform the activity. Other items that may affect the cost include the traffic accommodation to perform the sealing, methods and procedure, documentation, performance evaluation, project size and intersection types. In general, unit prices range from $3.00 per linear meter to $8.00 per linear meter for larger jobs. The contractor prices by project could vary by $1.00 to $2.00 per linear meter depending on the job size as well as other factors that may impact the productivity of the contractor. Reduced mobilization could lead to cost savings by having the municipalities work together and increase the size of the projects as well as coordinating their timings. Based on this information, the common cost for hot-poured crack sealing ranged from $3.50 to $4.00 per linear meter (Stantec Consulting, Ltd, 2013).

For clean-and-seal methods, it is the least labor-intensive form of crack sealing and requires two trucks, one for crack preparation and the other for sealing. In general, 1 to 3 workers are needed to operate the air blaster or lance, and another 1 to 3 workers will be operating the sealant applicators and blotting material. It is the fastest method of crack sealing and requires much lower working hours, with a unit price of typically $0.03 to $0.09 per linear meter depending on the size of the project.

As for the rout-and-seal method, the costs associated are higher due to the increased labor considerations. Extra workers are required to operate the routing machines, as well as to operate the truck for the second pass of sealant into the routed reservoirs. Furthermore, additional materials are needed to fill the reservoirs. For those reasons, the cost is approximately two to three times more than the clean-and-seal method, ranging from $0.15 to $0.25 per linear meter (Barman et al., 2019).

2.7. Material Parameters Affecting Performance

The behavior of crack sealants depends on the movement of the crack, as well as on the climatic conditions it is being subjected to. At low temperatures, the sealant extends whereas at high temperatures, it compresses to accommodate the pavement crack openings. In turn, those openings increase with decreasing temperature and decrease with increasing temperatures. At high service temperatures, the sealant may soften and be pulled out of the crack by tire passing, whereas at low temperatures, the crack opening may increase based on the environmental locations leading to either cohesive or adhesive failures (Al-Qadi et al., 2017). Furthermore, physical hardening may occur at lower temperatures and lead to the embrittlement of the material. Failures may occur within the sealant itself, or at the sealant-pavement crack wall interface.

When a crack is exposed to various forces, it mostly transfers them into movements that could be measured. Cracks experience two types of movements: horizontal and vertical. Horizontal movements occur due to thermal expansion and contraction because of temperature fluctuations. Meanwhile, vertical movements occur due to traffic loading. Based on past pavement maintenance experience, six main modes of failure were identified: (i) Adhesion failure, (ii) Cohesion failure, (iii) Settlement failure, (iv) Pullout of material failure, (v) Spalls or secondary crack around the sealed crack. Adhesive and cohesive failure are shown in .

Figure 7- Crack Sealant Failure in Adhesion and Cohesion in a Parking Lot

Adhesive failures occur when the sealant detaches from the crack walls or bottom creating an area for infiltrations (Smith et al., 1999). Cohesive failures occur when the sealant breaks into separate parts within its body (Erickson, 1989). Settlement failures happen when the sealant settles in the crack due to gravity by the decrease in viscosity at elevated temperatures. Pullout and tracking are common issues for newly applied sealants and occur at high temperatures with the passing of tires on the material. Partially cured sealants could be mostly removed with the passing of car tires (Sousa, 2012). 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 (Smith et al., 1999). The viscosity of the material largely affects this failure, as stiffer consistencies will lead to poor sealing. Furthermore, this could occur due to edge cracking, breaking away due to poor sawing and routing (Sousa, 2012). Several mechanical and chemical properties also affect the performance of asphalt crack sealants and are discussed in the subsections below.

2.7.1. Viscosity Properties

The sealant's apparent viscosity is one of the properties that greatly affect the initial bonding between the material and the edges of the crack. The appropriate viscosity at the manufacturer's recommended temperature will provide better filling and enhance bonding. Furthermore, it is essential to achieve a good flow, as it will ease pumping the material into the crack. Therefore, identifying the characteristics needed at installation is required to influence the rheological behavior of the material and achieve the desired performance. Although standard tests have been developed to measure the viscosity of fluids, they have not been proven to relate to field performance. A test procedure (Al-Qadi et al., 2008) was developed specifically to measure the apparent viscosity of sealants using the rotational viscometer used in the Superpave specifications.

2.7.2. Aging Properties

Aging is another factor affecting the sealant's performance in the field. As the material is heated in the melter, it undergoes chemical aging due to the high temperature it is being subjected to. This type of aging is chemical, whereas the material experiences irreversible changes to its chemical composition. Those changes affect the rheological properties of the material, and therefore its performance in the field. Aging procedures were tested on sealants to mimic the field conditions as closely as possible. A physical-chemical analysis was conducted, where the material was weathered and chemically aged. Sealants with good performance had components resistant to weathering and the ones with poor performance oxidized quickly. Sealant stiffening was experienced with aging, which led to different failure modes in combination. A study was conducted where 12 sealants were aged and weathered in Montreal, Canada for 9 years. Similarly, accelerated aging methods were tested in the lab and compared to the field measurements in terms of fingerprint composition (Fourier Transform Infrared Spectroscopy), weight loss upon heating, stiffness and relaxation and the separation of the bitumen from the polymer. The most effective way was found to be aging the sealant using the Accelerated Oven Aging method, where the material was aged at elevated temperatures and under pressure for a long duration.

2.7.3. Flow, Shear Thinning and Deformation Properties

Under the combination of shear stresses and higher service temperatures, asphalt crack sealants may fail in deformation. Furthermore, the material may be soft enough to be displaced, and picked up by car tire passing. In other words, low shear viscosity with respect to shear rate application causes the apparent viscosity of the material to decrease. This parameter is also known as shear thinning. This mimics the effect of traffic loads affecting the extent of the sealant flow and performance in the field under different stress conditions (Masson et al., 2007).

2.7.4. Adhesive Properties

Adhesive properties are critical for asphalt crack sealants as they ensure good and cost-efficient field performance. Furthermore, adhesion loss leads to premature sealant failures. Crack sealants should have adequate adhesive and cohesive properties to remain intact in the cracks for various environmental and pavement conditions. Adhesive failure is one of the most common failure types in sealants due to the poor adhesion capacity of the materials as well as the installation quality. They are generally characterized through mechanical biomaterial interface delamination tests and evaluated through fracture mechanics theories. The stresses at the interface can be either compressive, shear, bending, torsional or tensile and lead to different interface failures (Sawalha et al., 2017). The interfacial fracture energy is related to the adhesion strength and modulus of the material. As adhesion failure is similar to fracture, the concept of fracture could be divided into two general classification as cohesive failure, where the material separates from itself, and adhesive failure, where the material separates from a different material known as the substrate (Williams, 1969). Technically, the bond strength is one representation of the adhesion capacity of the material, where it represents the energy required to bring the material to a complete separation from the substrate. As for the interfacial fracture energy, it depends on the thermodynamic work of adhesion, fracture mechanics and rheology. It is a fundamental material property and is defined as the energy required to separate a unit area from an interface. In addition, it is the sum of the energy dissipated through a reversible component and a rate dependent deformation component related to viscous and plastic deformation (Bennett et al., 1974). This property is independent of geometry and could represent the inherent characteristic of a typical interface. It largely depends on surface preparation: it needs to remain constant if the interfacial fracture energy is used to assess adhesive strength for different materials using various geometries (Jiang & Penn, 1990).

For asphalt crack sealants, adhesion refers to the material adhering properly to the crack edges on the pavement surface. A sealant with good adhesion capacity can undergo both expansion and contraction, opposing the crack movement in cold and hot climates, without separating from the crack. The rheology of the material needs to accommodate for the adequate behavior at high and low temperatures, whereas high stiffness will lead to brittle behavior and poor performance. Furthermore, the expansion and contraction mechanism of the material can provide insight on the behavior of the sealant when poured in a crack in terms of adhesion, cohesion, and settlement failures. Furthermore, as asphalt crack sealants are mainly composed of asphalt binder, this binder is mostly responsible for the adhesion characteristics of the sealant. Moisture can still defuse over the binder over time, reducing its adhesive property to the aggregates from the pavement or induce changes to the overall properties of the sealant that may lead to further water damage. Recent studies have shown that when the binder is exposed to moisture for a long duration of time, water diffuses through the bitumen film and changes its properties leading to premature deterioration. This is due to the increase in concentration of the polar fractions in the binder, which are also responsible for the aging mechanism within the binder (Hung et al., 2017). On the other hand, aging is one of the reasons why sealants become more brittle and fail on the surface of the pavements. With the oxidation of the oils present, the sealant becomes less sticky and less adherent to the substrate. In addition, the loss of volatiles will lead to a brittle consistency which also reflects reduced movements with the crack.

2.7.5. Stiffness, Toughness and Tenacity Properties

The performance of sealants at low temperatures, in terms of stiffness, is another factor that needs to be considered. High stiffnesses at low temperatures will cause the material to crack, fail in either adhesion or cohesion, and lead to the failure of the material. Other important parameters such as toughness and tenacity give indication of how flexible and stretchable the material is at different temperatures. Higher tenacity values indicate a lower potential of failures and better performance. Similarly, a higher toughness value indicates that more work is needed to fail the sample, leading to better performance. In terms of stiffness and relaxation, the Bending Beam Rheometer (BBR) gives a good indication of lower temperature behavior by measuring the flexural creep at extreme lower temperatures. The behavior of the material depends on its composition and temperature. Different stress-strain curves were reported on the literature, where the material can have different failure modes **().** Brittle-plastic failures occur with little to no elongation after the peak load was applied, whereas ductile failures occur with continued stretching after reaching the peak load. Sealants with high polymer concentrations typically exhibit strain hardening, where a plastic flow region is clearly visible in the post-peak behavior.

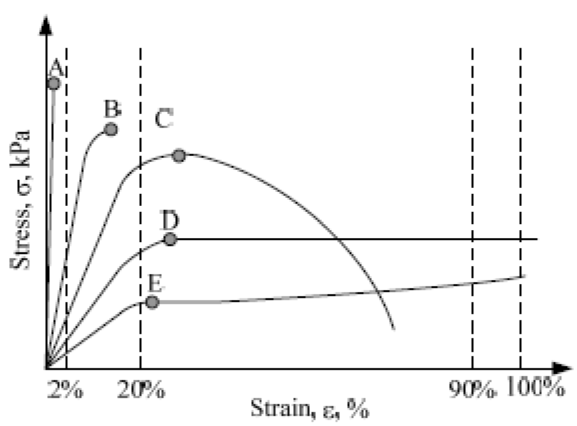


Figure 8- Stress-Strain Curves for Different Sealant Types, (Al-Qadi et al., 2009)

2.7.6. Thermal Behavior

As asphalt crack sealants are viscoelastic and therefore temperature susceptible, there is a gap in the literature in addressing the thermal parameters associated with the material. By tackling those parameters under different environmental conditions, the durability of the sealant may be improved as it accommodates to different climates. In hot climates, the sealant may have reduced softening effects which will reduce the potential for tracking with tire passing. As for colder climates, the brittle effect may be reduced by increased flexibility and reducing temperature susceptibility. Furthermore, studying the expansion and contraction of the materials will help in maintaining the integrity of the material subjected to the different crack movements. As sealants have been previously modified for performance improvements based on the literature, there is still a need to address the thermal properties of those materials, and how their durability can be advanced.

2.7.7. Moisture Susceptibility

Crack sealants are widely used to prevent moisture infiltration into the pavement structure. However, if the moisture conditions of the surroundings are not taken into consideration, the sealing treatment may become responsible for frequent failures and unsatisfactory performance. Several studies have shown that when asphalt crack sealants are subjected to prolonged exposure to water, cohesive and adhesive failure occurs, leading to the failure of the treatment. On the other hand, water entrapment, where a pavement system with crack sealant, will lead to stripping.

Several studies examined the cohesive properties of crack sealants under extensive heat and moisture. The cohesive properties were accounted for in terms of water-swelling rate, tensile strength, elastic recovery, and hardness. The results showed that those sealants experienced high swelling and significant reductions in the other parameters. This indicated that failure most likely will occur within the material itself, under cohesion, in extreme weather conditions (Chew, 2002). However, other studies (Fini, 2011) showed that different sealants performed differently when exposed to temperature and moisture. The bonding strength of the material was tested using a blister test, where the tensile strength and the Interfacial Fracture Energy were measured before and after conditioning. The bonding strength was also measured to decrease significantly. Another study conducted in North Carolina (Lamarre, Fini, & Abu-Lebdeh, 2016) investigated the effect of moisture on crack sealants used in hot, moderate and cold climates. A direct tension test (DTT) was conducted on conditioned sealants, and adhesion strength pre-failure was measured. The results indicated that water reduced the fracture energy and adhesion strength for all sealant types. The chemical and rheological properties of sealants were also studied when the material was exposed to moisture (Lamarre, Fini, & Aflaki, 2016). The tests were performed using the dynamic shear rheometer, bending beam rheometer, direct adhesion tester and Fourier Transform Infrared Spectroscopy. The results showed that the material had increased relaxation when exposed to water, which means that the time to dissipate stresses became longer. Other results included lower modulus of elasticity, peak load and fracture energy as well as accelerated adhesive failures when exposed to water. As for the FTIR results, they showed higher aging extents with the presence of water, which led to reduced performance of the material and great susceptibility to moisture.

2.8. Dominant Causes of Delamination in Crack Sealants

Aging is one of the major factors affecting the durability and the service life of sealants. Increase in age, leading to an increase of stiffness and hardening will lead to a decrease in elasticity and ductility of the material and therefore will lead to a decrease in durability and life span of the asphalt mixtures (Eberhardsteiner et al., 2015). As sealants mainly consist of asphalt binder (about 60%), the quality of that binder is greatly affected by oxidative aging and therefore directly affects the durability of the asphalt crack sealants. Ageing has two main mechanisms: chemical and physical. The first mechanism is highly related to the chemical composition of the binder, affecting the rheology. The processes referring to these ageing mechanisms are mainly oxidation, loss of volatiles, and exudation. Exudation is simply movement of the oily components of the binder to the aggregates (Lu & Isacsson, 2002). Oxidation is recognized to be the most important factor affecting the binder through ageing. Polar chemical functions are created within the bitumen molecules associated with oxygen, increasing its stiffness and hardness (Gamarra & Ossa, 2018). As for the physical mechanism, it reflects the physical hardening of the binder, which concerns the molecular structure of the specimen. Physical hardening causes this structure to be re-organized, also known as the Steric Hardening. The main factors affecting the aging of bitumen are time, heat, oxygen, sunlight and partially Beta and Gamma Rays. In general, ageing occurs at the surface and in some cases, within the structure (Yi-Qiu et al., 2005). The aging processes that appear in the bitumen are irreversible physically and chemically. On the chemical aspect, oxidative aging increases the asphaltene content of bitumen, and introduces more polar functional groups such as carbonyls and sulfoxides (Hou et al., 2018). As the asphaltene content increases, an imbalance in the other SARA fractions of the binder (Saturates, Aromatics, Resins and Asphaltenes) occurs (Schutte et al., 2015). Aromatics and saturates are responsible for viscosity, whereas asphaltenes contain polar polyaromatic compounds and contribute to the surface activity and adhesion of asphalt to mineral aggregate (Pernyeszi et al., 1998). Studies have shown that during ageing, the binder undergoes oxidation and dehydrogenation (the loss of an electron, which is the bond with a hydrogen compound). It is commonly accepted that aromatics change into resins who turn into asphaltenes with ageing whereas saturates stay unchanged. Furthermore, surface free energy, which is the energy required to disrupt chemical bonds, was shown to decrease with ageing. The more the specimen is aged, the stiffness increases, and it exhibits adhesion problems and is weakened with ageing. Thus, the adhesion property that occurs between bitumen and aggregates is important for durability and service life (Qu et al., 2018). The adhesion performance with the largest amount of asphaltene has been shown to have larger and stiffer bee-like structures and had damaging influence on the adhesive performance (Xu et al., 2016). The aging of asphalt causes the crystallization and aggregation of paraffins and asphaltenes, which must influence the adhesion behavior of asphalt (Rebelo et al., 2014).

Other factors leading to delamination in crack sealants include expansion and contraction of the crack, which will lead to stretching the material itself. This parameter is deemed very important reflecting the material's durability and need to be captured in the laboratory. A sealant will lower toughness and tenacity and will more likely detach from the surface of the crack and fail in adhesion. Sealants with higher toughness and tenacity can withstand greater crack movement with better stretchability. In addition, the thermal properties of the material itself are important in terms of adhesive performance, as greater expansion at lower temperatures will better accommodate contracting cracks in colder climates. In other words, the lack of stretchability of the sealants at lower temperatures may cause adhesive failures along the cracks as well.

In colder climatic conditions, the roads are salted as a response to snow and deicing. The salt not only affects the chemical composition of the sealant, but also affects the adhesive and stiffness properties and performance of the material leading to premature deterioration (Al-Qadi et al., 2017). Furthermore, studies have shown that the presence of moisture adversely affects the adhesive properties of asphalt binder, which is a main component of asphalt crack sealants. Moisture can still diffuse into the binder over time, reducing the binder adhesion to aggregates and causing changes into its chemical structure and yield its susceptibility to further water damage (Hung et al., 2017). Studies have shown that when asphalt binder is subjected to moisture for an extended period, an enrichment of the polar compounds at the surface due to the water exposure has been noted at the molecular level. The results pointed towards complex interactions between the water, wax, and surfactants in the bitumen as the bond characteristics are not well defined. An important consideration would be to understand the composition of the asphalt binder as the structure and composition may not be the same for all materials, and the interaction between the bitumen and aggregate interface may perform differently based on the composition. With extended exposure to moisture, studies showed that the surface microstructure changes significantly, with nano-bumps appearing on the bee-structure of the binder, previously referring to the asphaltenes fraction, in the binder. The evolution of the bee structure due to both aging and environmental conditions is responsible for the chemical change in viscosity, stiffness, and long-term performance. Furthermore, Atomic Force Microscopy (AFM) images followed by Fourier Transform Infrared spectroscopy (FTIR) showed that those nano-bumps are hypothesized to be para-phase resin absorbing water and seeping through the bee structure. At higher temperature and under water, the formation of this new phase was accelerated and appeared at the surface of the material.

For crack sealants, as water diffuses into the binder portion of its composition, the adhesion properties between sealant and wall of the pavement may be compromised in wet areas where the material is subjected to moisture for extended periods. At the interface of sealant and crack wall, the water properties, either salty or acidic, may also play a role in the adhesive mechanism and may affect the potential bond between the sealant and the pavement.

2.9. Summary

The efficacy of crack sealants depends on multiple factors, including viscosity, aging, shear stresses, adhesive properties, stiffness at low temperatures, thermal behavior, and susceptibility to moisture. Preserving an optimal viscosity profile is important to facilitate proper bonding and application ease, while aging processes can initiate irreversible chemical alterations that compromise rheological integrity and field performance.

Under the influence of shear stresses and elevated temperatures, crack sealants may undergo shear thinning, rendering them vulnerable to displacement and failure. Adhesive properties assume a pivotal role in mitigating premature deterioration, with mechanical assessments serving as benchmarks for evaluating adhesion quality. Furthermore, stiffness at low temperatures emerges as a critical determinant, as excessive rigidity can precipitate cracking or cohesion failure, thus imperiling overall effectiveness.

An understanding of thermal properties is imperative for fortifying durability across diverse climates. While diminished softening in hot environments may reduce tire tracking, increased flexibility in colder climates can mitigate brittleness and reduce temperature-induced vulnerabilities. Moisture susceptibility poses an additional challenge, as sealants may swell and experience internal failure, compromising both bonding strength and structural integrity, particularly with prolonged water exposure.

The process of aging intensifies these challenges, leading to increased stiffness and diminished elasticity, thereby limiting service life. Oxidative processes induce chemical transformations that stiffen sealants and compromise adhesive properties, while physical aging engenders molecular reorganization, further undermining performance. In colder climates, the compounding stressors of salt and moisture lead to degradation, emphasizing the need for preventive maintenance of adhesive properties.

In summary, the behavior and effectiveness of crack sealants are intricately related to a spectrum of factors, each having a distinct influence on material performance and durability. Addressing these challenges requires a comprehensive approach that includes careful attention to viscosity, aging, shear stresses, adhesive properties, thermal behavior, and moisture susceptibility, thereby ensuring optimal performance across varied environmental conditions.

2.10. Techniques Implemented to Improve Performance

In the previous sections, the common practice implemented to enhance the sealant performance was discussed. In addition to those techniques, modifying the material itself is another way of improving the durability and performance of the material. There are several techniques and modifications that have been implemented to improve the performance of crack sealants. Some of these include:

- Polymer modification: Polymer-modified sealants are made by adding polymers to the mix, which improves the flexibility, adhesion, and durability of the sealant. The use of polymer-modified sealants has been shown to increase the life of the sealant.

- Fiber reinforcement: Fibers can be added to the sealant mix to improve its strength and durability. The fibers help to prevent cracking and improve the resistance of the sealant to deformation and abrasion.
- Joint preparation: Proper preparation of the crack or joint is essential for effective sealing. This may involve cleaning the surface, removing debris and loose materials, and ensuring that the joint is dry and free of any contaminants.
- Crack filling and sealing: There are various techniques for filling and sealing cracks, including pouring, injecting, or applying the sealant with a brush or roller. The choice of technique will depend on the type and size of the crack, as well as the properties of the sealant.
- Quality control: Regular inspection and maintenance of the sealant are essential to ensure that it continues to perform effectively over time. This may involve monitoring for signs of cracking or deformation and carrying out repairs or resealing as necessary.

In the following section, the modifiers that are considered as part of this dissertation are discussed. Their effects on both asphalt mixtures and binders are presented. The addition of those modifiers into asphalt crack sealants is to be investigated in this study.

2.11. Modifiers Introduced into Bituminous Materials

2.11.1. Aerogel Modified Bituminous Materials "aMBx"

2.11.1.1. Background

The use of modifiers in asphalt has become a common way to improve its performance and meet the needs of the road. Polymer and crumb rubber are two common modifications that have been used to increase the stiffness of asphalt at high temperatures and reduce the potential for cracking at low temperatures (J. H. Collins et al., 1991), (E. Bruton, 2020). However, polymer modified bitumen (PMB) has some limitations such as low aging resistance, poor storage stability, and high cost (Zhu et al., 2014). The use of rubber in asphalt also has some downsides like recyclability, storage stability, workability, and fumes during the paving process. Even though these technologies were created to increase the lifespan of asphalt roads, the cost associated with their implementation has been a significant challenge. Therefore, more research is required to find new materials and improve the durability of asphalt roads. The temperature changes that asphalt pavements experience can lead to thermal cracking and permanent deformation. One possible solution to address this issue is to design mixtures that are less susceptible to temperature changes.

In 1956, Standard Oil tried using aerogel in bituminous materials such as asphalt mixtures. However, this process wasn't pursued further because of safety concerns related to the material. The aerogel particles have a low density (made of ~95% air) and need careful handling, which can be difficult in both laboratory and production plants. However, the use of aerogel in asphalt to reduce thermal cycling and increase durability is still a focus of research due to its promising thermal characteristics.

2.11.1.2. Product Development

The ASU research team developed an ultralight product called Aerogel Modified Bituminous Materials “aMBx” that uses pre-treated aerogel composites made of synthetic porous silica to address the safety concerns and ease the handling of the modifier in different settings. The encapsulator, in this case, is the asphalt binder coating the aerogel particles and reducing the probability of aerosol suspension and dust formation. The creation process of this material is further detailed in (Obando, Karam, & Kaloush, 2023; Obando Gamboa, 2022).

The team members are Carlos J. Obando, Ph.D. (Chief Technical Officer), Jolina Karam (Research and Development Scientist), Jose R. Medina, Ph.D., P.E. (Chief Business Development Officer) and Kamil E. Kaloush, Ph.D., PE. (Strategic Business Officer and Advisor). As a research scientist, Jolina was responsible for the initial product and coating mechanism development, as well as the asphalt binder testing associated with mixture performance testing.

This product can be used as a modifier in bituminous constituents for high-performance materials with unique thermal resistance properties, providing urban cooling benefits. The product is versatile and can be used in different infrastructure applications. shows the final composite "aMBx" compared to different types of materials such as lignin powder, cement, and fine aggregates. Currently, a patent application for aMBx has been filed with the United States Patent and Trademark Office (serial number 63/210,891 filed on June 15, 2021). The final composite has a relatively low thermal conductivity, ranging from 0.08 to 0.12 W/m.K and a density ranging from 0.32 to 0.38 g/cm^3.

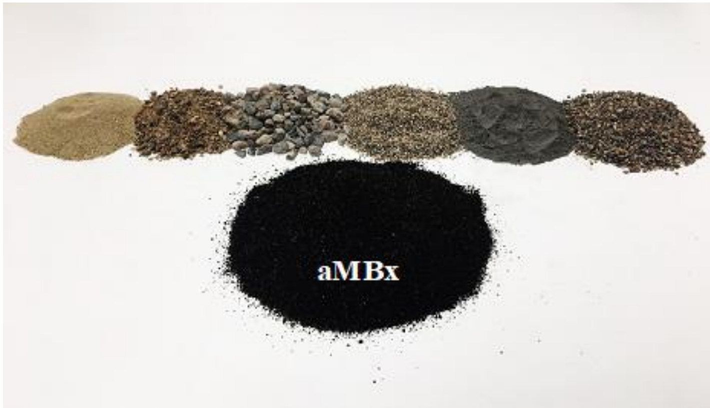


Figure 9- aMBx Composite.

The total size of the coated composite ranges from 0.1mm to 3mm as seen in .

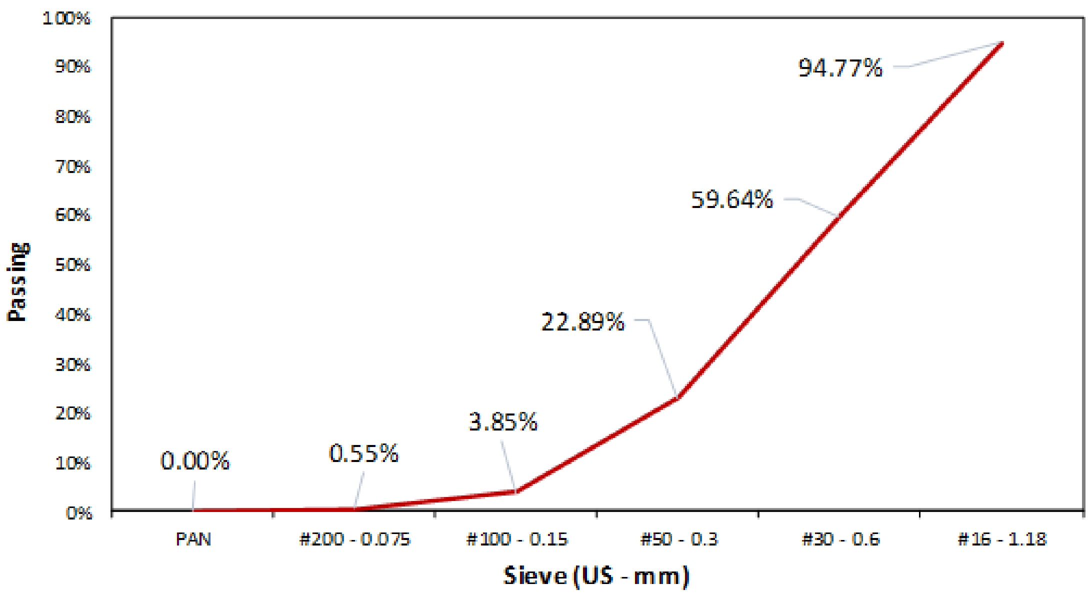


Figure 10- aMBx Particle Size Distribution

2.11.1.3. Performance Testing

The study tested three different percentages of aMBx (10%, 20%, and 30% by bitumen weight) and two methods of incorporating it into the mixture (wet and dry).

Preliminary testing was conducted by adding aerogel into asphalt binders to identify the potential performance improvements with regards to thermal susceptibility (Obando, Karam, & Kaloush, 2023). Different parameters with regards to thermal and performance properties were considered for laboratory testing such as viscosity ((ASTM D4402, 2002)), softening point (ASTM D36/D36M-14, 2020) penetration ((ASTM D5- 9, 2009, p. 9)), low and high temperature rheological properties ((AASHTO M 320, 2021), (AASHTO T 313- 19, 2019)) as well as thermal properties. The addition of aerogel at different contents showed potential improvements at high temperature settings, where asphalt binder experienced stiffening with an increase in softening point and viscosity as well as complex shear modulus. An improved softening temperature and better consistency were reported. Furthermore, the modified binders showed lower viscosity at lower temperatures, which is translated by less crack potential due to stiffening at low temperatures. Finally, it was shown that the aerogel modified binders were less affected by temperature changes. They had remarkable response in terms of thermal conductivity where the aerogel particles acted as an insulator when the binder was subjected to heat. However, in terms of low temperature stiffness, the results showed a slight decrease in the ability of the material to relax (low m-value). In general, the addition of Aerogel did improve the thermal susceptibility of bitumen, which would be advantageous in terms of permanent deformation and thermal cracking.

In terms of HMA mixtures (Obando Gamboa, 2022), the aMBx-modified mixtures were evaluated using several tests such as dynamic modulus (AASHTO T 342-11, 2011) Semi-Circular Bend Test (SCB) with crack month opening displacement (CMOD), moisture susceptibility (ASTM D4867, 2014), Hamburg wheel-track testing (AASHTO T 324, 2023, p. 324), and cyclic uniaxial fatigue (AASHTO TP 107) to characterize their properties. The thermal behavior of the mixtures was also analyzed with respect to thermal conductivity, specific heat capacity, and coefficient of thermal contraction. As different contents and methods of adding the aMBx into asphalt mixtures were evaluated, a 20% content by weight of the binder, added directly to the asphalt binder and then mixed with the aggregates showed the most promising results with an increase permanent deformation resistance and better stability. This method is referred to as the wet method. The results indicated that mixtures modified with aMBx had a higher specific heat capacity, suggesting a greater heat storage capacity that required more energy to heat the material. Heat transfer was also lower in these mixtures due to their lower thermal conductivity values, leading to lower temperature fluctuations. The expansion contraction test showed that the strains in the modified mixtures were lower than in the control mixture, implying a lower susceptibility to thermal stress and cracking. Tests for cracking potential, such as Semi-Circular Bending and fatigue, showed that modified mixtures using a wet method would have similar performance to the control at low temperatures. The results also showed that higher aMBx content in the mixture led to a stiffer behavior and improved performance at high temperatures.

2.11.2. Recycled Aerogel Composite for Construction Materials (RaC)

2.11.2.1. Background

The annual production cost of asphalt mixtures in the United States is approximately 40 billion US dollars, resulting in the creation of roughly 500 million tons of these mixtures each year. Every year, American drivers dispose of around 280 million tires, which translates to roughly one tire per individual in the United States. The importance of recyclability in sustainability and engineering is significant. In 2020, the Department of Energy reported that lubricating oil consumption in the US was around 2.47 billion gallons per year, with approximately 1.40 billion gallons available for recycling. Furthermore, the use of crumb rubber in asphalt has been shown to be highly advantageous, as it can absorb oils in the asphalt and preserve them during the aging process. As a result, the crumb rubber acts as a rejuvenator and helps maintain the oils in the binder, whereas traditional asphalt binders become more brittle and lose those fractions over time (E. Bruton, 2020; Noorvand et al., 2021).

2.11.2.2. Product Development

A recent development of interest is the use of aerogel-based modifiers, which can add thermal insulation to pavement and make it less susceptible to temperature changes. However, such modifications may result in undesirable performance aspects. For instance, while crumb rubber can improve the flexibility and strength of the mixture, it can also make it more susceptible to thermal changes in extreme weather. Similarly, aerogel-based modifiers can make the mixture stiffer and less performing in cold climates. To address these challenges, a new product called Recycled Aerogel Composite “RaC” has been suggested, which combines crumb rubber, waste oil, and aerogel at ASU. This product offers several benefits, including improved thermal resistance, performance, aging resistance, and durability. By increasing durability, the pavement's life span can be extended, reducing maintenance activities, and delaying distresses. Moreover, the addition of waste oil can enhance the activation or swelling of the crumb rubber while maintaining the necessary flexibility in the mixture and addressing the global recycling issues. A current disclosure application has been filed in the United States Patent and Trademark Office: serial number 63/485,183 filed on February 15, 2023.

This product is a new technology that combines rubber and aerogel in a single product, which has the added advantage of being encapsulated with waste oil, promoting the reuse of industry waste, and enhancing sustainability. On the other hand, aerogel on its own can make the material stiffer at lower temperatures. This issue can be addressed by adding rubber. The waste oil in the rubber could provide flexibility and elasticity, as it is a key component of bituminous materials. Additionally, the oil helps activate the rubber, making it more effective when added to the composite. Overall, this one product is hypothesized to provide the benefits of three combined components, without the negative side effects of each when used separately in bituminous materials. The primary goal of this technology is to enhance the performance of bituminous materials by leveraging proven modifiers that work well when combined. **Figure 11**shows the end-product of RaC.

Figure 11- Recycled Aerogel Composite

Additionally, high-speed mixers are not required to incorporate the product into other materials to achieve optimal performance. When it comes to aerogel, using it in its raw form can be hazardous due to the formation of dust clouds and electrostatic charges, which are directly linked to its lightweight properties. This product addresses these issues by encapsulating the aerogel, increasing its weight without compromising its insulating properties, making it safe to use in various applications. The encapsulation process ensures that both materials (rubber and aerogel) are evenly distributed throughout the product, promoting elasticity and thermal resistance, resulting in enhanced performance.

2.11.2.3. Product Manufacturing

The product manufacturing includes the pre-swelling of crumb rubber particles, and its addition to hot asphalt binder at very high speed. At later stages, aerogel is gradually added, forming the end-product.

2.11.2.4. Performance Testing

To evaluate the effectiveness of RaC, various tests were conducted on asphalt binders. A control sample of asphalt binder with Performance Grading (PG) 70-10 was used, which is commonly used for pavements in Arizona. To improve its performance, 20% of RaC was added based on the weight of the binder. The results of these tests were then compared with those of a polymer-modified binder (SBS) with a PG of 76-22, which has exceptional performance in both high temperature (76°C) and low temperature (-22°C) conditions. The tests carried out on the modified binders include studying the thermal susceptibility of the binders with laboratory tests including softening point (ASTM D36/D36M-14), standard penetration test (ASTM D5- 97), and rotational viscosity (ASTM D4402-02). The rheological properties at both high and low temperatures were also evaluated using the Dynamic Shear Rheometer for Performance Grading (ASTM D7175-08) and Multiple Stress Creep and Recovery (AASHTO M-332-14) testing as well as the Bending Beam Rheometer (AASHTO T 313-19) respectively. The bonding strength (BBS) (AASHTO TP 91) was also tested, in addition to the toughness and tenacity (ASTM D5801) parameters of the newly modified binder. Finally, the thermal parameters such as Thermal

Conductivity (Obando & Kaloush, 2022) and Specific Heat Capacity were measured to determine the thermal behavior associated with the addition of RaC to asphalt.

2.11.2.4.1. Rotational Viscosity

In terms of thermal susceptibility, the 20% RaC modified binder showed the smallest slope (VTSi) when compared to the control binder and SBS modified binder which refers to the lowest thermal susceptibility. The VTSi and Ai parameters have their own significance as they are used to represent the slope and y-intercept, respectively. When the VTSi slope is low, it indicates that the material behaves more stably at different temperatures. This means that flatter curves indicate a better thermal response and less deformation as seen in . Moreover, the Ai parameter represents the viscosity of the binder at low temperatures, and this parameter is lower for all binders modified with RaC. This indicates that the modified binders have a lower viscosity at lower temperatures, which leads to less cracking potential caused by stiffening at low temperatures.

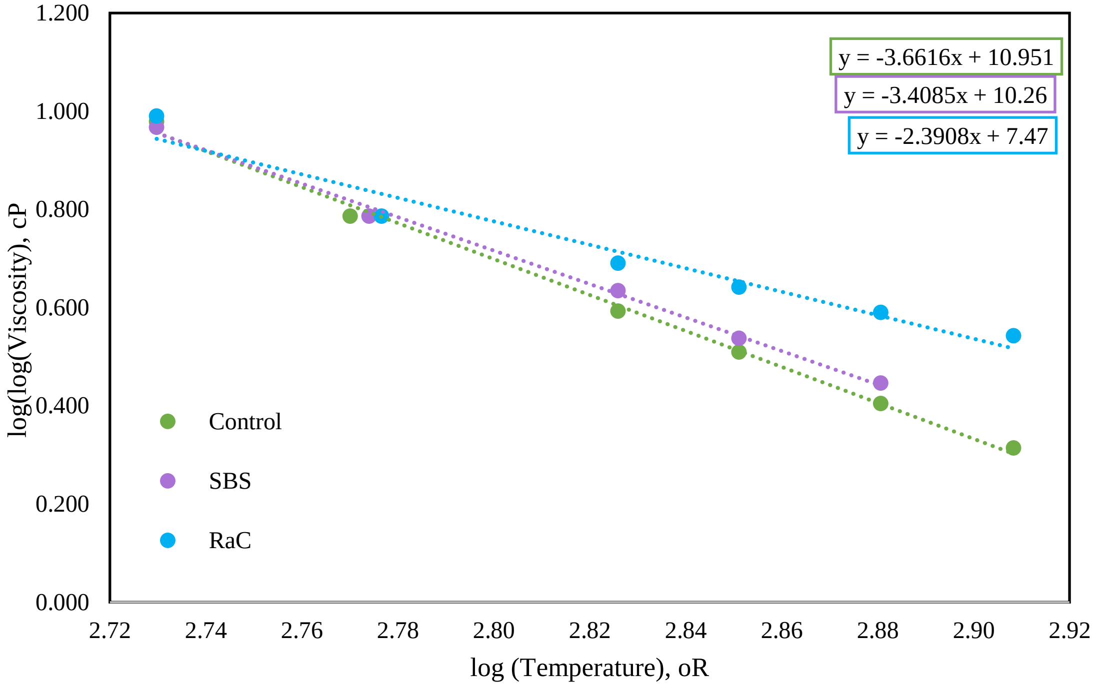


Figure 12- Rotational Viscosity Results Summary for RaC-Modified, SBS-Modified and Control Binders

2.11.2.4.2. Complex Shear Modulus, G*

In terms of rheology, the results show that the presence of RaC improves the binder's performance at high temperatures, as indicated by an increase in the complex modulus . On the other hand, at low temperatures, the modified binders show a decrease in modulus, indicating better performance under these conditions. Overall, mixing RaC with binders improves their response to high and low temperatures, resulting in enhanced resistance to rutting and cracking in asphalt pavements. In terms of high temperature performance grade measurements, the addition of 20% RaC to the PG70-10 binder caused a jump in the high temperature grade from 70^{o}C to 88^{o}C.

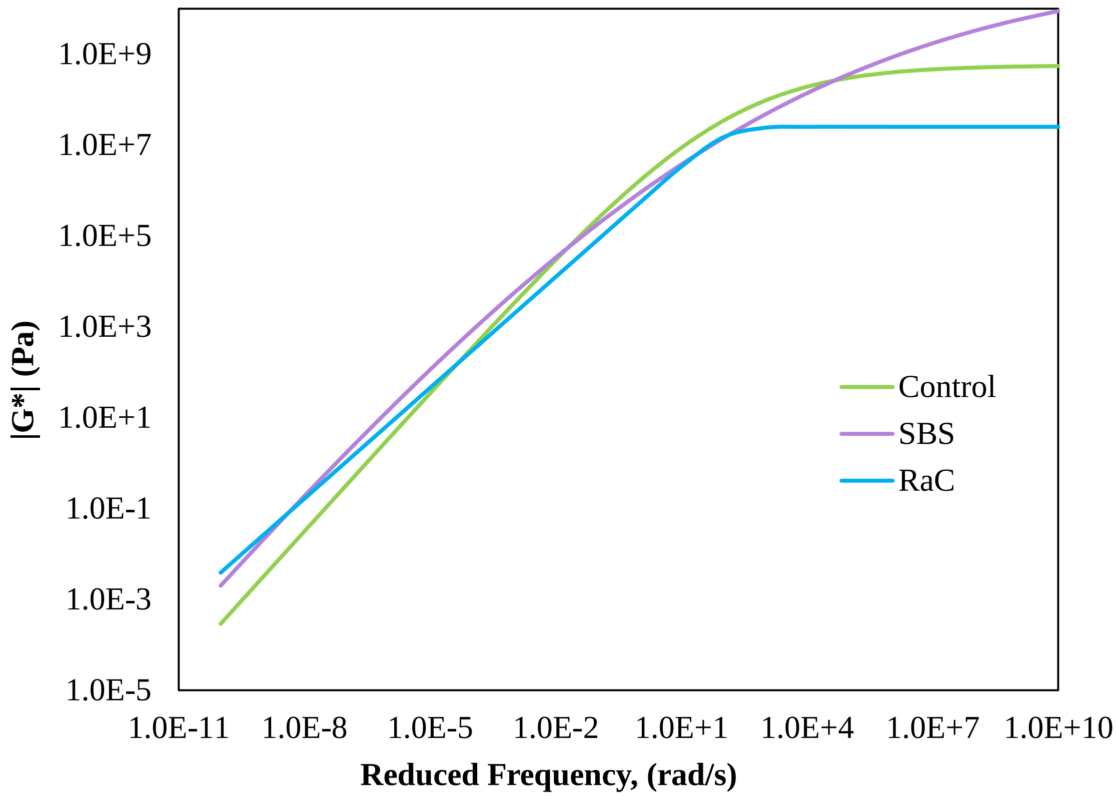


Figure 13 - Complex Shear Modulus Master Curves Results Summary for RaC-Modified, SBS-Modified and Control Binder

2.11.2.4.3. MSCR

As for the stress creep and recovery test, the accumulated permanent strain (which is represented by the rutting depth) and the percent of strain recovery under a cyclic load of 0.1s loading and 0.9s resting period are of interest. The recovery values for the RaC modified binders were significantly higher compared to control, at the high temperature grade testing temperature. When analyzing the non-recoverable creep compliance (Jnr), it is observed that its value decreases with the incorporation of RaC. This indicates that the specimens containing aSOR exhibit excellent resistance to rutting and perform well under such conditions. shows the results for both recovery and Jnr for the tested binders. The performance of the RaC-modified binders was found to be comparable to the PG76-22 SBS modified binder at higher service temperature.

Table 6- MSCR Results Summary for 0.1 kPa Creep Loading for RaC Modification

High Temperature PG (ºC)	Sample	Jnr (0.1)	Rec % (0.1)
70	PG70-10 (Control)	7.1	0.0
76	PG76-22 (SBS)	5.4	20.7
88	PG70-10 +20% RaC	4.2	15.5

2.11.2.4.4. Binder Bond Strength

In the pull-off test or BBS, failure had to be due to cohesion (i.e., failure within the binder itself) rather than adhesion, where the binder and substrate remain separated. According to , it can be concluded that samples modified with RaC showed excellent behavior. The addition of RaC did not negatively impact the bonding mechanism between the substrate (in this case, the aggregates) and the asphalt binder.

Table 7- BBS Results Summary for RaC Modification

BBS	Average (kPa)	Failure Mode
PG70-10 (Control)	401	Cohesive
PG76-22 (SBS)	417	Adhesive
PG70-10 +20% RaC WM	327	Cohesive

2.11.2.4.5. Thermal Properties

The thermal conductivity results were positive, as adding RaC to the binder led to a decrease in thermal conductivity. This means that the binder with RaC content is less susceptible to temperature changes, providing insulation properties to the binder. Lower thermal conductivity (k) reduces heat transfer, improving the performance of asphalt pavements at high temperatures. Additionally, the addition of RaC to the binder increased the specific heat capacity (Cp) of the mixture. The literature suggests that aerogel has a higher Cp than asphalt binder. Therefore, by adding RaC to asphalt binders, the Cp of the modified mixture increases. This combination of properties, with lower thermal conductivity and higher specific heat capacity, means that RaC -modified materials behave as an insulator, reducing the impact of external temperature changes. As a result, more energy is needed to raise the temperature of the material due to the higher specific heat capacity. provides a summary of the thermal conductivity results for the binders studied.

Table 8- Thermal Properties Results Summary for RaC Modification

Binder Type	**k (W/m°K)**	**C_p (J/Kg°K)**
PG70-10 (Control)	0.219	941
PG76-22 (SBS)	0.194	1,119
PG70-10 +20% RaC	0.188	989

2.11.2.4.6. Low Temperature Performance, Bending Beam Rheometer

This test was used to identify how well the sample performs at low temperatures by analyzing its stress-strain response. The m-value represents the slope of the logarithm of stiffness versus time, with higher m-values indicating a more flexible behavior at low temperatures. The goal is to ensure that the binder is soft enough and can deform quickly enough at low temperatures to prevent cracking. The Superpave binder specification requires a minimum m-value of 0.300 and a maximum creep stiffness limit of 300 MPa to prevent cracking.

The presence of RaC in the binder significantly improved its performance at low temperatures. The addition of RaC to a binder PG70-10 improved its low temperature performance grading by 13°C. This improvement makes an RaC-modified binder PG70-10 perform almost as well as an SBS binder PG76-22, promising a lower cracking potential at low temperatures. summarizes the results for control and modified binders, with temperature versus m-value and temperature versus stiffness measured at two different temperatures to obtain the low PG grading.

Table 9- BBR Results Summary for RaC Modification

Stiffness Evaluation	Maximum Stiffness 300 Mpa	Minimum m-value 0.300
	PG	**PG**
Control PG70-10	-13.06	-10.61
PG76-22 (SBS)	-27.73	-21.32
PG70-10 +20% RaC	-26.16	-16.10

2.11.2.4.7. Toughness and Tenacity

The MTS testing machine was used to evaluate the toughness and tenacity of the binders at room temperature. The procedure involved heating the binder until it was soft, pouring it into a tin can, and allowing it to cool down to room temperature before testing. The ASTM-recommended pull-out rate of 508mm/min was not used in this study, as a slower rate of 0.5mm/sec was considered to better assess the stretch and elasticity of the materials. Toughness was defined as the total area under the load vs. displacement curve, representing the work required to separate the tension head from the material. Tenacity referred to the stretch that occurred after the initial peak had been reached within the material. A binder with higher toughness and tenacity is considered stronger and more flexible. The results showed a significant improvement in both parameters for the modified binder at the same rate. The addition of 20% RaC yielded a binder with significantly improved tenacity, resulting in better elasticity without compromising strength. presents the results of this test for all the binders.

The benefits of this modifier are yet to be tested with sealing and filling materials, as different formulations may lead to different performance. However, its benefit was very encouraging in binder leading to potentially improved mixture performance.

Table 10- Toughness and Tenacity Results Summary for RaC Modification

Binder Type	Tenacity (N.mm)	Toughness (N.mm)
PG70-10 (Control)	1,490	2,710
PG76-22 (SBS)	3,215	4,426
PG70-10 +20%RaC WM	7,872	3,940

2.11.3. Pre-Activated Crumb Rubber (PCR)

2.11.3.1. Background

The main rationale for utilizing Asphalt Rubber in HMA is due to its substantially improved engineering properties compared to typical asphalt binders. Asphalt rubber binders can be tailored to perform adequately in any climate. Competent asphalt rubber binder designers typically consider climate conditions and available traffic data when designing the appropriate asphalt rubber product. At intermediate and high temperatures, the physical characteristics of Asphalt rubber binders differ considerably from those of conventional asphalt binders. The rubber component stiffens the binder and heightens elasticity (the extent of deformation that is reversible) across the pavement's temperature operating range, reducing pavement temperature susceptibility, and enhancing resistance to permanent deformation (rutting) and fatigue (California Department of Transportation, 2008)

However, the methods to incorporate rubber into binders are tedious and energy consuming. A high temperature of 190^{o}C and a mixing time of approximately 45 minutes are required to modify the binder, in addition to the associated costs of the blender that must be available at the plant. For the reasons stated above, a new rubber product called Pre-Activated Crumb Rubber "PCR" was suggested to overcome those issues shown in .

Figure 14- PCR Modifier

2.11.3.2. Product Development

The reacted and activated rubber is a novel Asphalt Rubber Binder consisting of regular soft bitumen, finely ground crumb rubber, and an Activated Mineral Binder Stabilizer (AMBS) in carefully optimized proportions. To create the pre-activated rubber, the ingredients undergo a brief hot blending and activation process in a purpose-built system, resulting in the formation of a dried granular activated rubber.

More specifically, the asphalt binder can be a typical soft binder used at common mixing temperatures for HMA without losing its workability when crumb rubber is added. As for the crumb rubber, it usually consists of processed ground scrap tires. Finally, the AMBS, which is a micro-scale binder stabilizer, is an activated micro-ground raw silica mineral.

This compound is a new and advanced elastomeric extender that has been found to improve the characteristics of regular bitumen to a greater degree than polymer modified asphalt and even higher than standard asphalt rubber blends. Furthermore, the PCR is also coated with a specific AMBS that adheres to the aggregates once dispersed into the asphalt binder. This mechanism was shown to improve the binder-aggregate interactions as well as the moisture damage resistance (Sousa, 2012).

2.11.3.3. Performance Testing

The addition of this PCR component into both asphalt binders and mixtures provided considerable benefits with respect to pavement performance. As the PCR content increased in the asphalt binder, the performance grade of the binder increased for both high and low temperature grades. Furthermore, the addition of PCR showed an increase in recovery and decrease in non-recoverable creep compliance values based on the Multiple Stress Creep and Recovery (MSCR) (AASHTO T 350, 2019) test. The rutting, fatigue and resilience of the modified mixes was shown to improve with the addition of PCR.

2.11.4. Synthetic Fibers (SF)

2.11.4.1. Background

The addition of fibers to asphalt can have several positive effects on its performance. Firstly, fibers can improve the mechanical properties of asphalt, such as increasing its stiffness and strength, and reducing deformation and cracking. This is particularly beneficial for asphalt pavements, which are subject to heavy traffic loads and environmental factors such as temperature fluctuations and moisture. Secondly, fibers can improve the durability of asphalt by enhancing its resistance to fatigue and thermal cracking. This can result in longer pavement life and lower maintenance costs. Thirdly, fibers can improve the workability and compaction of asphalt during construction, leading to better density and uniformity of the pavement. The specific performance benefits of fiber-reinforced asphalt depend on the type of fiber used, its dosage, and the characteristics of the asphalt mixture. For example, aramid fibers are known for their high tensile strength and can be effective in improving fatigue resistance, while glass fibers can improve the stiffness and cracking resistance of asphalt.

Fibers were also determined to have reinforcing effects and mechanisms for stabilizing and reinforcing asphalt binders. Studies have shown that the addition of fibers improved the asphalt's resistance to flow, where the rutting resistance was increasing. Furthermore, the results suggest that fibers can enhance the asphalt binder's resistance to rutting and flow, as well as its dynamic shear modulus. Fiber improves the asphalt matrix by spatial networking, adhesion, and stabilization of the binder. Polyester and polyacrylonitrile fibers seem to have a greater network effect than lignin and asbestos fibers, and their antenna-like features at the ends of the fibers further enhance this effect. Lignin fibers have the highest water absorption but the lowest thermostability. Both lignin and asbestos fibers have a greater impact on asphalt absorption and stabilization than polymer fibers (Chen & Xu, 2010). Other studies studied the reinforcing effects of various fibers on asphalt binder at low temperatures. To investigate the effects of fiber type and embedment length, as well as asphalt binder type on fiber pullout strength, studies conducted a laboratory test using multiple-fiber pullout (MFPT) from the asphalt matrix. In addition, they conducted a direct tensile test (DTT) to determine how the tensile properties of the fiber-reinforced asphalt (FRA) binder are affected by fiber (with or without fiber, fiber length, and dosage) and matrix (asphalt binder type and temperature). The MFPT test revealed that the coating effect of asphalt on the surface of fibers can increase the fiber pullout strength beyond the strength provided by the manufacturer. Aramid fibers require a longer embedment length to bond fully with asphalt than polyester fibers. The DTT test showed that adding enough polyester fiber can significantly improve the FRA's tensile properties, especially its failure tensile strain. While the asphalt matrix becomes more brittle at lower temperatures, the FRA maintains its tensile ductility, which warrants further study (Qian et al., 2014).

Other studies involved measuring the surface energy parameters of different asphalts and fibers, as well as the shear strength of various fiber-reinforced asphalts. The findings reveal that adding fibers can significantly enhance the shear strength of asphalt binder, and the reinforcement effect depends on the type of asphalt and fiber used. The results indicate that, for the same asphalt, basalt fiber has the best reinforcement effect, followed by the two lignin fibers. For the same fiber, asphalt rubber is the most reinforced, followed by SBS modified asphalt, asphalt No. 70, and asphalt No. 90. Moreover, higher surface energy of the fiber led to better fiber reinforcement effect for the same asphalt. The analysis revealed a positive correlation between the work of adhesion between asphalt and fiber and the effect of fiber reinforcement (Miao et al., 2019).

In terms of asphalt mixtures, the interaction of aramid fibers with the microstructure properties of asphalt mixtures were evaluated. The results showed that higher Nominal Maximum Aggregate Size (NMAS) led to better dispersion of aramid fibers in the asphalt mixture. Although aramid fibers did not affect the dynamic modulus of asphalt mixtures, they improved the fatigue and flow number mechanical performance. However, the degree of improvement varied depending on the mix composition (Noorvand et al., 2022).

2.11.4.2. Product

There are various types of fibers that can be used in asphalt mixtures, including but not limited to: polyester, polypropylene, polyethylene, aramid, carbon, glass, natural fibers (such as cellulose, cotton, jute, and hemp), and synthetic fibers (such as nylon, acrylic, and polyvinyl alcohol). Each type of fiber has different physical and chemical properties that affect its performance and effectiveness in reinforcing asphalt mixtures. The choice of fiber type depends on the specific application and the desired properties of the final asphalt mixture.

In particular, the fiber used in this study is a type of synthetic fiber () used in asphalt and concrete to enhance their mechanical properties. It will be referred to as “SF” throughout this document. It is made from a blend of copolymer polypropylene and polyethylene terephthalate (PET) materials, and is designed to improve the durability, strength, and resistance to cracking and rutting of asphalt and concrete surfaces. It is added to the asphalt or concrete mix during production and is uniformly distributed throughout the matrix. The fibers work by creating a three-dimensional network within the matrix, which helps to distribute stress and reduce the formation and propagation of cracks. This, in turn, can lead to longer lasting and more resilient asphalt and concrete surfaces. It can also be added to reinforce micro and slurry seal, at a recommended content of 0.25%. It was shown to control and reduce raveling.

Figure 15- Synthetic Fibers used in this Study.

2.12. Recent Studies about Sealant Modifications

To promote the adhesive properties of asphalt crack sealants, many modifiers have been introduced in the literature to extend the service life of this material. Modifiers have been added into asphalt binder to reduce their aging susceptibility, called rejuvenators. The working mechanisms of a hybrid bio-oil was recently investigated (Shariati et al., 2021). This agent plays a multifunctional agent by desorbing bitumen molecules from siliceous surfaces and peptizing them within the bitumen's colloidal structure. It other words, it counteracts the aging effects on the binder by neutralizing the polar interactions between the oxidized bitumen and silica and providing the chance for other hybrid bio-oil molecules to be deposited into the interface replacing the oxidized bitumen on the silica. Another aspect to improve the adhesive properties of the sealants would be by addressing the moisture damage susceptibility of the material. This bio-oil showed a high resistance to being replaced with water, which helps the bitumen to resist moisture-induced damages. A theoretical approach was used to predict the moisture susceptibility of the material ahead of time and may be implemented to avoid early deterioration. This technique is called "Polarization", whereas a polarizability factor is one of the conceptual descriptor indicatives of the formation of the instantaneous dipoles that are oriented in the field. Lower polarizability indicates lower chances for the chemical species to interact with others in their chemical environment. Another technique used in the lab was the Moisture-Induced Shear Thinning Index, which measures the loss of interfacial bonds between the binder and siliceous surfaces due to water exposure. Those techniques could be implemented to compare different sealants and identify their potential adhesive properties whereas high polarizability and high moisture-induced shear-thinning index indicated the highest susceptibility to moisture damage (Mousavi et al., 2020). As previously mentioned, rejuvenators are broadly used in asphalt binders to reduce their aging susceptibility. However, their susceptibility to moisture damage became a concern for different types and dosages. For this reason, studying the moisture susceptibility of those rejuvenators must be considered as well (E. H. Fini et al., 2020). It has been shown that the chemical composition of the rejuvenators could be tailored to enhance their resistance to moisture damage. Better performance was associated with amide and phenol structures, where hydrogen bonds are formed with silica surfaces, making them less displaceable by water molecules.

As the asphalt crack sealant ages, the SARA fractions were determined to shift from lower to higher polarity fractions, where the main oils of the binders are lost by volatilization. Another way to conserve the unaged properties of the sealant would be by the introduction of crumb rubber into the material. Crumb rubber was shown to absorb the oils from the binder when added. This process will limit the aging mechanism of the binder by gradually releasing the absorbed oils into the binder after aging. Crumb rubber can also be reacted and activated, referring to the fact that it has been pre-swollen before being added to the binder (Kedarisetty et al., 2016). The addition of such modifier into the sealant not only increases its resilience, but also promotes its toughness and tenacity as well as reducing its aging susceptibility (Liang, 2021). Those modifiers have been found to increase the recovery response of the binder, by making it more flexible. Such characteristic makes the sealant more resistant to adhesive failures, whereas it can sustain higher strains without failure.

Further evaluations were carried out in different fields to confirm the thresholds set for the grading system and performance-based guidelines of hot-poured asphalt crack sealants. The evaluations revealed that adhesive failure was the most common type of failure and that the most effective sealants had high adhesion capacity and moderate stiffness. In addition, selecting the appropriate pavement, crack type, and sealant material is crucial for clean and seal sections to perform well (Kedarisetty et al., 2016). It is necessary to enhance the performance of asphalt crack sealants based on the observed field failure modes, to improve their durability and cost-effectiveness. The mechanical and rheological properties of the material must be precisely managed and tailored to suit traffic and environmental conditions. To achieve this, various modifiers have been added to asphalt crack sealants with the primary goal of boosting their performance and durability (Zanzotto & Kennepohl, 1996). Researchers added carbon nanotubes (CNTs) and styrene-butadiene-styrene (SBS) to crack sealants to assess their effectiveness (Gong et al., 2021). Adding CNTs increased the viscosity of the sealants and had a beneficial impact on the material's aging resistance. This means that the sealant's hardening was decreased, while its elasticity was preserved. Additional research examined various ratios of rubber powder to SBS (Tan et al., 2013). The findings indicated that the highest amount of rubber content should not exceed 25%, as greater quantities may result in clumping when preparing the sample.

Other modifiers promote the thermal resistance of the materials, such as “aMBx (Obando Gamboa, 2022). This modifier acts as an insulator and reduces the thermal susceptibility of the material. By being less thermally susceptible, the accumulation of strain within the material would be reduced. Furthermore, higher toughness and tenacity were experienced with the addition of aMBx into crack sealant, in addition to reduced shear thinning/tire tracking potential. Tire tracking is also another mode of failure heavily exhibited by crack sealants, where the material is picked up by tire passing and leading to premature failures (Al-Qadi et al., 2017). Furthermore, testing the sealant modified with aMBx showed better performance in terms of binder bond strength testing, whereas higher strength was experienced with the addition of this modifier with observed cohesive failures. This material is expected to improve adhesive properties for the material. In addition, as this product is hydrophobic by nature, testing it for moisture resistance should be considered in the future works.

CHAPTER 3

3 EXPERIMENTAL PROGRAM AND TESTING

3.1. Experimental Program

The experimental program in this research study represents a series of tests done on two types of hot-poured asphalt crack sealants. The material was acquired by the manufacturers which had different types corresponding to a variety of applications in Phoenix Arizona. This suggested experimental program was tailored according to the different failure modes experienced by asphalt crack sealants in the field. The experiments have been conducted at the Advanced Pavement Laboratory at Arizona State University.

3.2. Materials

3.2.1. Asphalt Crack Sealant Types

The first type of sealant is typically used for crack sealing activities and will be referred to as “CS” in this study. This sealant is a hot-applied sealant used to fill cracks and joints in both asphalt and Portland cement concrete pavements for a wide range of climates. It is typically used in highways, streets, and airfield pavements. It has a high temperature grade of 70°C and a low temperature grade of -28°C.

The second type of sealant is typically used as crack filling and will be referred to as “CF” throughout the study. It is typically used in hot and dry climate areas with typical pavement temperatures of 76°C. It is also used in highways, streets, and airfield pavements, and has a high temperature grade of 76°C and a low temperature grade of -10°C.

The sealants have been stored, tested, and heated according to the manufacturer's recommended temperature of 193°C. This temperature was maintained throughout the modification process, to minimize the need to change the temperature while processing when compared to unmodified materials. It is important to note that this temperature is dependent on the material type and may change with different sealants from the market.

3.2.2. Modifiers

The two asphalt crack sealants mentioned in section 2.11 are to be modified targeting potential improvement to their durability and service life. The suggested modifiers for this study include the following:

- **aMBx**: Aerogel Modified Bituminous Materials
- **RaC**: Recycled Aerogel Composite for Construction Materials
- **PCR**: Pre-Activated Crumb Rubber
- **SF:** Synthetic Fibers

The specifications of those modifiers can be found in Section 2.11 of this document. These modifiers were chosen based on their performance in the literature and previous studies conducted at ASU (Chen & Xu, 2010; Noorvand et al., 2018, 2021; Obando, Karam, & Kaloush, 2023; Obando, Karam, Medina, et al., 2023) . They have been proven to improve asphalt binder and mixture performance at specific contents depending on the modification method (either wet or dry). The content of those modifiers as well as the modification methods are to be discussed in the sections below.

3.3. Testing Protocol

In this study, the typical failure modes for asphalt crack sealants were identified and detailed in **Section 2.4**. Accordingly, a testing protocol was derived to address those failures in terms of strength, durability, and thermal behavior. By having improved thermal resistance, the sealant's durability will also increase leading to a longer lifespan. For this reason, investigating the mechanical performance as well as thermal behavior is of interest to potentially improve the durability of the materials. The suggested testing protocol to identify how the modifiers are affecting the performance of the sealant is summarized in

Table 11 below. In order to depict the different behavior of the material at different temperatures and modification levels, testing procedures from the standard specifications were followed.

Table 11- Suggested Testing Protocol

Suggested Tests	Failure Type
Softening Point (ASTM D36/D36M-14, 2020), Cone Penetration Test, Brookfield Rotational Viscosity (ASTM D4402, 2002)	Settlement, Flow
Tracking and Shear Thinning (AASHTO TP 126, 2017)	Tracking, flow, high temperature softening
Bending Beam Rheometer (AASHTO TP 87, 2017)	Low temperature embrittlement, adhesion
MSCR (ASTM D8239-21a, 2021), Resilience	Elastic recovery, permanent strain
Toughness and Tenacity (ASTM 5801, 2017)	Adhesion, Cohesion
Bonding Strength (AASHTO T 361, 2016)	Adhesion, Cohesion (between material and asphalt concrete substrate), Moisture Susceptibility
Thermal Conductivity, Specific Heat Capacity (Obando & Kaloush, 2022)	Thermal Susceptibility
Expansion and Contraction (No Standard)	Adhesion, cohesion to pavement edges
Moisture Induced Shear Thinning Index (MISTI), (E. H. Fini et al., 2020)	Moisture Susceptibility

The tests mentioned in **Table 11** are to be conducted for both unaged and aged conditions, for different modification types and contents. Furthermore, an FTIR analysis was conducted to determine the aging level and identify the chemical changes induced by the modifiers into the sealing materials.

3.4. Testing Procedures

3.4.1. Modification Methods

As different modifiers are being introduced into the material, a homogeneous mixture must be achieved. Furthermore, the modifier's distribution within the sealant should be ensured. Different techniques were implemented to guarantee the proper distribution of the modifiers into the sealant. Those techniques are discussed in the sections below. The addition of such modifiers was considered in a way to allow proper modification by the manufacturer at the field level.

3.4.1.1. Aerogel Modified Bituminous Materials (aMBx) and Recycled Aerogel Composite (RaC) Modification

To achieve a good particle distribution, both Aerogel Modified Bituminous Materials (aMBx) and Recycled Aerogel Composite (RaC) were manually introduced into the sealant at the manufacturer's recommended heating temperature of 193^{o}C. The particles were gradually added and agitated with a wooden stick while maintaining the temperature of the material constant. Mechanical agitation was maintained for 3 minutes to achieve a good particle distribution. The different modifier contents were introduced into the sealant following the same procedure. While the material was still heated, samples for testing were poured and prepared.

3.4.1.2. Pre-Activated Crumb Rubber (PCR) Modification

The addition of Pre-Activated Crumb Rubber (PCR) into the asphalt crack sealant was different in terms of blending and particle distribution. To achieve an acceptable and homogeneous blend, the sealant was heated and maintained at a temperature of 193^{o}C. A high shear mixer was used to blend the particles into the material for a duration of 20 minutes at a speed of 800 rpm. Many attempts have been considered for different mixing time and speed. It was determined that a longer mixing time at an average speed allowed for a better distribution within the material. The temperature at which the material was heated was kept at 193^{o}C, as it is recommended by the manufacturer.

3.4.1.3. Synthetic Fiber (SF) Modification

Similar to the previous modifiers, the proper way of introducing Synthetic Fibers (SF) into the materials was investigated. It is important to find the right method of blending in the fibers, as they tend to clump within the material. A good distribution of the fibers is necessary. For this reason, the sealant was heated to the same recommended temperature of 193^{o}C. Different speeds and mixing time were evaluated using a high shear mixer, where high mixing speeds promoted clumping of the fibers at the center of the material, and around the mixing blade. Therefore, lower speeds and longer mixing time were shown to distribute the fibers more evenly within the sealant as well as reduce clumping of the fibers together. The total mixing time was determined to be around 30 minutes, at a speed of 800 rpm.

To better visualize the fiber distribution of the fibers within the material, the modified sealant was diluted using orange solution on top of a No.200 sieve. The diluted material went through the sieve, giving an indication about the fiber distribution within the material. **Figure 16** show the distributed fibers, where clumping was minimized.

Figure 16- Fiber Distribution Within Diluted Asphalt Crack Sealant

3.4.2. Aging Methods

To study the impact of the modifiers on the asphalt crack sealants, the testing protocol was implemented on both unaged and aged conditions. The improvement in terms of performance for the aged samples will determine the possible enhanced durability of the modified material. The analysis will rely on the measured rheological properties at the aged level, as well as the thermal and strength characteristics at the same level when compared to both control (unmodified) material under aged and unaged conditions. The aging has been done according to AASHTO TP 86: Accelerated Aging of Hot-Poured Asphalt Crack Sealants Using a Vacuum Oven (AASHTO TP 86, 2010). In this test method, 35g of material was aged under vacuum for 16 hours at 115^{o}C. According to (Al-Qadi et al., 2017), this method was the most effective in simulating the aging effect of the material in the laboratory from field conditions. It is assumed that this aging method brings the material close to the end of its service life (long-term aging).

In addition, short-term aging of the material was of interest to understand possible aging resistance of the modified material. For this purpose, the Rolling Thin Film Oven (RTFO) aging method was adopted (AASHTO T 240, 2017). The RTFO process involves taking unaged materials contained in cylindrical glass bottles and subjecting them to a temperature of 163°C for a duration of 85 minutes to simulate aging. Subsequently, the bottles are placed in a rotating carriage. This method was employed to accelerate the aging of sealant samples and mimic their state after being applied.

3.4.3. Laboratory Testing

3.4.3.1. Softening Point (ASTM D36/D36M-14, 2020), Resilience Test and Cone Penetration (ASTM D5329, 2020b)

The softening point test determines the temperature at which the viscosity of the tested sample reaches approximately 13,000 cP. This temperature measurement allows for evaluating the behavior of sealants in real-world conditions. It also indicates the point at which a sample can no longer bear the weight of a 3.5g steel ball. A higher softening point indicates that the material will remain stable at lower and intermediate temperatures in practical applications. To conduct this test, two rings containing modified and unmodified sealants were prepared. Two steel balls were placed at the center of the rings, and the entire setup was submerged in glycerin due to the sealant's stiffness compared to asphalt binders. The setup was then positioned on a heat plate throughout the test. The temperatures at which the steel balls touched the lower end of the frame were recorded as the softening point of the sample. For the resilience test, it measures the ability of the material to recover after a steel ball was forced into its surface. It can be carried for both unaged and aged conditions. Concerning the Cone Penetration, it is a measure of the consistency of the material by using a penetration cone instead of a needle with the same apparatus for the standard penetration test. The average of three results will be recorded and reported in this study. Both tests require the material to be poured into a metallic can and cooled down to room temperature before testing. Enough material should be poured into the container, almost reaching the rim.

3.4.3.2. Brookfield Rotational Viscosity (ASTM D4402, 2002)

This test examines the viscosity of modified and unmodified sealants under elevated temperatures. Inadequate viscosity can result in the sealant flowing out of the crack, while high viscosity can hinder proper crack filling and affect the bond between the sealant and the pavement surface. The sealant is evaluated using Temperature vs. Viscosity graphs, where smaller slopes (VTS_i) indicate lower temperature sensitivity of the material, and smaller intercepts (A_i) indicate better performance at low temperatures. **(Equation 3**, provided below, was utilized to plot the viscosity values of the sealant as a function of the test temperature:

$$LogLog\,\eta = A_i + VTS_i \times Log\,T_r \qquad \textbf{(Equation 3)}$$

Where,

$\boldsymbol{\eta}$: Viscosity in cP

A_i: Intercept of the viscosity line

VTS_i: Slope of the viscosity line

T_r: Temperature of sealant, in Rankine

Furthermore, this test is used to determine if the viscosity of the material is satisfactory according to the manufacturer's limitation of 10,000 cP at 204°C. a viscosity higher than the limitation will cause issues during field implementation and clumping of the sealant using conventional crack sealing equipment.

3.4.3.3. Tracking and Shear Thinning Test (AASHTO TP 126, 2018)

This method is employed to assess how well a crack sealant withstands tire tracking and shear thinning at elevated temperatures. The evaluation involves using a Dynamic Shear Rheometer (DSR) and conducting creep-recovery tests to measure flow and shear thinning parameters. The material under testing is placed between two 25 mm plates in the DSR and subjected to eight cycles of increasing stress during creep and recovery stages at various temperature settings. At the end of each cycle, the limiting shear rate is determined and plotted for each stress level. By utilizing the Ostwald-deWaele power-law fit (**(Equation 4)**, the obtained data yields two parameters: flow "C" and shear thinning exponent "P," which characterize the tested sealant. A higher convergence of the P value towards 1 indicates greater resistance to tracking. The C coefficient serves as an indicator of the sealant's resistance to flowing out of the crack. The test is conducted with shear stresses ranging from 25 Pa to 3200 Pa and temperatures ranging from 46°C to 82°C. A 1.5 mm gap is utilized to account for the presence of modifiers within the tested samples.

$$\sigma = C * \dot{\gamma}^{P} \qquad \textbf{(Equation 4)}$$

Where,

σ: shear stress applied in Pa

C: flow coefficient proportional to viscosity in Pa.s

$\dot{\gamma}$: shear rate applied in 1/s

P: shear thinning coefficient

In addition, this method is also used to evaluate the high temperature grade of the sealant. The limiting criteria to designate the high temperature grade spells out a value of C>4000 Pa.s and P>0.7.

3.4.3.4. Bending Beam Rheometer (AASHTO TP 87, 2017)

Depending on environmental conditions, the crack opening can widen at low temperatures, leading to potential cohesive or adhesive failures. To assess the behavior of the sealant under such conditions, the Bending Beam Rheometer (BBR) test and Binder Bonding Strength test were included in this study. The BBR test specifically examines the sealant's creep stiffness at extremely low temperatures and its flexibility down to -40°C. This test determines two key performance parameters: the average creep rate and the flexural creep stiffness at 240 seconds. The flexural creep stiffness helps evaluate the sealant's response to stress and strain over time at low temperatures, while the average creep rate indicates the rate of deformation of the sealant at the test temperature. A prismatic test specimen measuring 127 mm in length, 6.35 mm in width, and 12.7 mm in depth is subjected to a load for 240 seconds, followed by unloading for 480 seconds within a temperature-controlled fluid bath. Throughout the test, a constant load of 980±50 mN is applied, and the midpoint deflection of the specimen is monitored over time.

Furthermore, to determine the material's susceptibility to low temperature cracking, the critical temperature ΔT_c (**Equation 5**) was calculated based on T_{cs} **(Equation 6**), the critical stiffness temperature and T_{cm} (**Equation 7**), the critical relaxation temperature where both were measured after 60 seconds for an applied load of 300 MPa.

Values of ΔT_c lower than -5°C indicate that the material is susceptible to low-temperature cracking (Newcomb et al., 2021).

$$\Delta Tc = T_{c,s} - T_{c,m} \qquad \textbf{(Equation 5)}$$

$$T_{c,s} = T_1 + \left[\frac{Log(300) - Log(S_1)}{Log(S_1) - Log(S_2)} x(T_1 - T_2)\right] - 10 \qquad \textbf{(Equation 6)}$$

$$T_{c,m} = T_1 + \left[\frac{0.3 - m_1}{m_1 - m_2} x(T_1 - T_2)\right] - 10 \qquad \textbf{(Equation 7)}$$

Where,

T_1: First testing temperature (°C)

T_2: Second testing temperature (°C)

S_1: Stiffness at 60 seconds after loading at measured T_1 (MPa)

S_2: Stiffness at 60 seconds after loading at measured T_2 (MPa)

m_1: m-value at 60 seconds after loading at first testing temperature T_1

m_2: m-value at 60 seconds after loading at second testing temperature T_2

3.4.3.5. Multiple Stress Creep and Recovery Test (MSCR) (AASHTO T 350, 2019)

This test examines the elastic response and recovery percentage of the sealants under investigation, focusing on the non-recoverable creep compliance recovery at two stress levels: 0.1 kPa and 3.2 kPa. Once the high-performance grade temperature of the material has been determined through the Shear-thinning and tracking test (Section 3.4.3.3), the MSCR test is conducted at those specific temperatures. Each creep loading period lasts for 1 second and is followed by a 9-second recovery phase. Ten cycles of creep and recovery are performed at each stress level.

To accommodate the size of the modifiers, present in the sealant and prevent friction between the equipment and the sample, a 1.5 mm gap was introduced. The non-recoverable creep compliance, represented as "Jnr," measures the binder's irreversible strains in relation to the stress causing deformation. The recovery percentage (%Recovery) quantifies the amount of asphalt recovered during the rest period of the MSCR test by comparing the recovered strain to the original strain at the start of each creep and recovery cycle. Minimizing Jnr is desirable whereas a higher recovery percentage indicates a more elastic sealant, with lower accumulated strains in each loading cycle.

The testing temperature for both modified and unmodified materials is set as the high temperature grade determined in the previous "Shear thinning and tracking" test. Furthermore, both %Jnr Difference and %Jnr Slope (**Equation 8**) parameters were evaluated as part of the analysis. The initial purpose of implementing the %Jnr difference limit in the analysis of multiple stress creep and recovery test outcomes aimed to prevent the failure of an asphalt binder in real-world scenarios where it might encounter stresses or temperatures exceeding those simulated in the laboratory. However, there have been difficulties in meeting the %Jnr difference specification for asphalt materials characterized by low Jnr at 3.2kPa values, particularly below 0.5 kPa^{-1}. Recent observations highlighted challenges, with reported instances of %Jnr difference values exceeding 400% in some cases. In other words, asphalt materials with low Jnr at 3.2kPa exhibit an unfair %Jn Difference value. For this reason, the %Jnr slope suggested by (Stempihar et al., 2018) was used for this analysis.

$$\%\mathrm{J_{nr}}Slope = \frac{J_{nr3.2} - J_{nr0.1}}{3.1} \times 100 \quad \textbf{(Equation 8)}$$

3.4.3.6. Toughness and Tenacity (ASTM 5801, 2017)

This test evaluates the toughness and tenacity of both unmodified and modified sealants. It assesses the amount of force required to stretch the sealant and the maximum load it can withstand before the complete separation between the tension head and the material or within the material itself. Toughness is defined as the total work required to cause the separation of the tension head from the sample, while tenacity refers to the work required to stretch the sample once the initial resistance is overcome. To evaluate these parameters, a load vs displacement curve is obtained during the test. The toughness is calculated by determining the area under the entire curve, while tenacity is determined by calculating the remaining area after drawing a tangent line from the initial peak load on the curve.

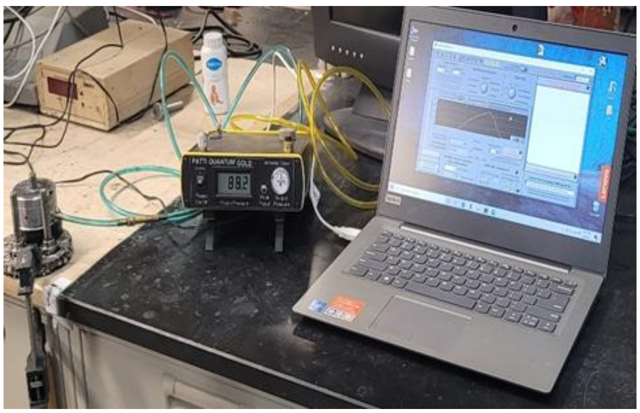
Initially designed for asphalt binders, this test has been adapted to accommodate the different material properties of sealants. The test involves pulling a tension head of specific size and shape from the sample at a controlled rate that is directly linked to the properties of the material being tested. Since sealants typically exhibit higher stiffness compared to asphalt binders due to their composition, a rate of 508 mm/min, previously established for binders, is not suitable. Instead, a new rate has been determined for all tested sealant specimens based on their observed stretch at room temperature. After multiple trials, it was determined that a rate of 120 mm/min for a 35g sample is appropriate (**Figure 17**). In Chapter 5 of this document, a thorough analysis to better characterize the material's behavior at different temperatures and pull-out rate is detailed. Based on the findings of Chapter 5, the testing pull-out rate and temperature were determined for the tested materials.

Figure 17- Toughness and Tenacity Testing Setup

3.4.3.7. Bonding Strength (AASHTO T 361, 2016)

Cohesion and adhesion failures are commonly observed in asphalt crack sealants as they undergo dilation at low temperatures and contraction at high temperatures, unlike the movement of pavement cracks. To quantify these failure modes and assess the bonding properties and compatibility of the sealant, the Binder Bonding Strength (BBS) test was conducted. The BBS test measures the tensile force required to remove a pull-off stub that is adhered to a solid substrate using the asphalt crack sealant.

For this experiment, a Type IV adhesion tester was utilized, employing stainless steel pull-off stubs with specific dimensions (**Figure 18a)**. These stubs have an inner diameter of 20 mm, outer diameter of 22 mm, and allow for a 0.8 mm thick sealant sample to be sandwiched between the stub and the substrate. The substrate used was a representative asphalt concrete disk that accurately represents the adhesive and cohesive failures observed on the actual pavement surface **(Figure 18b).**



(a)

(b)

Figure 18- BBS Testing Equipment: (a) Type IV tester; (b) Stubs and Substrate Samples

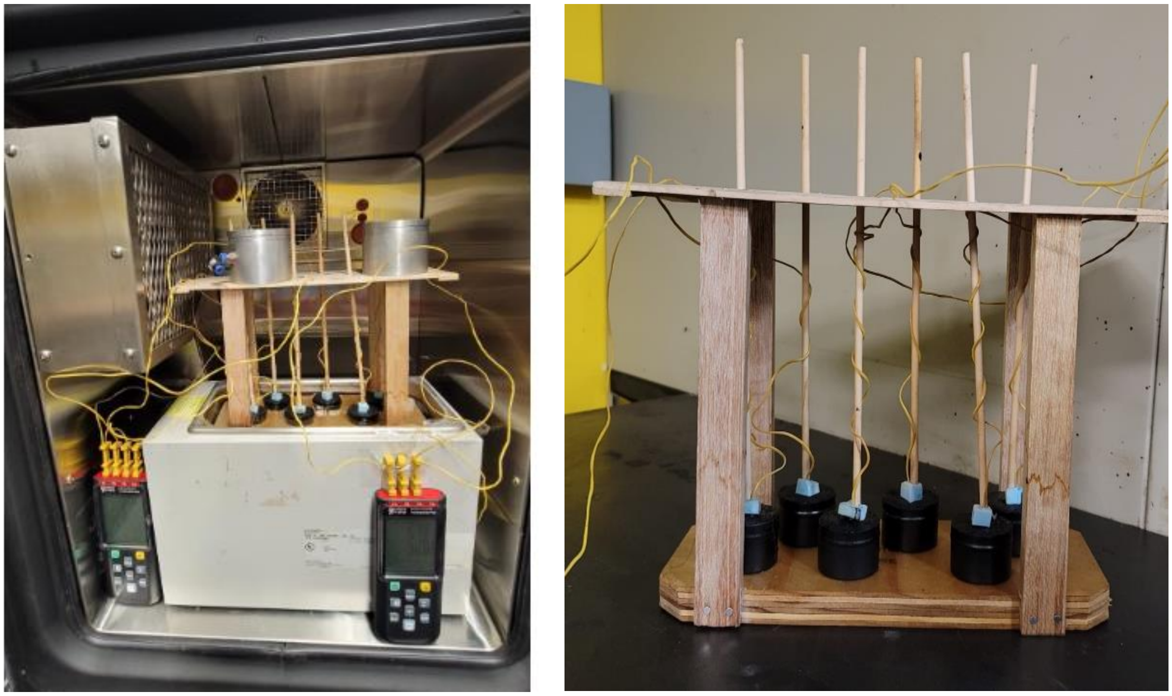
To mimic field conditions, the stubs were heated to the minimum recommended temperature of 193 °C before applying the sealant. Additionally, the appropriate pull-out rate for asphalt crack sealants had to be determined to assess the failure modes accurately. After multiple trials, it was found that a pull-out rate of approximately 1400 kPa/s (200 psi/sec) yielded the most reliable results. This experimental setup with the asphalt gyratory disk as the substrate and the stubs heated to the application temperature of the sealant aimed to simulate the adhesion and cohesion setting experienced in real-world scenarios.

The same test will be carried out under wet conditions. As soon as proper bonding is ensured between the material and the substate, the sample will be submerged in a water bath at 40^{o}C overnight. The difference between the pull-out strength of both conditioned (wet) and unconditioned (dry) strength with respect to the unconditioned strength will determine the effect of moisture on the tested material (D. Oldham et al., 2021). The adhesive failures are determined if more than 50% of the material is pulled out from the substrate, whereas cohesive failures are identified when more than 50% of the material remains on the substrate.

3.4.3.8. Thermal Conductivity and Specific Heat Capacity

The thermal conductivity of the samples was determined using a method developed by Obando et al. at Arizona State University (Obando & Kaloush, 2022) (US Patent 2022/0252532 A1 2022). A lower thermal conductivity indicates that the tested specimens allow less heat to infiltrate them. Cylinders made of modified and unmodified sealants were fabricated, measuring 25mm in height and 40mm in diameter.

To conduct the test, the initial temperature of each specimen was measured before immersing it in a water bath set at 35°C. The time taken for the temperature to reach a steady state, indicating the infiltration of external heat into the specimen, was recorded. **Figure 19** shows the test setup (a) and the samples ready to be tested (b).



(a) (b)

Figure 19- Thermal Conductivity Testing: (a) Test Setup; (b) Samples Ready to Be Tested

The specific heat capacity of the same cylindrical samples was determined using another testing method developed at ASU. In this method, the specimens were heated to 40°C using a conventional oven and then placed inside an insulating container that initially contained water at 25°C. This setup allowed for the measurement of heat exchange during the test. After a 20-minute interval, the initial and final temperatures of both the sample and the water were recorded. This data allowed for the evaluation of the heat exchange between the heated sample and the water at room temperature. The specific heat capacity was calculated using **(Equation 9** as follows:

$$SHC_{sample} = \frac{m_{water} * \Delta T_{water} * SHC_{Water}}{m_{sample} * \Delta T_{sample}} \qquad \textbf{(Equation 9)}$$

Where,

$\mathrm{SHC_{sample}}$: the specific heat capacity of the sample in $\mathrm{kg^{-1}.°K^{-1}}$

m_{water} : mass of the water poured into the container in kg

m_{sample} : the mass of the preheated sample in kg

ΔT_{water} and ΔT_{sample} : change in temperatures for the water and sample before and after the heat exchange in °C.

The experimental equipment used is shown in **Figure 20** below including the insulating container, thermocouple, sample mold and thermal gun.

Figure 20- Specific Heat Capacity Testing Equipment

3.4.3.9. Linear Expansion and Contraction Coefficient

To enhance the durability of sealants, it is crucial to understand their thermal behavior. This involves identifying how sealants expand and contract in response to temperature changes, as well as their ability to conduct heat. By gaining insight into these characteristics, it becomes possible to improve the sealant's durability.

An effective sealant should possess the capacity to stretch adequately when cracks expand, allowing it to accommodate the crack while remaining firmly adhered to the pavement surface. Additionally, the sealant should exhibit sufficient elasticity to endure the expansion and contraction of cracks without experiencing failure within the crack itself.

Since there was no standardized test available to measure these specific parameters, a novel testing setup was developed at Arizona State University. This setup was specifically designed to quantify the changes in thermally induced strains within viscoelastic materials, with a particular focus on asphalt crack sealants. The detailed procedure of the test development is included in Chapter 4. Figure 21 shows a crack sealant beam created for setup for testing under different thermal cycles.

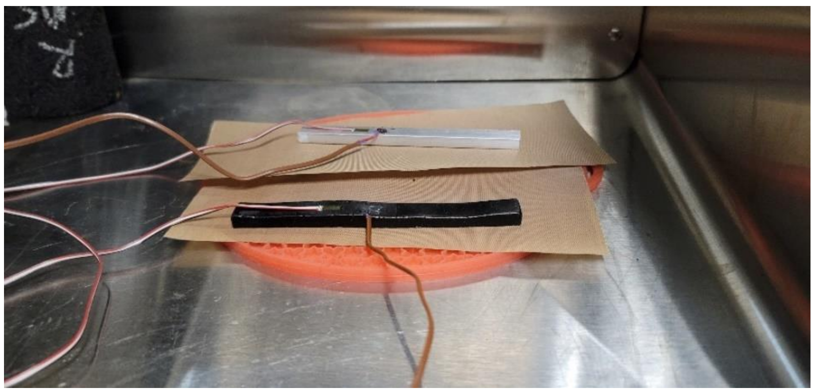


Figure 21- Linear Expansion and Contraction Sample Measurement

3.4.3.10. Moisture Induced Shear Thinning Index (MISTI) (D. J. Oldham et al., 2022)

The MISTI index was utilized to assess the intermolecular interaction within the sealant matrix. To evaluate the MISTI, the same DSR setup with a parallel plate and spindle system was used. The process involved applying a shear-rate ramp from 0.1 to 100 1/s to each specimen, with the viscosity being measured at each shear rate value. The testing temperature for each sample was adjusted to ensure a linear behavior and while maintaining the zero-shear viscosity value. By adjusting the temperature of each sample, the equi-viscosity concept was implemented whereas all samples were tested at different temperatures while achieving approximately similar zero-shear viscosities (D. J. Oldham et al., 2022). The slope of the shear-thinning viscosity zone with respect to shear rate was correlated to the molecular interaction of the sealant matrix, where a steeper shear-thinning slope reflects higher interactions. To determine the MISTI, the slope of the shear-thinning region is determined for both conditioned (wet) and unconditioned (dry) samples using a power-law equation (**Figure 22**).

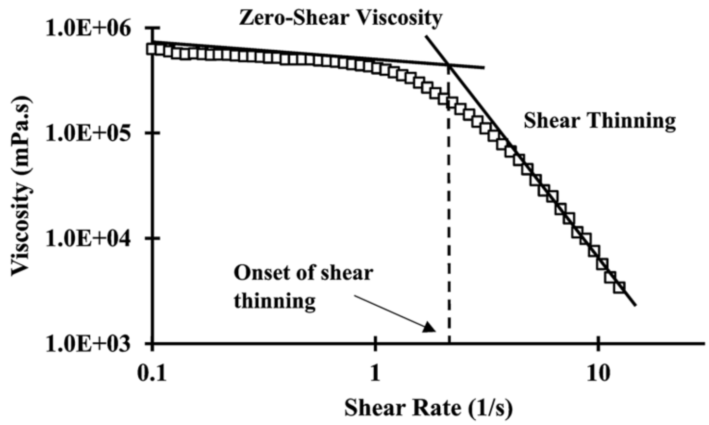


Figure 22- MISTI Results for Slope Determination of The Shear-Thinning Region

The onset of shear thinning is determined by the intersection of the two asymptotes from both shear-thinning and zero-shear viscosity regions. More specifically, before the onset of shear-thinning, the viscosity is independent of the shear rate applied. As the viscosity remains almost constant, it refers to the zero-shear viscosity of the material. After the onset of shear-thinning, the viscosity of the material begins to decrease. The MISTI is calculated as the ratio of the shear thinning value from the wet samples to the dry samples (**Equation 10**). The shear thinning values are determined from the slope of the curve within the shear-thinning region using a power-law trendline.

$$\text{MISTI} = \frac{\text{Power} - \text{Law Slope of Wet Sample}}{\text{Power} - \text{ Law Slope of Dry Sample}} \qquad \textbf{(Equation 10)}$$

In order to test for the MISTI, the test samples were prepared by adding glass beads to the asphalt crack sealants. The glass beads represent the aggregates in asphalt mixtures to ensure that the testing is repeatable. The samples were heated to elevated temperatures until they are liquid (193ºC), and the glass beads were manually introduced and hand-mixed accordingly for 5 minutes. An adequate glass bead to sealant ratio was selected to ensure that there are enough glass beads, without overlapping, to induce moisture damage. The size of the glass beads and content were kept constant throughout the testing.

The samples were prepared to be tested for both plate diameters, 25mm and 8mm with sample thicknesses of 1 and 2mm respectively. The samples were tested under both dry and wet conditions to be able to determine the index. For the dry conditioning, the samples were allowed to sit at room temperature after pouring for 1 hour before testing. As for the wet conditioning consisted of soaking the prepared samples in distilled water at a temperature of 60ºC for 24 hours. In total, 3 replicates for each condition and scenario were prepared for this study.

A sensitivity analysis for the corresponding sealant to glass bead ratio as well as plate diameter size was conducted. This analysis consisted of determining the best sealant to glass bead ratio, yielding the most linear portion with respect to the onset of shear thinning under both dry and wet conditions. Ratios of 1:1, 4:1 and 8:1 were evaluated using diameter plates of 25mm and 8mm. For CS, the ratio yielding the most satisfactory test results was 4:1, whereas a ratio of 8:1 was selected for CF given its consistency. The 25mm diameter plate also showed the best results, as more material was tested with the glass beads, leading to more stable results. Furthermore, as sealing materials are typically stiffer, the testing temperature yielding the zero-shear viscosity was found to be higher than the one for asphalt binders. For this reason, a 25mm plate was more suitable for this test.

3.4.3.11. Fourier Transform Infrared Spectroscopy (FTIR)

In this test, the chemical characteristics of the specimens are studied using infrared light. The testing machine emits radiation that can either be absorbed by the sample or pass through it. When the radiation is absorbed, it is converted into rotational or vibrational energy by the molecules in the sample. Each sample exhibits a unique spectrum, which reflects its chemical structure based on the absorption levels at different wavelengths.

This test is significant as it allows for the determination of the aging level of each tested sample and evaluates the impact of the addition of different modifiers into the sealant. The Carbonyl (C=O) and sulfoxide (S=O) bonds are of interest, and they are located at wavelengths from 1640 to 1755 cm^{-1} and between 984 and 1060 cm^{-1} respectively (Hofko et al., 2018). To calculate the C=O (**Equation 11**) and S=O indices (**Equation 12**), it is important to locate the reference aliphatic region, which spans from 1525 to 1355 cm^{-1} (**Table 12**).

$$I_{CO}=\frac{\text{Area around 1700 cm}^{-1}}{\text{Area around 1460 cm}^{-1}} \quad \textbf{(Equation 11)}$$

$$I_{SO}=\frac{\text{Area around 1030 cm}^{-1}}{\text{Area around 1460 cm}^{-1}} \quad \textbf{(Equation 12)}$$

Where,

I_{CO}: Carbonyl (C=O) index

And I_{SO}: Sulfoxide (S=O) index

Table 12- Integral Upper and Lower Wavelength Limits

Structural Group	Lower Wavelength Limit (cm^{-1})	Upper Wavelength Limit (cm^{-1})
C=O	1640	1755
S=O	984	1060
Reference Aliphatic	1525	1355

The presence and intensity of these peak stretches at the respective wavelengths provide insights into the different aging levels of the samples (Nivitha et al., 2016) as well as potential chemical changes induced by the addition of new modifiers into the material.

The interest behind this test was to identify the effect of PCR on the modified sealant. By adding PCR into the sealant, the aging effects on the material may be reduced, as rubber is pre-activated and could absorb the fractions providing the viscoelastic effect into the sealant. When the sealant is aged, only a portion of the resins will be evaporated and compensated by the presence of the suggested modifier. Studies have shown that binders modified with rubber have exhibited less aging over time (Abdelmagid & Feng, 2019)whereas crumb rubber swells and absorbs the lighter fractions present in the binder. In terms of chemical composition, the primary constituents of the non-oily and oily phases are asphaltenes and maltenes, respectively. According to the widely accepted colloidal model that depicts the internal structure of asphalt, asphalt behaves as a colloid containing micelles. In this model, fractions of asphaltenes are situated at the center of micelles, surrounded by a layer of lower molecular weight hydrocarbons, and dispersed in the oily phase. Consequently, the viscoelastic properties of asphalt materials are notably influenced by the ratio of asphaltenes to other fractions, such as maltenes. As the asphalt binder undergoes aging, polar aromatics transform into asphaltenes. Additionally, throughout the aging process, naphthalene aromatics shift to polar aromatics, which then oxidize and convert into asphaltenes. This transformation results in a decrease in maltenes content and an increase in asphaltene content (Airey et al., 2002).

3.5. Conclusions and summary

In this chapter, a summary of the materials, modifiers and testing procedures were presented. Two different materials will be evaluated, one crack filling referred to as CF and another crack sealant referred to as CS. The performance of those materials will be assessed using four different modifiers: aMBx, RaC, PCR and SF. The first modifier called aMBx stands for Aerogel Modified Bituminous Materials. Two different sources of aerogel were used for the evaluation, to determine the effect of different sizes on the performance of the material. The second modifier, RaC, refers to Recycled Aerogel Composite, and includes crumb rubber in the modifier. Third, PCR stands for Pre-activated Crumb Rubber, and was used to evaluate potential improvement in elasticity and flexibility. Finally, SF refers to Synthetic Fibers, were chosen to evaluate the effectiveness of fibers into the material given the background of this modifier improving bituminous materials in terms of stretchability and cracking resistance.

The testing procedures described tackle different failure modes observed in the field such as adhesion, cohesion, settlement, tracking, thermal susceptibility, and moisture susceptibility. The control and modified materials were tested under unaged and aged conditions, to determine the overall performance upon application and after a couple of years. The aging method chosen was using the accelerated vacuum oven. The tests include softening point, resilience, cone penetration test rotational viscosity, shear thinning and tracking where the failure modes tackled are settlement, flow, high temperature softening and tracking. As for the bending beam rheometer, the stiffness and relaxation capacity were targeting the low temperature embrittlement and adhesive failures. Other tests referring to adhesive and cohesive failures include toughness and tenacity, MSCR, and bond strength. With respect to thermal susceptibility, thermal conductivity, specific heat capacity and coefficient of thermal expansion were measured. Finally, for the moisture susceptibility, the bond strength under wet conditions as well as the moisture shear thinning index were chosen to determine the effect of moisture on the bonding properties and on the characteristics of the material respectively.

Finally, to ensure homogenous mixing and a good spread of the modifiers, the best modification methods were found as the following: mechanical mixing for aMBx and RaC methods at the manufacturer's recommended temperature of 193^{o}C; high speed mixing (800rpm) for 20 minutes for the PCR at the same temperature, and 30 minutes for the SF modification at the same temperature and speed.

CHAPTER 4

4 LINEAR EXPANSION AND CONTRACTION COEFFICIENT MEASUREMENT FOR BITUMINOUS MATERIALS

4.1. Introduction

The coefficient of thermal expansion (CTE) is one of the most important characteristics of the testing material to understand their behavior when it comes to temperature change. It refers to the rate at which a material expands with an increase in temperature. It is determined at a constant pressure without a phase change within the material. In general, the CTE depends on the bond strength between the atoms that make up the material. Covalent materials, such as diamond and crystals, have strong bonds between the atoms resulting in low CTEs. Although there is published research of CTEs for common metals and standard alloys, the need arises to measure this coefficient over a specific temperature range for new and modified materials. The interest is to be able to measure the CTE of asphalt binder and other asphalt-based materials, such as asphalt crack sealants. Those materials are viscoelastic and very temperature susceptible: they soften at increased temperatures and harden at lower temperatures. For this reason, measuring the CTE at specific temperatures without causing the phase change of those materials is needed. In addition, the literature doesn't report a present method to measure this coefficient for those types of material in an accurate way.

Historically, the classical method to measure this coefficient has been done using a Dilatometer (JoVE Science Education Database, 2023). This instrument measures the difference in expansion between a rod made from the testing material and a matching length of a material with known coefficient, such as vitreous silica. The differential expansion is measured with a sensitive dial indicator or a Linear Variable Differential Transducer (LVDT). Using a known material alongside the test sample will help in calibrating the experiment to have more accurate measurements. However, making measurements with a dilatometer is a delicate and demanding task. For this reason, this section proposes a new method of measuring the expansion and contraction of materials in an easier and more accurate way with respect to reference material. In the sections below, the new method is described and explained, including the sample geometry size and effect and calibration. A patent application for the proposed setup will be filed in the near future.

4.2. Methodology

The proposed method requires two strain gages where one is bonded to the test specimen and the other to a material of known coefficient to ensure the accuracy of the measurements. When a resistance strain gage is installed on a stress-free specimen and its temperature is changed, the output of the gage changes correspondingly. This is referred to as temperature induced apparent strain or thermal output. The resistivity of the grid alloy of the gage will change with the change in temperature. With this change, the grid is mechanically strained by an amount equal to the difference in expansion coefficients. Since the gage grid is made from a strain sensitive alloy, it produces a resistance change proportional to the thermally induced strain. In this setup, the materials needed as well as the procedure to set up the proposed experiment are explained.

4.3. Equipment Needed

The equipment used to measure the expansion and contraction of the bituminous materials are summarized below:

- Strain Gages: C4A-06-235SL-120-39P, Micro-Measurements
- Thermocouple type K
- Epoxy KwikWeld J-B Weld 8276b
- Super glue gel
- Teflon Sheets
- LabVIEW Software with Data Acquisition System by National Instruments
- Bending Beam Rheometer (BBR) molds for sample preparation
- Temperature controlled chamber

4.4. Sample Preparation

The sample size chosen for this experiment has the same dimension as the sample used for the Bending Beam Rheometer test (AASHTO TP 87, 2015) (127 mm long, 6.35mm wide and 12.7 mm deep), as it is an easy and repeatable way of replicating the sealant and binder samples with enough surface area to place a strain gage.

The samples to be tested are prepared by first making the materials liquid enough to be poured in the beam shaped molds. The mold must be greased prior to pouring the materials to allow for efficient removal of the molds at the time of testing. The samples should be left to cure overnight at room temperature, allowing the settlement of the material. The curing will allow the material to reach the desired consistency for testing as well as the structural integrity expected in the field upon material placement. After trimming the samples, the next step involves placing the strain gages on the smooth side of the beam by flipping the sample on side that was in contact with the mold. Before adhering the strain gage on the sample, it is important to make sure that the gage is working properly. By using a multimeter, the resistance difference between the three cables (Red, White, and Black) must be measured as follows:

- Black and White cables: 0 ohms
- Red and White cables: 120 ohms
- Red and Black cables: 120 ohms

If the measurements are different, the gage is then considered faulty and is discarded. The placing of the strain gage must be done with care. First, the surface of the sample should be cleaned by using a catalyst to allow proper bonding between sample and gage. The strain gage is then fixed on a piece of tape to help fix it on the sample at the desired location. The strain gage's side that shouldn't meet the sample is fixed on the tape. A drop of superglue is spread on the other side of the gage and is then gently pressed on the surface of sample for about one minute to allow the superglue to cure. The samples will still be in the mold at this point and will remain so until the samples are ready to be tested. After one minute, the tape is gently peeled out of the surface of the sample at an angle of 45°, leaving the gage in position.

Second comes the placing of the thermocouples at the surface of the sample to measure the temperature of the sample at every cycle. The thermocouples are fixed to the surface of the sample using epoxy glue with a curing time of 6 hours. It is important to make sure that the tip of the thermocouple is touching the surface of the sample. Otherwise, the temperature measurements recorded will be based on the properties of the epoxy and not the specimen to be tested. After waiting for 6 hours, the sample is ready to be tested. The mold is removed from the sample which is placed inside the chamber with a Teflon sheet underneath. This sheet will minimize the friction underneath the sample and allow the sample to be less restricted and move freely at the bottom.

The final setup, as well as the sample are shown in the figures below. **Figure 23** shows the computer that controls the temperature of the blue chamber on the left-hand side. In the middle circle, the computer gathering the strain and temperature measurements with LabVIEW is shown.

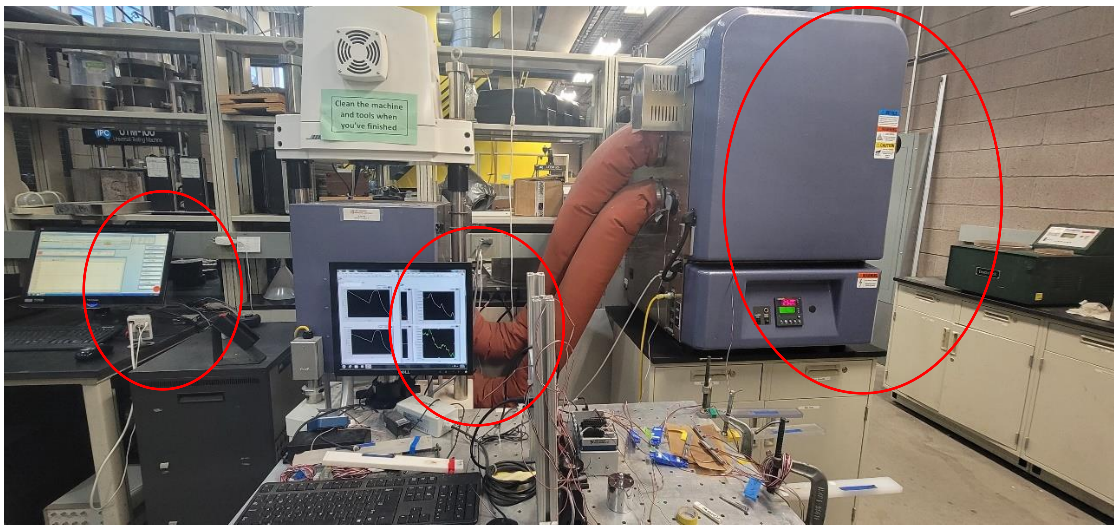


Figure 23- CTE Testing Equipment: Temperature controlling computer, data collection computer, conditioning chamber.

The second figure shows the aluminum sample ready to be tested inside the chamber.

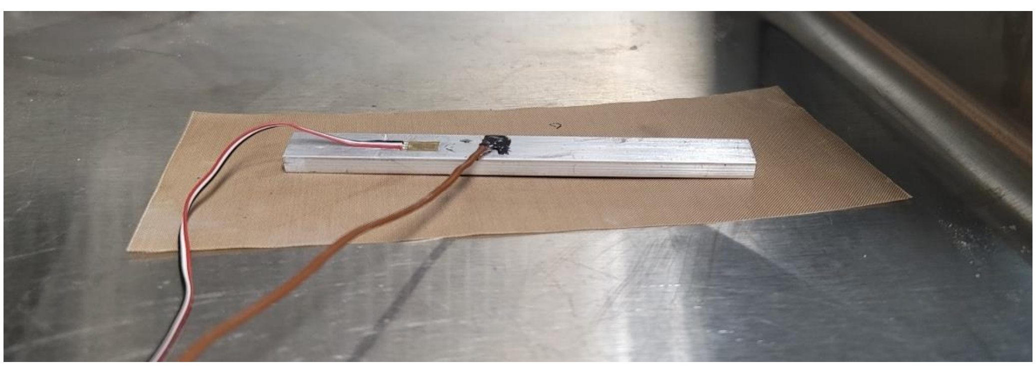


Figure 24- CTE Sample Ready to Be Tested

Figure 24 shows one sample ready to be tested with the stain gage adhered to the surface on the left, and a cured epoxy at the top of the thermocouple close to the placement of the strain gage. This setup will capture the temperature at a close location to where the strain is being measured. The specimen's dimension and geometry were determined analyzed in section 4.5.1.

The chamber, where the samples are placed for measurement, must be conditioned at least 1 hour prior to testing at the first temperature of interest. Ideally, the samples should be left to cure inside the chamber to minimize the deposition of debris at the surface of the sample and ensure the thermocouple position and adhesion without being disturbed. The temperature cycles are set up on the computer connected to the chamber. Multiple trials have been carried out to determine the optimum length of each cycle, the position and sheet types to be used underneath the sample. The length of each cycle was determined to be approximately 45 minutes before moving on to the next temperature. The sample temperature was measured to reach the target temperature within this allocated time, allowing for either expansion or contraction of the material. Furthermore, the use of the Teflon sheet yielded results closer to the literature when compared to other sheet types.

The setup available at Arizona State University allows testing four beams simultaneously for every cycle.

4.5. Calibration Procedure

4.5.1. Geometry Analysis

To determine if geometry of the specimen affected the measurements, beams with different lengths were tested using the same conditions at the same time in the conditioning chamber. The initial length, referred to as "Big" reflects the original size of the sample of 127mm. The other length considered as "Small", refers to half of the initial length. The results in **Table 13** showed that the length of the sample did not affect the reading measurements significantly. Therefore, the original length of the sample was adopted for the remaining testing. As for the width of the sample, it was considered wide enough as it provided a suitable surface for the placement of the gage. Since only linear expansion in the direction of the gage was desired, the width of the sample was minimized as much as possible to reduce errors in measurements as well as other expansion/contraction directions of the material. The materials of interest are anisotropic due to the modifiers implemented and the nature of the material itself.

Finally, for the thickness, a 12mm thickness was considered to be representative of the material's thickness including the possibility of having a considerate number of modifiers of different sizes, such as fibers, rubber etc. One other important geometry aspect that needs to be further evaluated in the future refers to the change in geometry of the sample after undergoing different thermal cycles. In this study, the samples' CTE was measured for temperature cycles ranging from 20 to 40^{o}C, where no significant changes to the geometry due to softening were observed. For this reason, the change in geometry was disregarded.

Table 13- Results of the CTE Geometry Analysis

Materials with Different Lengths	**Average Measurements (mm/mm.C)**	**Literature Values (mm/mm.C)**	**COV**
Big Aluminum	1.08E-05	2.36E-05	74%
Small Aluminum	9.38E-06	2.36E-05	86%
Big Brass	7.38E-06	1.87E-05	87%
Small Brass	6.72E-06	1.87E-05	94%

4.5.2. Material Characterization

Furthermore, different materials with known coefficient of expansion were tested using the setup. The measurements obtained were then compared to the values present in the literature. The materials were obtained in the same geometry described in the previous section as per the following from McMaster-Carr:

Table 14- Selected Specimens for CTE Calibration

Specimens Tested	Characteristics	Coefficient of Linear Expansion (mm/mm.C)
Aluminum	Multipurpose, 6061	2.36E-05
Brass	Ultra-machinable, 360	1.87E-05
Acrylic	Clear Scratch, UV-Resistant Cast	7.40E-05
Steel	Tight-Tolerance Low-Carbon, A36	1.20E-05
Stainless Steel	Multipurpose, 304	1.72E-05

The linear expansion coefficients for the reference materials are normally obtained from expansion between 20°C up to 100°C. For this reason, the suggested setup was run for those same temperatures in both expansion (from 20°C to 100°C) and contraction (from 100°C to 20°C) and the coefficients were calculated as explained in the section below. A calibration curve shown in **Figure 25** was developed comparing the measured values to the ones present in the literature for all the materials mentioned in **Table 14**. This curve will be used for all the measurements to be done using this setup. **Figure 25** shows the uncalibrated CTE values for the reference materials, where a linear trendline was fit to the data. The R^2 of 0.9969 suggests that a linear trendline is appropriate and accurate with respect to the obtained data. Then, the uncalibrated values were adjusted and shown in the same figure. The results of the calibration process are shown in **Table 15**. The coefficient of variation between the calibrated and literature values for the selected materials was acceptable with a maximum of 15% difference for Stainless steel.

Table 15- CTE Calibration Results

Materials	Uncalibrated Measurements (mm/mm.C)	Calibrated Measurements (mm/mm.C)	Literature Values (mm/mm.C)	COV
Aluminum	1.08E-05	2.43E-05	2.36E-05	-3%
Brass	7.38E-06	1.97E-05	1.87E-05	-5%
Acrylic	4.87E-05	7.42E-05	7.40E-05	0%
Steel	1.71E-06	1.23E-05	1.20E-05	-2%
Stainless Steel	3.61E-06	1.48E-05	1.72E-05	15%

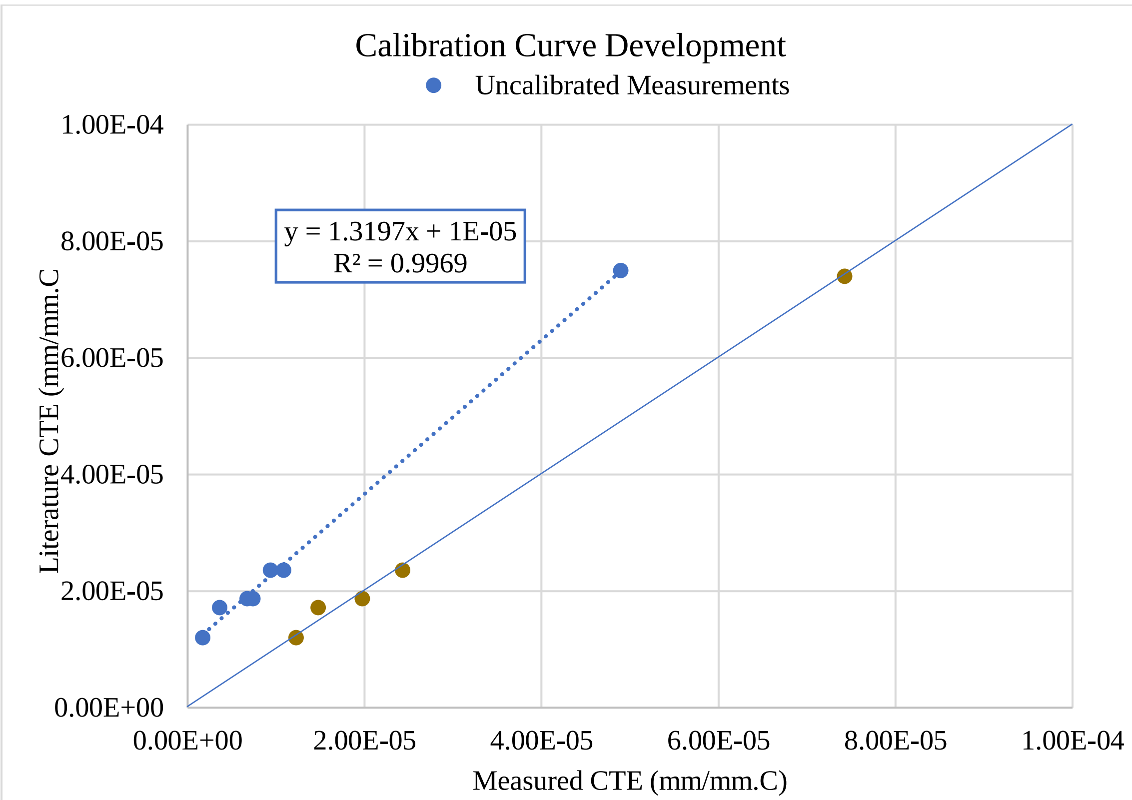


Figure 25- CTE Calibration Curve Development

4.6. CTE Calculations

After running the desired temperature cycles, the strains and temperatures were measured and recorded by LabVIEW. The CTE **(Equation 13)** in this experiment is calculated by the difference in temperature measured by the thermocouples for each sample, divided by the equivalent change in strain measured by the strain gage during the same time:

$$\alpha = \frac{\Delta T}{\Delta \varepsilon} \qquad \textbf{(Equation 13)}$$

Where,

α: coefficient of thermal expansion or contraction, in mm/mm.°C

ΔT: change in temperature, either increasing for expansion or decreasing for contraction, in °C

And Δε: change in strain during the same period cause by either the expansion or contraction of the material.

The coefficient of thermal expansion and contraction for each material is then found by averaging the CTE and the coefficient of thermal contraction found during testing. Other important considerations must be taken with respect to the softness of the material to be tested. Very soft material may soften at temperatures greater than 20°C. For this reason, the temperature cycle ranges must be carefully selected prior to testing.

4.7. Summary and Conclusion

A test setup was developed in this chapter to measure the expansion and contraction of the sealing material. The suggested procedure included the use of strain gages to measure the movement of the material at different temperature cycles, generated by a controlled conditioning chamber. The strain differences were recorded by a data acquisition system by means of LabVIEW. To minimize the friction at the bottom of the sample, a Teflon sheet was used. The difference in strains due to the temperature cycling, divided by the difference in measured temperatures were used to calculate the coefficient of linear expansion and contraction.

The geometry of the sealing material was evaluated to best reflect the expansion and contraction mechanisms. The BBR sample dimensions were chosen for ease of replication. It was found that the thickness of the material affects the reading, while the length did not. It is to be noted that the change in geometry induced by thermal cycling was disregarded in this study, as the maximum temperature reached for measurements was $40^{o}C$. No significant changes were observed at this stage. This effect needs to be further evaluated for standard submission.

Finally, a calibration round was conducted using different materials of known coefficients to offset the difference in readings. This test procedure can be used for both asphalt binders and crack sealants. To further evaluate the significance of this test, it is important to differentiate between the pavement's and sealant's expansion and contraction. Given that the amount of crack sealing is smaller than the pavement's geometry, its actual expansion and contraction is way smaller than the pavement movement. However, this test reflects on the material's ability to handle temperature changes by preserving its stability and integrity. If the material is opposing the movement of the pavement or the crack, its integrity with time will be jeopardized and premature failures will occur.

CHAPTER 5

5 CALIBRATION OF TOUGHNESS AND TENACITY TESTING

5.1. Introduction

Toughness and tenacity are two important properties of asphalt binders that affect their performance in pavement construction and maintenance. While these terms are often used interchangeably, they represent slightly different aspects of the material's behavior.

Toughness refers to the ability of an asphalt binder to resist cracking and deformation under stress or strain. It is a measure of the material's resistance to fracture. Asphalt binders with high toughness can withstand external forces and exhibit improved resistance to cracking and fatigue failure. Toughness is particularly critical in areas where the pavement experiences heavy traffic loads, temperature fluctuations, and aging effects.

On the other hand, tenacity refers to the adhesive and cohesive properties of an asphalt binder. It describes the ability of the binder to maintain its integrity and stickiness over time, ensuring proper bonding between aggregate particles and promoting overall pavement durability. A highly tenacious asphalt binder adheres well to the aggregate surface, forming a strong bond and minimizing the potential for moisture infiltration, stripping, or debonding.

Both toughness and tenacity of asphalt binders are influenced by their chemical composition, physical properties, and environmental conditions. Various tests and specifications are used to assess these properties, including the performance grade of the material, which categorizes binders based on their expected performance under different temperature conditions.

To enhance toughness and tenacity, modified asphalt binders are often used. These modified binders incorporate additives such as polymers, fibers, or rubber to improve their resistance to deformation, cracking, and aging. The addition of modifiers enhances the binder’s elasticity, flexibility, and adhesion properties, resulting in improved pavement performance and longevity. It’s important to note that the specific properties and performance requirements of asphalt binders can vary depending on regional factors, such as climate, traffic conditions, and pavement design standards. Therefore, local specifications and guidelines should be considered when evaluating and selecting asphalt binders for a particular application.

Concerning asphalt crack sealants, the toughness and tenacity parameters are of interest to evaluate their adhesive and cohesive properties, as well as their resistance to failure. The adaptation of this test for sealing materials would be helpful to better understand the material’s behavior under different temperatures and traffic conditions. In this chapter, this test was adapted to an asphalt crack sealing material tested under different pull-out rates and temperatures.

5.2. Methodology

In this section, the methodology implemented to characterize asphalt crack sealants is presented. Samples were prepared from a control asphalt crack sealant. They were tested at different temperatures for different pull-out rates.

The pull-out rate refers to the force required to dislodge or pull out a crack sealant material from an asphalt pavement crack. The effect of the pull-out rate on asphalt crack sealants is primarily related to their adhesion and performance characteristics.

Furthermore, the pull-out rate is often used as a measure of the adhesion strength between the crack sealant and the surrounding asphalt pavement.

Different crack sealant formulations may exhibit varying pull-out rates at different temperatures. Some sealants may perform well at moderate temperatures but exhibit reduced adhesion and higher pull-out rates at extreme temperatures. It is crucial to choose sealants that have been tested and proven to maintain their adhesion properties over a wide range of temperatures.

The combined effect of temperature and pull-out rate on crack sealants implies that selecting the appropriate sealant formulation for specific temperature conditions is vital. Manufacturers often provide guidelines and specifications regarding temperature ranges for application and expected performance, enabling the selection of sealants suitable for the local climate, and expected temperature fluctuations. Proper application techniques, including surface preparation and adherence to recommended temperature ranges, will help ensure effective crack sealing and long-lasting performance of the sealant.

To study the effect of both temperature and pull-out rates, four different temperatures were selected for testing: 10^{o}C, 25^{o}C, 35^{o}C and 50^{o}C. The sealing material chosen was CF, as described in Chapter 3, Section 3.2.1. Those temperatures were selected based on the typical pavement temperatures found in Phoenix, Arizona. In addition, 8 pull out rates were tested at those different temperatures at an increment of 0.5 mm/sec, starting from 0.5 mm/sec to 4.5 mm/sec.

5.3. Material Characterization

5.3.1. Temperature Analysis

By plotting toughness vs tenacity at each temperature and rate, it can be seen from **Figure 26** the higher the temperature, the two parameters tend to be closer in terms of magnitude. As mentioned previously, it is ideal to have higher values for both toughness and tenacity. However, at the higher end of the temperature scale used in this study, the values for toughness and tenacity tend to be lower at all pull out rates (50°C). This behavior is observed as the material is softer at higher temperatures.

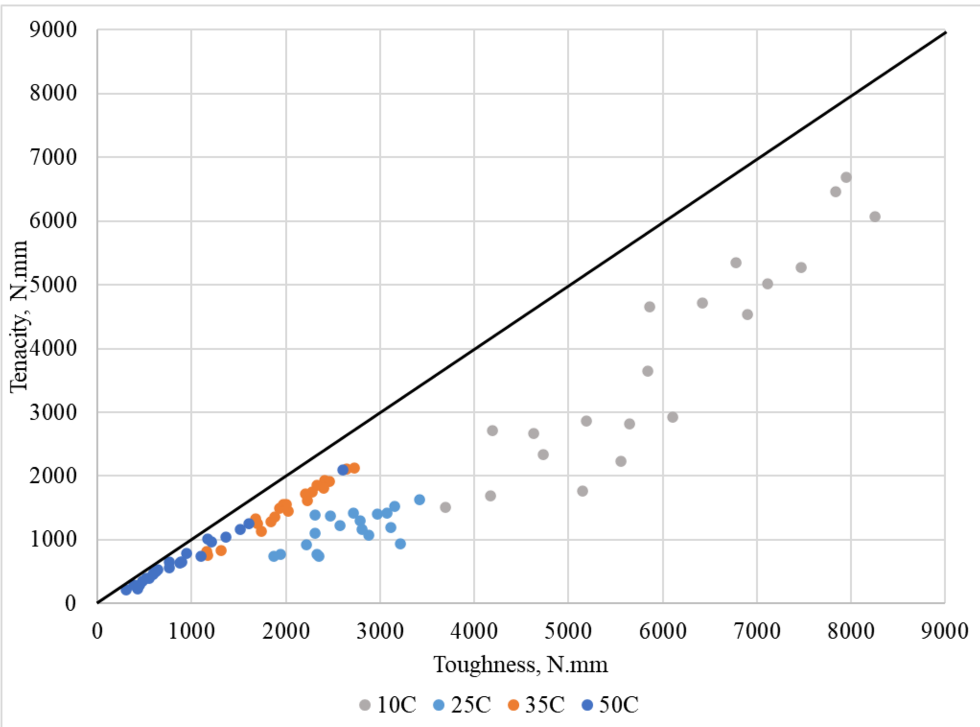


Figure 26- Toughness and Tenacity Temperature Analysis for Different Pull-out Rates for CF.

Furthermore, in terms of tenacity, as the material is more on the soft side, it is not very significant. As the measurements move towards lower temperatures, the behavior is more ideal at 35°C, where the parameters exhibit higher magnitudes and follow the bisector curve. For the 25°C, the toughness parameter is increasing for all measured rates, while maintaining an acceptable level for tenacity. The material becomes stiffer at lower temperatures and therefore requires higher strength to be separated from the tension head, which is justified by higher toughness values. However, for the 10°C measurements, a scatter pattern is identified, where the material has higher toughness and tenacity values. However, by comparing the two values, the toughness is much greater than the tenacity. As those values are obtained by integrating the area under the load vs displacement curve obtained, the higher tenacity value shown represents a greater area plotted, but not necessarily a larger stretch of the material. As asphalt crack sealants are viscoelastic materials, a stiffer behavior with lower stretchability is to be expected at lower temperatures.

Tenacity is defined as the material's ability to resist deformation and maintain structural integrity, changes with temperature. As the temperature decreases, the tenacity of bituminous materials generally decreases. At lower temperatures, asphalt materials become more rigid and brittle. They exhibit higher viscosity and stiffness, which can lead to cracking and reduced flexibility. This is known as low-temperature stiffness or susceptibility to thermal cracking. As a result, the tenacity of asphalt materials decreases in colder conditions. Conversely, as the temperature rises, asphalt binders soften and become more viscous. This increased flowability and reduced viscosity can result in rutting and deformation under heavy loads. The tenacity of asphalt binders decreases in hotter temperatures due to the reduced resistance to deformation. For this reason, an optimum performance and assessment of the material behavior are recommended to be evaluated at a temperature range between 25 and 35°C.

5.3.2. Pull Out Rate Analysis

In terms of pull-out rate analysis, the tenacity and toughness values have been plotted on two separate bar charts, **Figure 27** and **Figure 28** respectively.

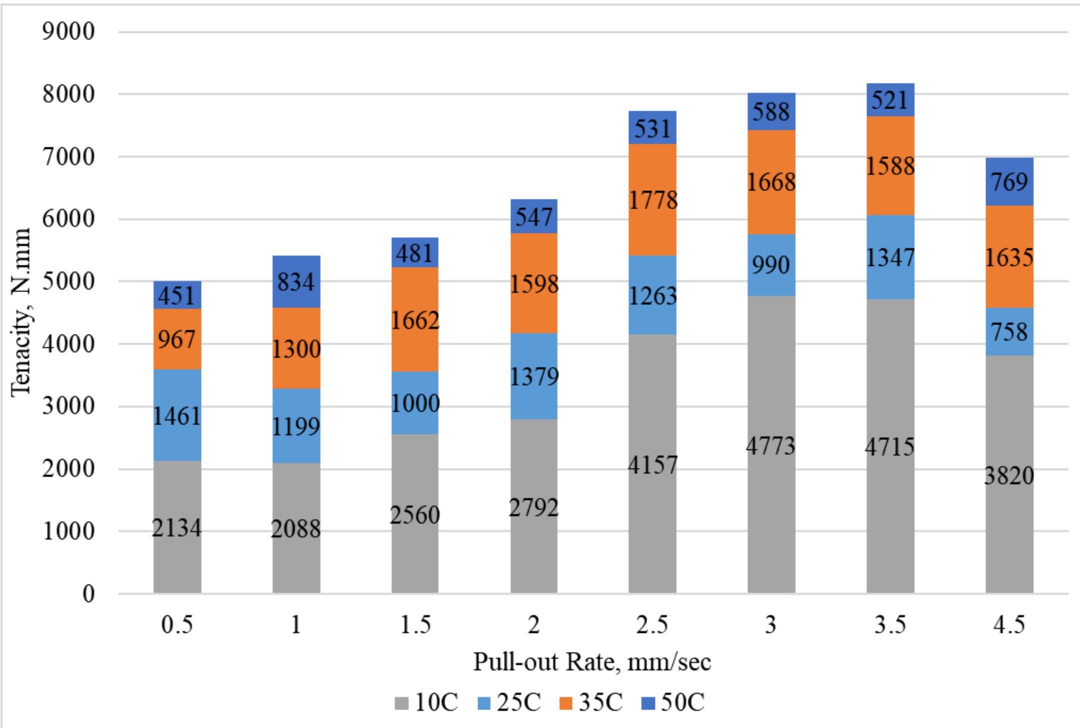


Figure 27- Tenacity Pull-out Rate Analysis at Different Temperatures for CF.

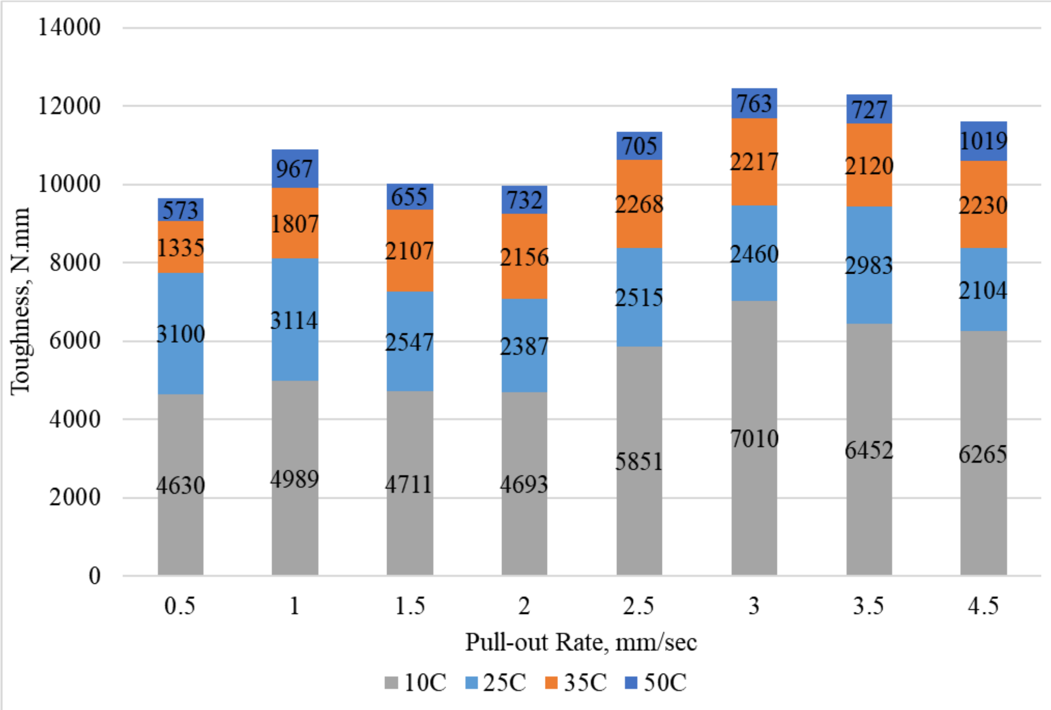


Figure 28- Toughness and Pull-Out Rate Analysis at Different Temperatures for CF.

Tenacity can also be influenced by the loading rate, which is the rate at which stress is applied to the material. In general, the tenacity tends to increase with higher loading rates. At lower loading rates, sealants have more time to deform and flow, resulting in increased relaxation and reduced resistance to deformation. This behavior is known as viscoelasticity, where the material exhibits both viscous (flow) and elastic (recovery) characteristics. At low loading rates, the sealant can deform more easily, leading to a lower tenacity. On the other hand, at higher loading rates, deformation occurs more rapidly, giving the material less time to flow and relax. This rapid loading creates higher stresses and strains, resulting in a greater resistance to deformation and higher tenacity. The higher loading rate limits the flow of the sealant, allowing it to exhibit more elastic behavior.

It's important to note that the influence of loading rate on the tenacity of a crack sealant is typically more prominent at lower temperatures. At higher temperatures, the sealant is generally softer and exhibits a higher flowability, making the loading rate effect less significant. It can be seen from **Figure 27** that the tenacity values of CF are higher in terms of magnitude but does increase with an increase in loading rate.

Taking a closer look at the tenacity values at each temperature measured, pull-out magnitude ranges were noted to generate higher tenacity values. For the lowest tested temperature, 10^{o}C, a loading rate ranging from 3 to 3.5mm/sec generated higher tenacity. For 25^{o}C, this range goes from 2 to 2.5 mm/sec. As for both temperatures of 35^{o}C and 55^{o}C, the tenacity values are almost equal for loading rates ranging from 1.5 to 4.5 mm/sec, which proves that the higher the temperature, the less significant the value of the loading rate is.

In terms of toughness, it refers to their ability to absorb energy without fracturing or failing, generally increases with higher loading rates. At lower loading rates, sealants have more time to deform and flow, which can result in greater relaxation and reduced toughness as well. However, rapid loading creates higher stresses and strains within the material, leading to increased toughness. The crack sealant is less likely to fracture or fail as it absorbs and dissipates energy more efficiently under the higher loading rate. It's worth noting that the relationship between loading rate and toughness of crack sealant is influenced by various factors, including temperature, binder composition, and the presence of additives or modifiers. Overall, the loading rate can significantly affect the toughness of the material, with higher loading rates generally resulting in increased toughness and improved resistance to fracture or failure.

In terms of measured toughness at different loading rates, a similar analysis to the tenacity values is conducted. At higher temperatures, the pull-out rate did not really affect toughness. At lower temperatures, higher toughness values were observed at different loading rates, ranging from 3 to 3.5 mm/sec. However, the loading rates at 25^{o}C, 35^{o}C, and 50^{o}C, comparable toughness values. Therefore, it can be concluded that the loading rate does not affect sealant's toughness values at higher temperatures, opposing to tenacity.

5.3.3. Peak Load Analysis

The peak load measured while testing for toughness and tenacity represents the maximum load the sample can take before failure. It can be seen from **Figure 29** that temperature largely affects the magnitude of the peak load: the higher the temperature, the lower the force measured. However, it can be noticed that the peak load at different temperatures occurs at different loading rates. A trend between the peak measurements is noticed, as the peak value increases with an increase in loading rate up to 3 mm/sec, where the peak load occurs. After that pull-out rate, a drop in the measured peak load is noticed at all temperatures. However, the drop was measured to be less significant at higher temperatures.

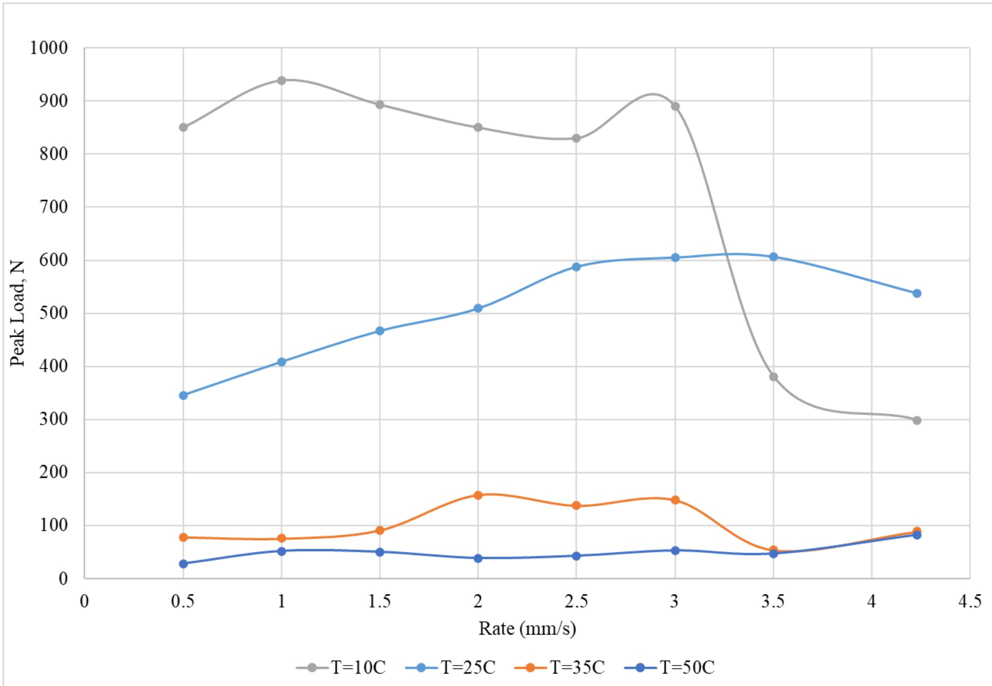


Figure 29- Peak Load Measured at Different Pull- Out Rates and Temperatures for CF.

5.4. Summary and Conclusions

This chapter evaluated the importance of toughness and tenacity within crack sealants in pavement construction. The importance and differences between toughness, denoting resistance to cracking and deformation, and tenacity, encompassing the adhesive and cohesive attributes of the sealant were highlighted. These characteristics are fundamental in ensuring the longevity and resilience of pavements against various environmental factors. To increase these properties, modified asphalt crack sealants, often incorporating additives such as polymers or rubber, are frequently employed.

The chapter explains the detailed testing methods for characterizing asphalt crack sealants, including careful analysis of temperature and pull-out rates. Results showed that elevated temperatures tend to yield softer behavior and reduced values for both toughness and tenacity, whereas lower temperatures lead to stiffer behavior with increased toughness with less pronounced changes in tenacity. Four different temperatures and 8 pull-out rates were used for the material characterization.

The study further reveals through the pull-out rate analysis that tenacity typically increases with higher loading rates, indicative of higher resistance to deformation. However, the effect of pulling rate on toughness varies with temperature, typically enhancing toughness, especially in colder conditions.

Peak load analysis underscores the substantial influence of temperature on the magnitude of peak load, with higher temperatures correspondingly yielding lower peak loads. Additionally, the relationship between maximum peak load and pulling rate follows a clear trend, increasing to a certain rate before decreasing, particularly noticeable at higher temperatures.

In conclusion, the chapter stresses the importance of fully understanding how sealants behave under different environmental conditions and emphasizes the critical role of selecting appropriate sealants tailored to specific regional requirements and expected temperature changes to ensure optimal road performance and longevity.

CHAPTER 6

6 CHARACTERIZATION AND ASSESSMENT OF AEROGEL MODIFIED BITUMINOUS MATERIALS MODIFIED SEALANTS

6.1. Introduction

It was hypothesized earlier that the aMBx material with extremely low thermal conductivity would enhance the properties of the asphalt crack sealants, making them more durable. In this chapter, the effect of adding "aMBx" into the two types of asphalt crack sealing materials is evaluated following the described testing protocol in Section 3.4. The performance of both crack sealing materials is also evaluated for two different aMBx types. These aMBx types are marginally different based on the quality of the raw aerogel used. The difference in performance for both sealant types will be assessed and presented at the end of this chapter. Preliminary testing required the determination of the optimum aMBx content for both sealants and aMBx types. The contents ranged from 2.5% to 20% by weight of the sealant.

6.2. Aerogel Modified Bituminous Materials (aMBx) Types

In order to produce aMBx, two different aerogel sources were used: AP1 and AP4. The characteristics of those two aerogels are found in the **Table 16** below:

Table 16- Aerogel Types Used to Produce aMBx.

Aerogel Type	**Grains Type**	**Max. Particle Diameter (μm)**	**Average Bulk Density (g/cm^3)**	**Avg. Thermal Conductivity (W/m.K)**	**Avg. Surface Area (m^2/g)**	**Avg. Pore Diameter (nm)**	**Avg. Porosity (>%)**
AP1	Particles	700	0.13	0.012	800	20	90
AP4	Granules	3500	0.18	0.020	850	60	90

The aMBx produced from those two types are called "EaMBx" from AP1, are "RaMBx" from AP4 sources. Given that AP4 had a higher density, less binder was needed to produce the aMBx using this source to achieve proper coating. As for AP1, more binder was needed to ensure proper coating of the particle. Therefore, lower EaMBx contents were added into the sealants to be tested (from 2.5% to 5% EaMBx content by weight). As for RaMBx, initial testing required testing modified sealants from 5% up to 20% RaMBx by weight of the sealant. Later, it was determined that the optimum aMBx content can't be greater than 10% by weight of the material because of temperature reduction and mixing issues.

6.3. Aerogel Modified Bituminous Materials (aMBx) Modification Test Results for Crack Sealant (CS)

6.3.1. Crack Sealant (CS) Modified with RaMBx Test Results

6.3.1.1. Softening Point, Resilience and Cone Penetration Test Results

In this section, the Softening Point, Resilience and Cone Penetration test results are reported for CS, using RaMBx for both unaged and aged conditions in **Table 17**.

Table 17- Softening Point, Resilience and CPT Test Results for CS using RaMBx.

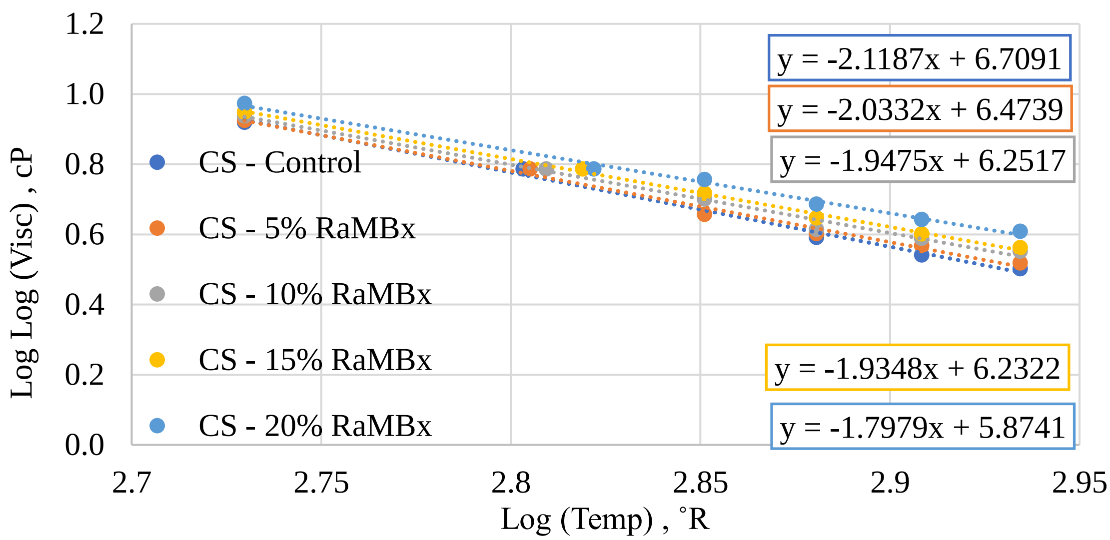
Sealant Type	Softening Point (ºC)	Resilience (%)	Cone Penetration (1/10 mm)
CS - Control	80	94	72.67
CS - 5% RaMBx	81.5	69	65
CS - 10% RaMBx	85	72	50
CS - 15% RaMBx	93	61	40
CS - 20% RaMBx	95.5	67	23.6
CS - Control Aged	82	68	45
CS - 5% RaMBx Aged	83	42	42
CS - 10% RaMBx Aged	86	55	36

It can be seen that the addition of RaMBx rendered the sealant stiffer, by increasing the softening point and decreasing the cone penetration results. Furthermore, a lower resilience was observed with the modification. The observed trends are consistent with the addition of the modifier into the material. As more aerogel was used to produce this type of aMBx, the consistency of the material was affected by the larger amount of aerogel present within the particle when compared to the binder content. This explains the stiffness increase of the modified material.

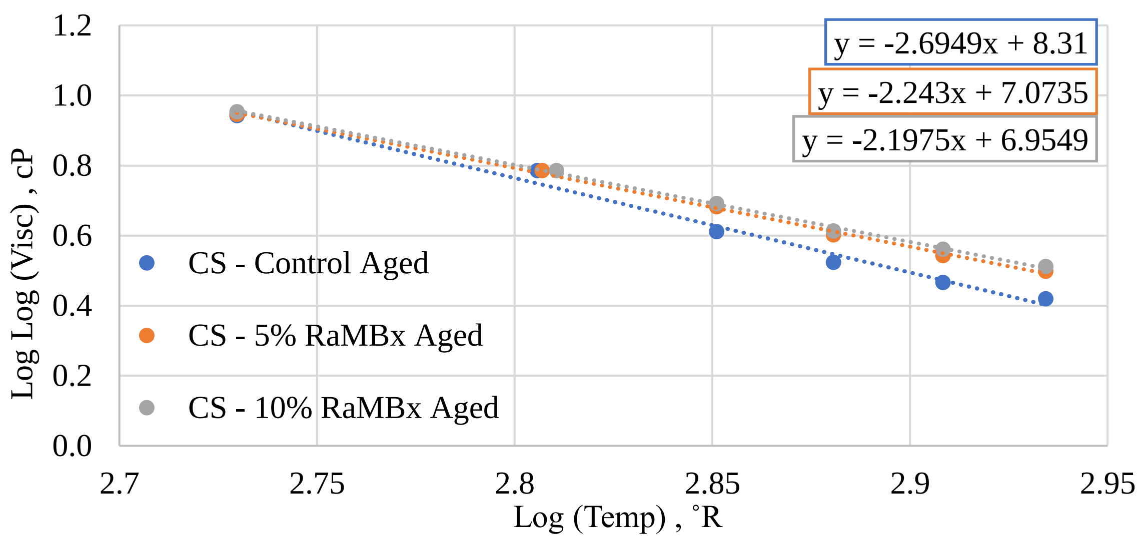
6.3.1.2. Rotational Viscosity Test Results

The Rotational Viscosity test gives indication about the temperature susceptibility of the modified material under both unaged and aged conditions. The slope and intercept for each modification level were obtained by plotting the measured viscosity with respect to the tested temperatures, from 121^{o}C to 204.4^{o}C. With the increase of RaMBx content, the slope became smaller leading to a flatter curve, reflecting a lower thermal susceptibility behavior and better stability of the material at elevated temperatures. In order to plot those curves, the results from previous section 8.3.1.1 such as softening point and cone penetration test were added to the Rotational Viscosity Test Results for both unaged (**Figure 30a**) and aged samples (**Figure 30b**). In terms of Intercept, it reflects the low temperature behavior of the material. According to the results, no significant improvement was reported with the addition of RaMBx. Similar trends were observed for the aged conditions, where the modified material was less thermal susceptible compared to control with smaller VTSi parameters and comparable Ai.

The results show a decrease in the slope parameter VSTi of 4% for the addition of 5% RaMBx, 8% for 10% RaMBx, 10% for 15% RaMBx and 15% for 20% RaMBx. A decrease of 18% was measured for 5% RaMBx and 10% RaMBx for the aged material for the VTSi parameter. Concerning the Ai, a less significant change within 4% was measured across all modification and aging levels.



(a)



(b)

Figure 30- Ai and VTSi Plots for CF using RaMBx: (a) Unaged Conditions; (b) Aged Conditions

Furthermore, the viscosity of the material at 204.4°C must be within the manufacturer's recommended viscosity limit of 10,000 cP. In the case of the modified sealant, they all satisfy this requirement (**Table 18**).

Table 18- Viscosity of CS using RaMBx at 204.4°C

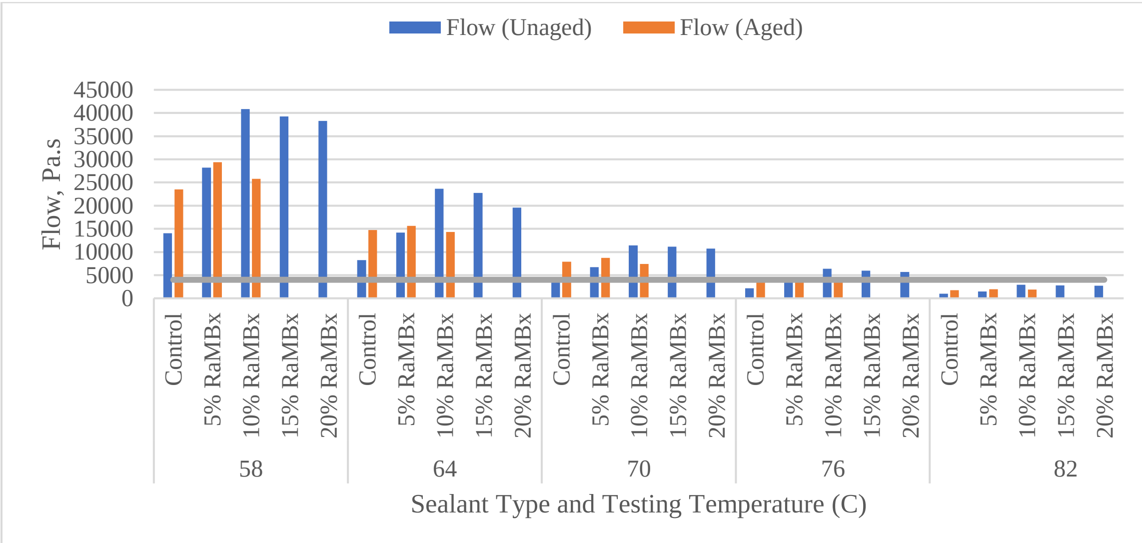
Sealant Type	Viscosity at 204.4°C (cP)
CS - 5% RaMBx	**1681.94**
CS - 10% RaMBx	**2821.33**
CS - 15% RaMBx	**3930.88**
CS - 20% RaMBx	**9411.76**

6.3.1.3. Shear Thinning and Tracking Test Results

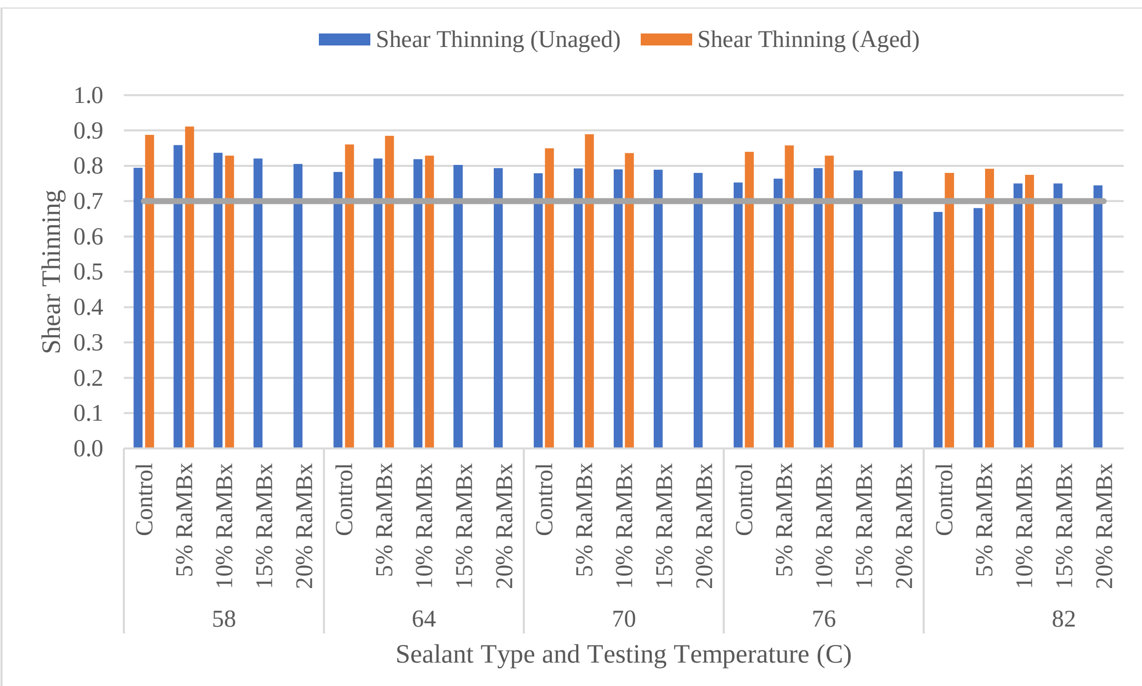
The parameter P obtained from the Ostwald-deWaele power-law equation **(Equation 4)** represents the shear thinning behavior of the sealant. Values of P closer to 1 represent better shear thinning resistance. In addition, according to the standard procedure of this test, values of P should be greater than 0.7. As for the flow parameter C, it should be greater than 4,000. This test is also used to determine the high temperature Sealant Grade of the tested sealants. The temperature at which both C and P parameter criteria are satisfied is considered to be the Sealant Grade. The results for flow and shear thinning parameters are found in **Figure 31a and Figure 31b** respectively below.

Based on the obtained results, an increase in both P and C is observed for the modified sealants for modification levels up to 10%, after which the results increase for 15% and 20% modification levels for the unaged conditions. Further insight was provided regarding the aged samples, where the performance of the sealants improved for 5% content. According to this test, the optimum content for RaMBx could be between 5% and

10% by weight of the sealant. The shear thinning parameter was improved for all modification levels, including elevated temperatures up to 82^oC.



(a)



(b)

Figure 31- Shear Thinning and Tracking Test Results for CS using RaMBx: (a) Flow Parameter "C"; (b) Shear Thinning Parameter "P".

Consequently, the high temperature sealant grades for the modified sealants are summarized in **Table 19** below.

Table 19- High Temperature Sealant Grade for CS Using RaMBx

Sealant Type	Sealant Grade (Unaged)	Sealant Grade (Aged)
CS - Control	70	70
CS - 5% RaMBx	70	76
CS - 10% RaMBx	76	76
CS - 15% RaMBx	82	-
CS - 20% RaMBx	82	-

A jump in the initial high temperature grade for the sealant was observed after the addition of 10% RaMBx for the unaged material, and at 5% RaMBx for the aged one.

6.3.1.4. Bending Beam Rheometer Test Results

The Bending Beam Rheometer test helps in identifying the low temperature behavior of the sealing material. The BBR test characterizes the sealant's creep stiffness at extremely low temperatures as well as its flexibility at low temperatures reaching -40°C. It determines two performance parameters: the average creep rate and the flexural creep stiffness at 240 seconds. The flexural creep stiffness is used to evaluate the low temperature stress strain time response, whereas the average creep rate designates the rate of deformation of the sealant at the test temperature. A higher m-value refers to the ability of the material to relax stresses, leading to improved performance at lower temperatures.

Table 20- BBR Test Results for CS using RaMBx.

Sealant Type	Stiffness, MPa	m-value
CS - Control	39.53	0.43
CS - 5% RaMBx	47.15	0.45
CS - 10% RaMBx	46.30	0.46
CS - Control Aged	57.10	0.36
CS - 5% RaMBx Aged	65.10	0.42
CS - 10% RaMBx Aged	90.20	0.32

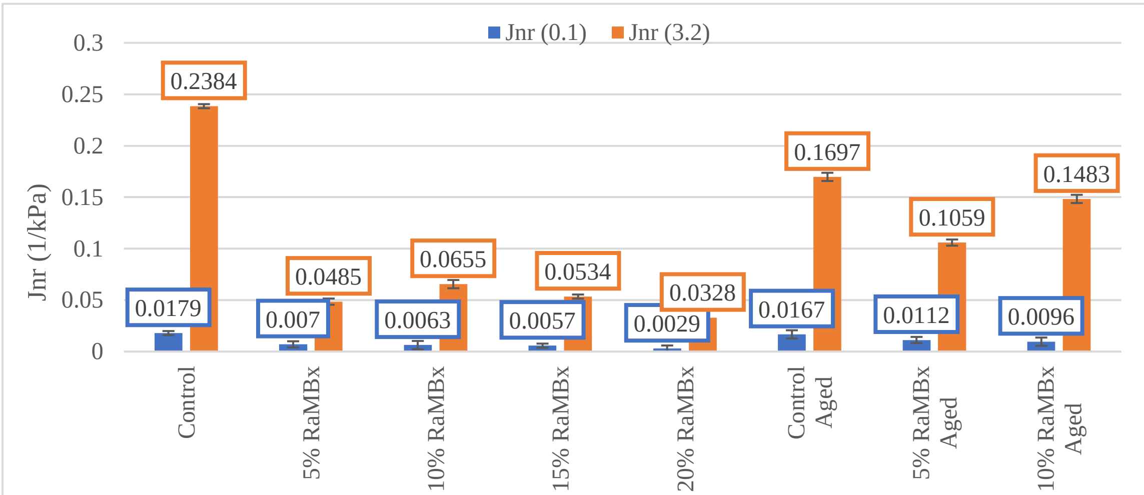
Aging can significantly impact the performance of the asphalt-based materials, leading to stiffer behavior, reduced relaxation capability, and increased cracking potential. Furthermore, a slower relaxation (lower m-value) will cause the material to build up internal stresses quickly and accelerate the occurrence of cracking after the internal stresses exceed the tensile strength of the material (Newcomb et al., 2021).

The addition of RaMBx increased the stiffness of the sealant by an average of 18% for both 5% and 10% RaMBx modified sealants. In terms of the m-value, the relaxation ability of the material was improved, for both unaged and aged conditions. Considering the preservation of the m-value at -40C for the aged material, a content of 5% RaMBx yielded satisfactory results with a slight increase in stiffness.

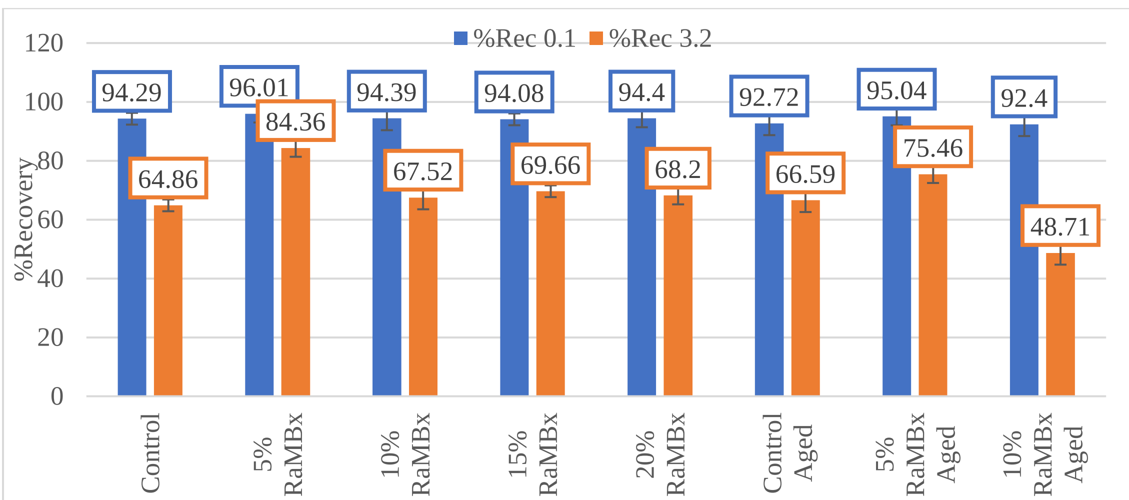
Furthermore, this improvement could be translated into a reduced aging susceptibility, given that the m-value before and after aging was measured to be nearly the same. At lower dosages, the addition of this modifier at lower dosage, reflects a good dispersion leading to reduced aging (Karnati et al., 2019).

6.3.1.5. Multiple Stress Creep and Recovery Test Results

This test identifies the elastic response and recovery percentage of the tested sealants while assessing the non-recoverable creep compliance recovery at two stress levels: 0.1 kPa and 3.2 kPa. After determining the high-performance grade temperature of the material from the shear-thinning and tracking test, this test was performed on the DSR using those temperatures. A 1.5 mm gap was adopted to accommodate the modifiers' size in the sealant to avoid causing friction between the equipment and the sample being tested. The non-recoverable creep compliance, Jnr, evaluates the sealant's non-recoverable strains with respect to the stress at which the deformation occurs. As for the %Recovery, a higher percent infers a more elastic sealant subsequently with lower accumulated strains in each loading cycle.



(a)



(b)

Figure 32- MSCR Test Results for CS Using RaMBx: (a) Jnr Results; (b) %Recovery Results

According to **Figure 32a**, it can be seen that the Jnr decreases when RaMBx was added to the sealant for both 0.1kPa and 3.2kPa loading conditions. However, a different trend was noticed for the 3.2kPa load, where the Jnr for 5% aMBx for both unaged and aged conditions show the best performance with a lower measured Jnr value of 0.0485 kPa^{-1} and 0.1059 kPa^{-1} respectively. As for the %Recovery shown in **Figure 32b**, the highest recovery percentage was obtained at 5% RaMBx modification level. For the 0.1 kPa stress level, the recovery percentage for all modification levels remained the same, showing that the modification did not alter the behavior of the material in the Linear Viscoelastic range (LVE). In the non-linear viscoelastic range, which is simulated by the 3.2 kPa stress level, RaMBx modification yielded much better recovery, which improves the sealant resistance to cohesive failure for contents up to 5%.

Following the shear thinning and tracking test results, the MSCR test results also point out that the 5% RaMBx content may be the optimum modification level for CF.

Another parameter of interest is the Jnr Slope, that gives indication about the stress sensitivity of the sealant. The results in **Table 21** show that the modified sealants had a low stress sensitivity, where the 5% RaMBx modified sealant was the best performing with a slope of 1.34 compared to 7.11 for control under unaged conditions, and 3.05 compared to 4.94 for control under aged conditions. Furthermore, according to AASHTO R 92-18 (AASHTO, 2018), plotting the %Recovery at 3.2 kPa versus the Jnr value at 3.2 kPa gives an indication about the elastic polymer modification of the asphalt-based material. According to the obtained results, all the tested specimens were found to be modified to an acceptable level.

Table 21- %Jnr Slope and Acceptance Level of Elastomeric Polymer for CS Using RaMBx

Sealant Type	Jnr Slope, %	Acceptable Level of Elastomeric Polymer at 3.2 kPa
CS - Control	7.11	Yes
CS - 5% RaMBx	1.34	Yes
CS - 10% RaMBx	1.91	Yes
CS - 15% RaMBx	1.54	Yes
CS - 20% RaMBx	0.96	Yes
CS - Control Aged	4.94	Yes
CS - 5% RaMBx Aged	3.05	Yes
CS - 10% RaMBx Aged	4.47	Yes

6.3.1.6. Toughness and Tenacity Test Results

The toughness and tenacity results in **Figure 33** showed significant improvement with the addition of RaMBx. The post-peak behavior, tenacity, was improved showing enhanced stretchability. For the addition of 5% RaMBx, an increase of 89% in terms of toughness and an increase in tenacity of 102% was measured compared to the control sealant. The toughness and tenacity increase for contents up to 10% RaMBx contents, aligning with the optimal RaMBx content hypothesis.

With respect to the aged material, comparable tenacity was measured for 5% RaMBx modified material to the aged control sealant. As the sealant aged, stiffening was measured, with higher viscosity measurements (Section 8.3.1.2) and low temperature stiffnesses (Section 8.3.1.4).

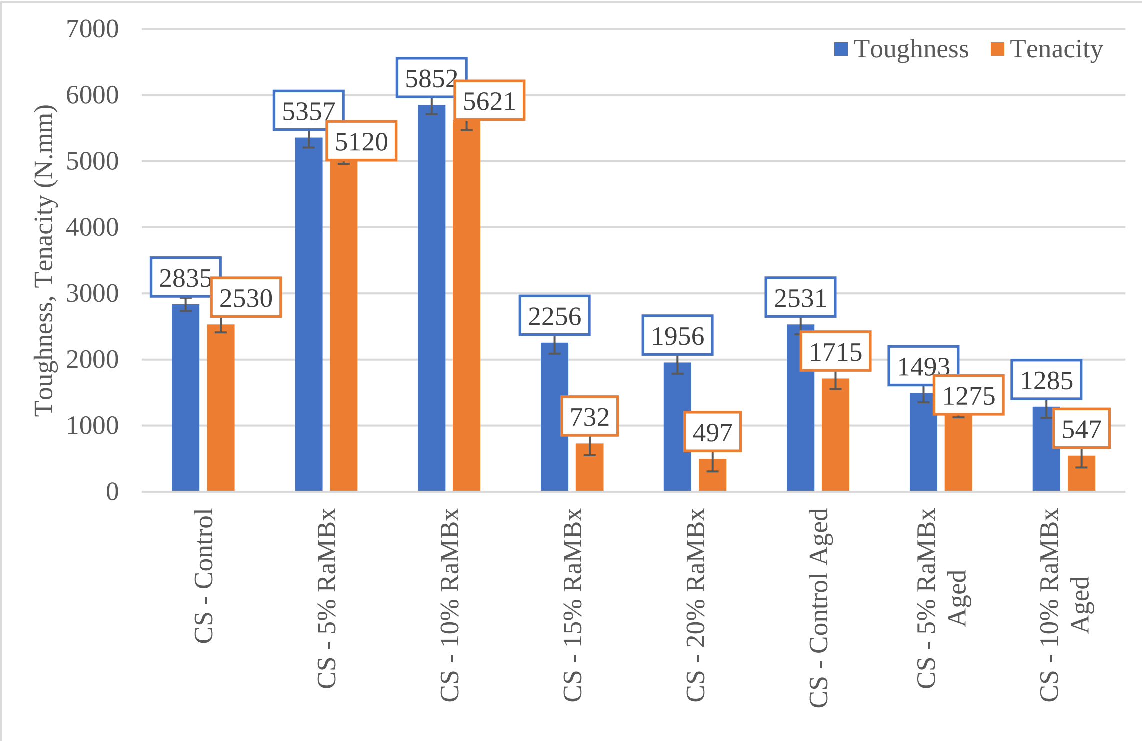


Figure 33- Toughness and Tenacity Results for CS Using RaMBx

6.3.1.7. Bond Strength Test Results

This test was performed using asphalt mixtures substrate, to represent a more realistic bonding mechanism in the field. The test was conducted on both aged and unaged samples, under wet and dry conditions.

The addition of RaMBx yielded comparable results (**Table 22**) in terms of bond strength for the unaged conditions for both wet and dry conditions. For the aged samples, an improved behavior was observed for the modified sealants. Furthermore, an important change was made in terms of the failure mode, whereas the control sealant failed in adhesive failure, and the 5% RaMBx Aged samples failed in cohesion with a pull-off strength moisture-susceptibility index of 3% compared to 9% for control. The results showed potential improved performance, switching from Adhesive to Cohesive failures with lower Pull-Off Strength Moisture Susceptibility Index.

Table 22- Binder Bond Strength Test Results for CS Using RaMBx

Sealant Types	Dry Pull-Out Strength (kPa)	Failure Modes	Wet Pull-Out Strength (kPa)	Failure Modes	Pull-Off Strength Moisture-Susceptibility Index
CS - Control	668.0	Cohesive	565.3	Adhesive	-15%
CS - 5% RaMBx	620.5	Cohesive	480.3	Cohesive	-23%
CS - 10% RaMBx	657.6	Cohesive	499.6	Adhesive	-24%
CS - 15% RaMBx	770.0	Adhesive	690.0	Adhesive	-10%
CS - 20% RaMBx	757.9	Adhesive	670.0	Adhesive	-12%
CS - Control Aged	1011.2	Adhesive	919.3	Adhesive	-9%
CS - 5% RaMBx Aged	925.1	Cohesive	890.2	Cohesive	-4%
CS - 10% RaMBx Aged	950.5	Cohesive	905.6	Adhesive	-5%

Furthermore, as adhesive failures are not desired, the content of RaMBx could be between 5% to 10% RaMBx contents as supported by the previous test results.

In combination with the results observed from the Bending Beam Rheometer, at lower dosages (around 5%), the RaMBx could absorb the acidic compounds implicated in moisture damage assessments. Due to the proper dispersion at lower concentrations, a better resistance to moisture and aging could be theorized (Hung et al., 2019).

6.3.1.8. Thermal Conductivity and Specific Heat Capacity Test Results

The thermal properties of the sealant give indication of their behavior in different climates under different temperatures. By being less thermally susceptible, the sealant will be unaffected to softening and stiffness at high and low temperatures. Lower thermal conductivity and higher specific heat capacity were measured (**Table 23**) with the addition of RaMBx. This reflects lower heat going through the material, and higher specific heat capacity reflects a higher amount of heat needed to raise the temperature of the material. The insulation effect of aerogel protected the material from temperature changes and makes it less sensitive to thermal stresses.

Table 23- Thermal Conductivity and Specific Heat Capacity Test Results for CS Using RaMBx

Sealant Type	k (W/m°K)	C_p (J/Kg°K)
CS - Control	0.11	1173
CS - 5% RaMBx	0.071	1170
CS - 10% RaMBx	0.065	1200
CS - 15% RaMBx	0.06	1318
CS - 20% RaMBx	0.057	1430
CS - Control Aged	0.107	1468
CS - 5% RaMBx Aged	0.11	1200
CS - 10% RaMBx Aged	0.112	1306

6.3.1.9. Linear Expansion and Contraction Test Results

When it comes to crack sealants in asphalt, both thermal expansion and contraction are important considerations, and the balance between them depends on the climate and environmental conditions of the specific location.

During hot temperatures, asphalt surfaces expand. If the crack sealant doesn't have sufficient flexibility to accommodate this expansion, it may crack or become dislodged, compromising its effectiveness. Therefore, in hot climates, a crack sealant with good resistance to thermal expansion is crucial. On the other hand, in colder temperatures, asphalt surfaces contract. If the crack sealant lacks the ability to contract along with the asphalt, it may pull away from the edges of the crack, leaving gaps and reducing its effectiveness. In summary, an ideal crack sealant should have a balance of properties, including flexibility, adhesion, and durability, to accommodate both thermal expansion and contraction. Ideally, the chosen sealant should have an appropriate CTE that closely matches those of the surrounding asphalt. This ensures that the sealant moves in sync with the pavement, maintaining a watertight seal throughout the year.

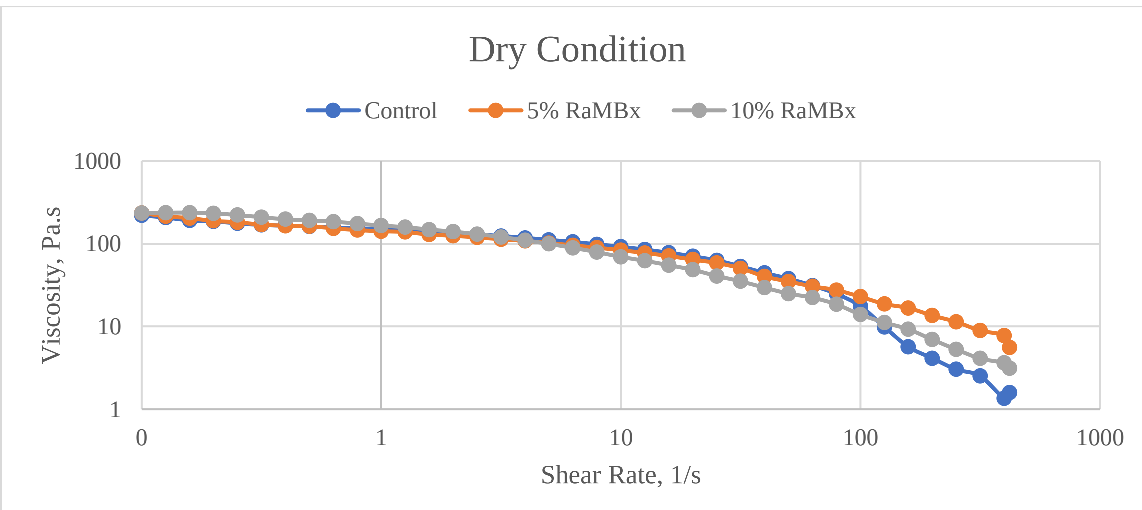
According to **Table 24**, the CTE of both control and 5% RaMBx modified CS were measured using the suggested setup in Chapter 4. It can be seen that the CTE measured for both materials is very close to the ones for asphalt pavements (Petersen et al., 2005), which is around 2.05E-05/ºC). Thus, it can be concluded that the addition of RaMBx, acting as an insulator to the sealant, allows the material to resist expansion at elevated temperatures and contraction at lower temperatures, preserving its integrity within the crack and extending its durability.

Table 24- Coefficient of Thermal Expansion for CS Using RaMBx

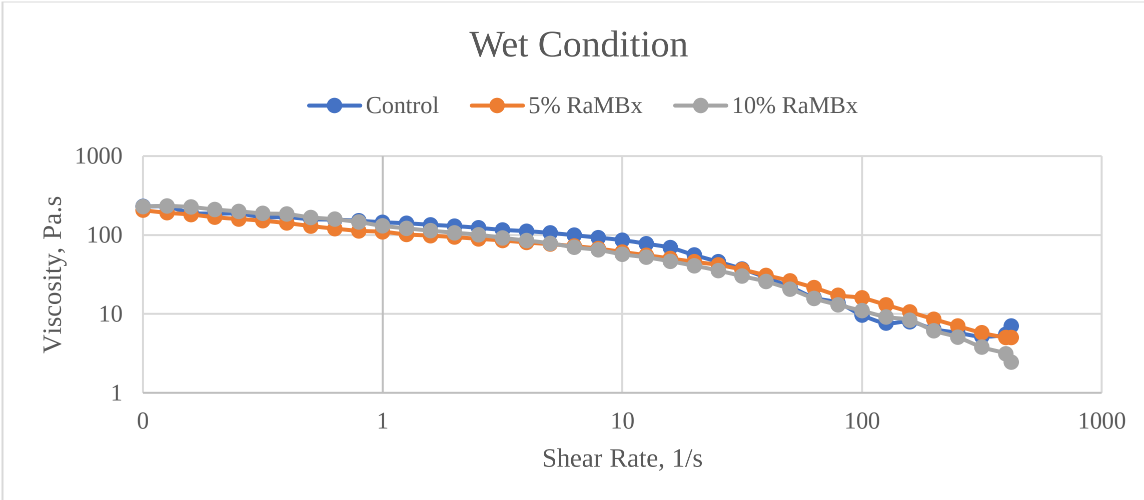
Sample	**Expansion Coefficient (/ºC)**	**Contraction Coefficient (/ºC)**	**Coefficient of Thermal Expansion, CTE ((/ºC)**
CS - Control	2.07E-05	2.31E-05	2.19E-05
CS - 5% RaMBx	1.69E-05	1.83E-05	1.76E-05
CS - Control Aged	1.96E-05	2.28E-05	2.12E-05
CS - 5% RaMBx Aged	2.00E-05	1.86E-05	1.93E-05

6.3.1.10. Moisture Induced Shear Thinning Index (MISTI) Test Results

The results of the MISTI Test can be interpreted in different ways to obtain various performance parameters. It can be used to further examine the cohesive properties of the sealant, by looking at the zero-shear viscosity and shear thinning behavior. Shear thinning occurring at higher shear rates refers to a delayed shear thinning behavior and higher cohesive energy. In addition, the slope of the power-law curve of the viscosity vs. shear rate gives indication of the intermolecular interactions within the material. Higher slope leads to lower viscosities at higher shear rates, leading to a lower resistance to shear and easier movement between the particles (less cohesion). It can be seen from **Figure 34a**, the dry condition testing, that the control sealant and 5% RaMBx modified sealant have comparable performance and similar shear thinning behavior, whereas the 10% RaMBx showed a sooner onset for shear thinning behavior. With respect to the wet conditioning of the samples shown in **Figure 34b**, the addition of RaMBx did delay the onset of shear thinning.



(a)



(b)

Figure 34- Shear Thinning Onset for CS Using RaMBx; (a) Dry Testing Conditions and (b) Wet Testing Conditions

In terms of the power-law slope results **(Table 25),** the slopes for both modified sealants are smaller than control, yielding to better cohesive resistance. With the delay in shear thinning observed in **Figure 34**, it can be concluded that the RaMBx modification yields to higher cohesive energy and better performance. The MISTI coefficient has a variation of 9% from 1 for both modified and unmodified sealants, which reflects an acceptable moisture shear thinning index.

Table 25- Power-Law Slopes and MISTI for CS Using RaMBx

Sample	Wet	Dry	MISTI
CS - Control	1.86	1.71	1.085
CS - 5% RaMBx	0.63	0.58	1.088
CS - 10 % RaMBx	0.75	0.68	1.102

6.3.2. Crack Sealant (CS) Modified with EaMBx Test Results

According to the results obtained for the crack seal CS modified with RaMBx, it was concluded that an optimum performance of the material was achieved for modification levels between 5 and 10% RaMBx contents by weight of the material. According to **Table 16**, the raw aerogel material AP4 used to make RaMBx has a higher density than AP1 (0.18 compared to 0.13 g/cm^3). Therefore, more binder was needed to weigh down the aerogel particles producing EaMBx. Accordingly, 2.5% EaMBx content was equivalent to 5% RaMBx, and 5% EaMBx was equivalent to 10% RaMBx. For all those reasons, the EaMBx contents were reduced. In the results sections of the EaMBx modification, a comparison of both aMBx based modifiers will be included.

6.3.2.1. Softening Point, Resilience and Cone Penetration Test Results

The results for the softening point, resilience, and cone penetration test for the EaMBx modified crack sealant CS are reported in **Table 26**. Similar trends were observed to the ones obtained for the RaMBx modifications, where higher softening points were obtained for both unaged and aged conditions, leading to reduced resilience and cone penetration results. Compared to the RaMBx modification, the softening point for both 2.5% EaMBx and 5% EaMBx modified CS experienced a jump by 10^{o}C more when compared to the 5% and 10% RaMBx modified CS for both aged and unaged sealants. For the resilience and cone penetration test, the results were comparable.

Table 26- Softening Point, Resilience, Cone Penetration Test Results for CS using EaMBx.

Sealant Type	Softening Point (ºC)	Resilience (%)	Cone Penetration (1/10 mm)
CS - Control	80	94	72.67
CS - 2.5% EaMBx	92.5	62	44
CS - 5% EaMBx	95.5	60	47
CS - Control Aged	82	68	45
CS - 2.5% EaMBx Aged	93.5	58	42
CS - 5% EaMBx Aged	97	56	41

6.3.2.2. Rotational Viscosity Test Results

In this section, the rotational viscosity test results are presented. The thermal susceptibility of the modified sealant was also shown with reduced slope (VTSi) parameters. As for the intercept (Ai) parameter, they remained comparable to the control CS. The results are summarized in **Table 27**. Both modifiers had the same effect on the sealant given the different source across all contents. At 5% EaMBx content, the results at the aged condition were reported to be greatly reduced, which may refer to an ideal content lower than 5%.

Table 27- Rotational Viscosity Test Results for CS Using RaMBx vs EaMBx.

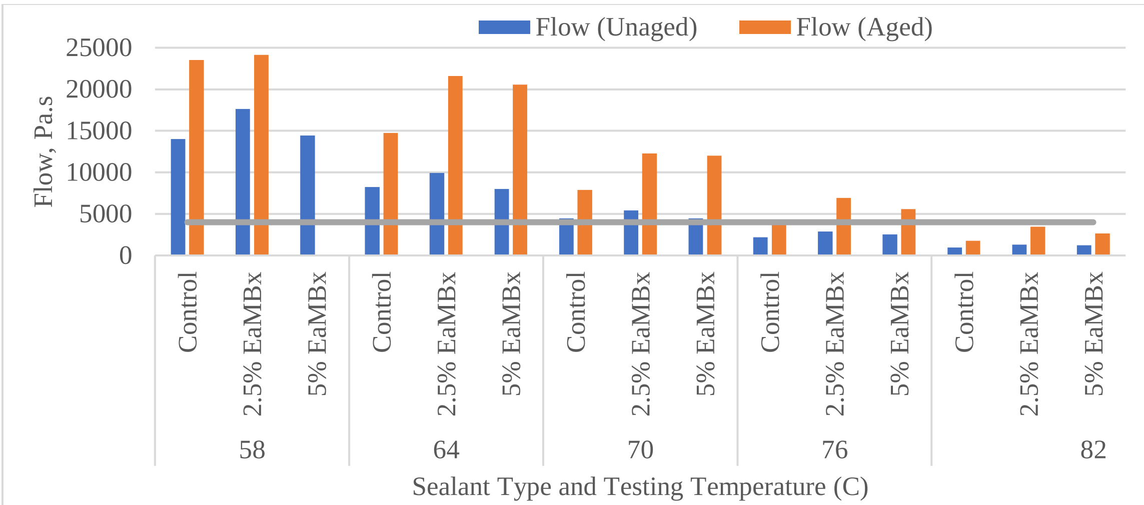
	CS- 2.5% EaMBx	CS - 5% EaMBx	CS - 2.5% EaMBx Aged	CS - 5% EaMBx Aged
Slope	2.093	1.986	2.1348	1.6253
Intercept	6.6616	6.3654	6.7813	5.3867

	CS - 5% RaMBx	CS - 10% RaMBx	CS - 5% RaMBx Aged	CS - 10% RaMBx Aged
Slope	2.0332	1.9475	2.243	2.1975
Intercept	6.4739	6.2517	7.0735	6.9549

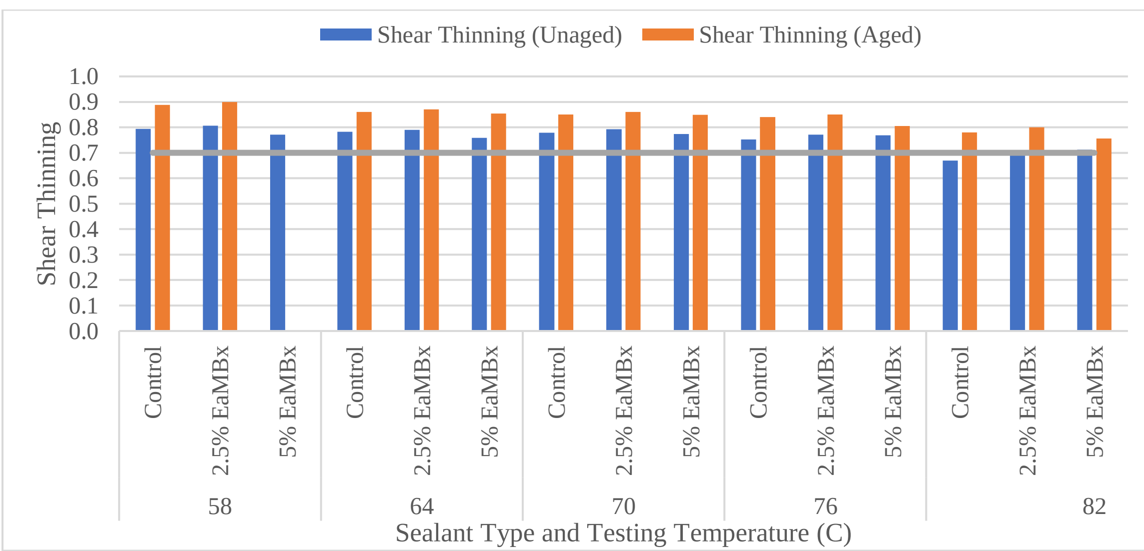
In terms of the viscosity of the material at 204.4^{o}C, the modified materials were still within the manufacturer's viscosity limit.

6.3.2.3. Shear Thinning and Tracking Results

The shear thinning and tracking results presented potential improvements for both the shear thinning parameter "P" and flow parameter "C" for unaged and aged samples. The results are shown in **Figure 35**, where the performance of 2.5% EaMBx modification was shown to have the best performance.



(a)



(b)

Figure 35- Shear Thinning and Tracking Test Results for CS Using EaMBx; (a) Flow Parameters, (b) Shear Thinning Parameters

In terms of high temperature performance grade, no changes were denoted for the unaged conditions for both contents (2.5% and 5%) and remained at a sealant grade of 70ºC. Under the aged conditions, the 5%EaMBx CS changed from 70 to 76ºC. Comparing the results to the RaMBx modified sealant, the sealant grade changed from 70 to 76 at the 10% RaMBx unaged, and for both 5% and 10% RaMBx aged conditions. Under aged conditions, the RaMBx includes a higher portion of aerogel compared to bituminous content, which contributes to stiffer performance and higher aging mechanism.

6.3.2.4. Bending Beam Rheometer Test Results

In terms of the BBR test results, the addition of EaMBx yielded the same effect as RaMBx: an increase in stiffness and comparable relaxation behavior at extreme temperatures. The samples were tested at -40ºC and summarized in **Table 28**.

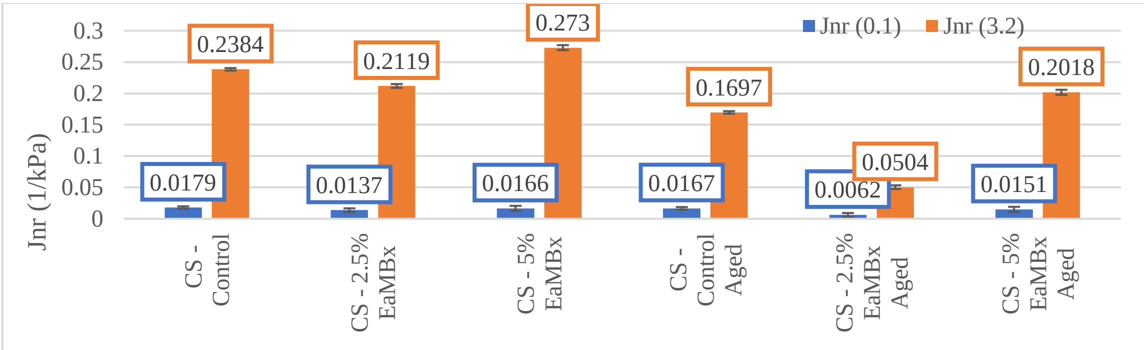
Due to the nature of the EaMBx (smaller diameter size, lower density, and lower porosity), the effect of the modifier on the sealant at low temperature slightly differs from the RaMBx. RaMBx having larger diameter and bigger pores, also added in larger quantities, allow for a larger relaxation modulus for comparable contents. In general, a small amount of well-distributed air voids can improve the relaxation properties of the material. This is because the air voids can act as stress relief points, allowing the material to relax and recover from stress. Similar aspects are observed in terms of m-value measurements, where they are comparable before and after aging due to its dispersion. This implies that the presence of aMBx may reduce the effect of aging on the sealing material.

Table 28- BBR Test Results for CS Using EaMBx

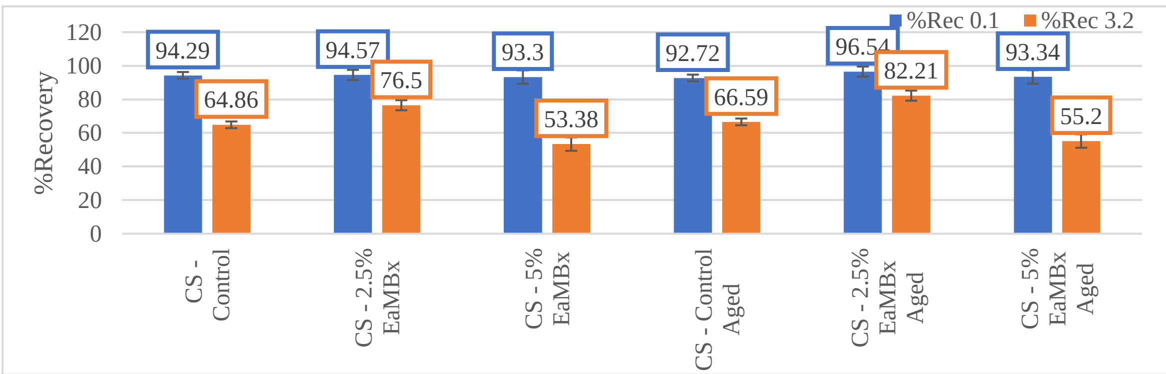
Sealant Type	Stiffness, MPa	m-value
CS - 2.5% EaMBx	37.4	0.35
CS - 2.5% EaMBx Aged	42.6	0.34
CS - 5% EaMBx	48.6	0.38
CS - 5% EaMBx Aged	76.1	0.33

6.3.2.5. Multiple Stress Creep and Recovery Test Results

The MSCR Test Results are also promising with the addition of EaMBx into the crack sealing material. The Jnr for 0.1 and 3.2 kPa load conditions are both lower than the control material as seen in **Figure 36a**. It can also be seen that the performance is optimum for contents up to 2.5% EaMBx, whereas the Jnr and %Recovery changes trends for 5% EaMBx contents. Considerable improvements were recorded for the aging conditions at 2.5% EaMBx, where the %Recovery at 3.2 kPa was measured to be 82.2% (**Figure 36b**) compared to 66.59% for control while maintaining a lower Jnr (0.0504 kPa^{-1} compared to 0.1697 kPa^{-1} for the control sealant).



(a)



(b)

Figure 36- MSCR Test Results for CS Using EaMBx: (a) Jnr Results; (b) %Recovery Results

Concerning the stress sensitivity (**Table 29**) of the CS modified with EaMBx, a great improvement was observed for the 2.5% EaMBx modified CS at the aged level, where the slope decreased from 4.94% to 1.43% when compared to the aged control CS.

Table 29- Jnr Slope and Acceptance Level of Elastomeric Polymer for CS Using EaMBx

Sealant Type	JnrSlope, %	Acceptable Level of Elastomeric Polymer at 3.2 kPa
CS - Control	7.11	Yes
CS - 2.5% EaMBx	6.39	Yes
CS - 5% EaMBx	8.27	Yes
CS - Control Aged	4.94	Yes
CS - 2.5% EaMBx Aged	1.43	Yes
CS - 5% EaMBx Aged	6.02	Yes

Concerning the % JnrSlope obtained using RaMBx, it was lower for the equivalent modified sealants.

6.3.2.6. Toughness and Tenacity Test Results

Toughness and tenacity for the EaMBx modified sealants, the results (**Figure 37**) were comparable for the unaged material. However, the aged, modified sealants showed improved toughness and tenacity with respect to control. Referring to the results observed for the RaMBx modified CS (**Figure 33**), the unaged sealant had higher toughness and tenacity. However, once aged, the EaMBx modified CS had a much better toughness and tenacity measurements. For the corresponding contents, the 5%RaMBx modified sealant showed a toughness of 1493 and tenacity of 1275 N.mm, compared to 2.5%EaMBx content showing a toughness of 3184 N.mm and tenacity for 2131 N.mm for the aged condition. A higher load was needed to fail the EaMBx modified sealant, leading to a better performance in the field in terms of both parameters. As the RaMBx had a higher concentration of aerogel, stiffer behavior may be observed than EaMBx modified material.

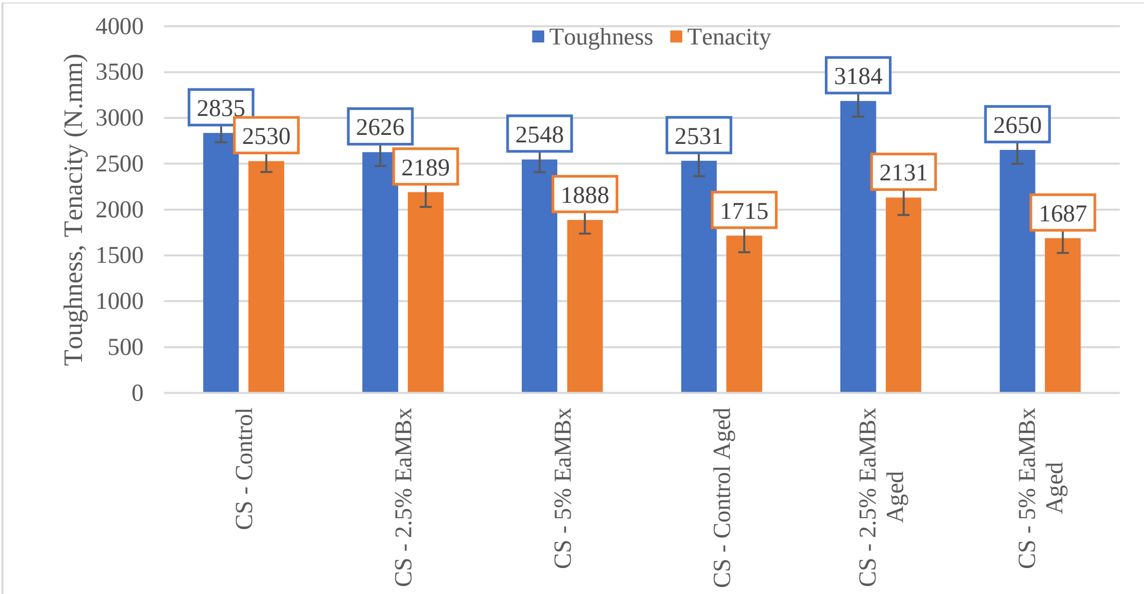


Figure 37- Toughness and Tenacity Results for CS Using EaMBx

6.3.2.7. Bond Strength Test Results

In terms of bond strength, the results are much more promising for the EaMBx modified sealant with better failure modes and increased pull-out strengths (**Table 30**). Given the higher toughness and tenacity values obtained in the previous section, higher bond strengths for the modified sealant may lead to an improved adhesion to the pavement and overall performance. With respect to the aged material, it can be seen that the modified material yielded better performance compared to the control. Furthermore, higher bond strength measurements were recorded for EaMBx compared to RaMBx for the unaged conditions. Similar to the RaMBx modification, the dispersion and nature of this material could potentially reduce the aging and improve the adhesive properties of the sealant.

Table 30- Binder Bond Strength Results for CS Using EaMBx

Sealant Types	Dry Pull-Out Strength (kPa)	Failure Modes	Wet Pull-Out Strength (kPa)	Failure Modes	Pull-off Strength Moisture-Susceptibility Index
CS - Control	668.0	Cohesive	565.3	Adhesive	-15%
CS - 2.5% EaMBx	1480	Cohesive	1138	Cohesive	-23%
CS - 5% EaMBx	1651	Cohesive	1254	Cohesive	-24%
CS - Control Aged	1011.2	Adhesive	919.3	Adhesive	-9%
CS - 2.5% EaMBx Aged	1423	Cohesive	1184	Cohesive	-17%
CS - 5% EaMBx Aged	1080	Cohesive	925	Cohesive	-14%

6.3.2.8. Thermal Conductivity and Specific Heat Capacity Test Results

The thermal conductivity and specific heat capacity results for the EaMBx modified sealant are found in **Table 31**. The thermal properties follow the same trends as seen with the RaMBx modification, with the corresponding contents having comparable thermal conductivity and specific heat capacity. However, it is noticed that the 2.5%EaMBx content yielded the lower thermal conductivity (0.062 W/m.K) with comparable specific heat capacity (1324 J/kg.K).

Table 31- Thermal Conductivity and Specific Heat Capacity Results for CS Using EaMBx

Sealant Type	k (W/m.K)	C_p (J/kg.K)
CS - Control	0.11	1173
CS - 2.5% EaMBx	0.062	1324
CS - 5% EaMBx	0.097	1354
CS - Control Aged	0.107	1468
CS - 2.5% EaMBx Aged	0.075	1359
CS - 5% EaMBx Aged	0.12	1436

6.3.2.9. Linear Expansion and Contraction, MISTI Test Results

According to the previous sections, while comparing the RaMBx and EaMBx modifications, the optimum modification level using both modifiers was shown to be 5%

by weight of the sealant for RaMBx and 2.5% for EaMBx. For this reason, the CTE and MISTI tests were run for the optimum aMBx modification level. The results for CTE are shown in **Table 32**, and are very similar to the ones obtained for the 5% RaMBx (1.76E-05). As for the MISTI (**Table 33**), the results were also promising, with a variation of 2% from dry to wet conditioning. This showed that the modified sealant wasn't affected by moisture.

Table 32- CTE Results for CS Using EaMBx

Sealant Type	Expansion	Contraction	CTE /C
CS - Control	2.07E-05	2.31E-05	2.19E-05
CS - 2.5% EaMBx	1.50E-05	1.81E-05	1.65E-05

Table 33- MISTI Results for CS Using EaMBx

Sealant Type	Wet	Dry	MISTI
CS - Control	1.86	1.714	1.085
CS - 2.5% EaMBx	0.708	0.694	1.020

6.3.3. Aerogel Modified Bituminous Materials (aMBx) Comparison and Analysis for Crack Sealant (CS)

In this section, the obtained results for both RaMBx and EaMBx at optimum performance will be compared and analyzed. As seen throughout the previous sections, the optimum performance was measured to be at 5% RaMBx and 2.5% EaMBx.

6.3.3.1. Bending Beam Rheometer Results

Low temperature behavior for both RaMBx and EaMBx was determined using the BBR test. According to **Table 34**, the RaMBx modified sealants showed higher stiffness at low temperature, and a higher m-value compared to the EaMBx modified sealants. As the EaMBx is smaller in size and promotes better dispersion, the low temperature stiffness was improved compared to RaMBx. The overall results show that the modification of the sealants with aMBx results in stiffer behavior but is still satisfactory at temperatures as low as -40^{o}C. Higher stiffness was measured with RaMBx due to the fact that more aerogel is part of the modifier compared to EaMBx. In terms of relaxation, the RaMBx provided higher porosity, promoting higher relaxation capacity. Both modifiers showed comparable if not improved m-value at lower temperatures, corresponding to potential reduced aging susceptibility of the sealant.

Table 34- BBR Results: RaMBx vs EaMBx Comparison

Sealant Type	Stiffness, MPa	m-value
CS - Control	39.53	0.43
CS - 2.5% EaMBx	37.4	0.35
CS - 5% RaMBx	47.15	0.45
CS - Control Aged	57.10	0.36
CS - 2.5% EaMBx Aged	42.6	0.34
CS - 5% RaMBx Aged	65.10	0.42

6.3.3.2. Multiple Stress Creep and Recovery Results

The size of a modifier in asphalt binder can influence its rheological properties, including recovery and non-recoverable creep compliance. Smaller-sized modifiers may have a higher surface area, allowing for better dispersion within the asphalt binder. This increased dispersion can lead to improved recovery properties. Smaller particles may create a more uniform network within the binder, contributing to better elastic recovery after deformation. In terms of Jnr, larger modifiers (RaMBx) may not disperse uniformly within the binder, potentially leading to regions of localized stress concentration. Under unaged conditions, the EaMBx modified CS yielded to lower Jnr due to the lower aerogel concentration contributing from the modifier. As more asphalt was added as part of this modifier, the aged conditions are more promising as RaMBx, as more binder was contributing to the recovery of the material. For this reason, as RaMBx has a higher aerogel concentration content, the results were stiffer under aged conditions. It can also be hypothesized that the presence of aerogel is insulating the material and not allowing the material to heat up as quickly as expected leading to better results under the MSCR.

6.3.3.3. Toughness and Tenacity Results

Size can also affect the toughness and tenacity of the sealant: larger modifiers can act as stress absorbers within the matrix, dissipating energy more effectively and delaying crack initiation leading to increased toughness. As for smaller modifiers, they can enhance intermolecular interactions and improve internal cohesion within the sealant. This can also contribute to toughness through a different mechanism compared to larger modifiers. In terms of tenacity, smaller modifiers can enhance adhesion between the sealant and pavement due to their larger surface area and potential for stronger interactions. This can lead to improved tenacity, as the sealant resists pull-off forces more effectively. As can be seen in **Table 35**, toughness and tenacity were found higher with the RaMBx, as the particle size was larger. Furthermore, when the curve has a higher magnitude, the values tend to be greater as well. However, when the material is aged, an improved tenacity was measured for the EaMBx modified sealant.

Table 35- Toughness and Tenacity: RaMBx vs EaMBx Comparison

Sealant Type	CS - Control	CS - 2.5% EaMBx	CS - 5% RaMBx	CS - Control Aged	CS - 2.5% EaMBx Aged	CS - 5% RaMBx Aged
Toughness	2835	2626	5357	2531	3184	1493
Tenacity	2530	2189	5120	1715	2131	1275

6.3.3.4. Bond Strength Results

The size of a modifier can play a complex role in influencing the bond strength of asphalt sealants, with the effects often depending on the specific modifier type and its interaction with the asphalt molecule. Smaller modifiers, such as EaMBx, can improve packing density and reduce internal voids, leading to better intermolecular interactions and potentially higher cohesive strength within the sealant. However, excessive modifications levels can reduce flexibility and lead to brittleness, negatively impacting adhesion with the pavement. Furthermore, smaller sizes can translate to a higher surface area per unit volume. This greater contact area allows for more extensive bonding between the modifier and asphalt, potentially leading to improved adhesion and cohesion within the sealant.

The modifier size can also significantly impact its distribution and dispersion within the sealant, whereas smaller modifiers typically exhibit better mixing and dispersibility, ensuring more uniform reinforcement throughout the matrix. This uniform distribution can lead to consistent bond strength improvement across the material. Conversely, larger modifiers might clump or agglomerate, creating localized areas of high and low modifier concentration, leading to uneven bond strength.

In **Table 36**, it can be clearly seen that a higher pull-out strength was measured for the EaMBx modified sealant, under both wet and dry conditions as well as unaged and aged scenarios. This supports the claims that a smaller particle size allows for a better dispersion of the modifiers and allows better adhesion to the substrate. The RaMBx appears to have better resistance to moisture, but still reveals lower pull-out strengths across all measurements.

Table 36- Bond Strength: RaMBx vs EaMBx Comparison

Sealant Types	Dry Pull-Out Strength (kPa)	Failure Modes	Wet Pull-Out Strength (kPa)	Failure Modes	Pull-Off Strength Moisture-Susceptibility Index
CS - Control	668	Cohesive	565	Adhesive	-15%
CS - 2.5% EaMBx	1480	Cohesive	1138	Cohesive	-23%
CS - 5% RaMBx	620.5	Cohesive	480.3	Cohesive	-23%
CS - Control Aged	1011	Adhesive	919	Adhesive	-9%
CS - 2.5% EaMBx Aged	1423	Cohesive	1184	Cohesive	-17%
CS - 5% RaMBx Aged	925.1	Cohesive	890.2	Cohesive	-4%

6.3.3.5. Thermal Properties Results

In terms of thermal properties, combining a lower thermal conductivity and higher specific heat capacity in an asphalt crack sealant can lead to a complex interplay of advantages and potential drawbacks. Both reduced thermal conductivity and higher specific heat capacity contribute to better resistance against high temperatures and thermal shock. This can reduce softening/melting in hot climates, mitigating thermal stresses, and ultimately minimize thermal cracking. Furthermore, the combined effect can lower the impact of rapid temperature fluctuations, reducing stress fatigue and promoting longer sealant lifespan. In **Table 37**, the comparison between both aMBx types is shown. The thermal conductivity of both modified sealants is comparable, with a slightly different specific heat capacity (higher for EaMBx). This could be attributed to the porosity of EaMBx, as highly porous materials tend to have lower thermal conductivity and higher specific heat capacity. During aging, lighter and less conductive components like saturates and aromatics decrease, while heavier and more conductive components like asphaltenes and resins increase. Asphaltenes have a more rigid and ordered structure, allowing for better heat transfer compared to the lighter fractions. Aging also alters the materials microstructure, increasing its stiffness and density. This denser packing of molecules reduces the number of air voids, which act as thermal insulators, and creates a more continuous pathway for heat to flow through the material.

Table 37- Thermal Properties: RaMBx vs EaMBx Comparison

Sealant Type	k (W/m.K)	C_p (J/kg.K)
CS - Control	0.11	1173
CS - 2.5% EaMBx	0.062	1324
CS - 5% RaMBx	0.071	1170
CS - Control Aged	0.107	1468
CS - 2.5% EaMBx Aged	0.075	1359
5% RaMBx Aged	0.11	1200

A lower thermal conductivity refers to a slower heat conduction. This could affect the setting process of the material as the heat will take longer to penetrate the sealant throughout its volume, slowing down the overall setting process. However, crack sealants normally cure through a chemical reaction, with sunlight playing a secondary role in the curing process and accelerate the drying process of the sealant's solvent carrier. As the solvent evaporates, it allows the chemical reaction between the binder and curing agent to proceed more quickly. As for a higher specific heat capacity, this indicates the material requires more heat energy to raise its temperature. While it might take longer to heat up initially, the high heat capacity helps the sealant retain heat more uniformly. This can be beneficial in preventing uneven setting, especially with fluctuating temperatures or exposure to direct sunlight. Therefore, it can promote more uniform setting throughout the sealant.

On the other hand, a lower coefficient of thermal expansion (CTE) in an asphalt crack sealant can offer several potential benefits for its performance. As Asphalt naturally expands and contracts with temperature changes, a lower CTE enhances the resistance to temperature extremes: In hot climates, a lower CTE sealant is less susceptible to softening or melting under high temperatures. Conversely, in cold climates, it may be less prone to cracking due to reduced contraction forces. In other words, a lower CTE will promote reduced softening of the material at higher temperatures within itself, and reduced contraction at lower temperatures, promoting material durability.

The optimal CTE range for a sealant depends on the local climate and traffic loads, whereas areas with significant temperature fluctuations and high traffic might benefit more from a moderate CTE reduction than extreme variations.

Furthermore, different modifiers have varying effects on both CTE and other properties. Selecting the appropriate modifier type and concentration is crucial for achieving the desired balance between thermal stability, adhesion, and application characteristics. Finally, the thickness and depth of the sealant can influence its thermal behavior. Thicker applications can compensate for slightly higher CTE values, while thinner sealants might require stricter CTE control for optimal performance.

To compare the RaMBx to the EaMBx (**Table 38**), both modifiers showed comparable CTE measurements where the material exhibited lower coefficient in both expansion and contraction experiments. By combining a lower CTE and good bond strength, the addition of aMBx to the sealant indicates promising results especially in hotter climate conditions. Other parameters combined such as %Recovery and tenacity promoted the performance of the modified material by allowing a better adaptation to crack movements.

Table 38- CTE Measurements: RaMBx vs EaMBx Comparison

Sample	Expansion	Contraction	CTE /C
CS - Control	2.07E-05	2.31E-05	2.19E-05
CS - 2.5% EaMBx	1.50E-05	1.81E-05	1.65E-05
CS - 5% RaMBx	1.69E-05	1.84E-05	1.76E-05

6.3.3.6. Moisture Shear Thinning Index Test Results

Based on the obtained results, the EaMBx showed a better resistance to moisture susceptibility. Higher density modifiers may contribute to better void filling and packing within the asphalt sealant matrix. Improved packing can reduce the potential for water infiltration, enhancing resistance to moisture-induced distress. Furthermore, higher-density modifiers can occupy a larger effective volume within the sealant. This increased volume can result in a more uniform distribution of modifiers, leading to enhanced resistance against moisture damage throughout the sealant.

As the EaMBx is smaller in size, a larger surface area promotes a better interaction with the sealant and an effective dispersion and adhesion, which can contribute to an improved moisture resistance. Since the RaMBx is larger in diameter and concentration, this may affect the dispersion of the particles within the sealant affecting its overall contribution (Hung et al., 2019).

Table 39- MISTI Measurements: RaMBx vs EaMBx Comparison

Sample	Wet	Dry	MISTI	Variation from 1
CS - Control	1.86	1.714	1.085	9%
CS - 2.5% EaMBx	0.708	0.694	1.020	2%
CS - 5% RaMBx	0.634	0.583	1.088	9%

6.4. Aerogel Modified Bituminous Materials (aMBx) Modification Test Results for Crack Filler (CF)

Given that CF is stiffer than CS due to being a crack filler, the percentages of aMBx added to the filler were limited to 5% by weight of the filler. Similar to CS, the optimum content for both RaMBx and EaMBx modifiers was found for the filler. However, due to the nature of the two different materials, a direct comparison can't be made. A final assessment determining the potential performance improvement will be done at the end of this chapter for the determined optimum modification content.

6.4.1. Crack Filler (CF) Modified with RaMBx Test Results

In this first part of the aMBx modification of the crack filling material, the results will be listed in the same order using RaMBx.

6.4.1.1. Softening Point, Resilience and Cone Penetration Test Results

According to the manufacturer's recommended specification limits for crack filling, the resilience of the material should be at 40% minimum, with a Cone Penetration value between 35 and 55. As for the softening point, a minimum value of 93^{o}C is required. According to the results obtained, the RaMBx modification made the filler stiffer, falling short of those requirements. Given that CF is stiffer by nature (Control) when compared to a conventional Crack sealing, the other properties are yet to be evaluated to determine an improved performance. According to the obtained results (**Table 40**), the control CF is within the manufacturer's recommended specifications for Resilience and Cone Penetration but not for Softening point. However, the 5%RaMBx was not found very far behind in terms of resilience (34%) and Softening Point (~88^{o}C).

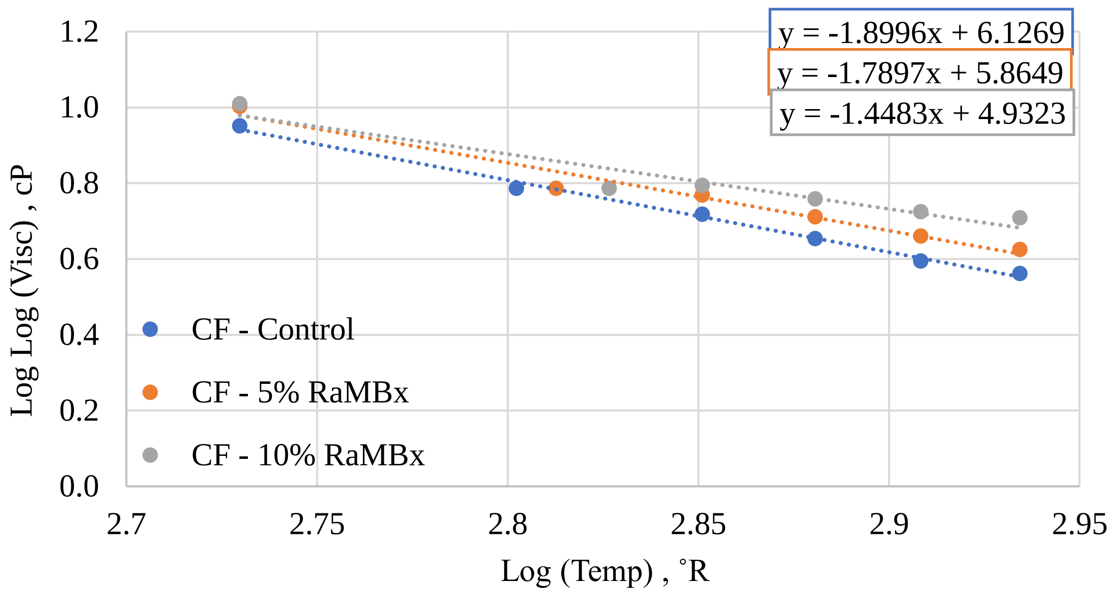
Table 40- Softening Point, Resilience and Cone Penetration Results for CF Using RaMBx

Sealant Type	Softening Point (°C)	Resilience (%)	Cone Penetration (1/10 mm)
CF - Control	79.25	45	38
CF - 5% RaMBx	87.75	34	12
CF - 10% RaMBx	99.5	29	10.25
CF - Control Aged	93	40	29
CF - 5% RaMBx Aged	94.75	30	10
CF - 10% RaMBx Aged	103.5	26	7

Overall, the other properties of the modified material will have to be evaluated to confirm that the results obtained in this section can be acceptable.

6.4.1.2. Rotational Viscosity Test Results

For the rotational viscosity test results, the addition of RaMBx to CF yielded an improved thermal resistance with reduced slope values and intercept. The viscosity of the material at 204°C was calculated for the modified CF and was found to be acceptable for modification levels up to 5% by weight of the filler. The results have shown a reduction in VTSi of 6% and Ai of 4% when compared to control, which means that the filler is less affected by temperature changes. The trends were observed for both unaged (**Figure 38a**) and aged material (**Figure 38b**). With respect to field applications, the viscosity of unaged material is of interest, in order to ensure proper pumping from the equipment. Furthermore, the trends show a potential improvement in the low temperature behavior with lower Ai values measured.



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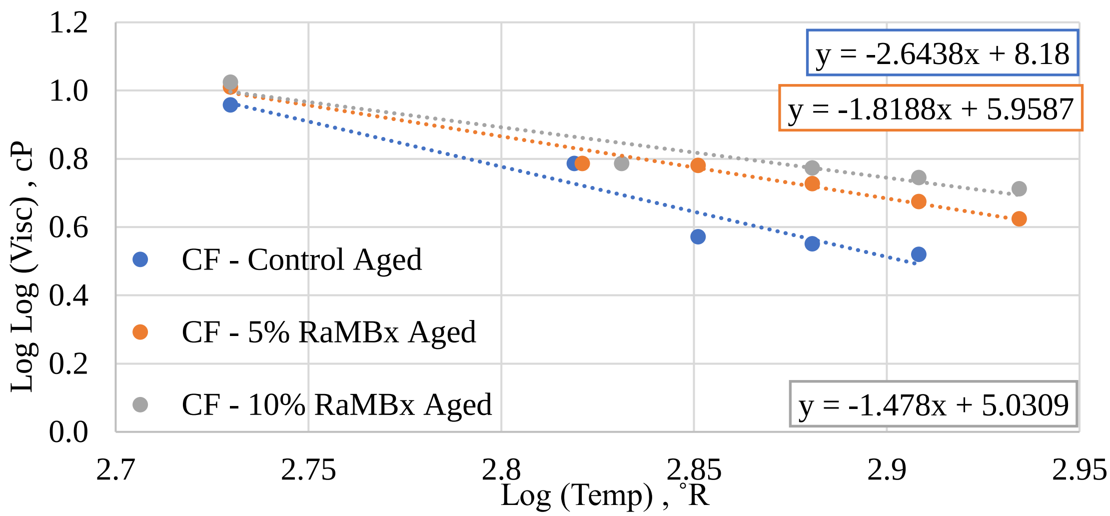

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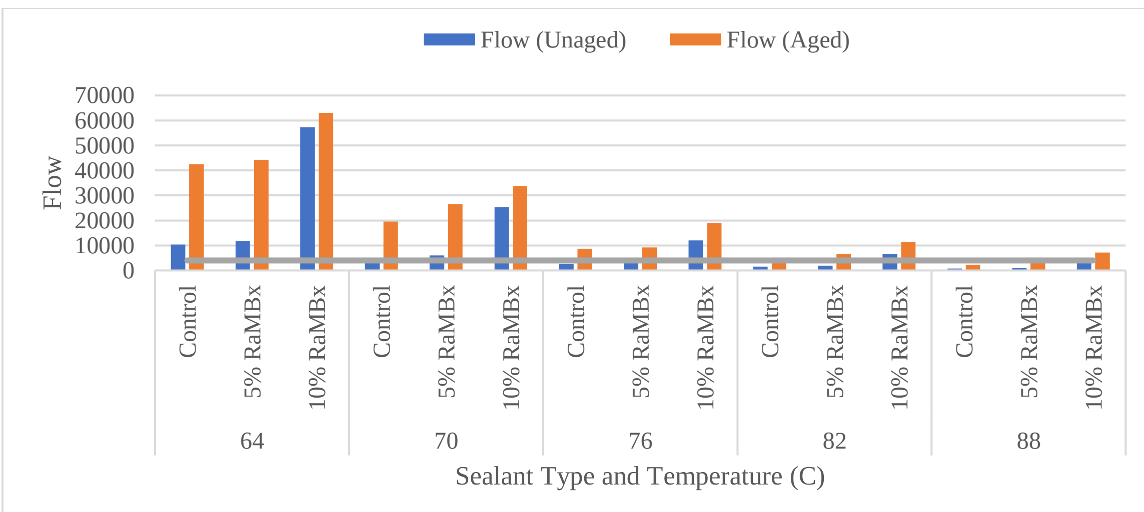
Figure 38- Rotational Viscosity Results for CF Using RaMBx: (a) Unaged Conditions and (b) Aged Conditions

As the pumping viscosity is crucial for optimum field performance, the 10% RaMBx modified CF is not recommended for future applications. The results are included for comparison.

6.4.1.3. Shear Thinning and Tracking Test Results

Similarly to the previously obtained results for the materials modified with aMBx, and more specifically RaMBx, the shear thinning parameter “P” increased for contents up to 5% by weight of CF. The flow parameter, being proportional to viscosity, is the ability of the sealant to resist flowing out of the crack. The results are shown in **Figure 39**.

The improvement was observed for both unaged and aged conditions, for 5%RaMBx.



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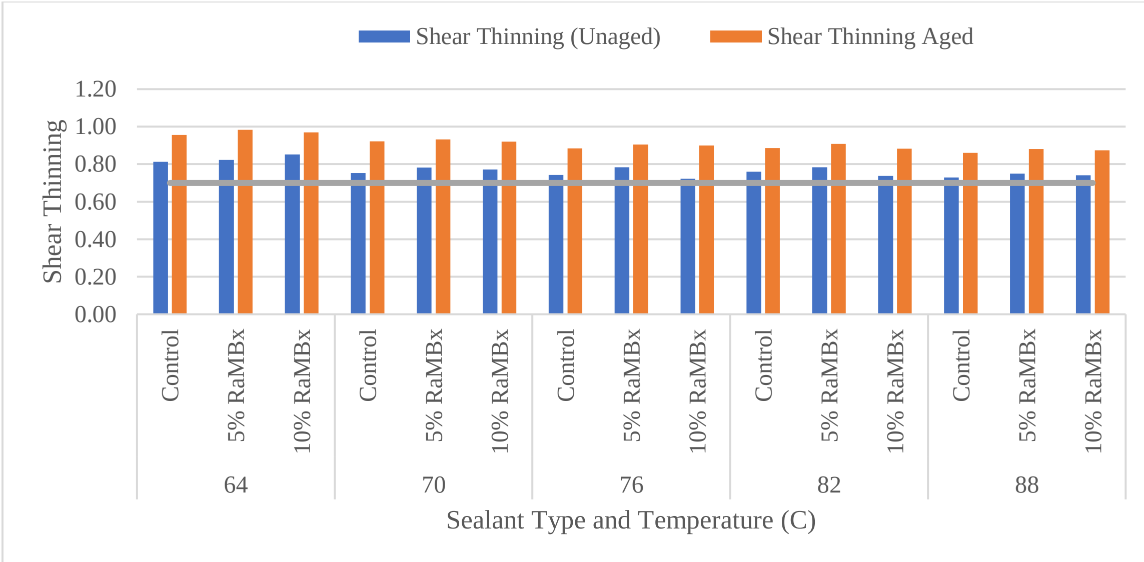

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Figure 39- Shear Thinning and Tracking Results for CF Using RaMBx; (a) Flow Parameter and (b) Shear Thinning Results

With respect to the high temperature grade of the modified sealant, a considerable jump in the temperatures was recorded for the aged sealant. Under unaged conditions, the addition of RaMBx for up to 5% content did not increase the high temperature grade of the material. However, under the aged conditions, the temperature increased by 1 grade for every 5% increase in content.

Table 41- High Temperature Grade of CF using RaMBx.

Sealant Type	Sealant Grade (Unaged)	Sealant Grade (Aged)
Control	70	82
5% RaMBx	70	88
10% RaMBx	82	94

6.4.1.4. Bending Beam Rheometer Test Results

The BBR Test results for the CF (**Table 42**) were conducted at a temperature of -10°C. Given the consistency of the material, testing it at lower temperatures was not practical. This filling material is very stiff, and the results were not acceptable according to the standard specifications. The measured stiffness and m-value for the modified material show comparable results at this test temperature, with no expected changed behavior.

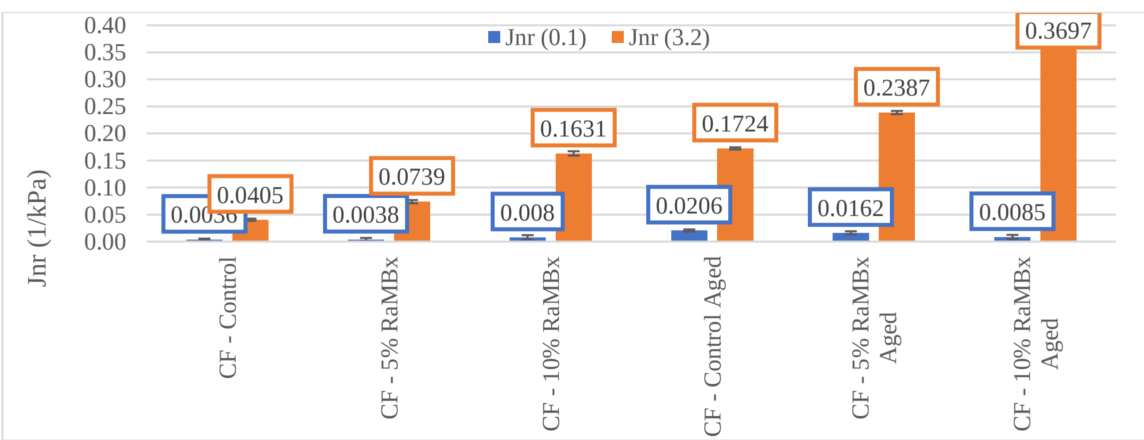
Table 42- BBR Results for CF Using RaMBx

Sealant Type	Stiffness (Mpa)	m-value
CF - Control	247.17	0.39
CF - 5% RaMBx	285.3	0.39

6.4.1.5. Multiple Stress Creep and Recovery Test Results

The MSCR test was run for the high temperature grades obtained from **Table 41**.

According to the results in **Figure 40**, the modified CF showed promising results for the 0.1kPa loading in terms of both Jnr and %Recovery. It is important to note that for each modification level, the test was carried out at different temperatures. As this modifier rendered the filler stiffer, increasing Jnr at 3.2kPa levels were measured for increased RaMBx contents, with reduced %Recovery as well. The results will have to be combined with the rest of the testing protocol for proper assessment.



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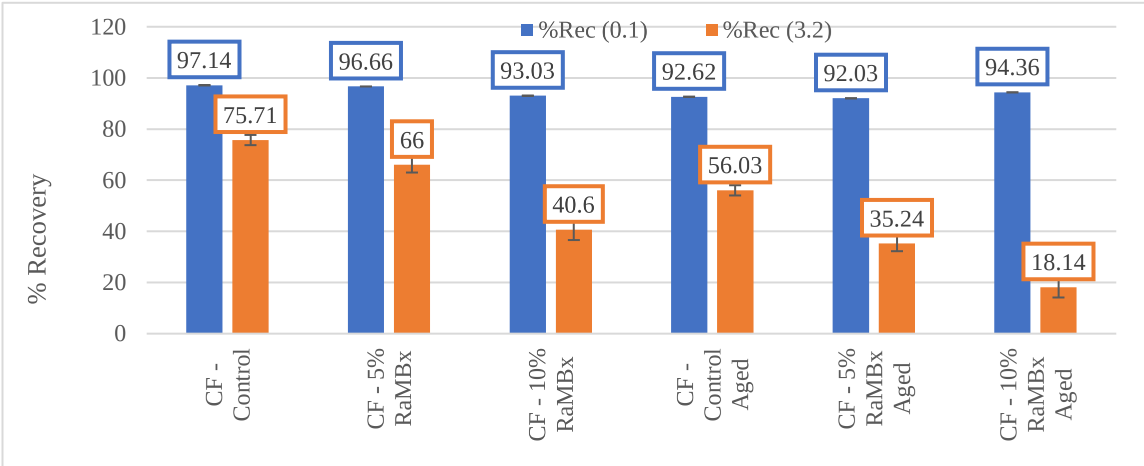


(b)

Figure 40- MSCR Test Results for CF Using EaMBx: (a) Jnr Results; (b) %Recovery Results

In terms of stress sensitivity, the filler did become more sensitive to different loading conditions (**Table 43**). The 5%RaMBx modified CF is considered to have an acceptable behavior to control under unaged conditions, considering they were tested at the same testing temperature. As for the aged conditions, the results differ slightly due to different testing conditions but are still considered acceptable.

Table 43- %Jnr Slope and Acceptance Level of Elastomeric Polymer for CF Using RaMBx

Sealant Type	%Jnr Slope	Acceptable Level of Elastomeric Polymer at 3.2 kPa
CF - Control	1.19	Yes
CF - 5% RaMBx	2.26	Yes
CF - 10% RaMBx	5.00	Yes
CF - Control Aged	4.90	Yes
CF - 5% RaMBx Aged	7.18	Yes
CF - 10% RaMBx Aged	11.65	Yes

6.4.1.6. Toughness and Tenacity Test Results

The results obtained in the toughness and tenacity test are consistent with the previous tests where CF experienced a stiffer behavior compared to control. The result shown in **Figure 41** reflect a decrease in both toughness and tenacity for the modified sealants with increasing RaMBx content. However, the tenacity of the modified sealant was still found to be comparable to the unmodified sealant for both scenarios.

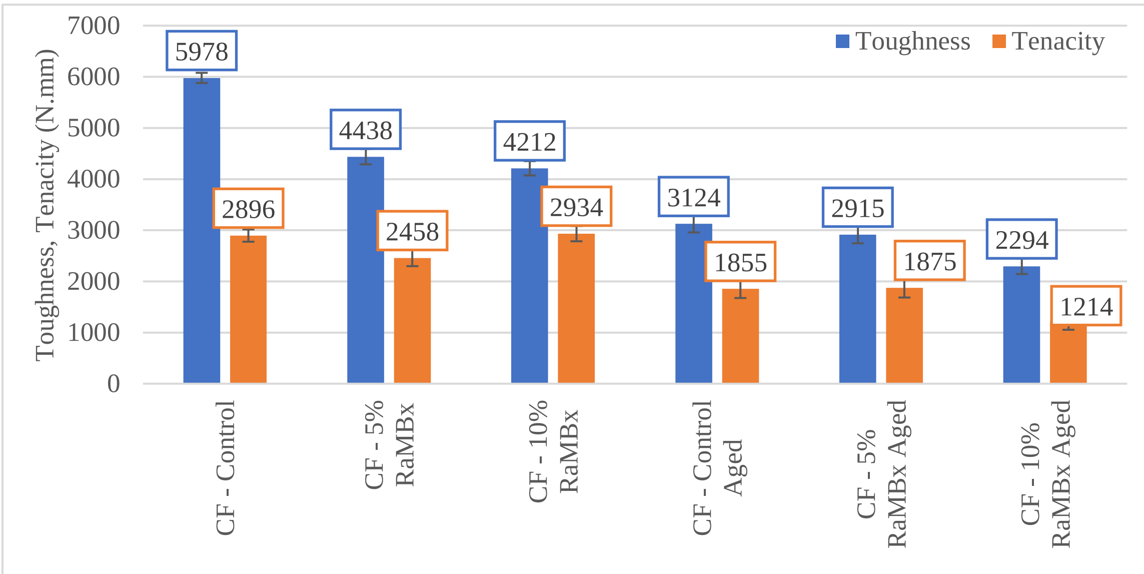


Figure 41- Toughness and Tenacity Results for CF Using RaMBx

6.4.1.7. Bond Strength Test Results

In terms of bond strength, the results (**Table 44**) were measured to be promising for the 5%RaMBx modified material, with a good performance in terms of mode of failure and pull-out strength moisture susceptibility. The failure mode was found to be cohesive where the control material failed in adhesion, and a reduction of pull-out strength of 14% was measured compared to a 31% for the control under aged conditions.

Table 44- Bond Strength Test Results for CF Using RaMBx

Sealant Types	Dry Pull-Out Strength (kPa)	Failure Modes	Wet Pull-Out Strength (kPa)	Failure Modes	Pull-Off Strength Moisture-Susceptibility Index
CF - Control	2305	Cohesive	2107	Adhesive	-9%
CF - 5% RaMBx	2057	Cohesive	1848	Cohesive	-10%
CF - 10% RaMBx	1793	Adhesive	1580	Adhesive	-12%
CF - Control Aged	2337	Adhesive	1620	Adhesive	-31%
CF - 5% RaMBx Aged	1954	Adhesive	1678	Cohesive	-14%
CF - 10% RaMBx Aged	2091	Adhesive	1908	Adhesive	-9%

6.4.1.8. Thermal Conductivity and Specific Heat Capacity Test Results

The other important aspect to look at is the thermal properties of the modified material. The modified material did experience a decrease in thermal properties in both aged and unaged conditions, which is expected with the addition of aMBx into the material. Furthermore, the specific heat capacity of the material increased, showing that the material requires more energy to heat up, leading to a lower temperature susceptibility in the field. So far, the modified CF was shown to be more brittle compared to the unmodified CF, while showing better failure modes and improved thermal performance. The thermal conductivity of the aged material was still found to be lower than the aged control, promoting the effect of RaMBx. However, thermal conductivity did increase due to the volatilization of the lighter fractions of the material.

Table 45- Thermal Conductivity and Specific Heat Capacity Results for CF Using RaMBx

Sealant Type	k (W/m·K)	C_p (J/kg·K)
CF - Control	0.22	1059
CF - 5% RaMBx	0.133	1432
CF - 10% RaMBx	0.157	1553
CF - Control Aged	0.19	1433
CF - 5% RaMBx Aged	0.154	1696
CF - 10% RaMBx Aged	0.167	2042

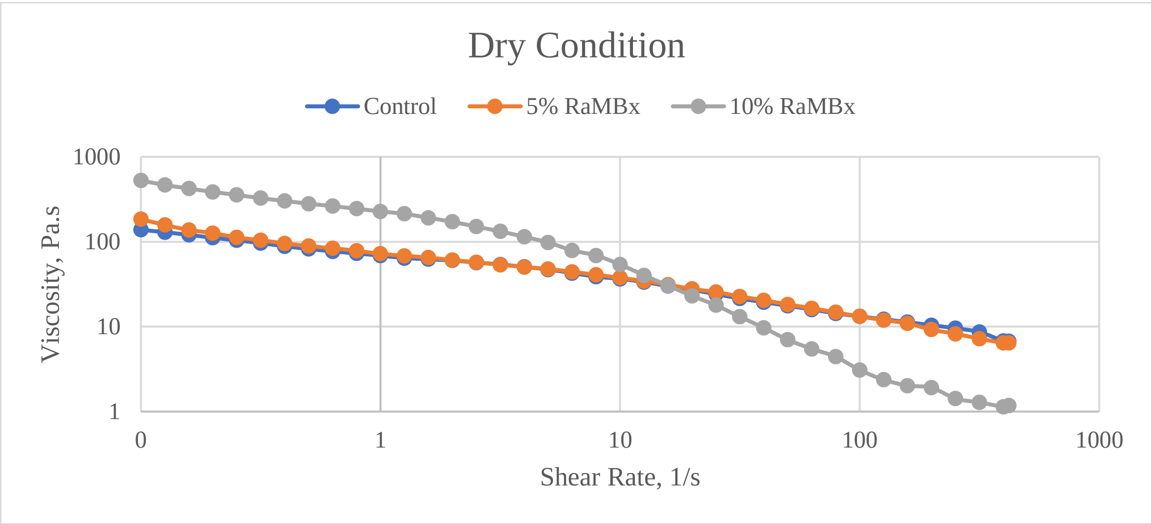
6.4.1.9. Linear Expansion and Contraction Test Results

The CTE of the material was measured for the optimum content observed based on the previous test results. The CTE of CF modified with 5% RaMBx was measured to be equal to 2.4E-05, compared to a CTE of 3.1E-05 for the control material. A reduction in the CTE with the addition of RaMBx was observed, similar to the CS results. This leads to an improvement with respect to the materials properties, reducing cracking of the material.

6.4.1.10. MISTI Test Results

The last test investigating the addition of RaMBx to CF is the MISTI, to identify the effect of moisture on the material. First, the onset of shear thinning was compared for the 3 materials, CF, CF with 5% RaMBx and 10% RaMBx. Due to the consistency of this material, the glass bead ratio was reduced from 4:1 to 8:1 to achieve more reliable results. This ratio was determined by trial and error by observing the zero-shear viscosity region. The goal was to achieve the most linear curve before reaching the onset of shear thinning.

However, due to the additions of RaMBx to the filler, reaching the same initial viscosity was not possible with the DSR used to carry out the testing. As can be seen from **Figure 42** below, the control and 5% RaMBx modified CF have very similar behavior in terms of shear thinning susceptibility. As for the 10% RaMBx modified CS, the shear thinning occurred earlier, at a shear rate of 2.51 for both wet and dry conditions. For the control filler, a stiffening effect occurred under wet conditions, showing a slight change in behavior due to moisture (**Figure 42b**). The 5% RaMBx showed a consistent behavior under wet conditions.



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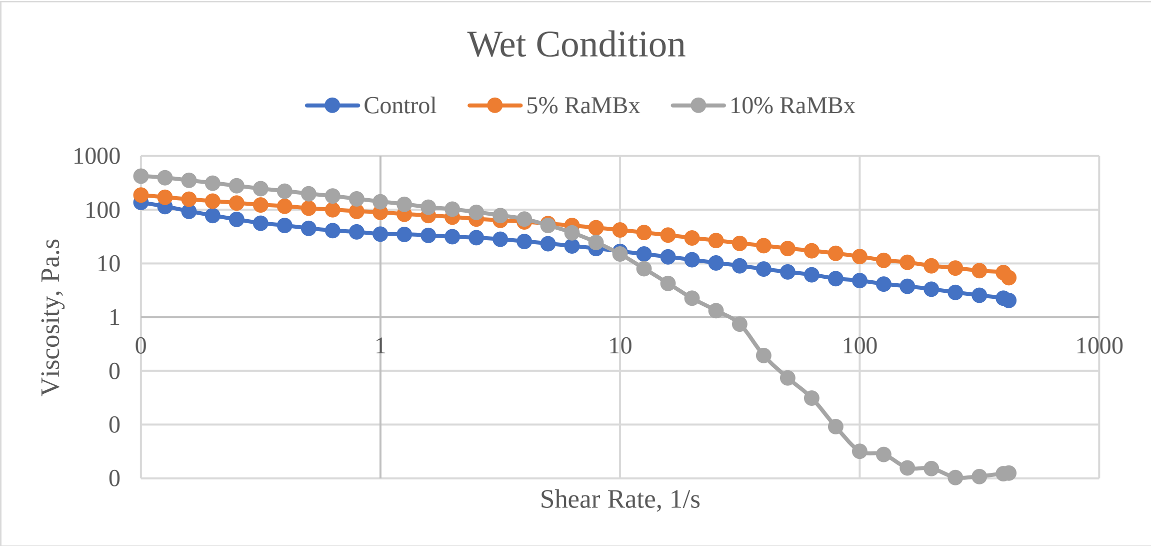


(b)

Figure 42- Shear Thinning Onset for CF Using RaMBx; (a) Dry Testing Conditions and (b) Wet Testing Conditions

As for the MISTI calculations, the 5%RaMBx showed improvement with respect to moisture susceptibility with a variation of 7% from unity for the MISTI coefficient (**Table 46**). The addition of RaMBx into the filler showed a potential improvement to moisture susceptibility, especially after a deterioration of the control CF by 27% when subjected to moisture. This may be due to the hydrophobic nature of aMBx, repelling water from the material.

Table 46- MISTI Test Results for CF Using RaMBx

Sealant Type	Wet	Dry	MISTI	Variation from 1
CF - Control	0.55	0.44	1.272	27%
CF - 5% RaMBx	0.49	0.46	1.066	7%
CF - 10% RaMBx	1.86	1.31	1.423	42%

6.4.2. Crack Filler (CF) Modified with EaMBx Test Results

In this second part of the aMBx modification of the crack filling material, the results will be listed in the same order using EaMBx.

6.4.2.1. Softening Point, Resilience and Cone Penetration Test Results

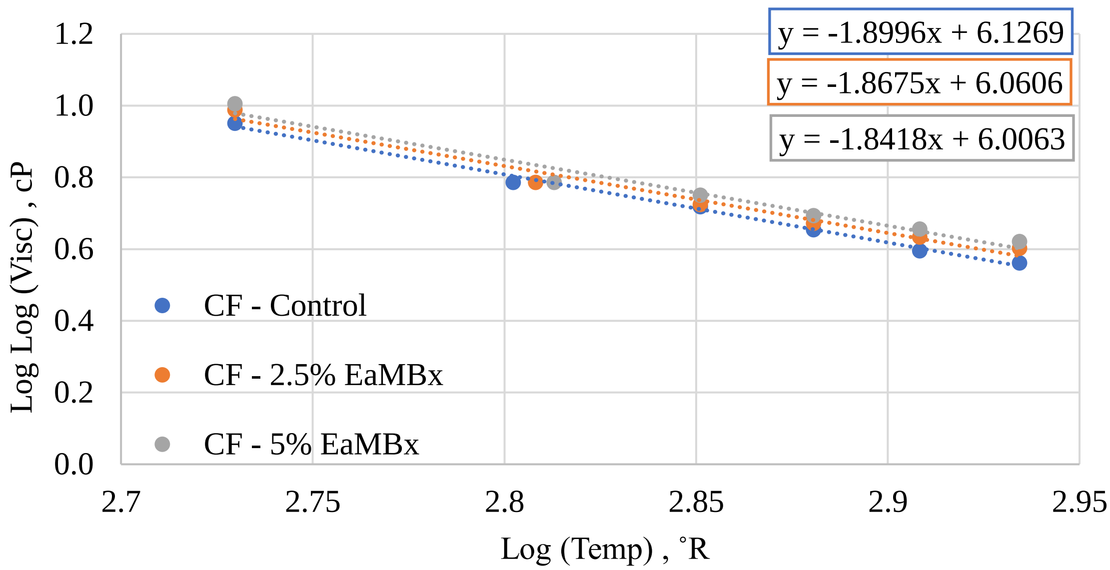
Concerning the EaMBx modified CF, the results were following a similar trend to RaMBx modified CF: increased softening points with reduced resilience and cone penetration results (**Table 47**). In terms of Resilience, the EaMBx modification caused a slightly larger reduction compared to the RaMBx's corresponding content. The cone penetration test results were comparable. In terms of behavior comparison, the softening point of EaMBx modified CF didn't go as high as RaMBx modified CF for the corresponding contents. This could be attributed to the size of the modifier and the difference in density between the two.

Table 47- Softening Point, Resilience and Cone Penetration Results for CF using EaMBx.

Sealant Type	Softening Point (ºC)	Resilience (%)	Cone Penetration (1/10 mm)
CF - Control	79.25	45	38
CF - 2.5% EaMBx	84	28	17
CF - 5% EaMBx	84.5	20	11.4
CF - Control Aged	93	40	29
CF - 2.5% EaMBx Aged	88	25	15
CF - 5% EaMBx Aged	92	16	9

6.4.2.2. Rotational Viscosity Test Results

The rotational viscosity test results show improvements in terms of VTSi parameters with smaller slopes (lower thermal susceptibility) and slightly smaller Ai parameters. The plots are show in **Figure 43**. In general, a 2% decrease in VTSi was measured for 2.5% and 3% decrease for 5% EaMBx contents when compared to control. As for Ai, an average decrease of 2% was measured when compared to control. However, the stiffening effect that occurred with the addition of EaMBx was lower compared to RaMBx. This has been manifested through lower viscosity values at 204.4ºC, making the modified CF passing the manufacturer’s viscosity limit for contents up to 5% EaMBx.



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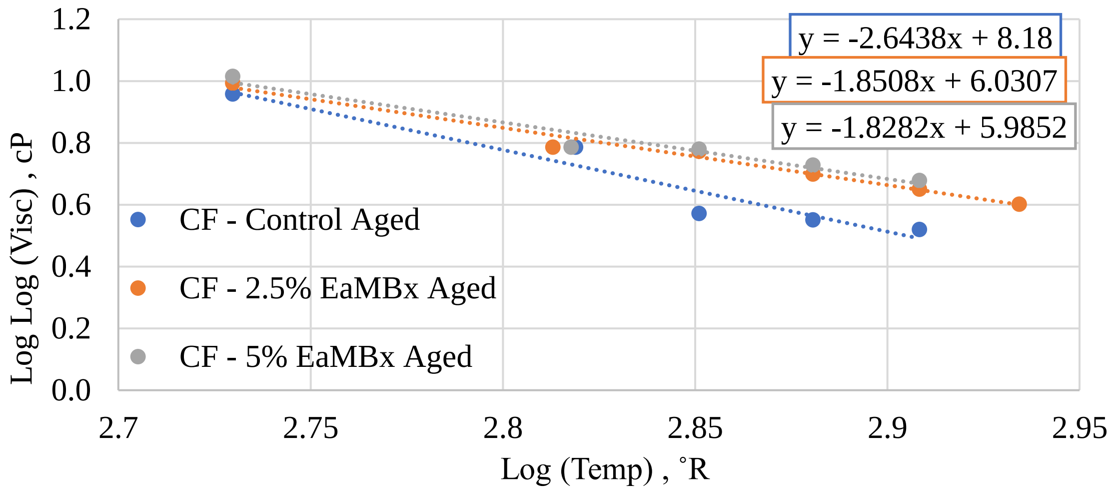
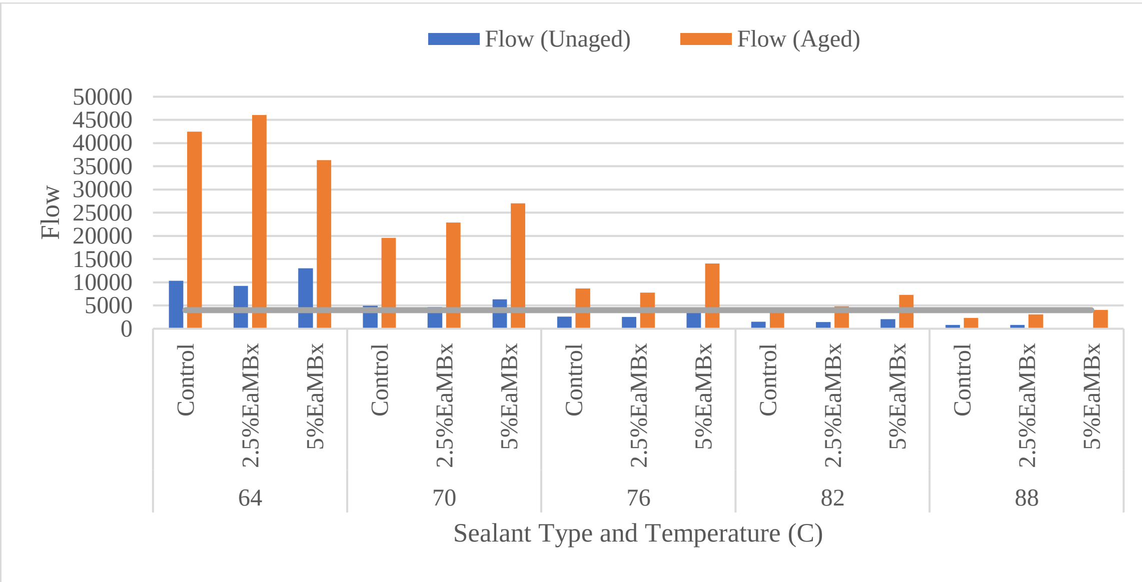


(b)

Figure 43- Rotational Viscosity Results of CF Using EaMBx: (a) Unaged Conditions and (b) Aged Conditions

6.4.2.3. Shear Thinning and Tracking Test Results

As for shear thinning and tracking results, improvements were measured with respect to both parameters for both EaMBx contents. However, when the material was aged, the performance was noted to be better only for the 2.5%EaMBx content. The results highlight the potential optimum content for EaMBx modification for the CF material, which could be 2.5% EaMBx. The insulating properties of aMBx make the material less susceptible to higher temperatures, which makes it more resistant to tracking.



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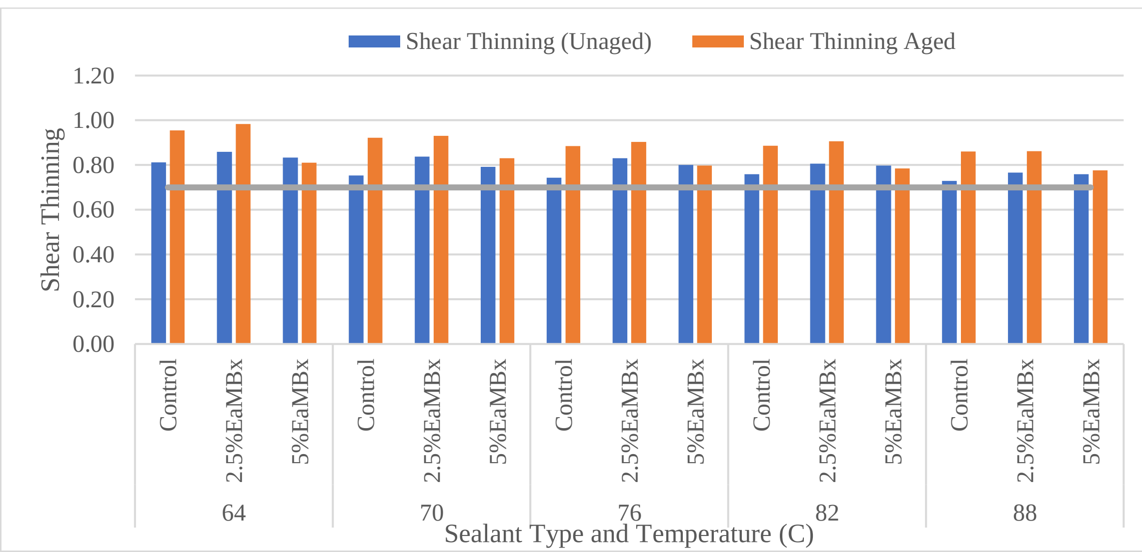


(b)

Figure 44- Shear Thinning and Tracking Test Results for CF Using EaMBx: (a) Flow Parameter and (b) Shear Thinning Parameter

In terms of high-performance grade (**Table 48**), the EaMBx modification did not affect the high temperature grade under unaged conditions. For the aged conditions, a jump of 1 grade was seen for 5% EaMBx modification level. Comparing the results to RaMBx, a jump was observed for the 10%RaMBx (equivalent to 5%EaMBx) under unaged conditions from 70 to 82, whereas a a higher temperature grade of 88 was measured for aged conditions for both 5% and 10% RaMBx (equivalent to 2.5 and 5% EaMBx). Therefore, a slightly higher stiffening effect can be attributed to the RaMBx modification.

Table 48- High-Performance Grades for CF Using EaMBx

Sealant Type	Sealant Grade (Unaged)	Sealant Grade (Aged)
Control	70	82
2.5% EaMBx	70	82
5% EaMBx	70	88

6.4.2.4. Bending Beam Rheometer Test Results

As the 2.5% EaMBx content looks promising so far, the CSBBR test was carried out in this section, at two different test temperatures: -10^{o}C and -16^{o}C. The stiffness and m-value of the material under aged conditions was measured at 240 seconds for both temperatures. Furthermore, the material's susceptibility to low temperature cracking was assessed based on the critical temperature ΔT_c calculation from **(Equation 5)** to **(Equation 7)** and are summarized in **Table 49**. It can be seen that the addition of EaMBx did slightly affect the low temperature behavior of the material, while preserving the relaxation capacity of the filler. Values of ΔT_c lower than -5°C indicate that the material is susceptible to low-temperature cracking (Newcomb et al., 2021). Accordingly, the addition of EaMBx provided a slight improvement (ΔT_c of 3), as the control material yielded a ΔT_c lower than

5. Furthermore, tat a temperature of -10, both materials show satisfactory m-values and acceptable stiffnesses which refers to the low temperature grade of the material. They both fail in terms of stiffness (greater than 300MPa) and m-value (lower than 0.3) at -16°C. Therefore, the addition of 2.5% EaMBx did not cause a change in the low temperature grade of the control material. The effect of adding aMBx into the filler yielded to similar m-value measurements, possibly resulting in lower aging susceptibility (Karnati et al., 2019).

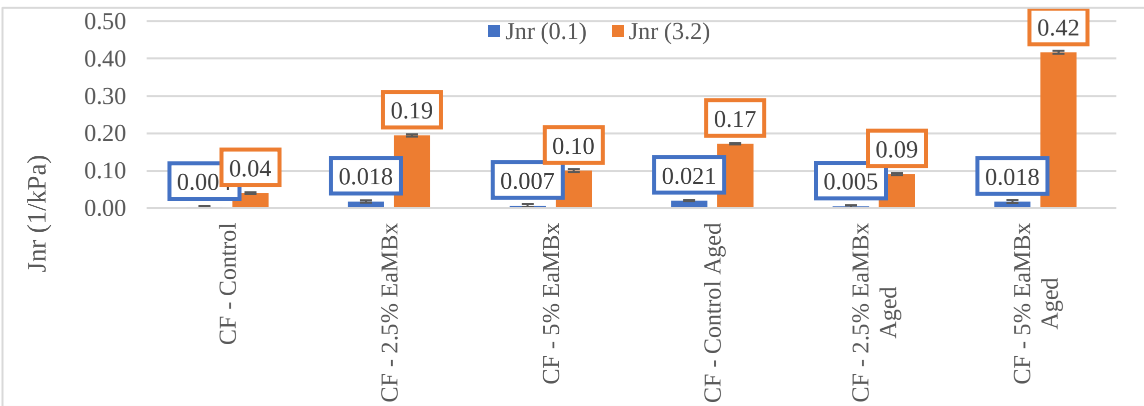
Table 49- Bending Beam Rheometer Results for CF Using EaMBx

	Temperature (°C)						
	-10 °C		**-16** °C				
Sample	**Stiffness**	**m value**	**Stiffness**	**m value**	**Tc,s**	**Tc,m**	**ΔTc**
CF - Control	247	0.3865	639	0.276	-21	-25	3
CF - 2.5% EaMBx	333	0.3385	671	0.2815	-19	-24	5

6.4.2.5. Multiple Stress Creep and Recovery Test Results

The MSCR Test was carried out based on the high temperature grade of the material determined in section 6.4.2.3. According to the results, as the control and the 2.5%EaMBx CF were tested at the same temperature for both unaged and aged conditions, the modified material showed promising performance with the addition of EaMBx under aged conditions. At higher testing temperatures for the 5%EaMBx modified CF, the Jnr still increased, which showed undesirable stiffening of the material.

As for the Jnr Slope (**Table 50**), the unaged material showed higher sensitivity at 2.5%EaMBx under unaged conditions but was less sensitive when aged. This shows a better stability under aged conditions for EaMBx modified materials. Comparing the results to RaMBx, the stress sensitivity of 5%RaMBx was shown to be more promising when unaged, but less stable under aged conditions. Furthermore, the %Recovery for 3.2kPa was higher across all modification levels for EaMBx modified CF. With respect to the measured Jnr, similar analysis can be concluded that a better stability was measured for aged EaMBx modified materials up to 2.5% modification levels. Under unaged conditions, RaMBx showed better Jnr performance. However, to determine which material will perform better in the field, aged conditions represent more drastic testing measurements. Therefore, considering the flexibility of the material and its stress sensitivity under aged conditions could be more representative of severe field conditions.



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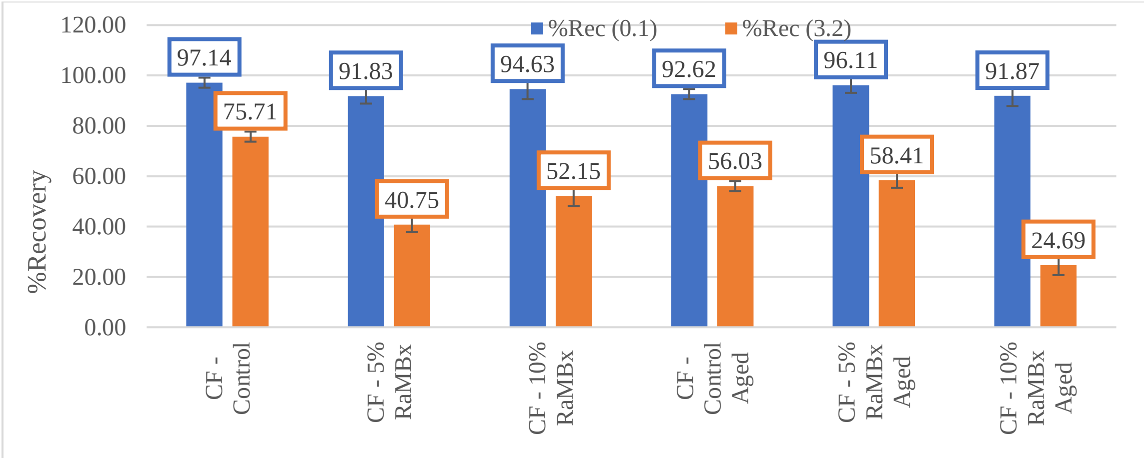


(b)

Figure 45- MSCR Results for CF Using EaMBx: (a) Jnr and (b) %Recovery.

Table 50- Stress Sensitivity and Acceptable Level of Elastomeric Polymer at 3.2kPa for CF using EaMBx.

JnrSlope, %	Acceptable Level of Elastomeric Polymer at 3.2 kPa
1.19	Yes
5.69	Yes
3.01	Yes
4.90	Yes
2.78	Yes
12.87	Yes

6.4.2.6. Toughness and Tenacity Test Results

In terms of toughness and tenacity, the modified material did affect the performance of the modified material. The toughness and tenacity both decreased (**Figure 46**) with the addition of EaMBx. However, when the material was aged, the properties were conserved. Comparing the results to the RaMBx modified CF, it can be seen that the unaged RaMBx modified material showed higher toughness and tenacity. The trends changed for the aged conditions, where the EaMBx modified material showed better performance. So far, the

EaMBx modified material shows improved performance, and better stability under aged conditions compared to the RaMBx modified CF.

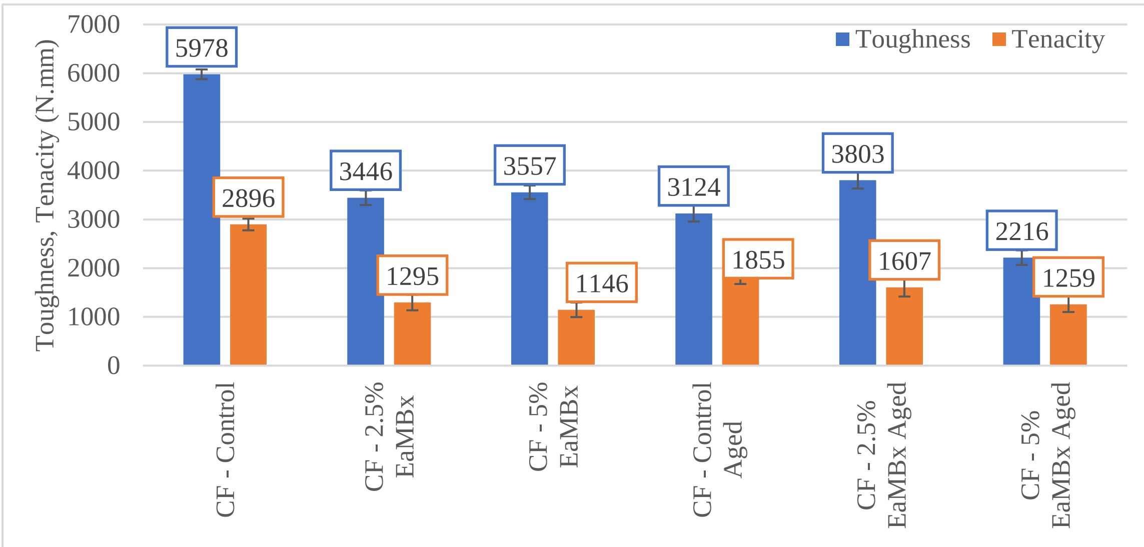


Figure 46- Toughness and Tenacity Results for CF Using EaMBx

6.4.2.7. Bond Strength Test Results

The results for the bond strength were shown to be very promising, where an increase in the Pull-Out strength for both wet and dry conditions was measured. Furthermore, the moisture susceptibility index was improved by almost double, especially under aged conditions for the 2.5% EaMBx modification. Concerning the failure modes, they were assessed as adhesive. However, the strength increase does compensate for that mode. Comparing the results with RaMBx modified CF, higher bond strengths were measured for EaMBx modification across all levels. Furthermore, for the Moisture Susceptibility Index, comparable results were obtained for 2.5%EaMBx compared to 5%RaMBx modification levels (15% vs 10% for unaged, and 14% for both under aged conditions). Impressive results were measured before and after aging in terms of bond strength, leading to the suggestion that aMBx has a good dispersion, combined with its ability to absorb the compounds corresponding to moisture damage under wet conditions, is benefitting the material at lower dosages.

Table 51- Bond Strength Results for CF Using EaMBx

Sealant Types	Dry Pull-Out Strength (kPa)	Failure Modes	Wet Pull-Out Strength (kPa)	Failure Modes	Pull-Off Strength Moisture-Susceptibility Index
CF - Control	2305	Cohesive	2107	Adhesive	-9%
CF - 2.5% EaMBx	3743	Cohesive	3183	Adhesive	-15%
CF - 5% EaMBx	1793	Adhesive	1580	Adhesive	-12%
CF - Control Aged	2337	Adhesive	1620	Adhesive	-31%
CF - 2.5% EaMBx Aged	3815	Adhesive	3298	Adhesive	-14%
CF - 5% EaMBx Aged	2252	Adhesive	1850	Adhesive	-18%

6.4.2.8. Thermal Conductivity and Specific Heat Capacity Test Results

The thermal properties results (**Table 52**) reflect a reduction in thermal conductivity and increase in specific heat capacity, which are expected trends when adding aMBx to sealing materials. A lower thermal conductivity was observed with the RaMBx modified filler. A lower thermal conductivity was observed with the RaMBx modified filler, which may be attributed to a bigger concentration of aerogel added to the material when producing aMBx.

Table 52- Thermal Conductivity and Specific Heat Capacity for CF Using EaMBx

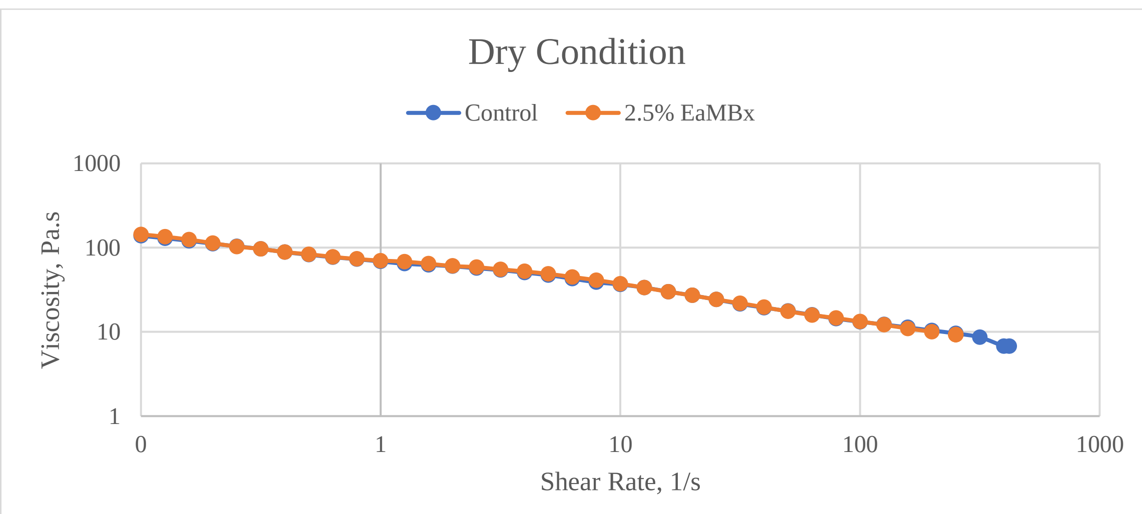
Sealant Type	k (W/m·K)	C_p (J/kg·K)
CF - Control	0.22	1059
CF - 2.5% EaMBx	0.198	1384
CF - 5% EaMBx	0.181	1516
CF - Control Aged	0.19	1433
CF - 2.5% EaMBx Aged	0.18	1548
CF - 5% EaMBx Aged	0.177	1505

6.4.2.9. Linear Thermal Expansion and Contraction Test Results

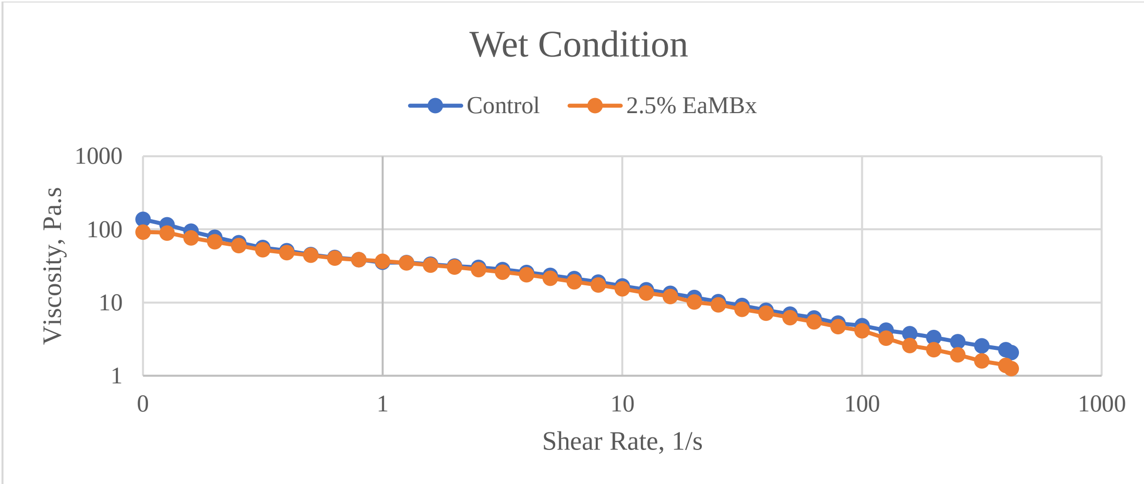
Similarly, the CTE for the EaMBx modified was reduced from 3.1E-05 (CF Control) to 2.35E-05. This reduction is slightly larger than the RaMBx modified CF, due to the stronger thermal properties of the aerogel incorporated in this case.

6.4.2.10. MISTI Test Results

Improved moisture susceptibility was already measured with the Bond Strength, whereas a reduction of the Pull-off moisture susceptibility index was reduced for EaMBx modified materials compared to the conventional sealing material. As the 2.5%EaMBx modification level is deemed to have the best performance, the MISTI was run for 2.5%EaMBx and control. Under dry conditions (**Figure 47a**), fairly similar behavior was measured. As for the wet conditions (**Figure 47b**), shear thinning occurred at very close shear rates for both materials.



(a)



(b)

Figure 47- Shear Thinning Onset for CF Using EaMBx: (a) Dry Conditions and (b) Wet Conditions

As for the MISTI calculations (**Table 53**), both indices are very close to each other, as inspected by the plots.

Table 53- MISTI Results for CF Using EaMBx

Sample	Wet	Dry	MISTI
CF - Control	0.554	0.435	1.272
CF - 2.5% EaMBx	0.562	0.453	1.240

6.5. Final Assessment for Aerogel Modified Bituminous Materials (aMBx) Modification

The addition of aMBx to asphalt crack sealant has the potential to offer several benefits.

aMBx has low density and high porosity, making it very lightweight and flexible. Adding it to the sealant can potentially increase its flexibility, allowing it to better accommodate movement in the asphalt caused by temperature changes and traffic. This flexibility could reduce stress on the sealant and potentially improve its resistance to cracking. Furthermore, it is also an excellent thermal insulator. This means it can help to reduce extreme temperature fluctuations within the material, which can contribute to its cracking. By mitigating these temperature variations, aerogel-modified sealants might offer improved durability in both hot and cold climates. Two different sources of aerogel were used to produce aMBx. Those sources had different particle size, thermal conductivity, density, and porosity. The aMBx produced from AP1, being the lighter weight aerogel with lower thermal conductivity was referred to as EaMBx, whereas the aMBx produced from the other source, AP4, was referred to as RaMBx. As AP4 had a heavier weight, less binder was needed to produce RaMBx with more aerogel content.

The results observed in this chapter favored the CS rather than CF, given that the filling material is originally stiffer. To begin with the results of CS, the optimum content of aMBx was found to be 2.5% EaMBx, equivalent to 5%RaMBx. In general, improved Jnr and %Recovery was observed for both types of aMBx, with a decrease in stress sensitivity. Lower Jnr values indicate better stress relaxation. This means the sealant can deform and flow under pressure, allowing it to better accommodate movement in the asphalt caused by temperature changes and traffic. Higher %Recovery values indicate better elasticity. This means the sealant can return to its original shape after being compressed, allowing it to maintain a tight seal and prevent water infiltration into the asphalt cracks.

Furthermore, higher toughness and tenacity were observed under both unaged and aged conditions, indicating potential improved performance in the field. In terms of bond strength, the modified CS performed better than control under different aging conditions, while maintaining a cohesive failure to the substrate.

The bond strength was performed under dry and wet conditions, with improvements measured in both. The Pull-Out Strength Moisture Susceptibility Index calculated showed equal effect under unaged conditions to control, but better resistance under aged conditions. The same results were observed in the MISTI test, where the moisture shear thinning was reduced for EaMBx modified material.

The biggest improvement related to aMBx refers to the improved thermal behavior, where thermal conductivity was reduced, leading to less temperature susceptibility in the field. Paired with a higher specific heat capacity, the material will be less susceptible to any temperature change, improving its tracking resistance, softening potential and settlement within the crack. In addition, the measured coefficient of thermal expansion and contraction was reduced. Such behavior may slightly influence the setting process of the sealant but may be beneficial to ensure proper bonding under cold temperatures. That being said, the BBR test results at -40^{o}C showed relatively increased stiffness, and acceptable relaxation capacity.

With respect to CF, the optimum content of EaMBx and RaMBx was also found to be around 2.5% and 5% respectively by weight of the material. Similar behavior as CS modified was observed. However, the toughness and tenacity as well as Jnr and %Recovery measurements were not as promising. This reflects the potential use of the filler, where traffic and strength are not a major requirement such as parking lots and low traffic volume roadways. The thermal benefit as well as moisture resistance and pull-out improvements were all observed for the modified CF. Finally, the low temperature behavior was also assessed at two different temperatures, -10 and -16^{o}C. Increased stiffness as well as comparable m-value were reported, with a reduced critical temperature (ΔT_c), indicating that the material is susceptible to low-temperature cracking. At the 5% aMBx modification for both CF and CS, the results showed a similar m-value measurement before and after aging, suggesting potential reduction in the aging susceptibility of the material. aMbx being silica based, has the potential to absorb the acidic compounds relating to increased moisture damage in wet conditions. The results were translated into improved overall adhesive performance under both dry and wet conditions, referring to a good dispersion. Higher dosages may lead to inadequate dispersion, potentially limiting the observed benefits on aging and moisture resistance.

CHAPTER 7

7 CHARACTERIZATION AND ASSESSMENT OF RECYCLED AEROGEL COMPOSITE MODIFIED SEALANTS

7.1. Introduction

Given the performance improvement due to the addition of aMBx to the sealing material at high temperatures, there was still a need for improvements in terms of elasticity and low temperature behavior. The addition of rubber by means of RaC was one way to introduce more flexibility to the sealing material, while providing the insulating benefits from aerogel. In this chapter, the addition of RaC will be investigated for both CS and CF, where the optimum modifier content will also be assessed. The same testing protocol will be implemented for this modifier. Two modification levels were considered for analysis according to the previous tests indicating an approximate optimum aerogel content around 5% by weight of the sealant. According to the composition of RaC, the two modification levels considered were 5% and 7.5% by weight of the materials CS and CF.

7.2. Recycled Aerogel Composite (RaC) Modification Test Results for Crack Sealant (CS)

7.2.1. Softening Point, Resilience and Cone Penetration Test Results

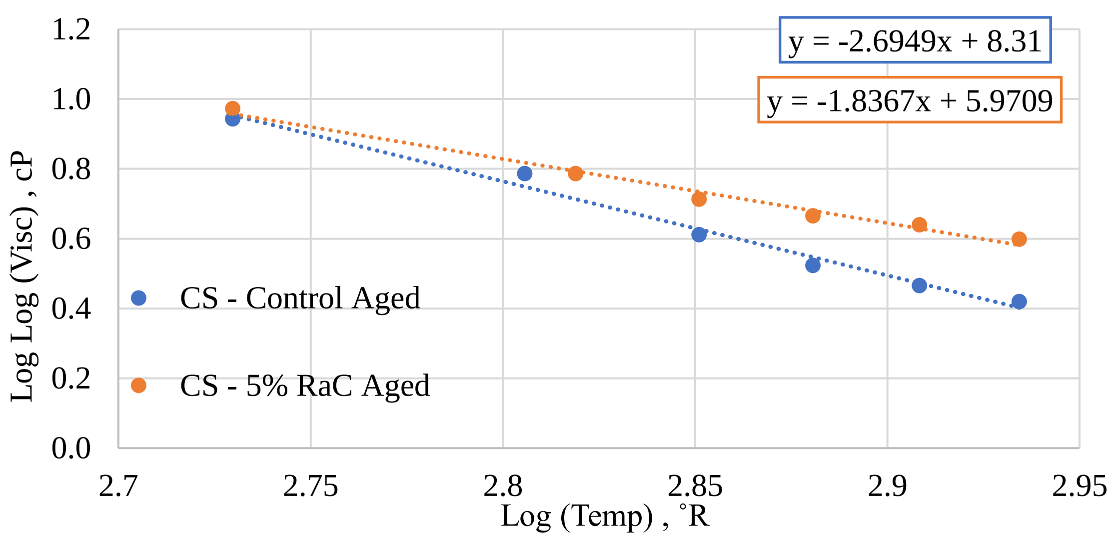
The results (**Table 54**) for the RaC modification indicate that the material experienced stiffening behavior, with a reduced resilience and cone penetration at higher softening points under both aged and unaged conditions. This behavior was expected, as the addition of crumb rubber combined with aerogel will eventually lead to stiffer performance. Given the manufacturer’s recommendations, the modified CS is considered satisfactory for the minimum resilience of 60%, softening point of at least 80 and cone penetration of maximum 90. The stiffness of the modified material needs to be monitored following the testing protocol to avoid failures in adhesion.

Table 54- Softening Point, Resilience and Cone Penetration Results for CS Using RaC

Sealant Type	Softening Point (ºC)	Resilience (%)	Cone Penetration (1/10 mm)
CS - Control	80	94	72.67
CS - 5% RaC	87.5	56	32.75
CS - 7.5% RaC	96.5	63	31
CS - Control Aged	82	67.5	45
CS - 5% RaC Aged	93	49	24
CS - 7.5% RaC Aged	99	54	23

7.2.2. Rotational Viscosity Test Results

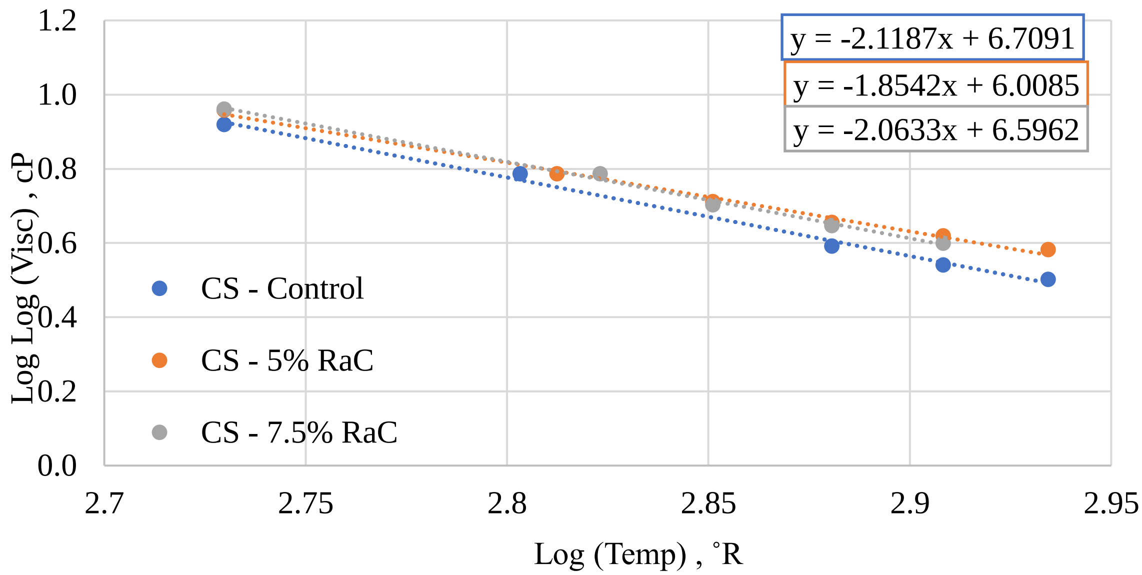
The rotational viscosity results of the modified CS material are shown in**(a)**



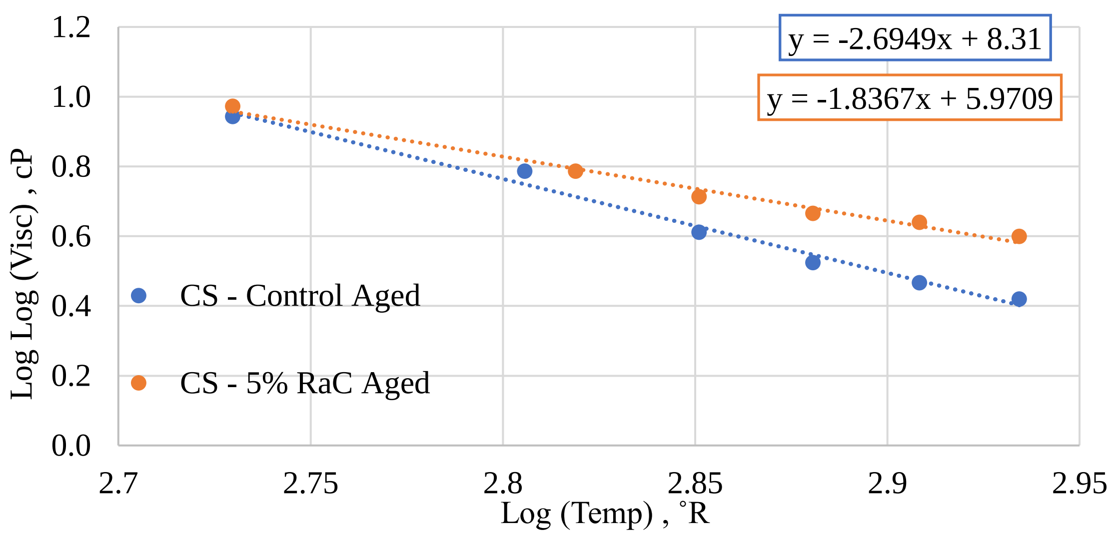
(b)

Figure 48. The results show the potential benefit of adding both aerogel and rubber to contents up to 5%, with a reduction in both VTSi and Ai parameters. The addition of RaC up to 7.5% to the material still provided temperature susceptibility reduction when

compared to control. However, this increased content does not provide significant improvement compared to the 5% modification level. Furthermore, under aged conditions, it can be clearly seen that the addition of RaC didn't affect the thermal susceptibility of the material. In other words, the presence of RaC under aged conditions helped with the aging mechanism of the sealant by possibly preserving its properties (**Figure 48b**).



(a)

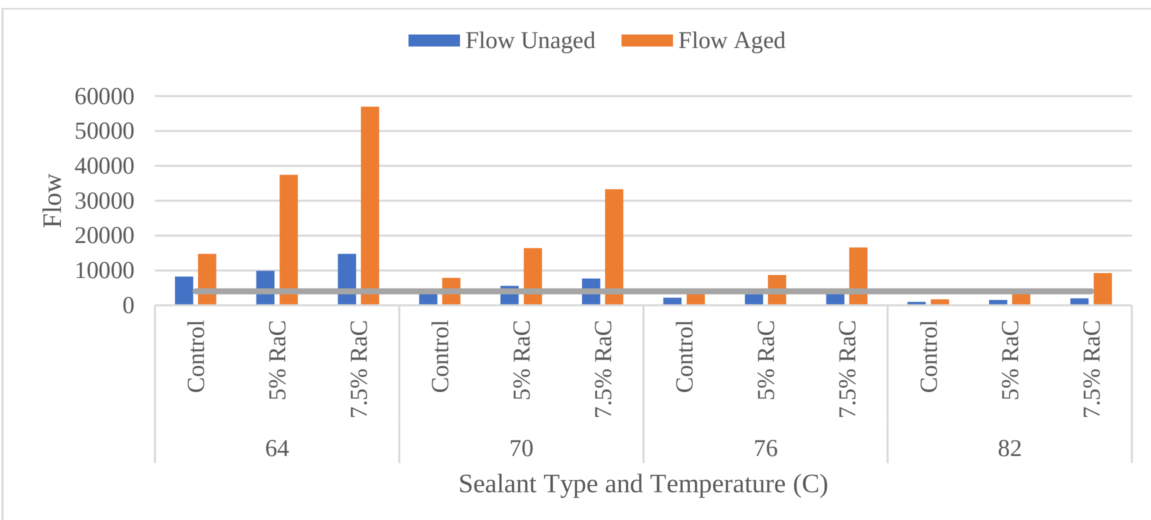


(b)

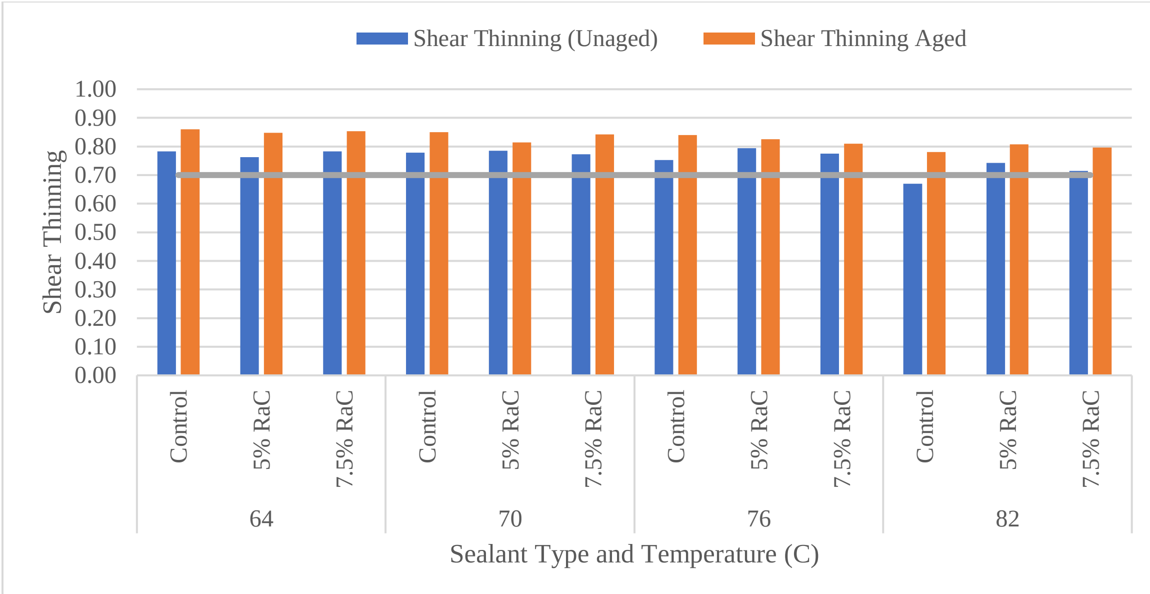
Figure 48- Rotational Viscosity Test Results for CS Using RaC: (a) Unaged Conditions and (b) Aged Conditions

7.2.3. Shear Thinning and Tracking Test Results

In terms of shear thinning, the 5%RaC modification shows improved behavior for temperatures higher than 70ºC under the unaged conditions. This refers to higher tracking resistance, by making the material less sticky. Furthermore, the flow parameter was also increased, making the material stiffer. The improved performance was noted for contents up to 5%, whereas the shear thinning behavior of the 7.5%RaC modified sealant was measured to be very comparable to the unmodified sealant. The results are shown in **Figure 49a** and **Figure 49b.**



(a)



(b)

Figure 49- Shear Thinning and Flow Results for CS Using RaC

The high temperature grades for the materials were also assessed from this test and are found in **Table 55**. A jump in temperature grade was only recorded at 7.5% RaC content.

Table 55- High Temperature Grade for CS Using RaC

Sealant Type	Sealant Grade (Unaged)	Sealant Grade (Aged)
Control	70	70
5% RaC	70	82
7.5% RaC	76	88

7.2.4. Bending Beam Rheometer Test Results

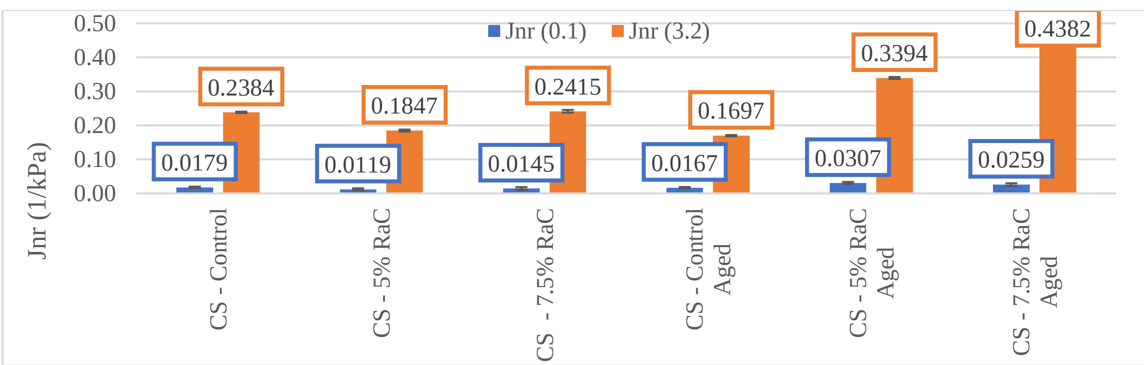
In terms of low temperature behavior, the addition of RaC up to 5% content tested at -40°C yielded comparable results at lower temperatures with no drastic effect at lower temperatures. The results (**Table 56**) showed promising results, as the addition of aerogel and rubber did not compromise the performance of the material at low temperatures.

Table 56- BBR Results for CS Using RaC

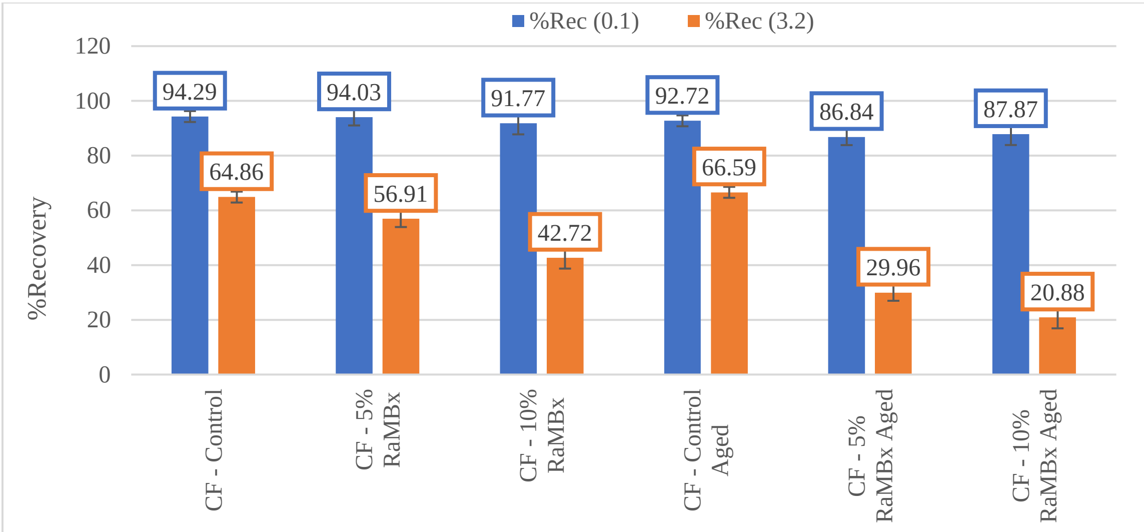
Sealant Type	Stiffness	m-value
CS - Control	39.53	0.43
CS - 5% RaC	35.3	0.39

7.2.5. Multiple Stress Creep and Recovery Test Results

With respect to the MSCR test results, the results showed improved performance for unaged 5%RaC samples. Alternatively, the 7.5%RaC content showed comparable performance to the control under unaged conditions. However, when the sealant was aged, the performance of the modified material decreased. This could be explained by the fact that the modifier size is large compared to the size of the tested sample which could alter the results obtained from the DSR as a larger portion of the tested sample is coming from the presence of the particle. In this case where RaC was originally pre-swelled with waste vegetable oil, its addition made the material more susceptible to permanent deformation for contents greater than 5%. It is important to note that the aged material was tested at higher temperatures compared to control, where Jnr and %Recovery naturally increase and decrease respectively as the material becomes softer.



(a)



(b)

Figure 50- MSCR Results for CS Using RaC: (a) Jnr and (b) %Recovery

7.2.6. Toughness and Tenacity Test Results

The toughness and tenacity results obtained in **Figure 51** for the RaC modified CS show a great decrease in both properties, hinting to the hardened behavior of the sealant due to the presence of both aerogel and crumb rubber at the same time. The presence of such modifier so far does not seem compatible with crack sealing, as both toughness and tenacity are crucial parameters to ensure the ability of the material to accommodate crack movements.

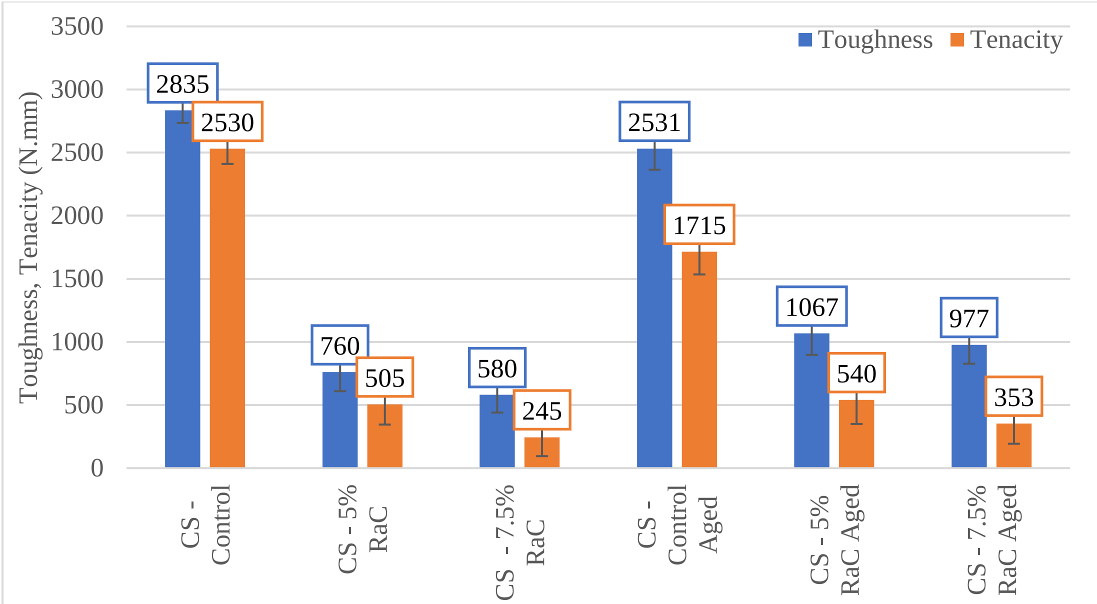


Figure 51- Toughness and Tenacity Results for CS Using RaC

7.2.7. Bond Strength Test Results

Alternatively, the consistency of the modified material yielded positive results with respect to bond strength, where an increase in both dry and wet pull-out strength was measured for both aged and unaged modified CS. Furthermore, an improved moisture susceptibility index was calculated for unaged conditions (**Table 57**). The failure modes were shown to be promising, where cohesive failures were observed during testing. Higher bond strength, cohesive failures and acceptable moisture susceptibility index were recorded. This could be attributed to the stiffer sealant, without compromising its adhesive properties so far.

Table 57- Bond Strength Results for CS Using RaC

Sealant Types	Dry Pull-Out Strength (kPa)	Failure Modes	Wet Pull-Out Strength (kPa)	Failure Modes	Pull-Off Strength Moisture-Susceptibility Index
CS - Control	668	Cohesive	565	Adhesive	-15%
CS - 5% RaC	1149	Cohesive	1069	Cohesive	-7%
CS - 7.5% RaC	1264	Adhesive	1149	Cohesive	-9%
CS - Control Aged	1011	Adhesive	919	Adhesive	-9%
CS - 5% RaC Aged	1344	Cohesive	1207	Cohesive	-10%
CS - 7.5% RaC Aged	1321	Cohesive	1034	Cohesive	-22%

7.2.8. Thermal Conductivity and Specific Heat Capacity Test Results

The thermal properties of the RaC modified CS are summarized in **Table 58**. In general, the addition of RaC slightly increased both thermal conductivity and specific heat capacity of CS. Lighter components within the binder typically exhibit lower thermal conductivity than heavier ones. During aging, lighter components with lower conductivity tend to volatilize and evaporate. This leaves behind a higher concentration of heavier components with higher thermal conductivity, contributing to the overall increase. Both crumb rubber and aerogel were notoriously known for decreasing the thermal conductivity of asphalt binder. The increase in thermal conductivity could be attributed to the presence of recycled oil, that could alter the thermal properties of the sealant. The measured increase is still considered to be minimal. On the other hand, the increase in specific heat capacity relates to more heat required to heat the sealant, making it less susceptible to softening.

Table 58- Thermal Conductivity and Specific Heat Capacity Results for CS Using RaC

Sealant Type	k (W/m.K)	C_p (J/kg.K)
CS - Control	0.110	1173
CS - 5% RaC	0.133	1374
CS - 7.5% RaC	0.129	1669
CS - Control Aged	0.107	1468
CS - 5% RaC Aged	0.146	1843
CS - 7.5% RaC Aged	0.139	2899

7.2.9. Linear Expansion and Contraction Test Results

A high coefficient means the sealant expands and contracts significantly with temperature changes, creating more stress on the sealant and increasing the risk of both cohesive and adhesive failures. A lower coefficient reflects less movement in response to temperature changes, minimizing stress on the sealant and promoting better adherence. This leads to a longer lifespan of the sealant and a better sealing against possible infiltration. The presence of RaC benefits the sealant by reducing the material’s ability to expand at high temperatures, improving its overall performance (**Table 59**).

Table 59- Linear Expansion and Contraction Results for CS Using Rac

Sealant Type	Expansion	Contraction	CTE /ºC
CS - Control	2.07E-05	2.31E-05	2.19E-05
CS - 5% RaC	1.22E-05	2.18E-05	1.70E-05

7.3. Recycled Aerogel Composite (RaC) Modification Test Results for Crack Filler (CF)

In general, the CS modified with RaC results were not promising. However, this may be due to the different composition of the material as well as the compatibility of the material with the modifier. It is worth testing the effect of RaC on CF, given the different composition of the sealing material. The same testing protocol was followed throughout this section.

7.3.1. Softening Point, Resilience and Cone Penetration Test Results

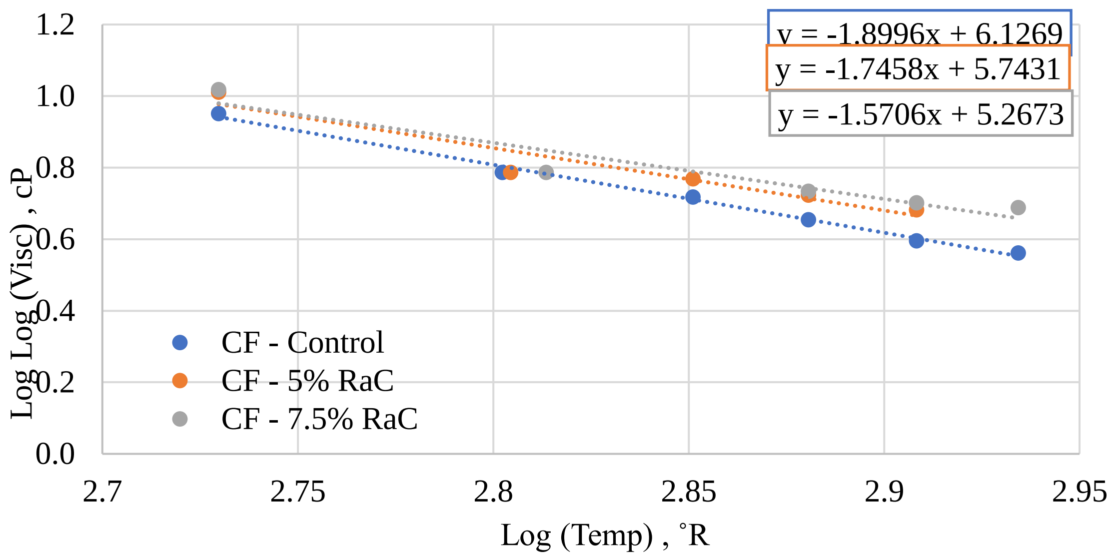
According to the results shown in **Table 60** below, the effect of RaC on CF was slightly different than on CS. In other words, the stiffening effect was not as drastic when compared to the control material. The resilience of the modified material was still considered to fall within the manufacturer’s limits. However, the cone penetration test results showed stiffer behavior.

Table 60- Softening Point, Resilience and Cone Penetration Results for CF Using RaC

Sealant Type	Softening Point (C)	Resilience (%)	Cone Penetration (1/10 mm)
CF - Control	79.25	45	38
CF - 5% RaC	81	27	10
CF - 7.5% RaC	88.5	30	9
CF - Control Aged	93	40	29
CF - 5% RaC Aged	94	30	11.67
CF - 7.5% RaC Aged	104.5	30	8.25

7.3.2. Rotational Viscosity Test Results

With respect to the rotational viscosity test results (**Figure 52**), the addition of RaC did in fact reduce the Ai and VTSi parameters of the material, resulting in a decrease in thermal susceptibility. This was attributed to the stiffer behavior as well as the aerogel's effect on the material. An average reduction in the slope was found to be around 9% for 5% RaC modification and around 15% for 7.5%RaC.



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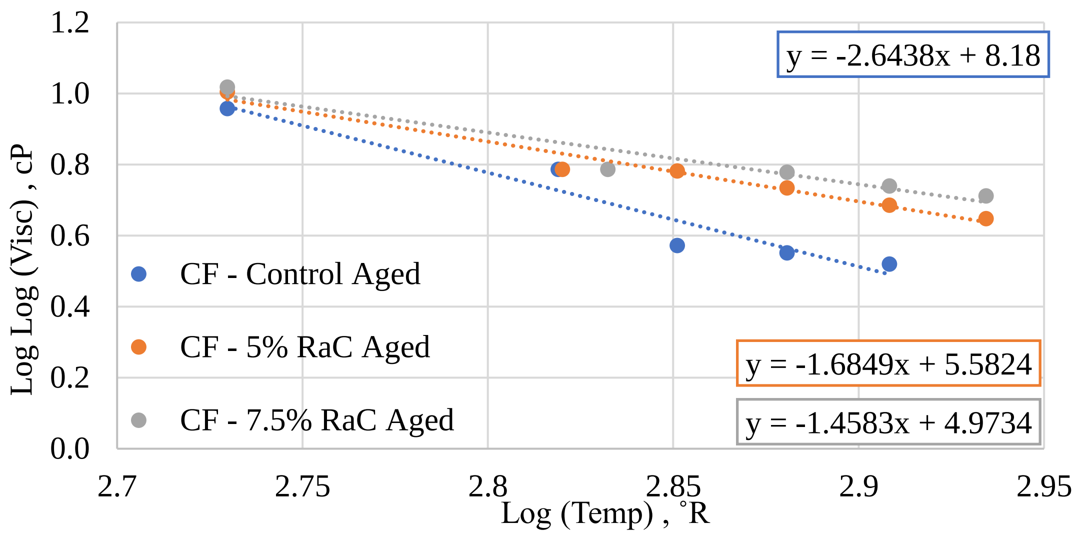
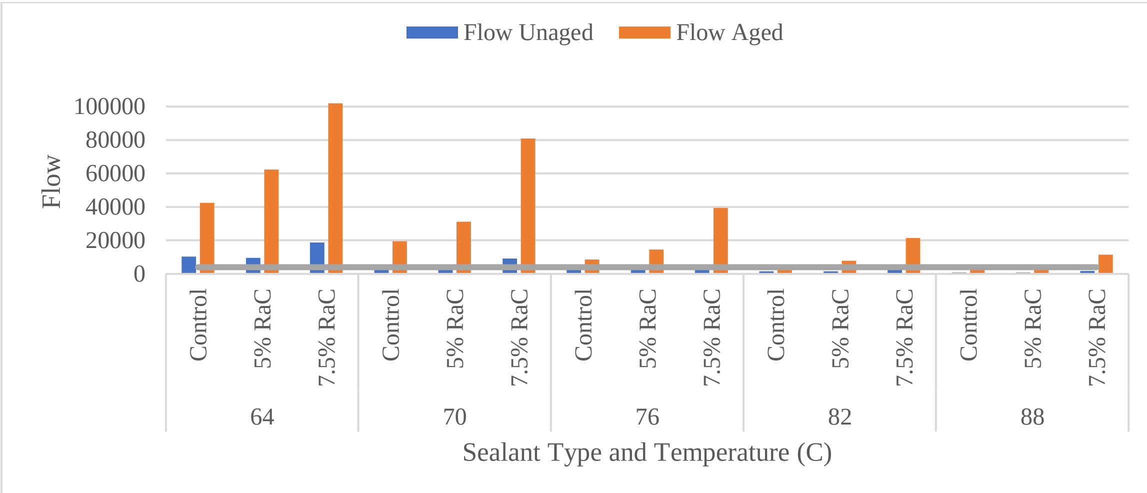


(b)

Figure 52- Rotational Viscosity Results for CF Using RaC for (a) Unaged Conditions and (b) Aged Conditions

7.3.3. Shear Thinning and Tracking Test Results

As can be seen from the results in **Figure 53**, the shear thinning resistance with RaC was improved under unaged conditions, in addition to the flow parameter. This test is important under unaged conditions as the sealant needs to fill the crack properly without being sticky to reduce tracking potential. The RaC promotes less sticky behavior according to the results, where higher C and P were measured for 5%RaC contents. This reflects on the optimum content of RaC using CF, which appears to be around 5%. The high temperature grade of the material was determined from this test as well (**Table 61**), where the 5%RaC has the same high temperature grade as the control material of 70°C. The 7.5%RaC showed a higher sealant grade of 76°C under unaged conditions. Under aged conditions, both 5% RaC and 7.5%RaC showed higher sealant grades of 88°C and 94°C respectively. This suggests that RaC caused the material to have a slightly higher SG when compared to RaMBx and EaMBx modifications under aged conditions, due to the additional presence of rubber in the particles.



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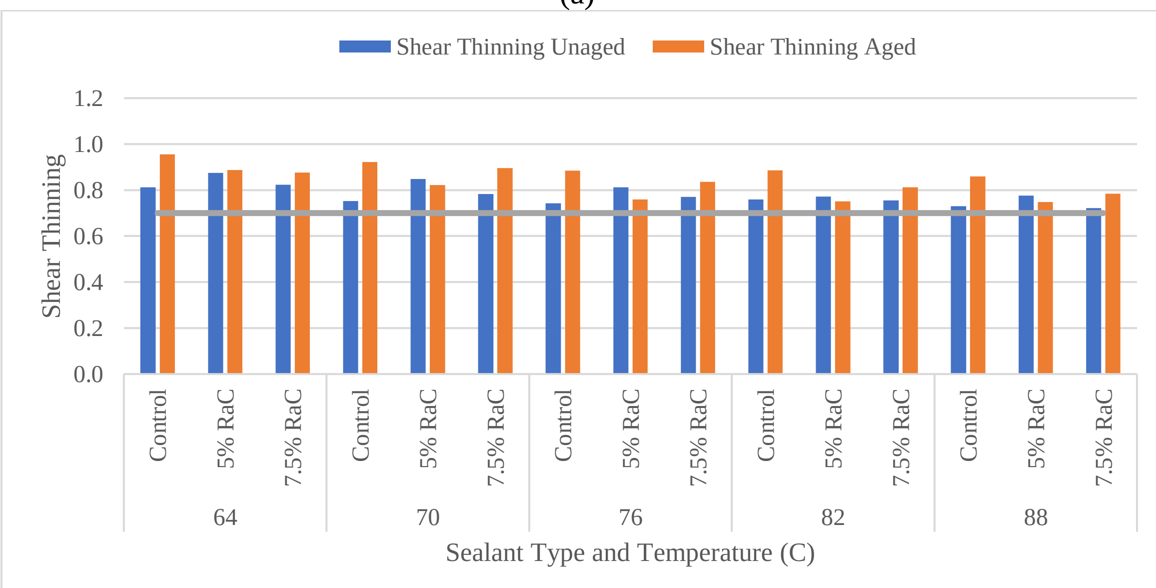


(b)

Figure 53- Shear Thinning and Tracking Results for CF Using RaC: (a) Flow and (b) Shear Thinning

Table 61- High Temperature Sealant Grade of CF Using RaC

Sealant Type	Sealant Grade (Unaged)	Sealant Grade (Aged)
Control	70	82
5% RaC	70	88
7.5% RaC	76	94

7.3.4. Bending Beam Rheometer Test Results

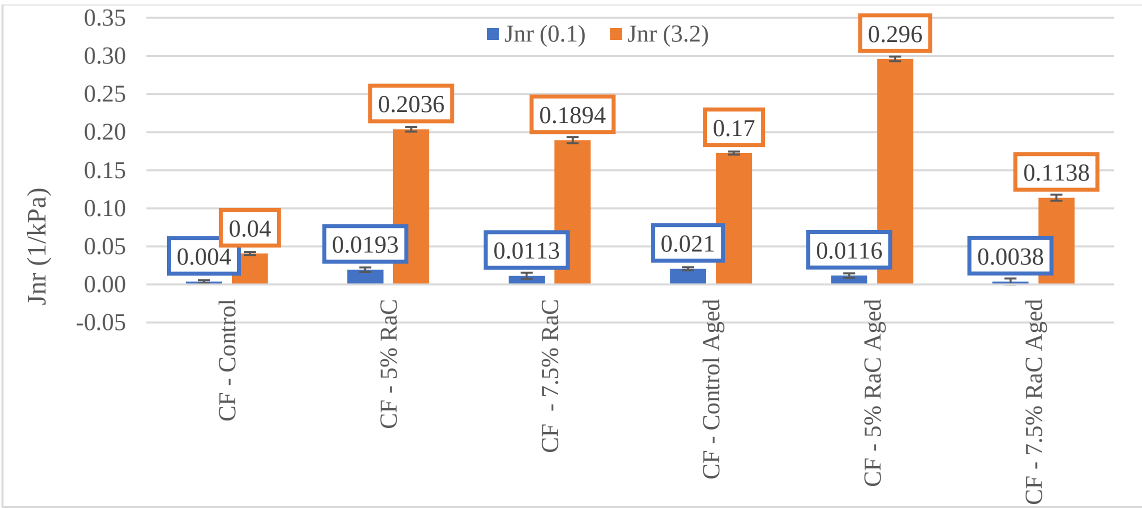
According to the CSBBR results obtained in **Table 62**, it can be seen that the CF material showed comparable results to the control material at lower temperatures. With a low temperature grade of -10^{o}C, RaC did not affect the low temperature behavior of the material negatively despite the increased stiffness of the material. The relaxation ability of CF was preserved at both temperatures, with a slight increase in stiffness at -16^{o}C. Furthermore, the material's susceptibility to cracking was reduced with a decreasing ΔTc from 3 to 1. By comparing those results to the ones obtained for the EaMBx modification, it was noticed that the rubber did in fact compensate for the effect of aerogel at low temperatures, where CF 2.5%EaMBx showed a higher ΔTc of 5 for the same temperatures.

Table 62- Bending Beam Rheometer Results for CF Using RaC

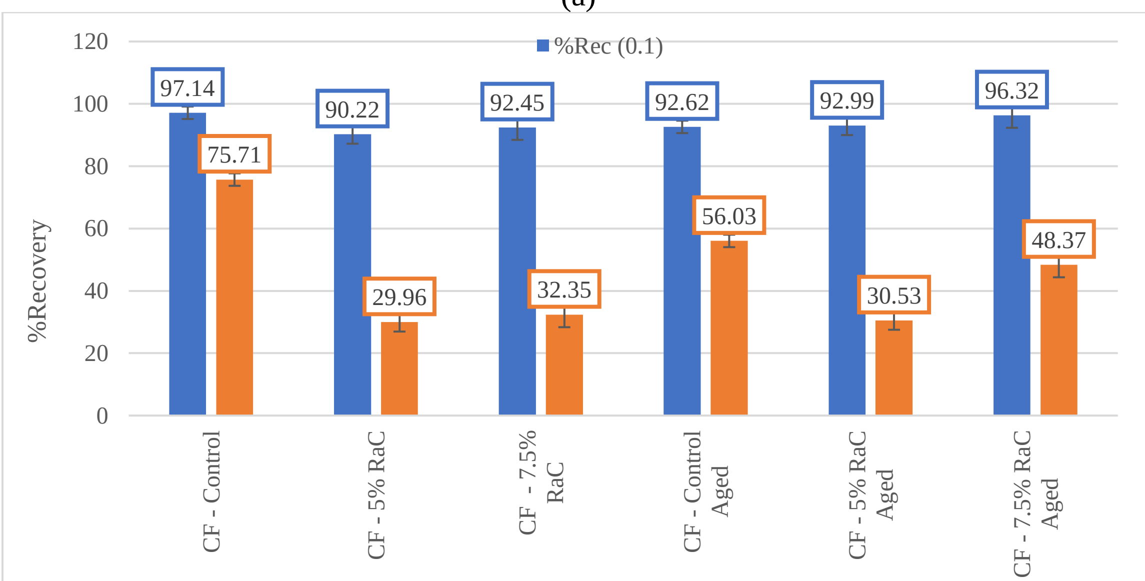
	Temperature (^{o}C)						
	-10		-16				
Sealant Type	**Stiffness**	**m value**	**Stiffness**	**m value**	**Tc,s**	**Tc,m**	**ΔTc**
CF - Control	247.172	0.3865	638.521	0.276	-21	-25	3
CF - 5% RaC	184.624	0.349	734.721	0.252	-22	-23	1

7.3.5. Multiple Stress Creep and Recovery Test Results

The results of the MSCR Test for the RaC modified material did not show promising performance due to the fact that the presence of those particles under the DSR impact negatively the results. In general, the addition of rubber should improve the elasticity of the material, which is not reflected in the results shown in **Figure 54**. As larger particles are present within the tested sample, less sealing material is available to be assessed. For this reason, the MSCR test was not considered to be representative of the performance of RaC on either sealing material, CF or CS. As for the stress sensitivity, the modification did impact the %JnrSlope and lead to its increase with the addition of RaC, as this parameter depends on the measured Jnr values.



(a)



(b)

Figure 54- MSCR Results for CF Using RaC: (a) Jnr and (b)%Recovery.

7.3.6. Toughness and Tenacity Test Results

The results of toughness and tenacity shown in **Figure 55** do not seem to align with the expected trends when adding rubber to sealing material. Both characteristics decreased with the addition of RaC, indicating that the material is stiffer at room temperature compared to the control CF. The results were more promising than the ones obtained for CS, showing that RaC may be more compatible with CF than CS.

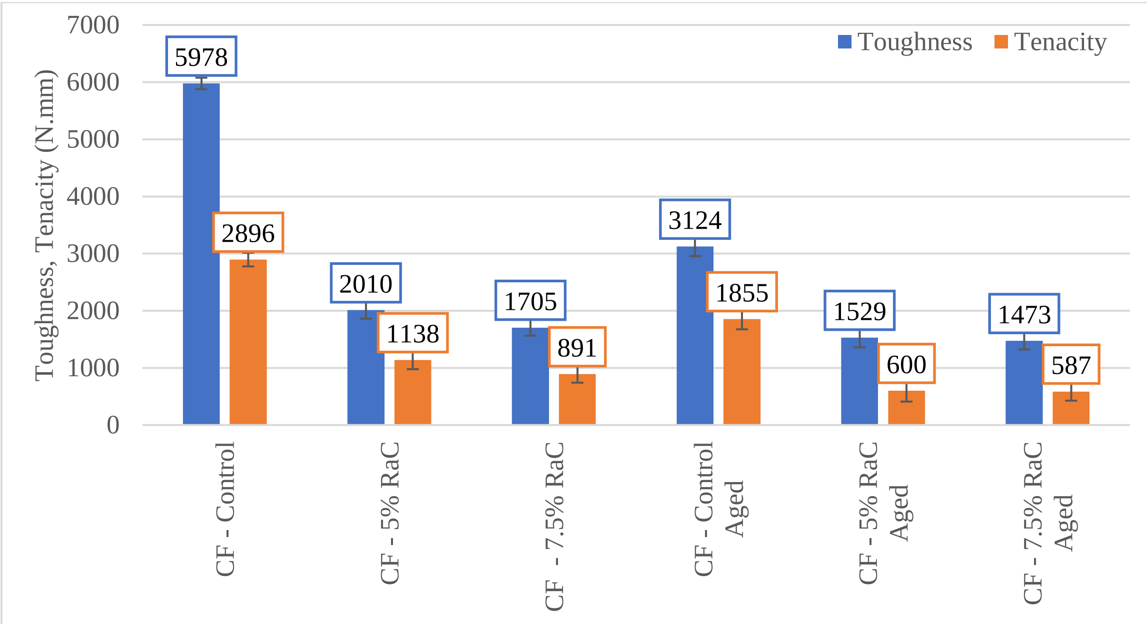


Figure 55- Toughness and Tenacity Results for CF Using RaC

7.3.7. Bond Strength Test Results

Despite the addition to the modifier which allows less surface area to adhere to the substrate, the results of the bond strength were comparable results to control, and an improvement in terms of moisture susceptibility with contents up to 5%. The results showed improvement compared to EaMBx modification bond results, as well as RaMBx. Furthermore, the bond strength results showed an increase in pull-out strength compared to all modifiers so far under both dry and wet conditions.

Table 63- Bond Strength Results for CF Using RaC

Sealant Types	Dry Pull-Out Strength (kPa)	Failure Modes	Wet Pull-Out Strength (kPa)	Failure Modes	Pull-Off Strength Moisture-Susceptibility Index
CF - Control	2305	Cohesive	2107	Adhesive	-9%
CF - 5% RaC	2172	Cohesive	2041	Cohesive	-6%
CF - 7.5% RaC	2140	Adhesive	2068	Cohesive	-3%
CF - Control Aged	2337	Adhesive	1620	Adhesive	-31%
CF - 5% RaC Aged	2068	Cohesive	1958	Adhesive	-5%
CF - 7.5% RaC Aged	1804	Adhesive	1292	Adhesive	-28%

7.3.8. Thermal Conductivity and Specific Heat Capacity Test Results

In general, the addition of crumb rubber will reduce the thermal conductivity of bituminous materials, given their lower thermal conductivity properties. Furthermore, the addition of insulating aerogel will also result in a reduction in thermal conductivity of the modified material. The results shown in **Table 64** prove such trends, with lower measured thermal conductivity across all tested contents, for both aging conditions. Furthermore, the specific heat capacity of the modified material increased, leading to needing more energy to heat up the material, making it less susceptible to temperature change.

Table 64- Thermal Conductivity and Specific Heat Capacity Results for CF Using RaC

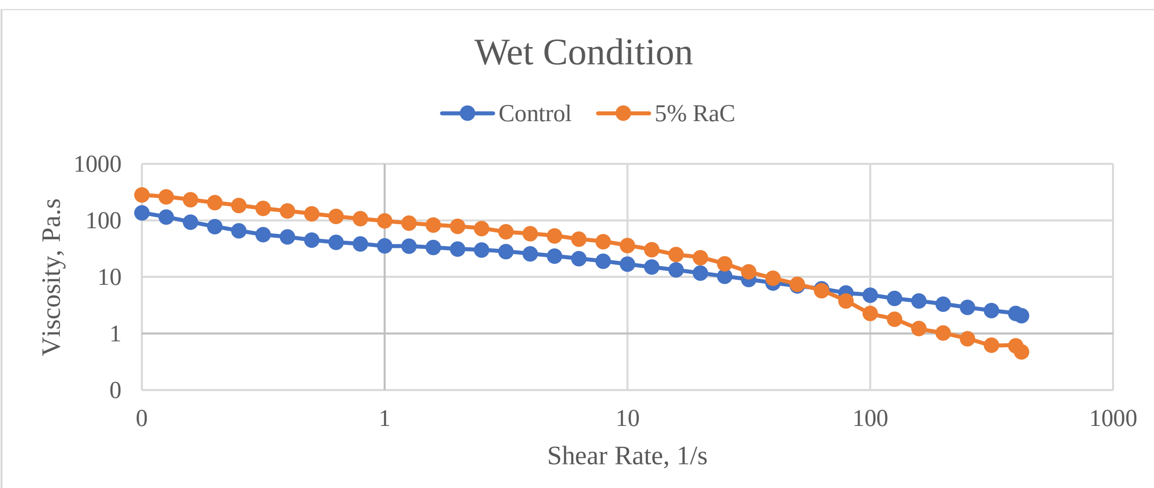
Sealant Type	k (W/m·K)	C_p (J/kg·K)
CF - Control	0.22	1059
CF - 5% RaC	0.208	1190
CF - 7.5% RaC	0.189	1669
CF - Control Aged	0.19	1433
CF - 5% RaC Aged	0.173	1455
CF - 7.5% RaC Aged	0.183	1873

7.3.9. Linear Expansion and Contraction Test Results

The RaC modified CF yielded lower CTE compared to control, equivalent to 2.53E-05. The addition of RaC yielded a lower CTE due to the presence of both aerogel and crumb rubber, leading to a potential better performance in the field. Observing the results from the thermal behavior, the addition of RaC did impact positively the behavior of the sealant by reducing its thermal susceptibility.

7.3.10. MISTI Test Results

As the modified material was found to be stiffer, achieving the same initial viscosity was out of the DSR's temperature testing capabilities. However, it can be seen from the **Figure 56a** that the modification under wet and dry conditions yielded to a slight reduction in shear thinning resistance. The onset of shear thinning occurred slightly sooner for the 5% RaC modified CF. The MISTI test results (**Table 65**) showed comparable results compared to control, given the nature of the material and the difficulties in achieving a zero-shear viscosity with a linear behavior.



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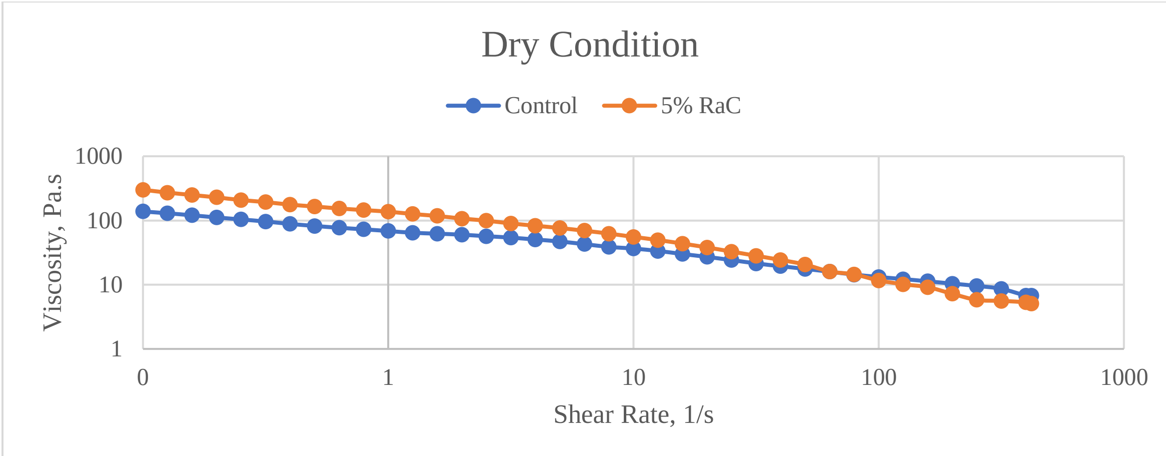


(b)

Figure 56- MISTI Test Results for CF Using RaC: (a) Wet Conditions and (b) Dry Conditions

Table 65- MISTI Coefficient Results for CF Using RaC

Sample	Wet	Dry	MISTI	Variation from 1
CF - Control	0.554	0.435	1.272	27%
CF - 5% RaC	0.941	0.743	1.266	27%

7.4. Recycled Aerogel Composite (RaC) Modification assessment, conclusions, and summary

In this chapter, both CF and CS were modified using RaC, a composite product including both aerogel and pre-swelled crumb rubber. The crumb rubber was pre-swelled to avoid the absorption of the lighter fractions of the asphalt. The performance of the RaC modified materials differed as the two sealing materials have different compositions.

The effectiveness of RaC on CS wasn't very positive, as the addition of RaC stiffened the material leading in decreased performance in terms of toughness and tenacity, MSCR, and moisture susceptibility. The flexibility of the CS was compromised, which may lead to decreased performance in the field in terms of adhesion properties and durability. The sealant may not accommodate the crack's excessive movement. However, the material was shown to have decreased thermal susceptibility and better tensile strength under both wet and dry conditions leading. Furthermore, the coefficient of thermal expansion CTE decreased, leading to lower chances of cracking. As CS has a different formulation compared to CF including polyurethane and rubberized asphalt, adding additional rubber affected its consistency and decreased its flexibility. The discussed improved parameters were observed for contents up to 5%, which suggests that in areas where moisture and high temperature climates are of concerns, the addition of RaC could be an option to improve the material's performance.

Concerning CF, as this material contains no or very low rubber content, the addition of RaC improved its performance in terms of bond strength (with cohesive failures), low temperature cracking, thermal susceptibility as well as shear thinning and tracking resistance. The addition of rubber into the material helped in low temperature behavior, where the stiffness and m-value were measured at two different temperatures. The results showed improved cracking resistance with decreasing ΔT_c values. No effect was noticed with respect to moisture susceptibility. In terms of toughness and tenacity, those characteristics decreased but were still considered acceptable. The addition of rubber increased the stiffness of the material but did not jeopardize its flexibility in this case. The results observed from the MSCR were deemed inconclusive, as the presence of those particles was more prominent than the material itself under the DSR's plate. For contents up to 5% by weight of the material, it can be concluded that the CF had improved performance and flexibility while maintaining the insulating benefits of aerogel.

CHAPTER 8

8 CHARACTERIZATION AND ASSESSMENT OF PRE-ACTIVATED CRUMB RUBBER MODIFIED SEALANTS

8.1. Introduction

In this chapter, the addition of PCR for both sealing materials was investigated. PCR, which is derived from pre-activated crumb rubber, is believed to provide additional flexibility to the sealants and therefore improve their performance. Other important characteristics need to be evaluated following the same testing protocol suggested in the previous chapters to ensure that the major sealing properties were not compromised.

On the other hand, the addition of PCR into the material was done at high temperature, high mixing speed using a high shear mixer for 20 minutes as described in section 3.4.1.2 to allow homogeneous dispersion of the particles in the sealing material. For CS, the modification levels considered were 5% and 10% by weight of the material. As for CF, the modification levels were 2.5%, 5%, and 7.5% by weight of the material.

8.2. Pre-Activated Crumb Rubber (PCR) Modification Test Results for Crack Sealant (CS)

8.2.1. Softening Point, Resilience and Cone Penetration Test Results

The addition of PCR to CS increased the softening point temperature and decreased the cone penetration and resilience of the material, showing potential stiffer performance.

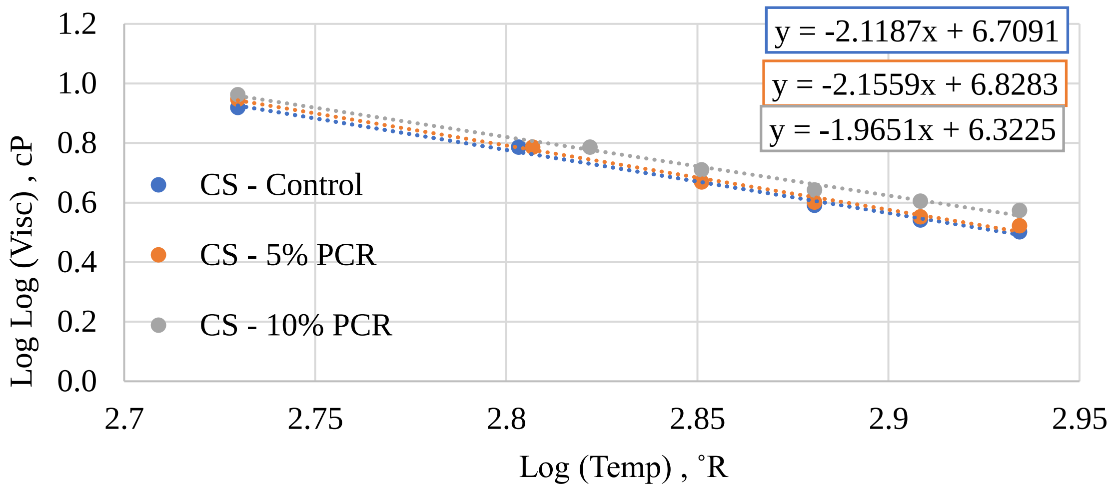
However, the interesting behavior occurs at the aging level, where the modified material's properties were preserved in terms of resilience and cone penetration, when compared to the aged control sealant. The 10% PCR modified material showed improved resilience behavior compared to control under aged conditions. As the sealant ages, the lighter weight fractions evaporate leaving the material stiffer. In the case of this modifier, a hypothesis where the rubber introduced into the material would absorb those lighter fractions from the sealant, contributing to its preserved performance under aged conditions.

Table 66- Softening Point, Resilience and Cone Penetration Results for CS Using PCR

Sealant Type	Softening Point (ºC)	Resilience (%)	Cone Penetration (1/10 mm)
CS - Control	80	94	72.67
CS - 5% PCR	83	70	41.33
CS - 10% PCR	95.5	71.5	30
CS - Control Aged	82	67.5	45
CS - 5% PCR Aged	88.5	68	57
CS - 10% PCR Aged	96	72	36.67

8.2.2. Rotational Viscosity Test Results

The rotational viscosity test results show that the 5%PCR content did not affect the viscosity of the material. However, the 10%PCR content does reflect a slight temperature susceptibility reduction with a decrease in both the VTSi and Ai parameters (**Figure 57a**). The behavior of the modified material under aged conditions reflects the same trend observed in the previous section, whereas the parameters of the aged, modified material were conserved, despite the aging mechanism occurring (**Figure 57b**).



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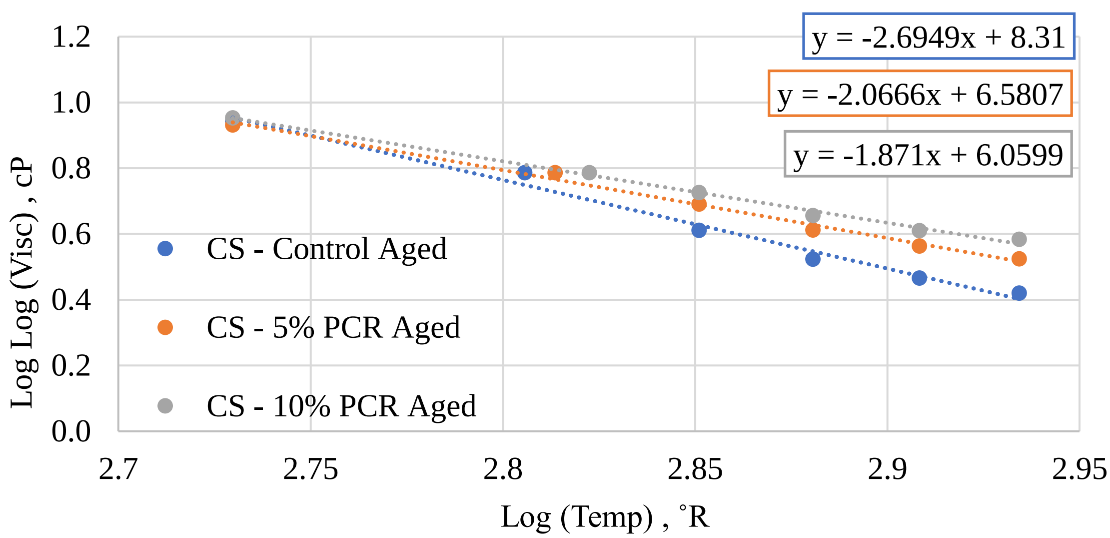


(b)

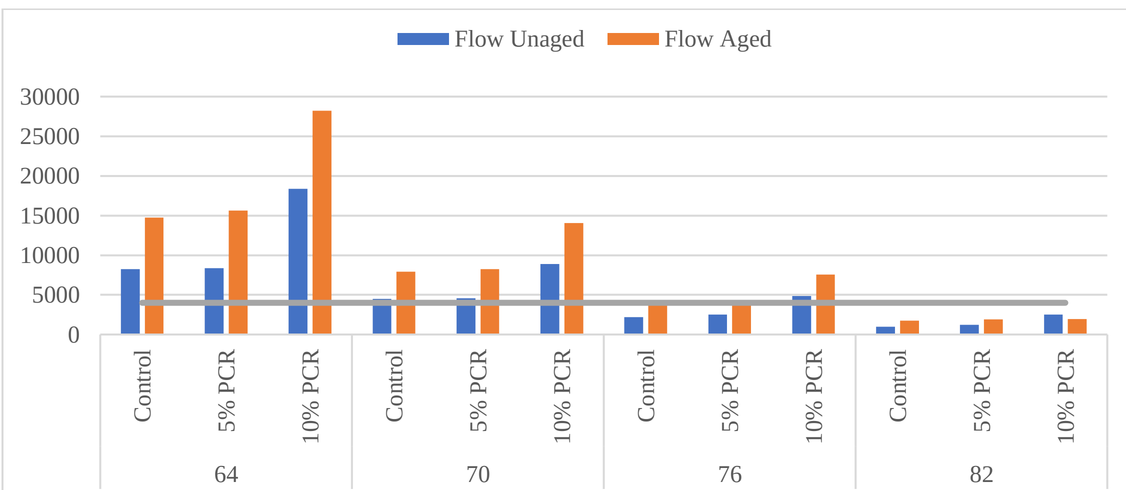
Figure 57- Rotational Viscosity Results for CS Using PCR: (a) Unaged Conditions and (b) Aged Conditions

8.2.3. Shear Thinning and Tracking Test Results

The results of the shear thinning and tracking show better performance in terms of tracking, with increasing P and C parameters with increasing PCR contents. In other words, when poured into the crack, the material would be less tacky and more resistant to tire passing. Furthermore, the setting time of the material would be reduced, allowing faster traffic activities. However, the adhesive properties will need to be evaluated as faster setting may cause the material to poorly adhere to the edges of the cracks. The high temperature grade of the material shown in **Table 67** show that 5%PCR content yielded the same high temperature grade as control. It can be clearly seen that the aged high temperature grade of the modified material did not increase as much as the aged control sample for both 5%PCR and 10%PCR, supporting the claim that aging was mitigated for the PCR modified materials given that the modified material underwent the same aging conditions.

Table 67- High Temperature Grade for CS Using PCR

Sealant Type	Sealant Grade (Unaged)	Sealant Grade (Aged)
Control	70	82
5% PCR	70	76
10% PCR	76	76



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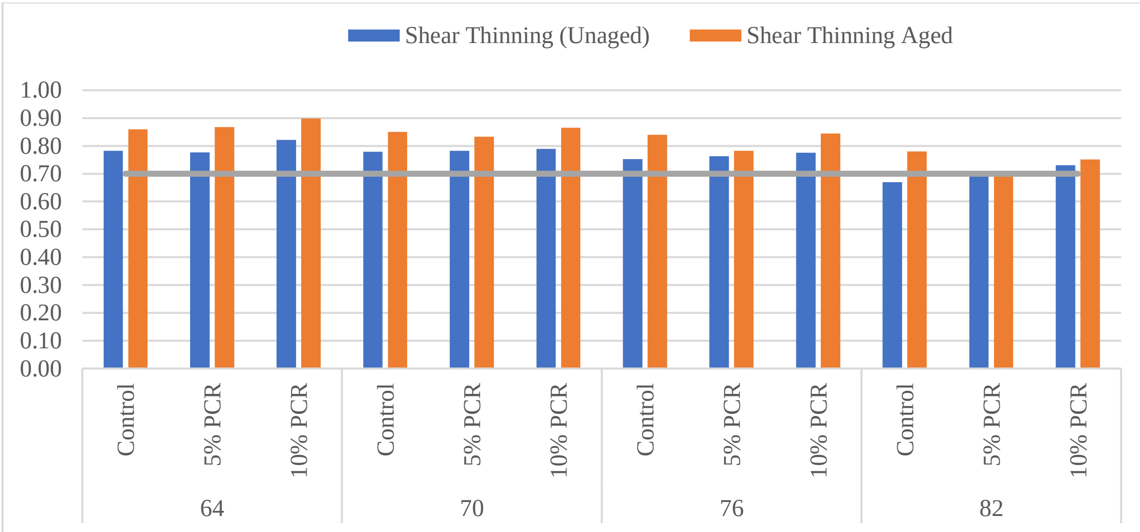


(b)

Figure 58- Shear Thinning and Tracking Results for CS Using PCR: (a) Flow Parameters and (b) Shear Thinning Parameter

8.2.4. Bending Beam Rheometer Test Results

The BBR test was conducted at a temperature as low as -40°C. The results in **Table 68** showed an increase in stiffness for the modified material under unaged conditions, and acceptable m-value. Under aging conditions, the modified materials had comparable stiffness to the unaged conditions. The results show flexibility at extreme low temperature with good relaxation ability under aged conditions for contents up to 5%PCR.

Table 68- Bending Beam Rheometer Results for CS Using PCR

Sealant Type	Stiffness, MPa	m-value
CS - Control	39.53	0.43
CS - 5% PCR	88.55	0.3
CS - 10% PCR	97.3	0.256
CS - Control Aged	57.10	0.36
CS - 5% PCR Aged	78.8	0.373
CS - 10% PCR Aged	82.5	0.123

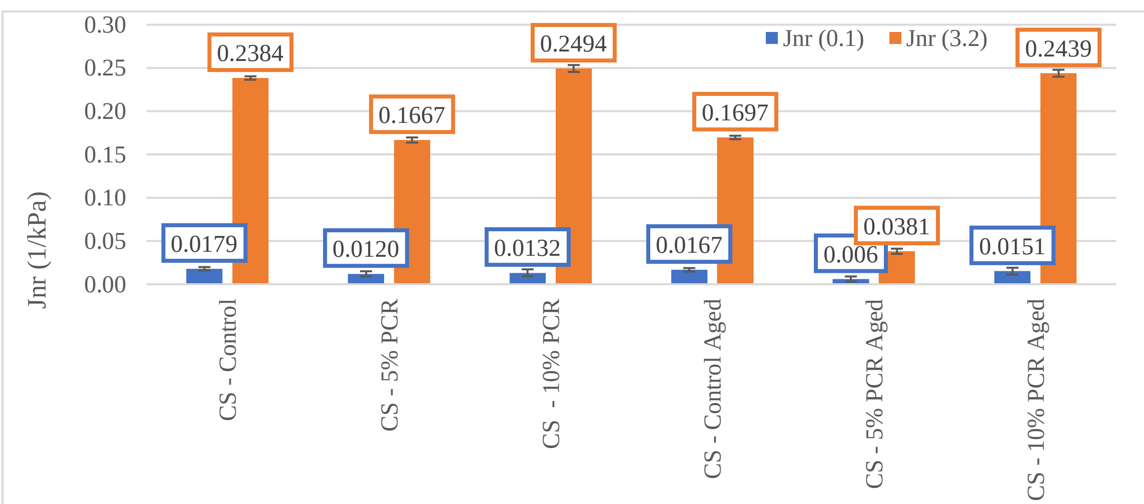
8.2.5. Multiple Stress Creep and Recovery Test Results

The MSCR test results reflected the increased elasticity provided by the addition of PCR into the sealing material, improving its Jnr values as well as recovery percentage for contents up to 5% by weight of the material. Based on the previous test results, the optimum content of PCR for CS could be between 5% and 10%. The %Recovery for the modified material showed impressive results, especially for the aged samples.

As for the stress sensitivity (**Table 69**) of the modified material, the %JnrSlope performed very well, where it decreased for 5%PCR under both unaged and aged conditions.

Table 69-%JnrSlope for CS Using PCR

Sealant Type	%JnrSlope	Acceptable Level of Elastomeric Polymer at 3.2 kPa
CS - Control	7.11	Yes
CS - 5% PCR	4.99	Yes
CS - 10% PCR	7.62	Yes
CS - Control Aged	4.94	Yes
CS - 5% PCR Aged	1.04	Yes
CS - 10% PCR Aged	7.38	Yes



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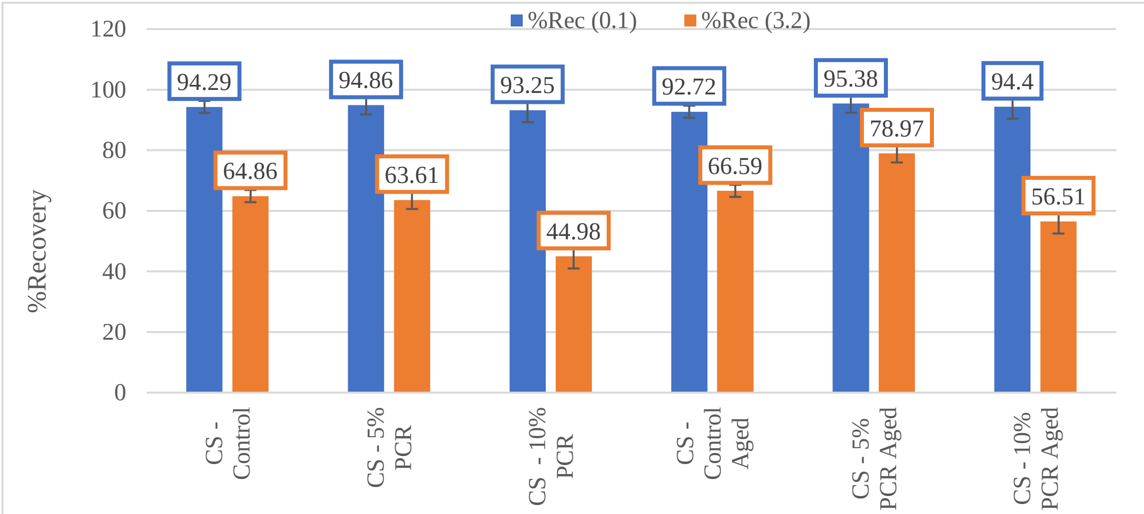


(b)

Figure 59- MSCR Results for CS Using PCR: (a) Jnr and (b) %Recovery.

8.2.6. Toughness and Tenacity Test Results

The toughness and tenacity of the modified material yielded promising results, especially under aged conditions with an increased tenacity and comparable toughness values to control. Compared to the other modifiers, the tenacity of the PCR modified CS scores the highest under aged conditions so far. Furthermore, toughness values were considered to be acceptable. The improved performance in this case lies in the improved tenacity of the material, leading to a better ability to withstand crack movements in the field.

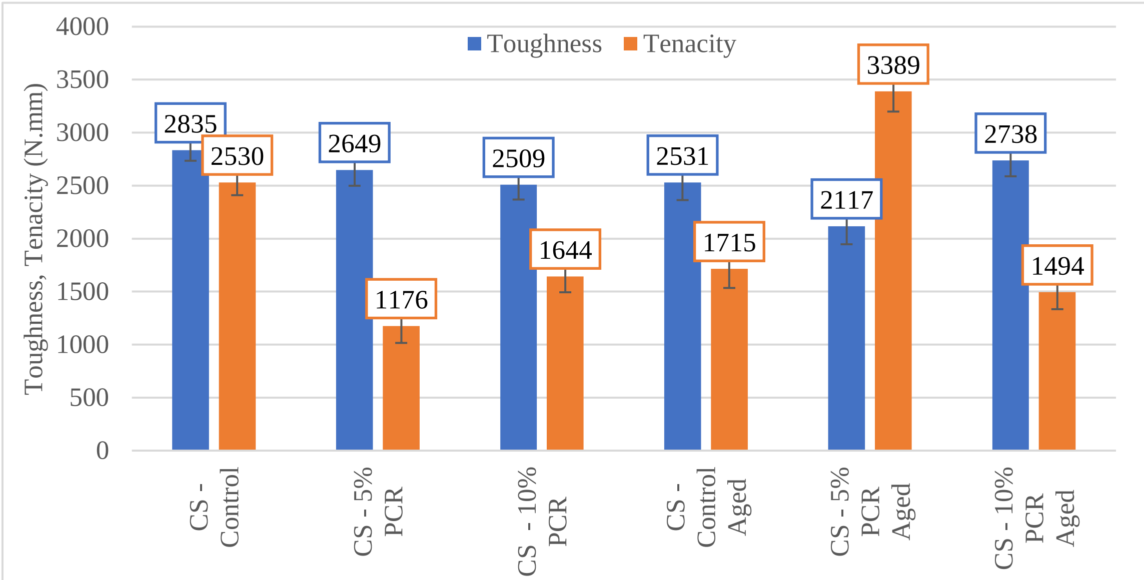


Figure 60- Toughness and Tenacity Results for CS Using PCR

8.2.7. Bond Strength Test Results

The results from the bond strength showed a higher tensile strength, or pull-out strength of the material from the pavement substate (**Table 70**). However, the presence of the rubber affected the nature of the failure mode, from cohesive to adhesive failures. Nonetheless, the addition of PCR doesn't seem to negatively affect the tensile strength of the material with the presence of moisture. When compared to control, the moisture susceptibility index measured was way lower, indicating that PCR somehow maintained the same strength under both dry and wet conditions.

Table 70- Bond Strength Results for CS Using PCR

Sealant Types	Dry Pull-Out Strength (kPa)	Failure Modes	Wet Pull-Out Strength (kPa)	Failure Modes	Pull-Off Strength Moisture-Susceptibility Index
CS - Control	668	Cohesive	565	Adhesive	-15%
CS - 5% PCR	1003	Adhesive	1174	Adhesive	17%
CS - 10% PCR	957	Adhesive	996	Adhesive	4%
CS - Control Aged	1011	Adhesive	919	Adhesive	-9%
CS - 5% PCR Aged	1023	Adhesive	1034	Adhesive	1%
CS - 10% PCR Aged	1007	Adhesive	1021	Adhesive	1%

8.2.8. Thermal Conductivity and Specific Heat Capacity Test Results

The thermal properties of the modified material naturally decrease with the addition of PCR, as crumb rubber has a slightly lower thermal conductivity when compared to bituminous materials (**Table 71**). As for the specific heat capacity, the presence of the modifier showed increased specific heat capacity against the expected trend. This may be due to the slightly stiffer behavior of the modified material as seen in the softening point results, needing higher temperatures to soften.

Table 71- Thermal Conductivity and Specific Heat Capacity of CS Using PCR

Sealant Type	k (W/m·K)	C_p (J/Kg·K)
CS - Control	0.11	1173
CS - 5% PCR	0.107	1608
CS - 10% PCR	0.096	2323
CS - Control Aged	0.107	1468
CS - 5% PCR Aged	0.101	1683
CS - 10% PCR Aged	0.112	2384

8.2.9. Linear Expansion and Contraction Test Results

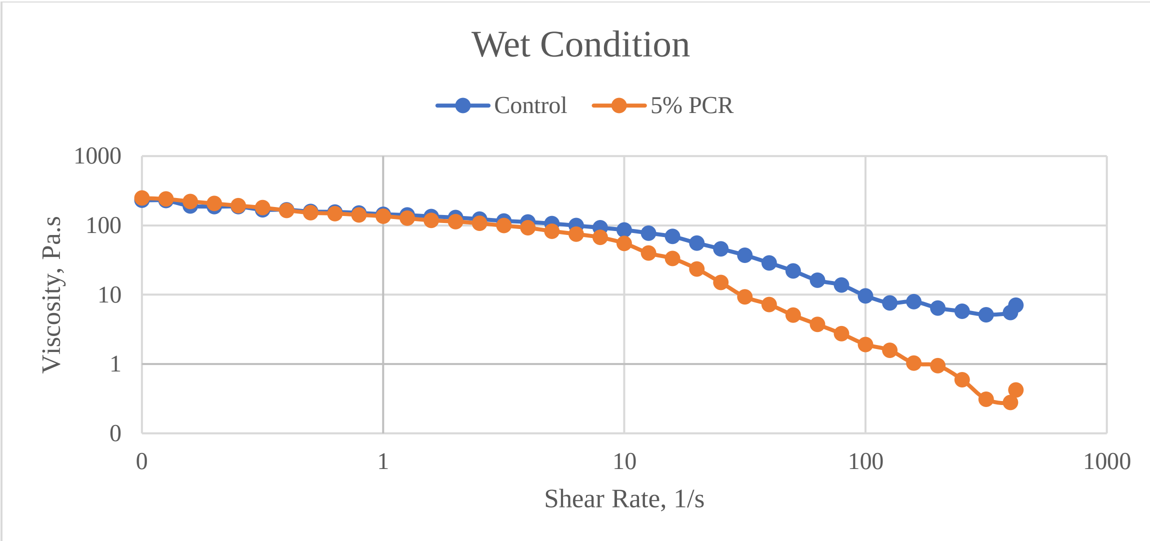
The addition of PCR into the sealant improved its expansion and contraction coefficient (**Table 72**), leading to better cracking resistance and better crack movement adaptation. A lower coefficient translates to less cracking and improved pavement durability, especially in colder climates. Both expansion and contraction coefficients were reduced when compared to control, leading to better performance at high temperatures, meaning the material will not expand and flow out of the crack as well as low temperature contraction, leading to better behavior in the crack.

Table 72- Linear Expansion and Contraction Coefficient for CS Using PCR

Sealant Type	Expansion	Contraction	CTE /C
CS - Control	2.07E-05	2.31E-05	2.19E-05
CS - 10% PCR	1.75E-05	1.99E-05	1.87E-05

8.2.10. MISTI Test Results

One drawback of rubber relates to increased moisture susceptibility, where water absorption in the crumb rubber can lead to swelling and internal stresses within the material. The results of the MISTI testing do reflect this disadvantage with a faster shear thinning behavior, and higher MISTI coefficient for wet conditions when compared to the control material (**Figure 61**a). For dry conditions, the modified material had a better resistance to shear thinning than control. Overall, the MISTI coefficient for 10%PCR content was found to be 1.657 (**Table 73**) indicating a higher moisture susceptibility.



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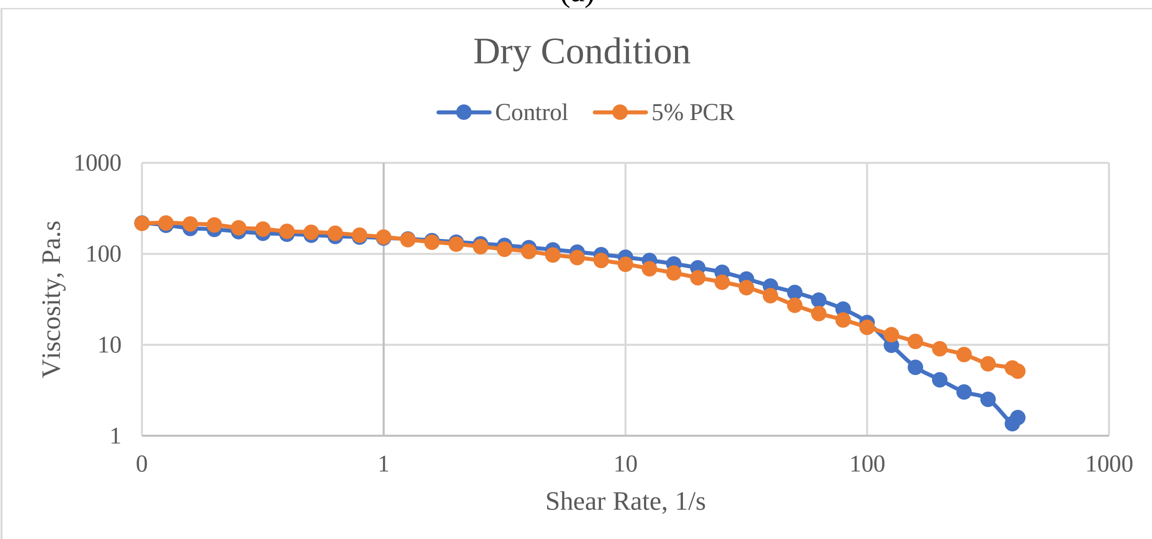


(b)

Figure 61- MISTI Testing for CS Using PCR for (a) Wet Conditions and (b) Dry Conditions

Table 73- MISTI Coefficients for CS Using PCR

Sample	Wet	Dry	MISTI
CS - Control	1.86	1.714	1.085
CS - 5% PCR	1.2	0.724	1.657

8.3. Pre-Activated Crumb Rubber (PCR) Modification Test Results for Crack Filler (CF)

8.3.1. Softening Point, Resilience and Cone Penetration Test Results

The results for those tests shown in **Table 74** show comparable resilience and cone penetration for all modification levels compared to the control material. Furthermore, under aged conditions, the results remained comparable to the unaged conditions with a slight increase in the softening point. Overall, the addition of PCR slightly stiffened the material without compromising its effectiveness. It can also be seen that the properties were conserved with aging due to the presence of PCR in the material.

Table 74- Softening Point, Resilience and Cone Penetration Results for CF Using PCR

Sealant Type	Softening Point (ºC)	Resilience (%)	Cone Penetration (1/10 mm)
CF - Control	79.25	45	38
CF - 2.5% PCR	87	41	33
CF - 5% PCR	91	37	29
CF - 7.5% PCR	95	32	28
CF - Control Aged	93	40	29
CF - 2.5% PCR Aged	92.5	42	30
CF - 5% PCR Aged	94	36	28
CF - 7.5% PCR Aged	96	33	26

8.3.2. Rotational Viscosity Test Results

The rotational viscosity test results show a slight variation in Ai and VTSi with the addition of PCR. The results are very comparable to the control material. The results show increased slope and intercept measurements. The full thermal behavior needs to be evaluated following the remaining testing procedure. So far, the results show approximately the same expected performance for the modified sealant as the control material.

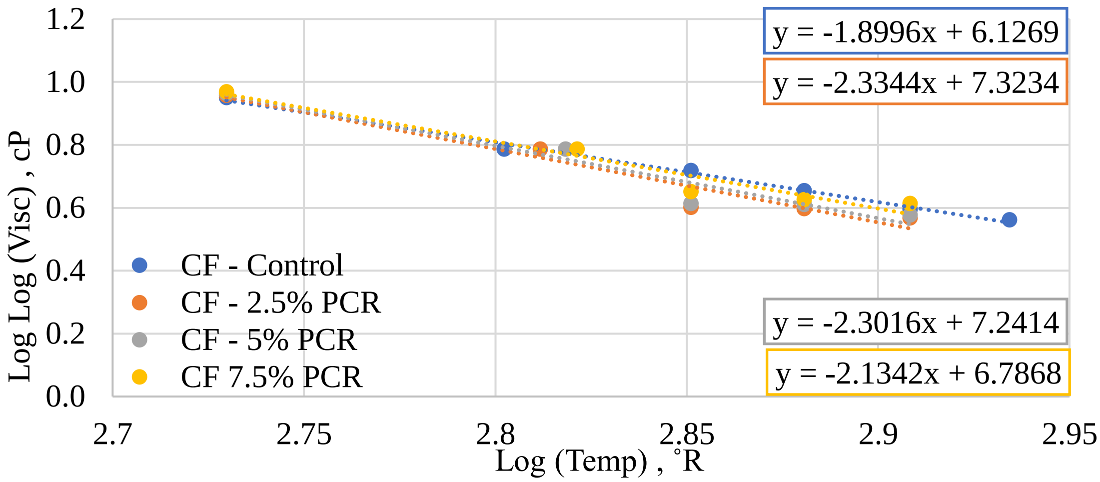
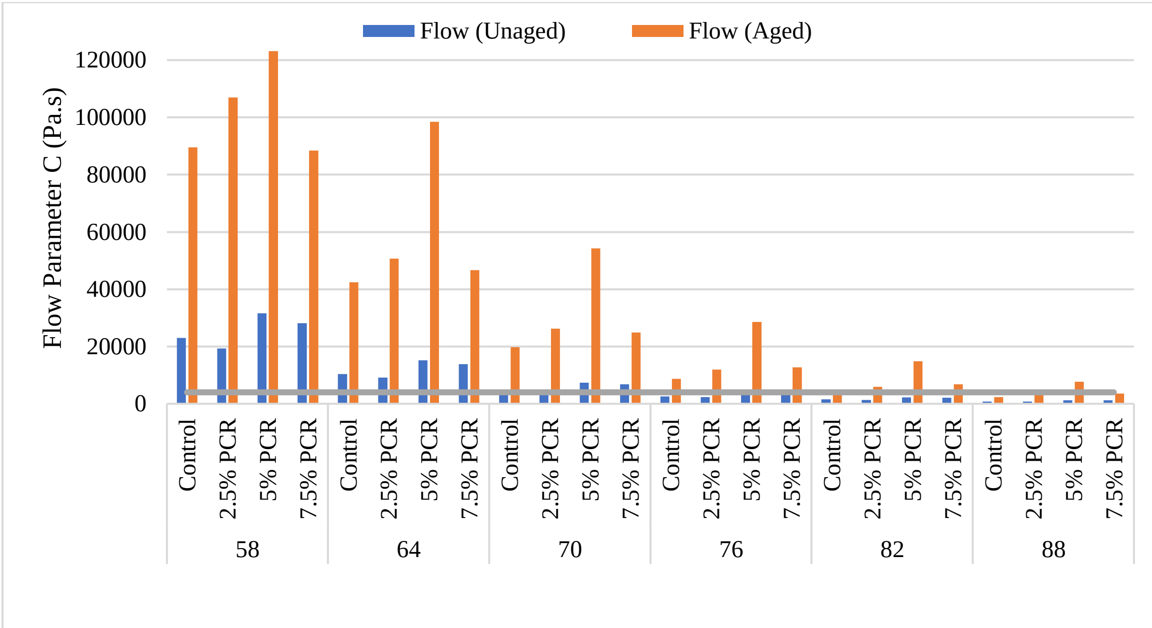


Figure 62- Rotational Viscosity Results for CF Using PCR

8.3.3. Shear Thinning and Tracking Test Results

The shear thinning and tracking resistance were evaluated for unaged and aged sealants respectively and shown in **Figure 63a** and **Figure 63b.** Based on the results, the flow parameter, which is proportional to the viscosity at each test temperature increased for PCR content up to 5%. As for the shear thinning, it has greatly improved for all contents when compared to the control sealant. This means that the modified sealant has better stability at high temperature and greater tracking resistance to the passing of car tires. It was also noted that the PG grade of the modified sealants changed, based on the criterion mentioned previously. The closer the shear thinning value, the better: P>0.7 and C>4000. The control sealant was tested to have a high temperature grade of 70°C, and a high temperature grade of 82°C when aged. For the modified sealants, the new high temperature grades are shown in **Table 75**. As the performance grade is only attributed at increments of 6^{o}C, the true temperature at which the criteria failed was included to reflect the actual performance grade of the modified sealants.



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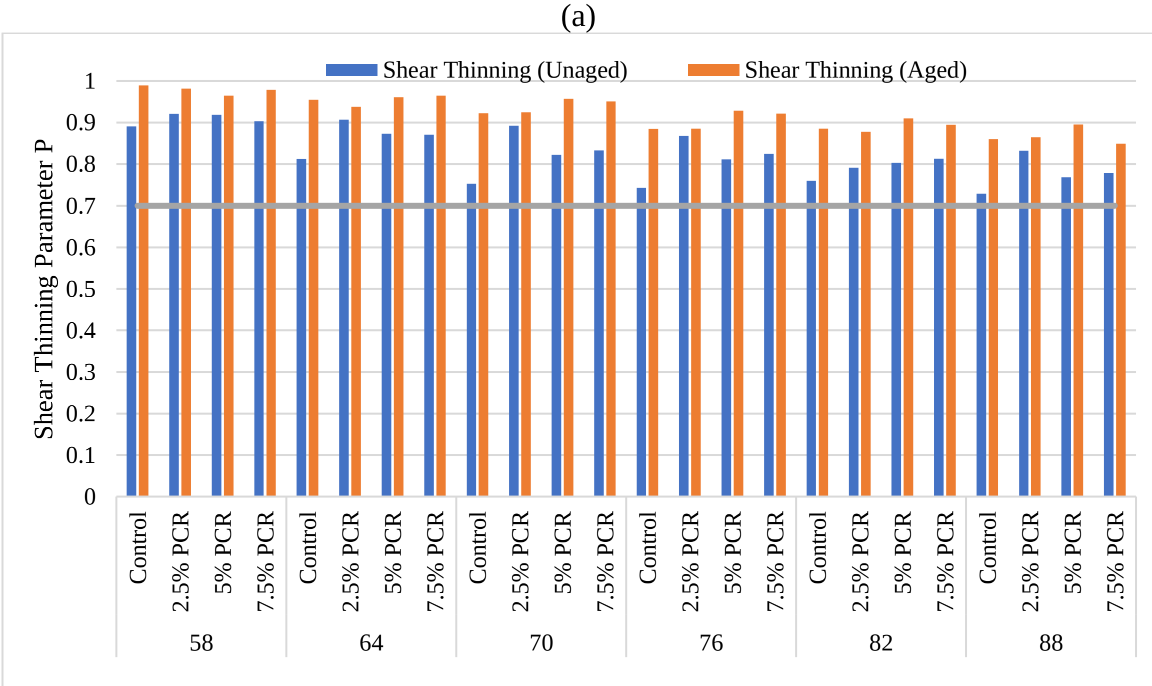


(b)

Figure 63- Shear Thinning and Tracking for CF Using PCR: (a) Flow and (b) Shear Thinning

Table 75- High Temperature Performance Grade for CF Using PCR

Sealant Type	High PG Temperature Unaged, (True Temperature)	High PG Temperature Aged, (True Temperature)
CF - Control	70 (70)	82 (83)
CF - 2.5% PCR	70 (70)	82 (86)
CF - 5% PCR	70 (75.8)	88
CF - 7.5% PCR	70 (74.9)	82 (87.4)

8.3.4. Bending Beam Rheometer Test Results

To evaluate the low temperature behavior of the material, unaged and aged sealants with PCR contents up to 7.5% were tested at -10°C. The results show an increase in stiffness with an increasing PCR content. Despite the increased stiffness, the measured m-values remained acceptable (greater than 0.3) for up to 5% PCR content for both aging conditions. Another trend was observed, whereas after short-term aging, the relaxation parameter for the modified sealant remained comparable to the aged control sample at test temperature: the ability of the material to relax at low temperatures was preserved. Aging can significantly impact the performance of the asphalt-based materials, leading to stiffer behavior, reduced relaxation capability, and increased cracking potential. Furthermore, a slower relaxation (lower m-value) will cause the material to build up internal stresses quickly and accelerate the occurrence of cracking after the internal stresses exceed the tensile strength of the material. (Aldagari, 2021; Newcomb, 2021). Another testing temperature was considered, -20°C to evaluate the low temperature cracking of the material with the progress of aging by calculating the critical temperature ΔT_c. The results in **Table 76** show that for unaged conditions, up to 5% PCR contents, the sealants show low susceptibility to low temperature cracking as the ΔT_c are equal to -5. However, when aged, this property goes up to -12 for control, -10 for 2.5% PCR and -13 for both 5% and 7.5%

PCR contents. Those results show comparable behavior to the control sealant, showing a slight improvement for the modified material given the improved m-values.

Table 76- BBR Results for CF Using PCR

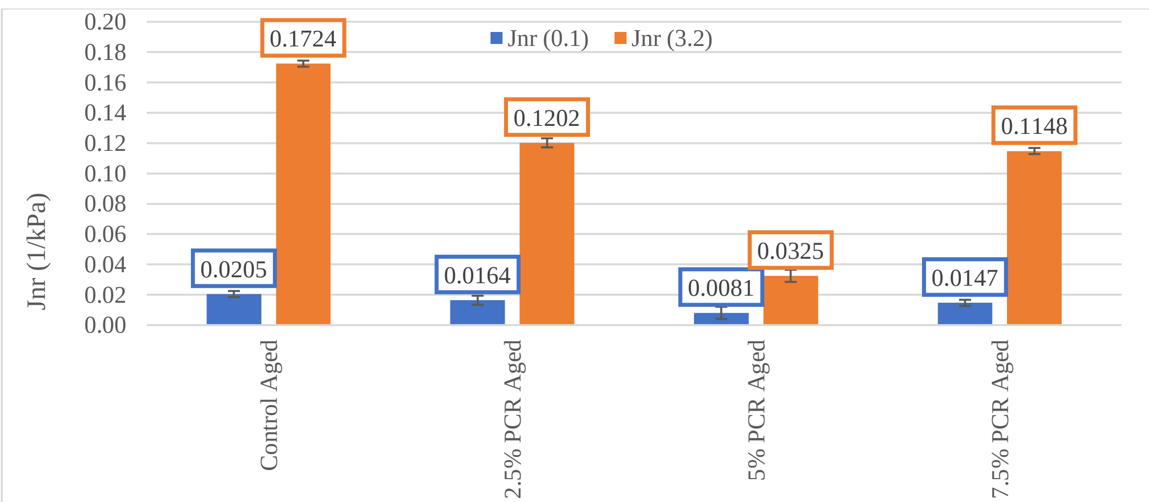
	Temperature (ºC)						
	-10		-20				
Sealant Type	**Stiffness**	**m value**	**Stiffness**	**m value**	**Tc,s**	**Tc,m**	**Tc**
CF - Control	58	0.37	185	0.28	-34	-28	-6
CF - 2.5% PCR	64	0.35	203	0.29	-33	-29	-5
CF - 5% PCR	71	0.37	228	0.27	-32	-27	-5
CF - 7.5% PCR	83	0.32	192	0.26	-35	-23	-13
CF - Control Aged	78	0.31	221	0.22	-33	-21	-12
CF - 2.5% PCR Aged	98	0.32	263	0.23	-31	-22	-10
CF - 5% PCR Aged	92	0.30	242	0.23	-32	-19	-13
CF - 7.5% PCR Aged	124	0.29	274	0.22	-31	-18	-13

8.3.5. Multiple Stress Creep and Recovery Test Results

It can be seen from the results (**Figure 64)** that the PCR modified sealants had lower strain response and better recovery behavior than control sealant, especially considering that the samples tested are aged. The test was carried out at the high temperature grade of each sealant, which was determined from the shear thinning tests for all samples **(Table 75).**

The percent recovery in addition to the non-recoverable creep at 0.1 KPa and 3.2 KPa stress levels for the three sealants, are presented in **Figure 64a** and **Figure 64b**. The Jnr values decreased with the addition of PCR up to 5% content. This gives a further indication about the optimum PCR content that could be added to the sealants, whereas greater contents lead to inefficient and decreased performance (as seen for the 7.5% PCR content). In other words, a decreasing Jnr relates to a higher resistance to permanent deformation (Mehrnaz Mirsepahi, 2020). For the 0.1 kPa stress level, the recovery percentage for all modification levels remained the same, showing that the modification did not alter the behavior of the material in the Linear Viscoelastic range (LVE). In the non-linear viscoelastic range, which is simulated by the 3.2 kPa stress level, PCR modification yielded much better recovery, which improves the sealant resistance to cohesive failure for contents up to 5%. In terms of non-recoverable creep values, especially at the 3.2 kPa stress level, PCR modified sealants showed less non-recoverable strain values, which confirms the sealant's resistance to cohesive failure. Therefore, the addition of PCR up to 5% by weight improved both the Jnr and Recovery of the material.

With respect to stress sensitivity, the PCR modified CF showed less stress sensitivity by reflecting lower %JnrSlope values (**Table 77**), translating into promising performance.



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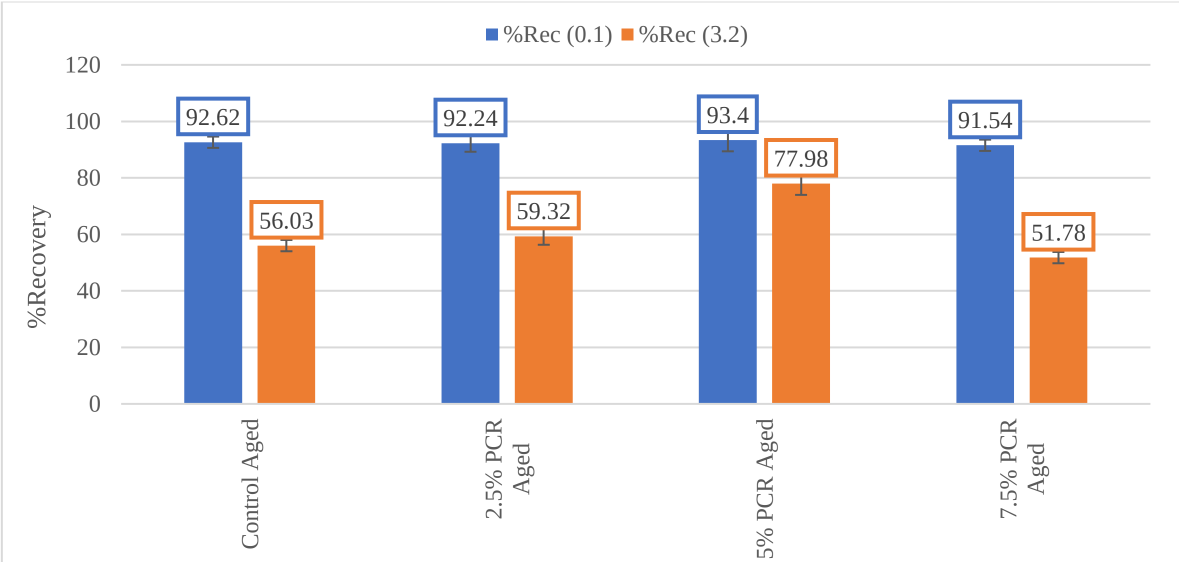


(b)

Figure 64- MSCR Results for CF Using PCR: (a) Jnr and (b) %Recovery.

Table 77- %JnrSlope for CF Using PCR

Sealant Type	%Jnr Slope	Acceptable Level of Elastomeric Polymer at 3.2kPa
Control Aged	4.90	Yes
2.5% PCR Aged	3.35	Yes
5% PCR Aged	0.79	Yes
7.5% PCR Aged	3.23	No

8.3.6. Toughness and Tenacity Test Results

The toughness and tenacity results showed significant improvement with the addition of PCR in terms of tenacity (**Figure 65**). This means that the post-peak behavior was improved with enhanced stretchability. The interesting results are shown on the aged sealant's side, where both toughness and tenacity results were maintained with the presence of PCR. In terms of chemical composition, the primary constituents of the non-oily and oily phases are asphaltenes and maltenes, respectively. According to the widely accepted colloidal model that depicts the internal structure of asphalt, asphalt behaves as a colloid containing micelles. In this model, fractions of asphaltenes are situated at the center of micelles, surrounded by a layer of lower molecular weight hydrocarbons, and dispersed in the oily phase. Consequently, the viscoelastic properties of asphalt materials are notably influenced by the ratio of asphaltenes to other fractions, such as maltenes. As the asphalt binder undergoes aging, polar aromatics transform into asphaltenes. Additionally, throughout the aging process, naphthalene aromatics shift to polar aromatics, which then oxidize and convert into asphaltenes. This transformation results in a decrease in maltenes content and an increase in asphaltene content (G. D. Airey, 2002).

The presence of PCR in the sealant reflects an elastic behavior when aged, referring to the fact that rubber contributes to the composition of the sealants. The aging of the modified material was minimized compared to the aged control sealant, yielding to better performance in aged conditions.

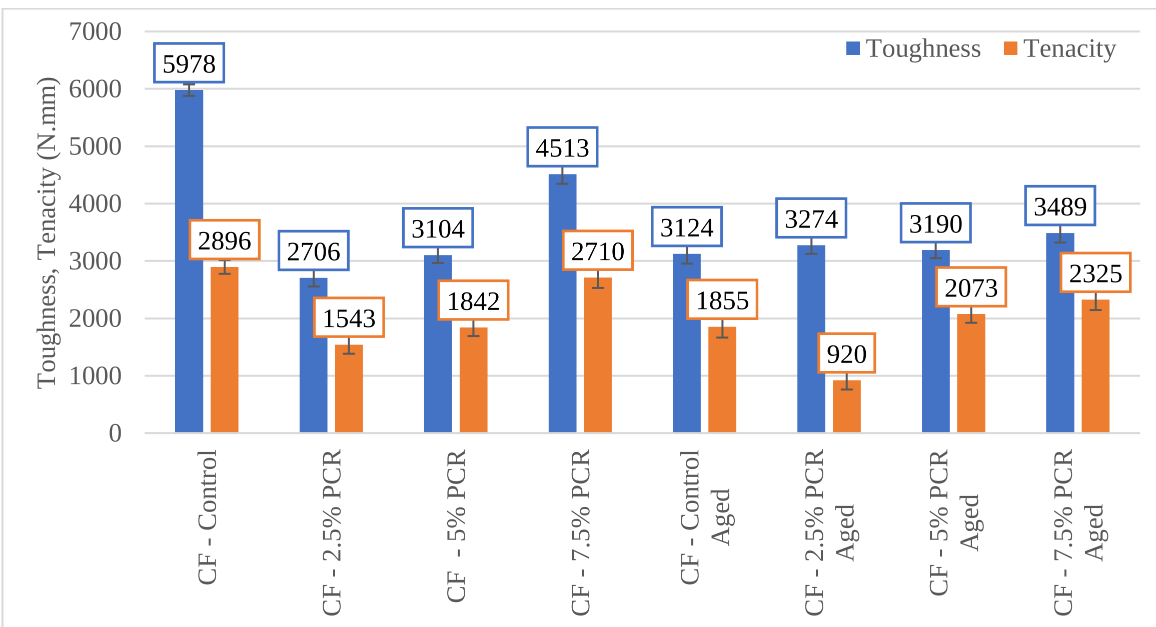


Figure 65- Toughness and Tenacity Results for CF Using PCR

8.3.7. Bond Strength Test Results

For all the reported results, the PCR particles were adhering to the substrate, leading to adhesive failures with the modified sealants. However, due to the positive toughness and tenacity results, adhesion was not considered to be a big concern, as those parameters also reflect adhesion of the material to aggregates (Liang, 2017). The dry pull-out strength showed promising results, under both aged and unaged conditions. However, under wet conditions the bonding of the modified sealant was negatively affected by the presence of rubber, leading to a higher moisture susceptibility. Similar behavior was observed in the presence of moisture and rubber.

Table 78- Bond Strength Results for CF Using PCR

Sealant Types	Dry Pull-Out Strength (kPa)	Failure Modes	Wet Pull-Out Strength (kPa)	Failure Modes	Pull-Off Strength Moisture-Susceptibility Index
CF - Control	2305	Cohesive	2107	Adhesive	-9%
CF - 2.5% PCR	2369	Cohesive	1820	Adhesive	-23%
CF - 5% PCR	2332	Cohesive	1778	Adhesive	-24%
CF - 7.5% PCR	2234	Adhesive	1540	Adhesive	-31%
CF - Control Aged	2337	Adhesive	1620	Adhesive	-31%
CF - 2.5% PCR Aged	1918	Adhesive	1252	Adhesive	-35%
CF - 5% PCR Aged	1933	Adhesive	1149	Adhesive	-41%
CF - 7.5% PCR Aged	2174	Adhesive	1260	Adhesive	-42%

8.3.8. Thermal Conductivity and Specific Heat Capacity Test Results

With respect to thermal properties, the thermal conductivity for the PCR modified CF seemed to remain the same under both aged and unaged conditions. The same analysis was attributed to the specific heat capacity of the modified material, whereas the values were comparable under aging conditions. The addition of PCR reduced the thermal susceptibility of the material overall.

Table 79- Thermal Properties Results for CF Using PCR

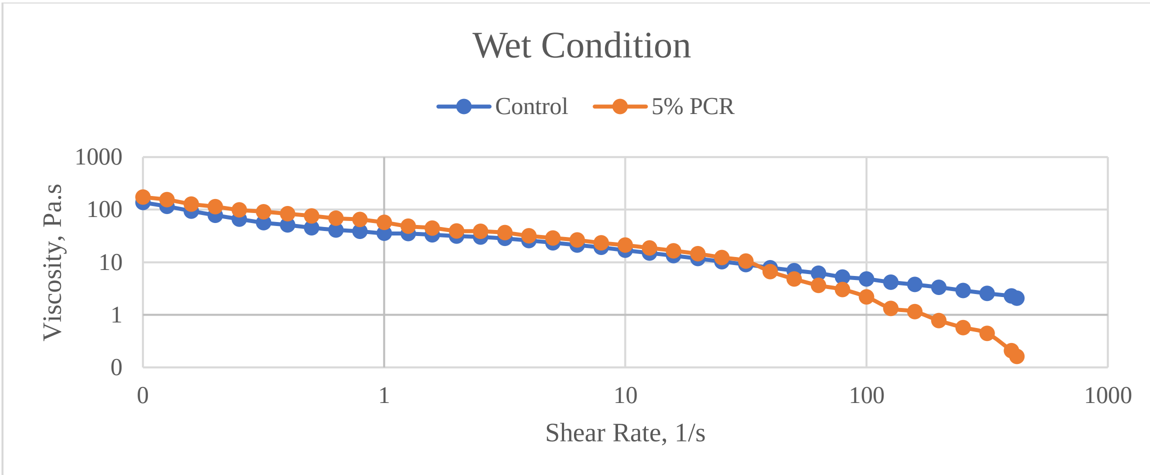
Sealant Type	k (W/m·K)	C_p (J/kg.K)
CF - Control	0.22	1059
CF - 2.5% PCR	0.11	950
CF - 5% PCR	0.16	861
CF - 7.5% PCR	0.11	923
CF - Control Aged	0.19	1433
CF - 2.5% PCR Aged	0.12	1063
CF - 5% PCR Aged	0.13	863
CF - 7.5% PCR Aged	0.10	1217

8.3.9. Linear Expansion and Contraction Test Results

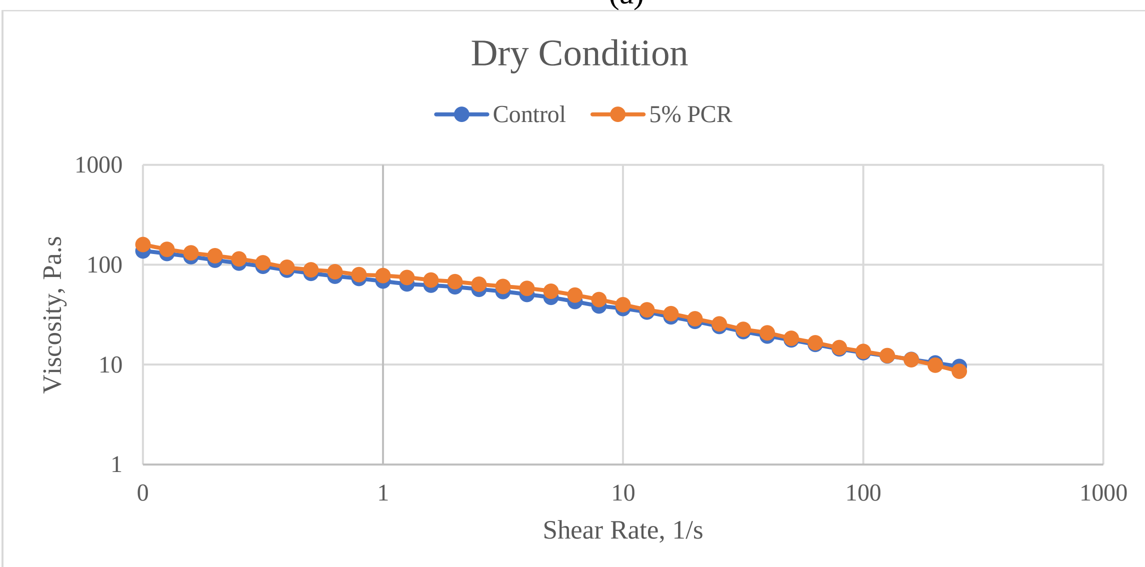
Similarly, the CTE of the PCR modified CF was measured for the optimum content found, 5% PCR. The CTE of the modified CF was measured to be equal to 2.6E-05, compared to 3.1E-05 for control. This shows a reduction in the coefficient, showing that the material will better accommodate the crack movement at different temperatures.

8.3.10. MISTI Test Results

In this section, the moisture susceptibility of the material was also evaluated to confirm the observed behavior in the bond strength test results (Section 8.3.7). The MISTI test results under dry conditions for the modified material have similar behavior to the control material. However, the wet testing showed a decrease in performance as expected. The onset of shear thinning occurred for the wet modified PCR before the control sealant as seen in **Figure 66.** As for the MISTI coefficient, it was found to be very close to the one obtained for CS, equal to 1.646 and denoting the pronounced moisture susceptibility induced with the addition of PCR.



(a)



(b)

Figure 66- MISTI Testing for CF Using PCR: (a) Wet Condition and (b) Dry Condition

8.3.11. Fourier Transform Infrared Spectroscopy (FTIR) Test Results

This test uses infrared light to study the chemical characteristics of the specimens. The radiation sent by the testing machine can be either absorbed by the sample or passed through it. The absorbed radiation is converted into rotational/vibrational energy by the sample molecules. Each sample will have a unique spectrum, reflecting its chemical structure based on the absorption levels for different wavelengths. This test is of interest as it will determine the aging level of each sample tested, and the effect of the addition of the

PCR into the sealant. For each chemical compound located at a specific wavelength, the absorbance level indicates the concentration or the amount of that compound within the tested specimen. The Carbonyl (C=O) and sulfoxide (S=O) bonds are of interest, and they are located at wavelengths from 1640 to 1755 cm^{-1} and between 984 and 1060 cm^{-1} respectively (Bernhard Hofko, 2017). The difference between peak stretches at those wavelengths for the unaged and aged specimens refer to different aging levels (M.R. Nivitha, 2016). To calculate the C=O and S=O indices, it is important to locate the reference aliphatic region, which spans from 1525 to 1355 cm^{-1} (**Table 12**).

$$I_{CO} = \frac{\text{Area around } 1700\ cm^{-1}}{\text{Area around } 1460\ cm^{-1}}$$ **(Equation 14)**

$$I_{SO} = \frac{\text{Area around } 1030\ cm^{-1}}{\text{Area around } 1460\ cm^{-1}}$$ **(Equation 15)**

Where,

I_{CO}: Carbonyl (C=O) index

And I_{SO}: Sulfoxide (S=O) index

Table 80- Integral Upper and Lower Wavelength Limits

Structural Group	Lower Wavelength Limit (cm^{-1})	Upper Wavelength Limit (cm^{-1})
C=O	1640	1755
S=O	984	1060
Reference Aliphatic	1525	1355

In order to calculate the C=O **(Equation 11)** and S=O (**(Equation 12)** indices before and after aging, the area under the obtained spectra (**Figure 67**) were obtained for both aging conditions according to (**Table 12**). Those limits are also shown on **Figure 67** for reference. It is apparent that aging did occur for the control sealant, with greater absorption of both compounds. As for the modified sealant, the levels of sulfoxides remained comparably the same (increase by 3%), whereas for the carbonyls a 23% increase occurred compared to a 26% increase for the control sealant **(Table 81)**. Those results confirm that the presence of PCR limits the aging of the material, making it more durable in the field.

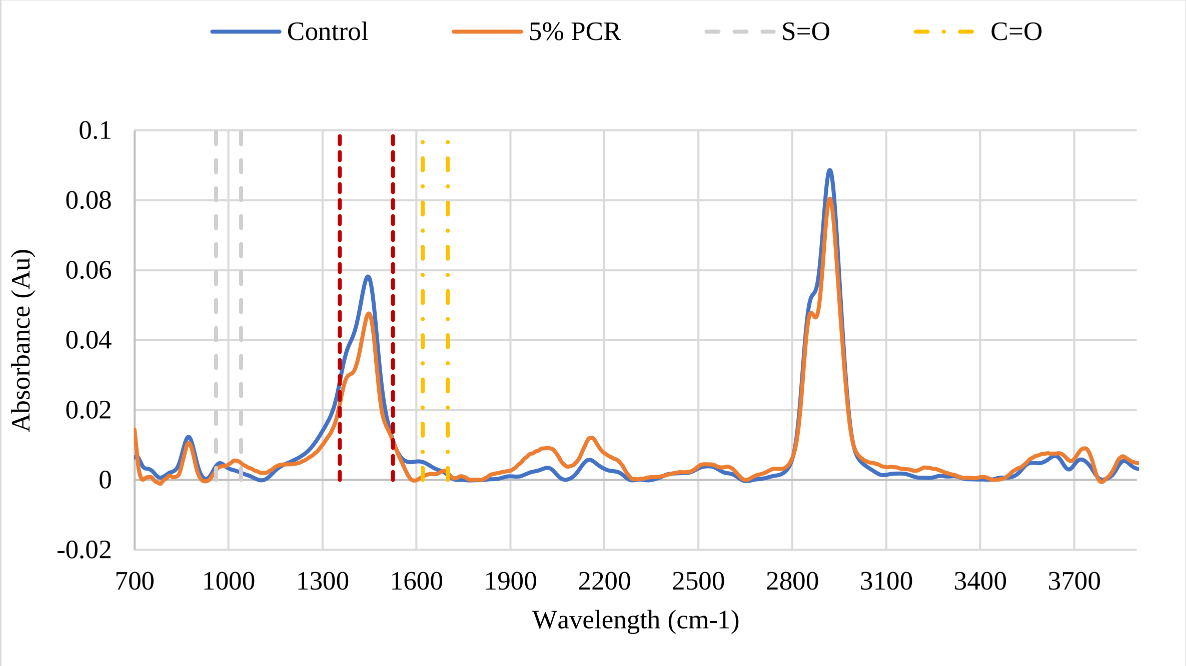


Figure 67- FTIR Spectra for Control and 5% PCR Modified Sealant

Table 81- FTIR Results

Sealant Type	S=O Index	C=O Index	% Increase (S=O)	% Increase (C=O)
Control	0.046	0.060	68%	26%
Control Aged	0.077	0.076		
5% PCR	0.074	0.046	3%	23%
5% PCR Aged	0.076	0.056		

8.4. Pre-Activated Crumb Rubber (PCR) Modification assessment, conclusions, and summary

The use of PCR in hot applied crack sealants was shown to offer potential for improving their performance and longevity. The testing protocol outlined in this study addressed crucial failure modes such as adhesion, cohesion, and resistance to aging, providing a comprehensive approach to improve the material properties. The sealant type used in this study was widely used in hot and dry climatic areas. This sealant was modified with PCR for 2.5%, 5% and 7.5% contents by weight of the material. The results show that PCR has potentially improved the properties of the sealant, leading to extended life span in the field.

- The softening point results showed increased softening temperature with the addition of PCR, referring to less settlement failures in the field.
- Having slightly stiffer material, the rotational viscosity results showed a lower temperature susceptible material with increasing PCR contents up to 5%.
- In terms of shear thinning and tracking resistance, at the established new performance grade, the modified sealants exhibited higher shear thinning and

tracking resistance compared to control as well as comparable flow parameters to the control material.

- As for the BBR low temperature testing, the modified sealants showed a higher relaxation capability (higher m-value) when compared to the control sealant. This showed that the material can release stress quicker, improving their service life at lower temperatures. Furthermore, in terms of critical temperature, the modified material showed a lower potential to low temperature cracking with ΔT_c values close to -5^{o}C. For the aged materials, the results of ΔT_c were comparable to the control, showing a slight improvement.
- The addition of PCR increased the elasticity through improvement in the creep and recovery behavior of the sealant, for contents up to 5% PCR. The %Jnr slope was evaluated for each material, to detect the sensitivity to the load changes in the field. The %Jnr slope for the modified material was shown to decrease with the addition of PCR. Furthermore, the %Recovery of the 5% PCR aged material was found to be higher than control for both sealing materials.
- Toughness, which is the work required to fracture the sealant was measured to be comparable for different PCR contents for both aged and unaged materials. In terms of tenacity, which represents the post-peak behavior and the stretchability of the material, it was reported to improve as well for modified materials.
- For the bonding results, they were reported to be comparable to the control material, with an improved observed failure mode (cohesive instead of adhesive). However, the bond behavior under wet conditions was shown to be more susceptible to failure than the dry conditions, highlighting one drawback of asphalt rubber.

- The thermal properties of the modified material showed improved expansion and contraction coefficient, with slightly reduced thermal properties. This highlighted the lower thermal susceptibility of the material, leading to better stability and improved performance in the field. Furthermore, a lower CTE was measured, leading to a better crack movement accommodation for different climates.
- This drawback was also observed with the MISTI Test results, where the addition of PCR affected the shear thinning onset of the material, leading to increased moisture susceptibility.
- The FTIR results were conducted on both control and 5% PCR on unaged and aged samples. The carbonyl and sulfoxide indices were calculated in both scenarios, showing that the control sealant exhibited a larger aging mechanism, where an increase of 68% vs 3% in sulfoxide and 26% vs 23% in carbonyl indices were found. This shows that the addition of PCR to the material potentially limited the aging of the modified material by absorbing the lower molecular weight fractions and preserving the properties of the sealant. This in turn will increase the durability of the material with delayed aging, leading to increased elasticity for a longer duration of time.

CHAPTER 9

9 CHARACTERIZATION AND ASSESSMENT OF SYNTHETIC FIBERS MODIFIED SEALANTS

9.1. Introduction

In this chapter, the addition of Synthetic Fibers (SF) for both sealing materials was investigated. They are derived from spandex and are believed to improve the stretchability of the material. This will potentially support the movement of the sealant within the crack by proving strength and flexibility to the sealant. In general, fibers can increase the viscosity of the material, making it more resistant to stripping and water penetration. They also affect the stress distribution within the material by distributing it more evenly, reducing the risk of cracking. Finally, fibers can improve the adhesion of the material by creating stronger bonding capabilities. Furthermore, fibers can reduce the moisture susceptibility of the material, as it can create a barrier through the material limiting the water penetration. However, the fiber content must be determined, as excessive fibers can lead to the opposite performance and affect the interaction between pavement and sealant.

The best way to introduce the fibers into the sealant was to be determined to achieve homogeneous dispersion of the fibers within the material. The optimized method was explained in detail in Section 3.4.1.3. Contents of 0.5% SF and 1% SF for CS by weight of the material were tested and performance was assessed accordingly. As for CF, only 0.5% SF was tested based on the obtained results. Both materials will be compared simultaneously under unaged conditions. The length of the fibers received was measured, and the average was found to be around 3.9cm. The fibers used were randomly selected from the sample bag, where 25 fibers were chosen and measured.

9.2. Synthetic Fiber (SF) Modification Test Results for Crack Sealant (CS) and Crack Filler (CF)

9.2.1. Softening Point, Resilience and Cone Penetration Test Results

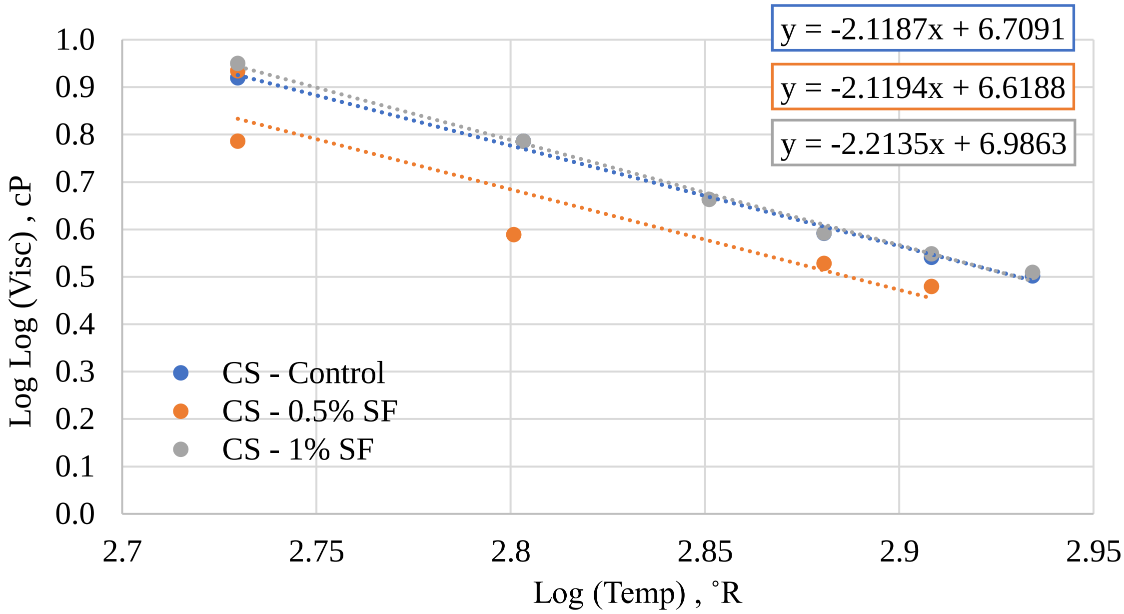
The addition of fibers to CS didn't alter the softening point but did seem to affect the cone penetration and resilience results with the addition of fibers (**Table 82**). The higher the fiber content, the lower the results obtained. As for CF, a higher softening point, lower resilience and cone penetration results were observed, leaning into a stiffer behavior. Overall, increased stiffness can be deduced by the addition of CF.

Table 82- Softening Point, Resilience and Cone Penetration Results for CS and CF Using SF

Sealant Type	Softening Point (ºC)	Resilience (%)	Cone Penetration (1/10 mm)
CS - Control	80	94	72.67
CS - 0.5% SF	78	78	53.8
CS - 1% SF	80	80	38.8
CF - Control	79.25	45	38
CF - 0.5% SF	90	24	23.8

9.2.2. Rotational Viscosity Test Results

The rotational viscosity test results for both materials, shown in **Figure 68a** and **Figure 68b**, indicate that no changes in thermal susceptibility occurred for both materials. All VTSi and Ai parameters were relatively the same across all contents. For the 1% SF modified CF, a slightly higher VTSi was measured, showing that excess fiber content will render the material slightly stiffer and less temperature susceptible.



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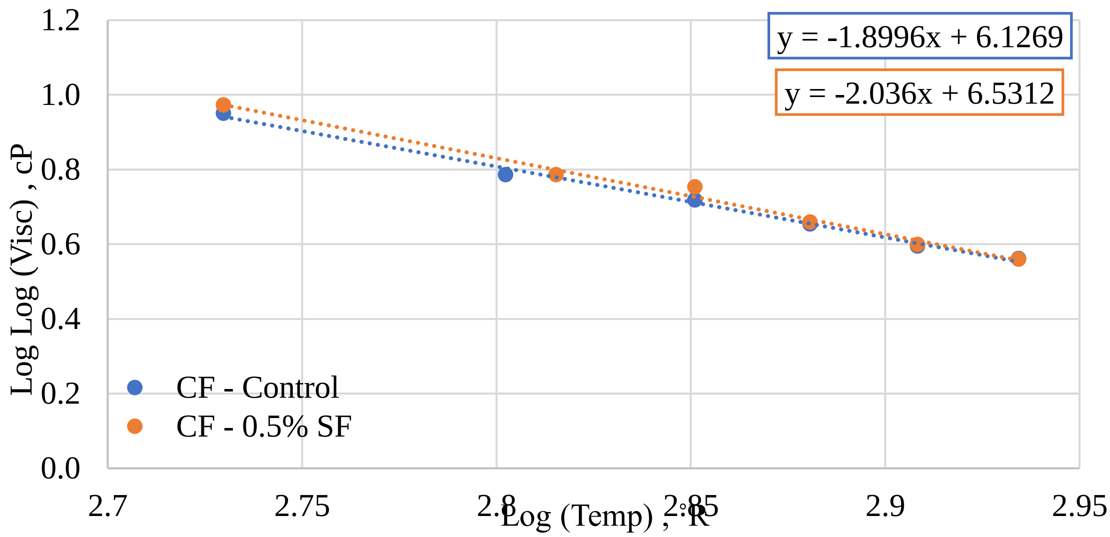
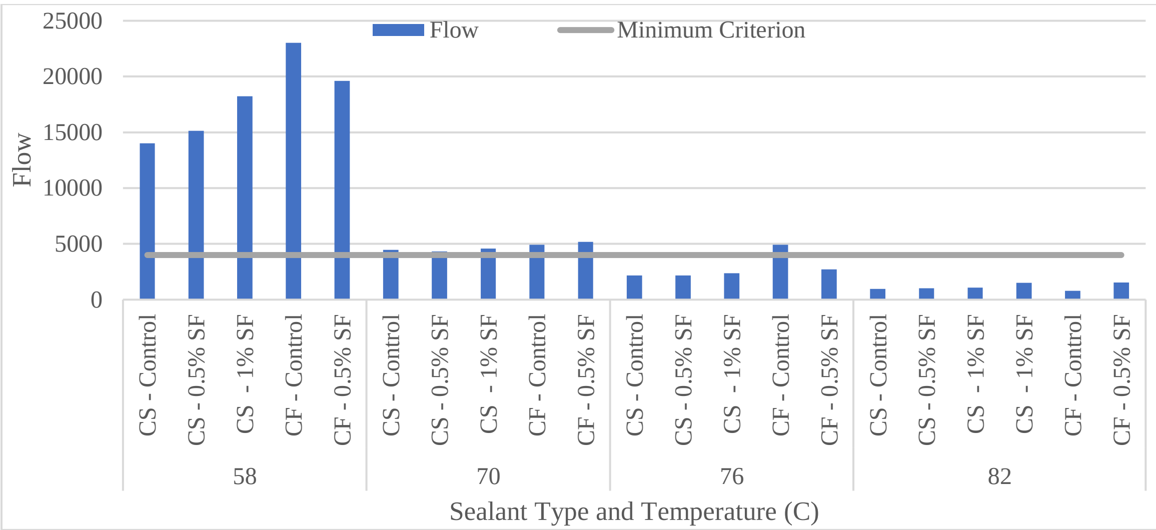


(b)

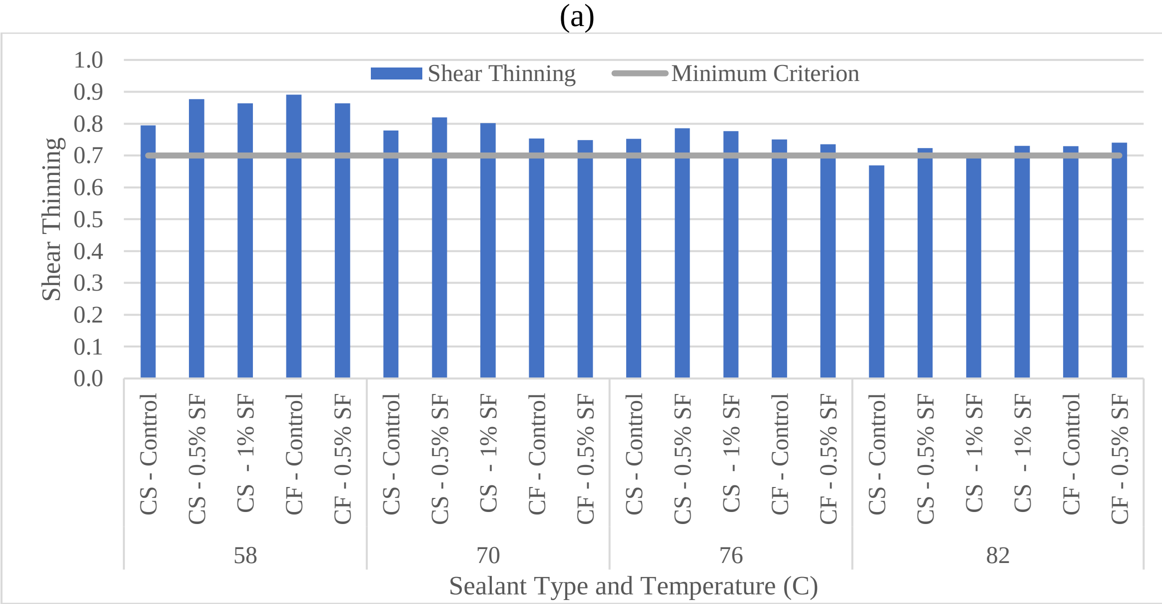
Figure 68- Rotational Viscosity Results Using SF for (a) CS Sealing Material and (b) CF Filling Material

9.2.3. Shear Thinning and Tracking Test Results

The flow parameter for the SF modified sealing material was very comparable for the CS modified material (**Figure 69a**). Across all temperatures, not causing the CS to change in high temperature grade (remaining at 70°C). As for CF, the results show a slight difference in the flow parameter, leading to a decrease in the high temperature grade of the CF from 76ºC to 70ºC. However, the results led to a slightly improved shear thinning/ tracking resistance with the addition of fibers. All in all, the addition of fibers slightly improved the performance of the material but was not very impressive at this point of testing. So far, 0.5% SF for CS seemed to induce the best outcome throughout the test results. As for CF, the addition of fibers did not seem very useful.



(a)



(b)

Figure 69- Shear Thinning and Tracking Results for CS and CF Using SF: (a) Flow Parameter and (b) Shear Thinning Parameter

9.2.4. Bending Beam Rheometer Test Results

On the other hand, for the low temperature behavior, the stiffness of the modified material did increase with a reduction in the relaxation capacity of the material. For the 0.5%SF for CS, the relaxation capacity was still satisfactory, with an acceptable stiffness at temperatures as low as -40°C. For this reason, the fibers were considered to slightly increase the stiffness behavior of the modified CS but were deemed to remain acceptable. For the CF, the low temperature stiffness was too high to begin with. The stiffness was measured at a higher temperature of -10°C. The same trend was observed, where stiffness was increased, and m-value decreased. Overall, the addition of fiber once again did not significantly alter the performance of the material at low temperatures.

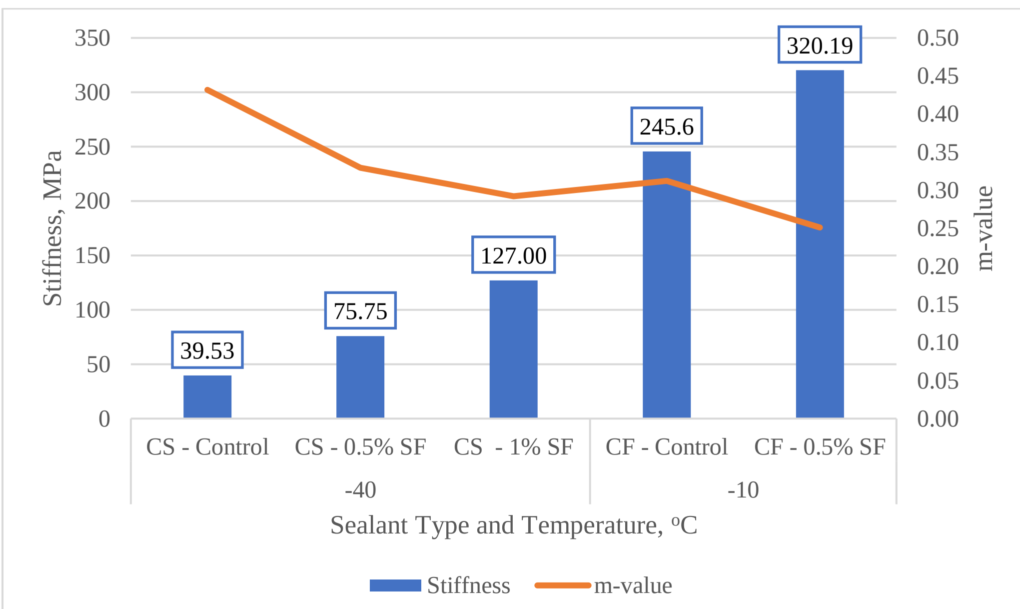
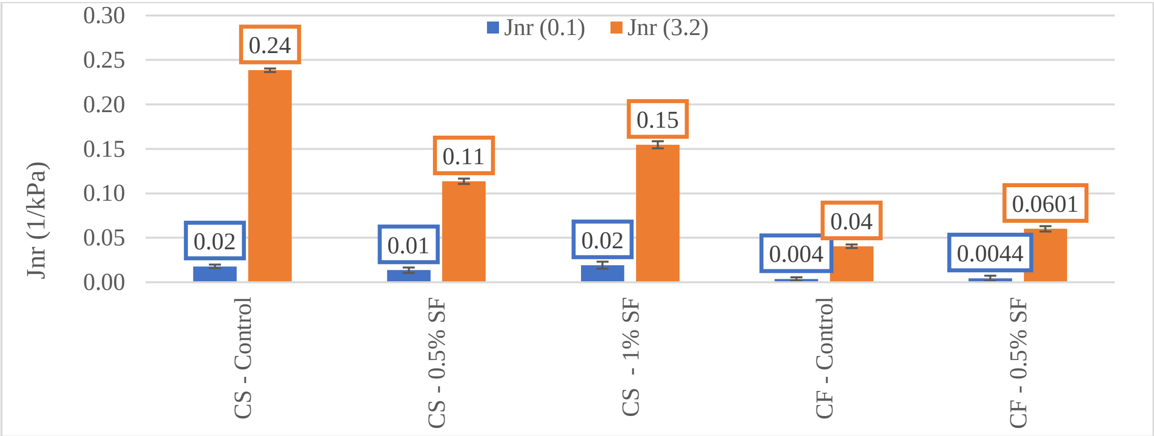


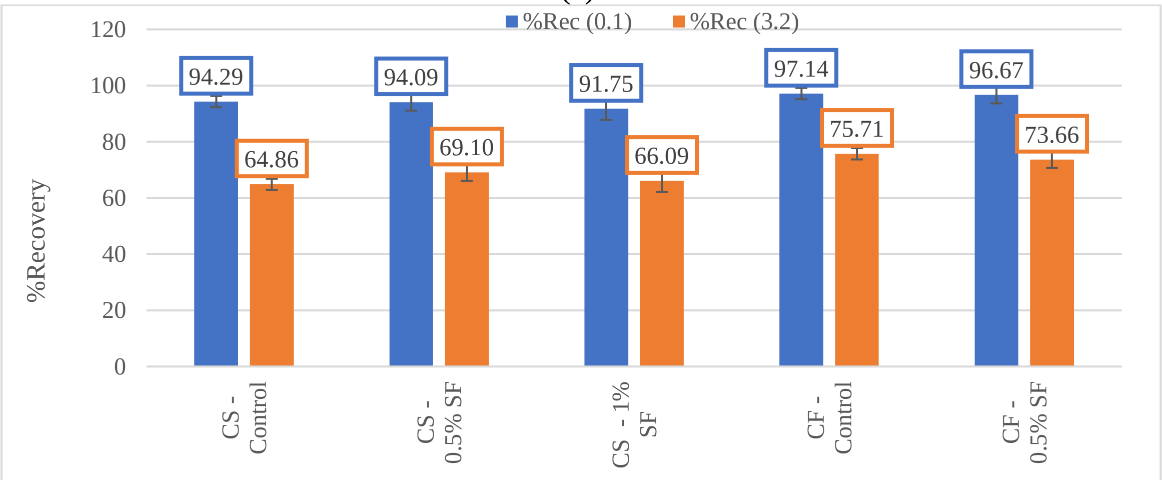
Figure 70- Bending Beam Rheometer Results for CS and CF Using SF

9.2.5. Multiple Stress Creep and Recovery Test Results

The MSCR Test results show promising and improved test results in terms of both Jnr and %Recovery for both 0.1 and 3.2 kPa loading conditions, especially for the 0.5%SF modified CS. No improvement was measured for CF modified with 0.5%SF. The fibers improved the recovery of the material as well as its non-recoverable creep (**Figure 71**).



(a)



(b)

Figure 71- MSCR Results for CS and CF Using SF: (a) Jnr and (b) %Recovery.

Furthermore, the stress sensitivity of both CS and CF modified with SF was greatly reduced (**Table 83**) when compared to the control materials, which leads to very promising elastic and flexible performance.

Table 83- %Jnr Slope Results for CS and CF Using SF

Sealant Type	%Jnr Slope	Acceptable Level of Elastomeric Polymer at 3.2kPa
CS - Control	7.11	Yes
CS - 0.5% SF	3.23	Yes
CS - 1% SF	4.37	Yes
CF - Control	1.19	Yes
CF - 0.5% SF	1.80	Yes

9.2.6. Toughness and Tenacity Test Results

Other promising findings were the toughness and tenacity parameters, where improved performance was measured as SF were added. Asphalt pavements naturally experience expansion and contraction due to temperature fluctuations. Cracks can widen and narrow with these movements. A tough sealant needs to be able to absorb and distribute these stresses without cracking itself. Furthermore, a tenacious sealant needs to adhere strongly to the asphalt surface and the crack edges to prevent the sealant from being dislodged or pulled out under traffic loads. For this reason, increasing both parameters are of interest to improve the performance of the material in the field. This test must be accompanied by the bond strength test, to ensure proper failures of the material in the field. As it can be seen from **Figure 72**, the toughness and tenacity of the 0.5%SF CS increased by 18% and 11% respectively. As for the 1%SF modified CS, the toughness and tenacity of the material increased by 40% and 43% respectively. This increase is very promising in terms of performance.

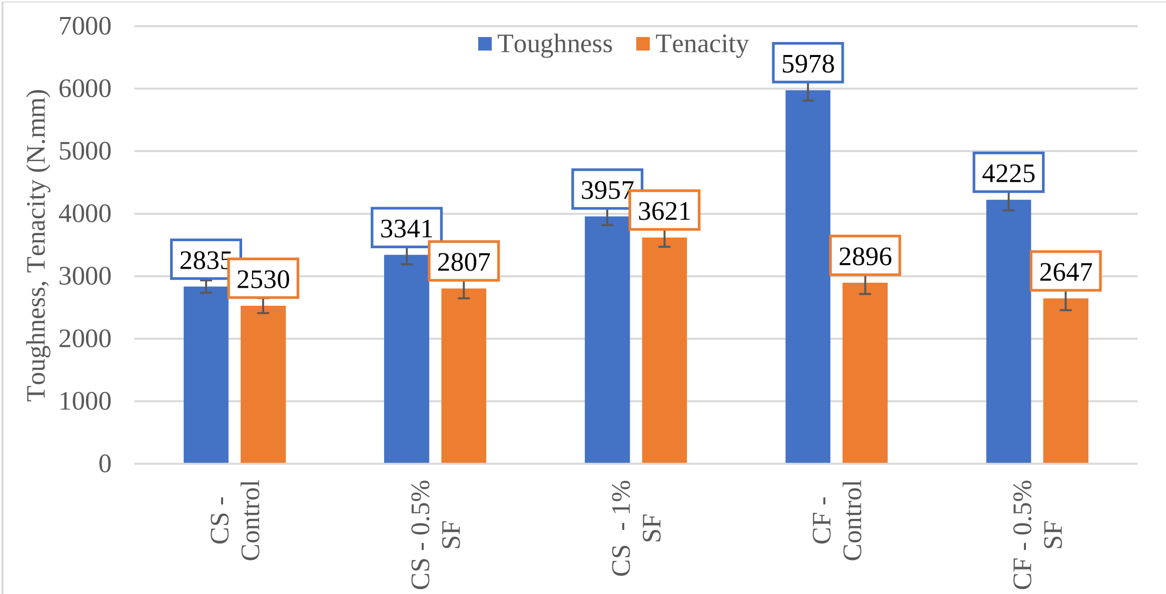


Figure 72- Toughness and Tenacity Results for CS and CF Using SF

9.2.7. Bond Strength Test Results

The bond strength results shown in **Table 84** show very good improvements in terms of tensile strength with the modified material with SF. The dry strength increased by 70% for 0.5%SF, and 72% for 1%SF modified CS. As for the wet strength, it increased by 139% and 173% for 0.5% SF and 1% SF modified CS respectively. Furthermore, the moisture susceptibility pull-off strength index showed an improved moisture resistance, with 19% and 35% enhanced moisture performance for 0.5% and 1% SF modified CS respectively. As for CF, the results were not as pronounced, with a comparable dry tensile strength. For the wet conditions, the strength did improve by about 80%. The observed failure under dry conditions was reported to be cohesive, compared to adhesive for wet conditions.

Table 84- Bond Strength Test Results for CS and CF Using SF

Sealant Types	Dry Pull-Out Strength (kPa)	Failure Modes	Wet Pull-Out Strength (kPa)	Failure Modes	Pull-Off Strength Moisture-Susceptibility Index
CS - Control	668	Cohesive	565	Adhesive	-15%
CS - 0.5% SF	1133	Cohesive	1350	Adhesive	19%
CS - 1% SF	1147	Cohesive	1544	Adhesive	35%
CF - Control	2305	Cohesive	2107	Adhesive	-9%
CF - 0.5% SF	2149	Cohesive	3803	Adhesive	77%

9.2.8. Thermal Conductivity and Specific Heat Capacity Test Results

The thermal properties (**Table 85**) of the modified materials, CF and CS were not impacted with the addition of SF at any content, which is in line with previously measured properties (Rotational Viscosity and Shear Thinning and Tracking test results). Therefore, it can be safely concluded that the addition of those fibers did not impact the thermal behavior of the sealing material.

Table 85- Thermal Conductivity and Specific Heat Capacity Results for CS and CF Using SF

Sealant Type	k (W/m.K)	C_p (J/kg.K)
CS - Control	0.11	1173
CS - 0.5% SF	0.11	1210
CS - 1% SF	0.10	1250
CF - Control	0.22	1059
CF - 0.5% SF	0.19	1121

9.2.9. Linear Expansion and Contraction Test Results

The CTE for the SF modified CS and CF was measured and summarized in **Table 86**. A slight reduction was measured with the addition of fibers. However, based on the previous section, the addition of fibers did not alter the thermal behavior of the material, which was also reflected in this test. This highlighted that the addition of SF only provided improved mechanical performance.

Table 86- CTE Results for CS and CF Using SF

Sealant Type	CTE
CS - Control	2.19E-05
CS - 0.5% SF	2.08E-05
CF - Control	3.09E-05
CF - 0.5% SF	2.90E-05

9.2.10. MISTI Test Results

The MISTI test results for the CS and CF modified materials with SF showed improvements in terms of MISTI, as expected. The addition of fibers improves moisture susceptibility of the material. For CS, the MISTI was found to be 1.062 and 1.121 for CF.

9.3. Synthetic Fiber (SF) Modification Assessment, Conclusions, and Summary

The addition of fibers into crack sealing and filling materials may improve the performance of the material in different aspects. Fibers may help with better stress dissipation within the material, leading to higher strengths and crack movements accommodations. By distributing stresses more evenly, fibers can reduce the formation of microcracks that can serve as pathways for water ingress.

First of all, the addition of SF was shown to improve the non-recoverable creep compliance and %Recovery, by making the material more elastic with increased recovery under both loading conditions. Furthermore, the %JnrSlope of the modified sealants was greatly reduced, proving that the material will be more durable and less sensitive to different loading conditions in the field. So far, the test results show potential increased durability. For shear thinning and tracking results, rotational viscosity and thermal properties measurements, no significant improvements were made, as the results were very comparable to the control materials for all conditions.

On the other hand, the low temperature behavior of the material was affected by the fibers, where increased stiffness and slightly reduced m-value was recorded, leading to slightly increased stiffnesses at reduced temperatures. However, the measured properties were still considered to be acceptable at reduced temperatures of -40^{o}C.

In order to ensure the behavior of the fiber modified material, the toughness and tenacity test was conducted and showed promising results. Both toughness and tenacity parameters were greatly improved with respect to the control material, proving that the SF modified CS and CF will adhere to the pavement longer and accommodate excessive movements. Furthermore, higher toughness leads to higher energy required to fail the sealant, which in turn refers to prolonged lifespan.

To ensure that the proper failure modes are to be expected, the bond strength test results showed extremely positive results, where the dry strengths were improved by 70%, and wet strengths were increased by over 140%. This showed that not only the bonding properties were improved, but also that the moisture susceptibility of the material was enhanced by about 30% compared to control. The fibers were acting as a physical barrier, hindering the infiltration and migration of water within the material. This reduces the interaction between water and the sealant, which can weaken the adhesive bond between the binder and the aggregate in the mixture.

CHAPTER 10

10 MULTI-CRITERIA DECISION MAKING AND COST ANALYSIS

10.1. Introduction

In today's dynamic and competitive environment, decision-making processes are becoming increasingly complex, especially in fields such as engineering, management, finance, and environmental studies. With multiple options available, decision-makers often find themselves confronted with the challenge of selecting the most suitable alternative from a set of alternatives characterized by multiple criteria. To address this challenge, various decision-making methods have been developed and applied in different domains. One such method that has gained significant attention due to its simplicity and effectiveness is the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Introduced by Hwang and Yoon in 1981, TOPSIS has since emerged as a powerful multi-criteria decision-making tool widely used in both academic research and practical applications.

TOPSIS is grounded in the concept of identifying the alternative that strikes the best balance between being similar to the ideal solution and different to the negative solution across multiple criteria. By comparing alternatives against a set of predefined criteria, it facilitates the ranking of alternatives according to their proximity to the ideal solution while minimizing their distance from the negative solution. The main advantages of using this method refer to the integration of both quantitative and qualitative criteria, thereby accommodating diverse decision contexts and preferences. This chapter aims to provide a comprehensive overview of TOPSIS analysis conducted to determine the best modifier

(EaMBx, RaMBx, RaC, PCR and SF) for different scenarios based on laboratory testing. Those scenarios include different material applications, climates, and locations.

In the following sections, the methodology followed to conduct the TOPSIS analysis will be discussed, and a final ranking decision will be recommended.

10.2. Methodology

The TOPSIS analysis compares alternatives following a set of decision criteria. The first step consists of creating the decision matrix, that includes all the alternatives and criteria that the decision will be based on. This matrix is then normalized for each criterion.

The next step involves assigning scores or weights to the set of criteria in order of importance. Those weights are either calculated by using an AHP method (Analytic Hierarchy Process) or determined otherwise. The weighted matrix was then found by multiplying each normalized criterion value by the assigned weight.

The positive solutions were found by first identifying the best-case scenario of each criterion (either increasing value or decreasing value, depending on the desired outcome). Similarly, the worst-case scenario of each criterion was determined, opposing the behavior of the positive solution obtained. The magnitude of the distance for each criterion from both positive and negative solutions was calculated based on its normalized value. This step was repeated for all material alternatives, yielding to its final ranking among all alternatives. The final ranking was obtained by calculating the relative closeness of each alternative.

10.2.1. Survey

In this study, a survey was conducted where different scenarios were suggested for crack sealing and crack filling applications: crack sealing was assumed to be applied on roadways with traffic (scenario 2), whereas crack filling was assumed to be applied in parking lots with minimal to no traffic (scenario 1). This survey was sent to industry and academic professionals to determine the importance of different factors affecting the performance of asphalt crack sealants, based on their professional expertise and knowledge. The participants include crack sealant manufacturers, city engineers, contractors, and committee members of the Arizona Pavement Conference. The audience of the survey was targeted to ensure that the results of the survey are valid and adequate for analysis. To obtain more accurate results, a more elaborate survey could be conducted and presented to the same audience.

Four different factors were identified and defined for each of the two scenarios as follows:

1) Flexibility and stretchability: ability of the material to stretch (i.e., tenacity, recovery)
2) Strength: ability of the material to sustain traffic, bonding, and pull-out (i.e., stiffness, toughness)
3) Thermal Resistance: susceptibility of the material at different temperatures (i.e., thermal conductivity, specific heat capacity, thermal expansion, and contraction)
4) Moisture Resistance: susceptibility of the material to moisture (i.e., wet bonding, moisture shear thinning)

The participants were asked to rate each factor, from 1 to 5 where 1 is "least important" and 5 is "Extremely Important" based on their experience for both parking lots (Scenario 1, using crack filler) and roadways (Scenario 2, using crack sealant). A screenshot of the survey is shown in APPENDIX A.

After collecting the results from the survey, the individual scores for each factor relative to the other were calculated based on the obtained responses. A total of 24 responses were recorded. Each of the suggested factors represent testing parameters obtained from the laboratory testing for each modifier. In other words, those factors are categories representing important parameters obtained from the laboratory testing, that affect the sealant performance in the field. The most prominent failure modes observed in the field were tackled by the suggested testing protocol, as explained in Section 3.1. The scores and the weights for each criterion and parameters were found and explained in APPENDIX A.

10.2.2. Factors and Parameters

For the flexibility factor, the parameters considered were Tenacity, %JnrSlope, Stiffness and m-value. Tenacity, defined as the post-peak behavior of the material, is a direct measure of how flexible and stretchable the sealant is under specific testing conditions. As for the %JnrSlope, it represents the sensitivity of the material to different loading conditions in terms of accumulated strain or permanent deformation. The %Recovery on the other hand, measures the material's ability to go back to its original condition. Concerning the m-value, it was considered as the material's ability to release the stresses. The stiffness directly refers to the toughness of the material. However, as stiffer materials tend to have higher toughness, stiffness needs to remain within acceptable ranges to avoid sudden and brittle failures of the material in the field, especially at low temperatures. This factor is important for the sealant's ability to be able to accommodate the crack movements under different climatic conditions. The list of parameters with the corresponding factors are found in **Table 87**.

For the strength factor, Dry Bond Strength, Toughness and Shear Thinning Parameter were considered. This factor reflects the strength of the material, in addition to its cohesive and adhesive properties. Toughness, being the energy required to fail the material, reflects to the maximum load the material can handle before either detaching from the edge of the crack, or failing in cohesion. The Bond strength represents the tensile strength needed to pull the material from the substrate, related to the toughness and stiffness of the material as well as the adhesive properties of the sealant. Finally, the shear thinning parameter, P, refers to the material's resistance to tire tracking and being pulled out of the crack. This factor is highly important at both extreme low and high temperatures, where at higher temperatures the strength of the sealant may decrease due to the softening behavior of the material. At higher temperatures, the material may settle at the bottom of the crack and be picked up by traffic.

The third factor, thermal resistance, represents the material's sensitivity to temperature change and its ability to perform at different temperatures. Thermal conductivity and specific heat capacity show the sealant's material to conduct heat and the energy required to heat up the material. Lower k and higher Cp show that the sealant is less affected by temperature change. Furthermore, the VTSi gives indication about the temperature susceptibility of the sealant as well as its ability to perform at low temperatures. The CTE is also a very crucial parameter, where the sealant will be subjected to different thermal cycles and move accordingly. Lower CTE will reflect better performing sealant with lower cracking potential.

Finally, the last factor, Moisture resistance where the MISTI parameter, Wet Bond Strength and the Pull-Out Moisture Susceptibility Index are all referring to the effect of moisture on the sealing material. MISTI represents the effect of moisture on the sealing material and its ability to adhere to the pavement with the presence of moisture. The wet bond strength is a measure of the strength of the material under wet conditions, depicting its adhesive and cohesive performance. As for the Pull-out moisture susceptibility index, it represents the effect of moisture on the adhesive and cohesive performance of material when tested on the substrate. The effect of those three parameters shows how susceptible or resistant the material is to moisture in the field, which is also one of the reasons why the sealant degrades faster with time.

Table 87- Parameters and Factors Used for TOPSIS Analysis

Parameter	Category
Tenacity	Flexibility
%Jnr Slope	Flexibility
m-value	Flexibility
Stiffness	Flexibility
Dry Bond Strength	Strength
Toughness	Strength
Shear Thinning	Strength
k	Thermal Resistance
Cp	Thermal Resistance
CTE	Thermal Resistance
VTSi	Thermal Resistance
MISTI	Moisture Resistance
Wet Bond Strength	Moisture Resistance
Pull-Out Moisture Susceptibility Index	Moisture Resistance

The detailed analysis for the scores found for each factor can be found in APPENDIX A. Each parameter, as described in **Table 87**, was assigned an individual score according to an AHP (Analytical Hierarchy Process) analysis and the weights were calculated for each scenario (**Table 88**).

Table 88- AHP Weights for Each Parameter under Different Scenarios and Climates

Conditions	**Scenario 1 – Crack Filler**		**Scenario 2 – Crack Sealant**	
Parameters	Hot	Cold	Hot	Cold
Tenacity	0.074	0.090	0.155	0.186
%Jnr Slope	0.087	0.054	0.183	0.111
m-value	0.053	0.076	0.111	0.157
Stiffness	0.063	0.064	0.131	0.132
Dry Bond	0.024	0.029	0.043	0.051
Toughness	0.021	0.025	0.036	0.043
Shear Thinning	0.029	0.021	0.050	0.036
k	0.053	0.058	0.031	0.033
Cp	0.063	0.064	0.037	0.037
CTE	0.074	0.072	0.044	0.042
VTSi	0.087	0.081	0.052	0.047
MISTI	0.104	0.113	0.036	0.039
Wet Bond	0.123	0.134	0.043	0.046
Pull-Out Moisture Susceptibility Index	0.145	0.119	0.050	0.041

The values that were used from the previous for each parameter were picked from both unaged and aged conditions, based on which scenario was more critical for analysis and for a particular case. The conditions for each parameter are summarized in **Table 89**. The flexibility parameters are normally more critical under aged conditions, given that the material loses its stretchability with the loss of its oil fractions. One exception goes for the %Jnr Slope and %Recovery, as the material is more susceptible to permanent deformation when it is unaged at elevated temperatures. Concerning the strength of the material, the parameters were also critical under aged conditions, where they tend to decrease. The exception in this case is the tracking resistance, as it is more crucial under unaged conditions: the sealant/filler has a higher susceptibility to tracking and is stickier when unaged. As for the thermal parameters were considered under unaged conditions, as they set the path for aged behavior as well. The unaged material tends to be more affected by temperature change. Those parameters also affect the initial placement of the material, including setting and adhesive properties. Finally, the moisture parameters were considered under aged conditions, given that the material will have reduced bonding capacity at this stage. For the MISTI parameter, shear thinning normally occurs at earlier stages under unaged conditions, which is why unaged conditions were considered more critical in this case.

Table 89- Parameters Used Aging Conditions

Parameters	Aging Conditions
Tenacity	Aged
%Jnr Slope	Unaged
m-value	Aged
Stiffness	Aged
Dry Bond	Aged
Toughness	Aged
Shear Thinning/Tracking	Unaged
k	Unaged
Cp	Unaged
CTE	Unaged
Ai	Unaged
MISTI	Unaged
Wet Bond	Aged
Pull-Out Moisture Susceptibility Index	Aged

10.3. Results and Analysis

After running the TOPSIS analysis using the weights for each parameter shown in **Table 88**, the rankings from 1 to 6 for each scenario and climate are shown in **Table 92** and **Table 93**. The rankings were obtained after calculating the best and worst distances leading to a final score. According to the results, the different climates did not yield different results given that the parameters that are affected by climate did not have a significant weight compared to the others. In general, the stiffness of the material at lower temperatures presents a potential drawback as it would limit the performance of the material and lead to cracking. Choosing a material with adequate stiffness in both conditions would yield to acceptable performance under hot and cold climatic conditions.

Concerning the results obtained, the fiber modified materials for all scenarios and climates were ranking first due to the increased stretchability, bond strength and moisture resistance.

The results of the survey showed that the flexibility, thermal and moisture resistance factors were the governing ones, and the strength comes with the lowest importance for the crack filler (**Table 90**). For the crack sealant, the results showed that flexibility is the governing parameter over all the other three, while they are equally important in a secondary position (**Table 91**).

Table 90- Survey Results for the Crack Filler

Sc1- Crack Filler	Flexibility	Strength	Thermal Resistance	Moisture Resistance
Flexibility	1	3	1	0.5
Strength	0.33	1	0.33	0.25
Thermal Resistance	1	3	1	0.50
Moisture Resistance	2	4	2	1

Table 91- Survey Results for the Crack Sealant

Sc2	Flexibility	Strength	Thermal Resistance	Moisture Resistance
Flexibility	1.0	3.0	4.0	3.0
Strength	0.3	1.0	1.0	1.0
Thermal Resistance	0.3	1.0	1.0	1.0
Moisture Resistance	0.3	1.0	1.0	1.0

For the crack filler (**Table 92**), it can be seen from the results that both fibers and EaMBx modifiers bring potentially improved performance compared to control given both cold and hot conditions. The other modifiers were found to be a little bit stiffer, with the other parameters not making the cut. Furthermore, the m-value at lower temperatures had a higher weight compared to hot temperatures, in addition to the stiffness of the material. The other parameters were kept at the same importance as they relate to the condition of the filler itself during any condition. The PCR modified filler scored 6, as it reported the highest moisture susceptibility, comparable thermal properties to control and increased stress sensitivity. The RaMBx modified CF provides better thermal properties and reduced thermal susceptibility, moisture resistance, improved tracking resistance, acceptable stiffness, and m-values as well as %Jnr Slope. For those reasons, where climatic fluctuations are an issue, this material would provide a more durable and improved performance.

As for the CS ranking results (**Table 93**), the flexibility factor governing lead to boosting both PCR and SF modified sealants, followed by the RaMBx and EaMBx modified materials. As traffic plays a big role in this scenario, having a more flexible material is crucial to accommodate crack movements with change of climatic conditions. So far, the results seemed to be reasonable given the obtained results from the laboratory testing. The RaC modified material performed poorly in terms of flexibility, which is why its 6th position is justified. Finally, it can be concluded that the suggested modifiers were ranked and shown to improve the performance of both CF and CS under hot and colder climates based on the tested properties.

It is to be noted that the modification method also plays a role, as well as how easy and readily available the modifier could be implemented:

1) At the manufacturing stage, which could be more challenging for the PCR and the SF to ensure temperature control and high-speed mixing. This process is more favorable for the aMBx modification.
2) The second option would be to assume that all modifications are done at the same stage, making each modification equal in terms of added cost for field production.
3) The third option would be to consider the actual scenario of each modification: manufacturing levels for SF and PCR, and in the field blending unit for the aMBx modifications.

By considering those 3 cases, the aMBx modifications are shown to be the most favorable as they are the easiest to implement at both field and manufacturing levels. This increases their likelihood of being used, which should be considered when making a decision. Furthermore, being an insulator, the aMBx modification will allow for faster cooling at the manufacturer once it has been added to the material, leading to faster packaging. In the field and depending on the mass of the modified material, the aMBx will retain heat for a short period of time and then release it as it is being poured (smaller thermal mass) due to its low thermal conductivity and high specific heat capacity properties. It is important to note that the obtained ranking was based on the scores from the survey, and that different responses may lead to different rankings to some extent. The parameters corresponding to the criteria were measured in the laboratory and still represent the potential performance of the modified sealant and filler.

Table 92- Rankings for CF

Sc1 – Filler	**Ranking**	
Sealant Type	Hot	Cold
CF – Control	5	5
CF – 2.5% EaMBx	2	2
CF – 5% RaMBx	3	3
CF – 5% RaC	4	4
CF – 5% PCR	6	6
CF – 0.5% SF	1	1

Table 93- Rankings for CS

Sc2 – Sealant	**Ranking**	
Sealant Type	Hot	Cold
CS – Control	5	5
CS – 2.5% EaMBx	4	3
CS – 5% RaMBx	3	4
CS – 5% RaC	6	6
CS – 5% PCR	2	2
CS – 0.5% SF	1	1

10.4. Crack Sealing and Filling Cost and Analysis

Identifying the cost of those modifiers plays a crucial role in determining the effectiveness of the modification. With respect to the rankings obtained in the previous section, the cost of the modifier, in addition to the cost of the control material need to be considered. A life cycle cost analysis needs to be conducted to determine the breakeven period and support the additional initial cost of each modifier. However, field measurements need to support such study to identify how the improvements seen in terms of laboratory measurements translate into field measurements.

In this section, the breakdown of a conventional crack sealant activity is presented, along with the cost of each modifier with respect to the optimum content determined throughout the study. The costs were derived for an average crack dimension of 25.4mm width, 50mm depth per 1 linear meter in distance. An overband of 76.2mm in width and 1.6mm in depth (the recommended dimension) was added for crack sealing. For this kind of application, 1.87kg/m of material was needed with 10% waste considered. The cost of the material from any retailer was found to be 3.38$/kg for the crack sealant CS.

The base cost of crack sealant (CS) was found to be 6.57 $/m, with a 0.25$/m included for labor.

For crack filling, the cost labor was less due to fewer procedures and was considered to be 0.15$/m. Therefore, the final cost for crack filling was found to be 5.55$/m, with a cost of 2.89$/kg for the crack filler CF.

Concerning the modifiers, the cost of each modifier is shown in **Table 94** below. The cost of asphalt binder was considered to be on average of $549 per metric ton. The cost of the modifiers was calculated based on the respective ratios of each component.

Table 94- Cost of the Modifiers ($/m) at Optimum Content

Modifier Type	Cost, $/m
5% RaMBx	1.36
5% EaMBx	1.59
5% PCR	0.1
5% RaC	2.78
0.5% SF	0.12

Finally, the final cost per linear meter of the modified materials is found in **Table 95** below.

Table 95- Cost of Control and Modified Material in $/m

Material Type	CS Cost, $/m	CF Cost, $/m
Control	6.57	5.55
2.5% EaMBx	8.16	7.14
5% RaMBx	7.93	6.91
5% RaC	9.35	8.33
5% PCR	6.66	5.64
0.5% SF	6.69	5.67

According to the results obtained in the lab, the price increase is justifiable, given the potential field performance improvement. Furthermore, different sources of aerogel could be used to produce the aMBx and RaC modifiers, which could affect the price and bring it lower.

In summary, TOPSIS involves several steps. Initially, a decision matrix is created with alternatives and criteria, which is then normalized. Criteria are assigned weights, that were determined through an Analytic Hierarchy Process (AHP). Weighted scores were calculated for each criterion. Positive and negative solutions are identified based on best and worst-case scenarios for each criterion. Distances from these solutions are calculated for each alternative, leading to rankings. Additionally, a survey was conducted to identify factors affecting asphalt sealant performance, which were then incorporated into the analysis. The analysis yielded rankings for different modifiers under various scenarios and climates. It was found that flexibility, thermal, and moisture resistance were critical factors affecting sealant performance. Fiber-modified materials consistently ranked highest across scenarios due to their improved properties in these areas. The results indicated that the choice of modifier significantly impacts the performance of crack sealing and filling materials when compared to the control material, leading to potential improvements in the field. Associating costs to those rankings, field performance measurements need to be done in order to conduct a proper life cycle assessment. The cost increase with respect to each modifier and corresponding to each ranking obtained appears to be justifiable given proper field implementation would occur.

10.5. Preliminary Life Cycle Cost Analysis

A preliminary life cycle cost Analysis (LCCA) was developed to better quantify the costs associated with the use of the modifiers into both crack sealant and filler. Two analysis periods were considered: 10 and 20 years, with a discount rate of 5.50%.

The next step involves quantifying the improvements of using such modifiers on the life span of control crack sealants and fillers. Considering the properties of each material as shown in **Table 89**, the percent change from the control properties were calculated for each modifier. By the means of the weights obtained from the survey as calculated in **Table 88**, the percent change of each parameter was multiplied by the corresponding weight. An overall percentage change was obtained, reflecting the potential improvement of the modified material with respect to control.

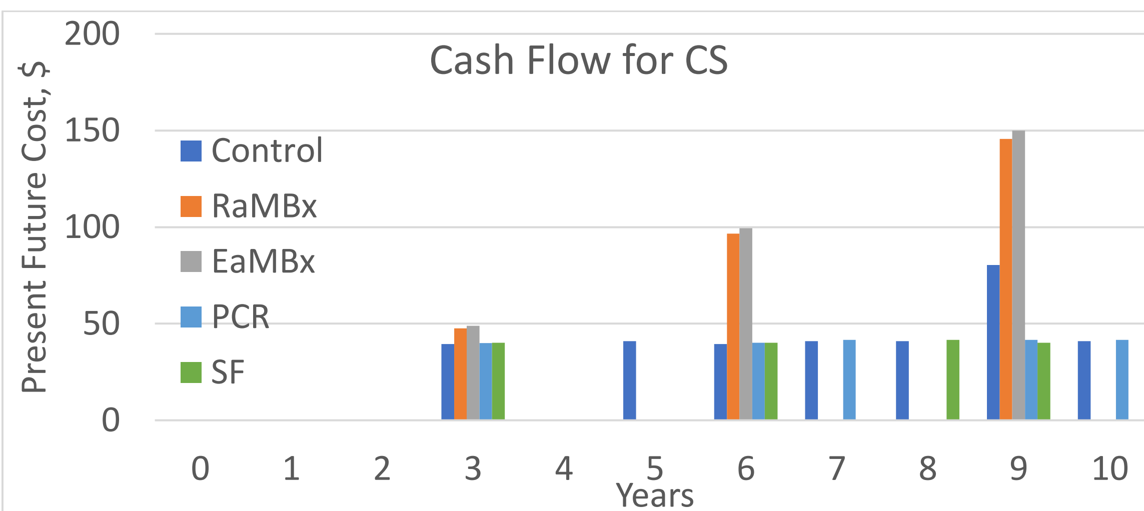
By assuming that both control sealant and filler have a life span of 2 years, the improvements shown in **Table 96** in terms of years were generated and used for the LCCA.

Table 96- Calculated Improvement for CS and CF in Number of Years

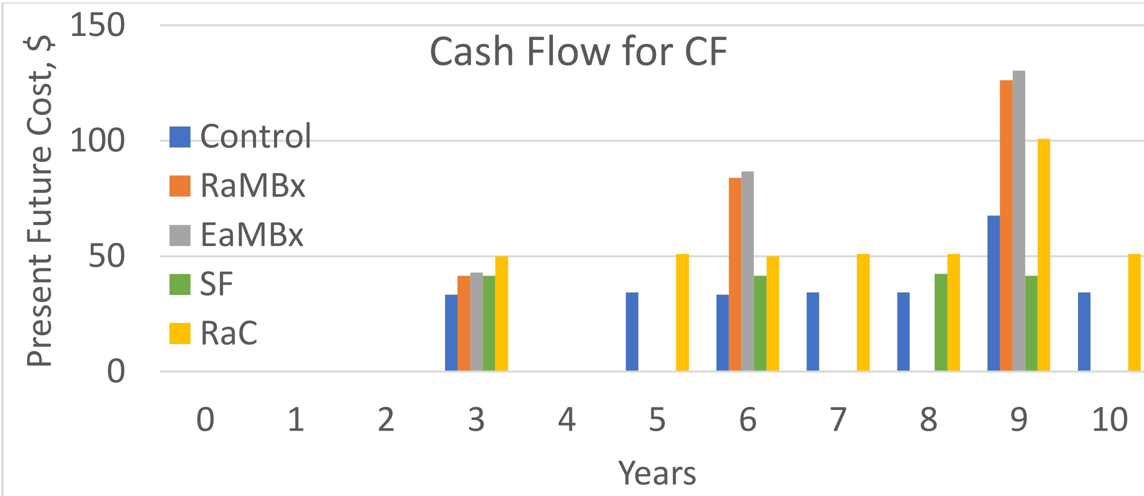
Material Type	CS, Life Span in # Years	CF, Life Span in # Years
Control	2	2
2.5% EaMBx	3	3
5% RaMBx	3	3
5% RaC	<2	2
5% PCR	4	<2
0.5% SF	5	5

For the LCCA, it was also assumed that cracks appeared on the surface of the pavement every 3 years, at a frequency of 6 linear meters. Every 3 years, the old treatment was replaced, and the new cracks were rehabilitated. The total length of the pavement was considered to be 200 meters.

In figure and figure, the cash flow for the 10-year analysis period was presented for both CS and CF, showing the Present Future Value calculated every year. It can be seen that the frequency of maintenance while implementing the modified material was decreased when compared to control, which refers to slower and fewer maintenance activities along the analysis periods.



(a)



(b)

Figure 73- Cash Flows for 10-year Analysis Period for (a) Crack Sealing Materials and (b) Crack Filling Materials

In terms of Net Present Value (NPV), show in **Table 97** and **Table 98**, it can be seen that there is a potential saving when implementing those modifiers across the analysis periods, in addition to less frequent maintenance activities.

Table 97- Net Present Value for CS for both 10 and 20 years

Material Type, CS	Net Present Value, $ for 10 years	Net Present Value, $ for 20 years
Control	221.72	659.83
5% RaMBx	200.55	523.91
2.5% EaMBx	206.34	538.94
5% PCR	141.81	370.68
0.5% SF	115.17	312.48

Table 98- Net Present Value for CF for both 10 and 20 years

Material Type, CF	Net Present Value, $ for 10 years	Net Present Value, $ for 20 years
Control	186.26	742.02
5% RaMBx	174.09	453.92
2.5% EaMBx	179.88	468.95
5% PCR	277.98	824.38
0.5% SF	118.63	263.74

For CS, an average cost saving of 14% was found for using aMBx modification, where PCR yielded an average cost reduction of 40%, and SF of 50%. As for CF, the RaC modification showed an increase in cost, as the cost of this modifier was too high to start. The raw materials used to produce RaC were premium and are not cost efficient at this stage of the study. Concerning the other modifiers, similar cost reductions were observed compared to CS. In conclusion, aMBx, PCR and SF showed potential improvements based on the laboratory test results with significant cost savings and reduced maintenance activities.

CHAPTER 11

11 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

11.1. Summary

Asphalt crack sealing and filling are one of the low-cost maintenance techniques for both asphalt and concrete pavements. When properly installed, they prevent water and debris penetration into the depths of the pavement structure, therefore, extending the life span of the pavement. As cracking is one of the primary pavement distresses, the use of asphalt crack sealants and fillers is essential for early preventive maintenance. Furthermore, the market growth of sealants was estimated to be worth around $861.9 million in 2022, projected to increase to $1.1 billion in 2028, with the biggest shares in North America. For this reason, there is a need to constantly improve the performance of those materials under different climatic traffic conditions targeting the most prominent failure modes seen in the field: adhesive (primarily), cohesive, tracking, and settlement.

Testing protocols were implemented to tackle each failure mode in the Advanced Pavement Laboratory at ASU. Two different materials were evaluated, one used as a crack sealant (CS) and another used as crack filler (CF) in hot a dry climatic conditions. Four different modifiers were used to evaluate potential improvements: Aerogel Modified Bituminous Materials (aMBx), Recycled Aerogel Composite (RaC), Preactivated Crumb Rubber (PCR) and Synthetic Fibers (SF). Those modifiers were chosen as they provide different characteristics: aMBx known for its excellent thermal resistance properties, RaC for the presence of both aerogel and rubber to increase the low temperature flexibility, PCR and SF for both their increased flexibility and strength. Two sources of aerogel were evaluated as part of the aMBx testing, to determine the effectiveness of different sources on the material. The first source had a lighter density and lower thermal conductivity, whereas the second source had larger particles and higher density.

The best modification method and content for each modifier was determined for both CF and CS. The testing protocol included tests relating to strength, rheology, and thermal properties such as softening point, cone penetration test, rotational viscosity, tracking and shear thinning, bending beam rheometer, MSCR, toughness and tenacity, bond strength, thermal parameters (thermal conductivity, specific heat capacity and a novel setup developed in this study for expansion and contraction, CTE) as well as moisture shear thinning.

For the crack sealing results, the optimum content for EaMBx was found to be 2.5% by weight of the material, comparable to the optimum of 5% RaMBx. The results showed reduced thermal susceptibility of the material, lower thermal conductivity and higher specific heat capacity and greatly reduced CTE. The addition of aMBx promoted the lower thermal susceptibility of the material, leading to better performance in terms of shear thinning and tracking at elevated temperatures and improved adhesive properties (as measured by the bond strength and shear thinning and tracking tests). One drawback was observed in terms of moisture susceptibility, where EaMBx was slightly affected by moisture in terms of adhesion to a pavement sample substrate. Further studies are recommended to better assess the effect of water on the modified material. In general, the RaMBx provided more balanced results with reduced stress sensitivity and better relaxation and low temperatures. As the presence of RaMBx yielded to a higher content of aerogel by ratio, the toughness and tenacity of the material decreased, but improved the thermal and moisture susceptibility of the material. This difference could be attributed to the difference in porosity of both materials.

Concerning the RaC modification, the optimum content was found to be 5% by weight of the sealant. However, the presence of both rubber and aerogel made the sealant too stiff to be able to accommodate crack movement, leading to a possible poor performance in the field. Furthermore, reduced toughness, tenacity and recovery were measured, supporting that claim. Despite the good thermal resistance, this modifier may be more suitable for paving rather than sealing activities.

On the other hand, the PCR modification yielded very good laboratory performance results, with increased tenacity, bond strength and recovery while maintaining an acceptable low temperature stiffness. The thermal properties on the other slightly improved due to the natural stiffening of the sealant due to the rubber addition. However, one drawback of the PCR addition was observed in terms of moisture shear thinning, where the adhesion of the material may be compromised with long exposures to moisture.

Finally, for the SF modification, improvements in terms of toughness, tenacity, bonding, and moisture resistance were greatly improved. No thermal improvement was noticed, but favorable performance results were obtained, which translates to better predicted performance in the field. Low temperature behavior was also improved, along with the stress sensitivity, which supports very promising expectations in the field.

Moving on to the modifications of the crack filling material, CF, the results for the aMBx modified material showed a lower temperature susceptibility, improved tracking resistance and comparable performance at lower temperatures. In terms of toughness and tenacity, a light decrease was measured for both RaMBx and EaMBx sources. In terms of bond strength measurements, the EaMBx modified material showed a higher tensile strength under both dry and wet conditions, where the RaMBx showed comparable strength to control CF. In terms of %Jnr Slope or stress sensitivity, the RaMBx modified material showed comparable sensitivity to the control, leading to a slight favor in the terms of aerogel sources. Furthermore, better relaxation capacity was measured at lower temperatures, as well as moisture resistance. With regards to thermal properties, the parameters were more pronounced for the RaMBx modifier, as the larger aerogel size may have contributed to the material.

For the RaC modifier, the filler showed unfavorable performance, due to increased stiffness of the material and reduced flexibility.

As for the PCR modified material, improved performance was measured in terms of toughness, tenacity, bond strength and tracking resistance. In terms of thermal behavior, they remained comparable to the control before and after aging, not affecting the thermal performance of the material. In parking lot situations, the thermal behavior has merit to be improved, which can affect the behavior in extreme conditions for PCR modified filler. It can be concluded that the PCR modification greatly improved the strength and stretchability of the material, leading to better adhesion to the edges of the crack. The major benefit of the addition of PCR into the material was the preservation of the age level of the material. In other words, the crumb rubber absorbed the lightweight fractions present in the sealant, delaying its aging and conserving its unaged properties. Those results were confirmed based on FTIR analyses, where the C=O and S=O bonds before and after aging were obtained. However, the drawback was measured in terms of moisture susceptibility of the material, where both MISTI and the Pull-Out Moisture Susceptibility Index were showing increased susceptibility that may affect the overall performance of the material in heavy rain situations.

Finally, for the SF modified CF, all performance parameters were improved, with exceptional resistance to moisture. The fibers were shown to improve the cohesion of the material, which could lead to reducing moisture penetration and providing reinforcement within the material itself. Increased toughness, tenacity, bonding strength as well as reduction in stress sensitivity all lead to positive field performance prediction. Furthermore, increased thermal conductivity and reduced specific heat capacity promoted the thermal behavior of the filling material. However, at lower temperatures, the material had comparable behavior to control. Given all the measured performance, this material modification is promising.

To determine which modified material would be the best performing one, a TOPSIS analysis was conducted. Four general criteria were evaluated: Flexibility, Strength, Thermal and Moisture resistance. A survey was conducted and sent to both academia and work professionals, ranking those four criteria in order of importance for both roadways and parking lots. The results of this survey were used to develop the TOPSIS analysis and rank the different modified CF and CS according to both hot and cold climates. Based on the tested properties of the materials at optimum contents for each modifier, the importance of the laboratory tested parameters were assigned and the weights were found using an AHP analysis. The final rankings showed that the modifiers did improve the performance of both CF and CS under both climate conditions based on the parameters obtained from laboratory testing.

11.2. Conclusions

Asphalt crack sealant and filler modification is a complex topic, where a lot of factors must be considered such as application method, climatic conditions, and location (either parking lot or roadways). Four different modifiers were introduced into two different sealing materials, to improve their durability and performance in the field following a testing protocol in the laboratory. The first modifier, aMBx, was incorporated into the material. As this material is made of encapsulated aerogel, two different sources of aerogel of different sizes and properties were used to produce the modifier. The effect of those different sources was evaluated, and different outcomes were noted. In general, the EaMBx was produced where more binder was needed to cover the aerogel particles. This phenomenon led to better toughness, tenacity and bonding properties while improving the thermal properties of the material. Given that aerogel is an excellent insulator, reducing the thermal susceptibility of the sealing material would extend its properties, providing more stability in the field. On the other hand, the second aerogel type used to make RaMBx had higher density, larger pore size and needed less binder for coating. The pores were acting as stress absorbing agents, where higher %Recovery and lower stress sensitivity were measured. Furthermore, RaMBx had a higher impact on viscosity, and low temperature stiffness was measured to be higher. It was concluded that the aMBx modification showed promising performance improvements with contents as low as 2.5% by weight of the material. Furthermore, it showed promising enhancements at higher temperatures or hot climate settings.

If aging is of a concern where direct sunlight is an issue and moisture is not present, the addition of PCR was shown to be promising in terms of performance, if those two conditions are met. The addition of PCR was proven to reduce the effect of aging by absorbing the lighter fractions of the sealant and conserving its properties. For CS, PCR showed improved tenacity and good thermal resistance despite the effect of moisture. As for RaC, CS showed better thermal resistance but excessive stiff behavior. The filling material, CF, seemed to better interact with rubber in general, as the results obtained in terms of toughness, tenacity, and low temperature behavior. The thermal properties measured showed a lower thermal conductivity and specific heat capacity, promoting faster setting which could be very beneficial in colder climates. It was concluded that the PCR modification showed good performance overall for hot and cold areas where moisture is not a concern.

On the other hand, for the filling material, aMBx showed improved thermal resistance, tracking and toughness measurements, reflecting a good performance in hot climates. RaC modification showed improved bonding and low temperature performance, but still lower expected performance in terms of toughness and tenacity.

If excessive crack movement and traffic were an issue, the addition of SF showed promising results across all tested parameters, with exceptional moisture resistance. It was concluded that the application of fibers would be beneficial for both types of material and applications. The results obtained based on the 0.5% SF modification for both CF and CS ranked #1, under both cold and hot conditions. Improved flexibility, strength, moisture, and thermal resistance were measured for both materials using SF.

Concerning the design of the CTE test setup, it resulted in robust measurements enough to capture the effect of different modifiers. A lower coefficient of expansion at higher temperatures, when the crack is closing, refers to the material's ability to resist flowing out of the crack. As for low coefficient of contraction, as the crack opens at lower temperatures, the material will resist contracting, leading to enhanced stability.

Based on the obtained laboratory testing and MCDM results, the modified materials deemed promising improved performance in the field. Given that the control materials ranked #5 under both conditions, the modifications are predicted to increase the lifespan of the material depending on the ranking and application method. The TOPSIS ranking successfully showed the results obtained from the laboratory testing: good structure to bring all those complexities to a meaningful and rational solution.

To quantify the actual number of years the material will last, proper field evaluation and placement should be conducted and monitored with the favorable modifier. Finally, the average cost of crack sealing and crack filling were calculated for an average crack size per linear meter, and the cost of each modifier was added according to the optimum content by weight. The aerogel-based modifiers were found to be more on the expensive side. However, this cost could be further reduced depending on the sources of aerogel, which could further encourage its implementation. The conducted LCCA showed a lower net present value and a reduced maintenance activity across the analysis periods of 10 and 20 years, justifying the increased cost added to the control sealant and filler for modification.

Finally, based on the results, there is still room for manufacturers to keep modifying and tweaking the existing material to improve performance.

11.3. Recommendations

For follow up work and future recommendations, the following is offered:

- Introduce the modifications to potential manufacturers and ensure that the modification can be integrated at the formulation level. It may be difficult to consider field or on-site modification as some modifiers require high speed/shear mixing.
- The CTE test setup should be further evaluated for standard procedures and consider changes in the geometry of the material after several thermal cycles.
- To have an accurate LCCA, this study should be supported by field measurements to be able to reflect the improved performance in terms of life span of the material.
- Comparing the modified sealants in this study to other modifications currently present in the market would be helpful to further understand sealant modification at the manufacturer level.
- Field implementation comparing the different modifiers to control under different traffic and climatic conditions would further confirm the results obtained in the laboratory. As the sealant and filler methods of application were not included as part of the study, the other external factors affecting sealant performance must be evaluated.
- Conducting a follow up detailed survey with all the suggested parameters would generate updated results and scores, leading to a better rankings and better understanding of the parameters at hand.

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APPENDIX A

MCDM: TOPSIS OF FACTORS AFFECTING ASPHALT CRACK SEALANT PERFORMANCE

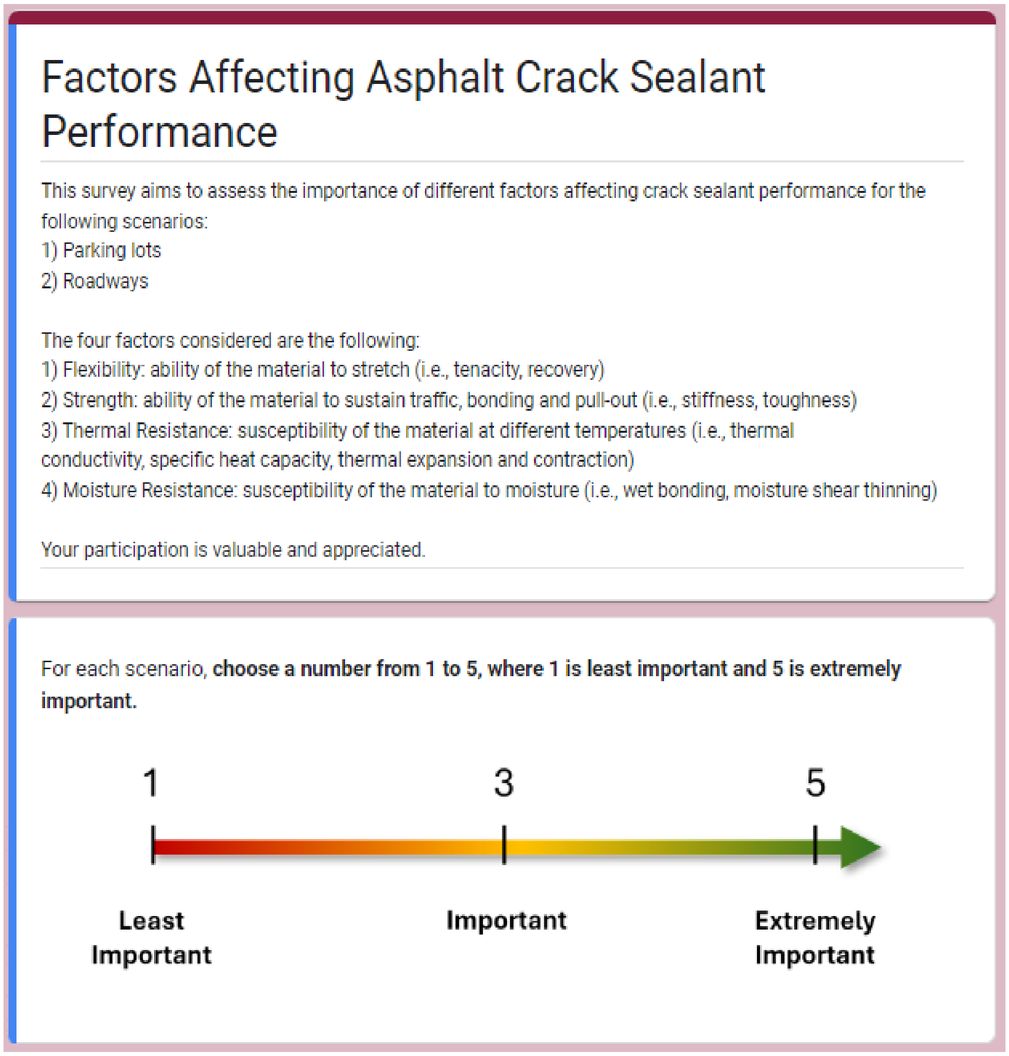
1 TOPSIS: Step by Step

The first step involved in conducting a TOPSIS analysis is to define the alternatives and criteria. Concerning the alternatives, the four modifies at optimum contents were chosen for each CF and CS, and the decision criteria were selected, as described in Chapter 10. The table with all the parameters considered is included at the end of this appendix (**Table 100** and **Table 101**).

The next step required building the decision matrix, with the alternatives as rows and criteria as columns. The matrix was filled with performance scores of each alternative for each criterion. Those performance scores were obtained by the means of a short survey (**Figure 74**) that was sent to academic and field professionals, ranking the four criteria from 1 to 5, 1 being Least important and 5 being Extremely Important.

1.1. Survey Results Analysis

In order to determine the intensity for each of the four criteria, the data collected was processed. The next step involved calculating the difference between the scores for each criterion. This was used as the relative importance of each criterion with respect to the other. The average was found for each relative importance of each criterion for both scenario 1 and scenario 2 (**Figure 75a** and **Figure 75b**).



Factors Affecting Asphalt Crack Sealant Performance

This survey aims to assess the importance of different factors affecting crack sealant performance for the following scenarios:
1) Parking lots
2) Roadways

The four factors considered are the following:
1) Flexibility: ability of the material to stretch (i.e., tenacity, recovery)
2) Strength: ability of the material to sustain traffic, bonding and pull-out (i.e., stiffness, toughness)
3) Thermal Resistance: susceptibility of the material at different temperatures (i.e., thermal conductivity, specific heat capacity, thermal expansion and contraction)
4) Moisture Resistance: susceptibility of the material to moisture (i.e., wet bonding, moisture shear thinning)

Your participation is valuable and appreciated.

For each scenario, **choose a number from 1 to 5, where 1 is least important and 5 is extremely important.**

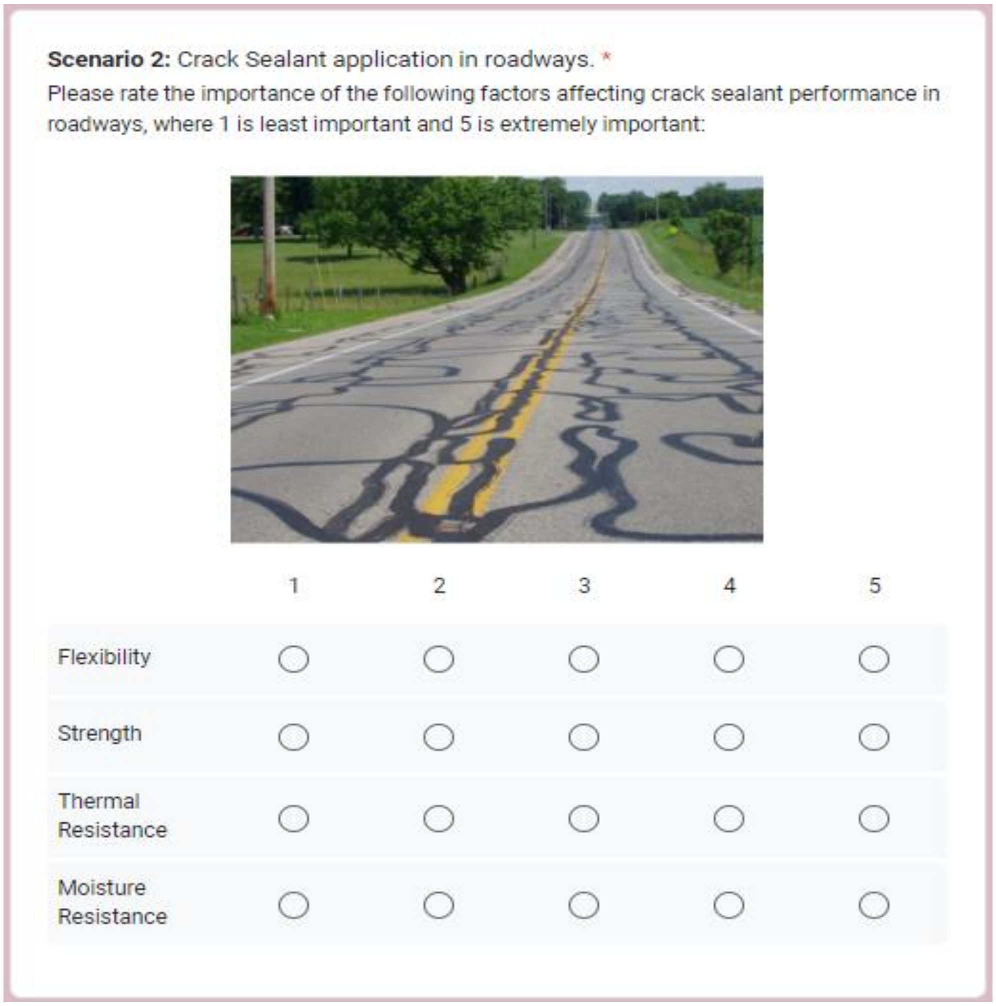
(a)

Scenario 1: Crack Sealant application in parking lots. *

Please rate the importance of the following factors affecting crack sealant performance in a parking lot, where 1 is least important and 5 is extremely important:

	1	2	3	4	5
Flexibility	◯	◯	◯	◯	◯
Strength	◯	◯	◯	◯	◯
Thermal Resistance	◯	◯	◯	◯	◯
Moisture Resistance	◯	◯	◯	◯	◯

(b)



Scenario 2: Crack Sealant application in roadways. *

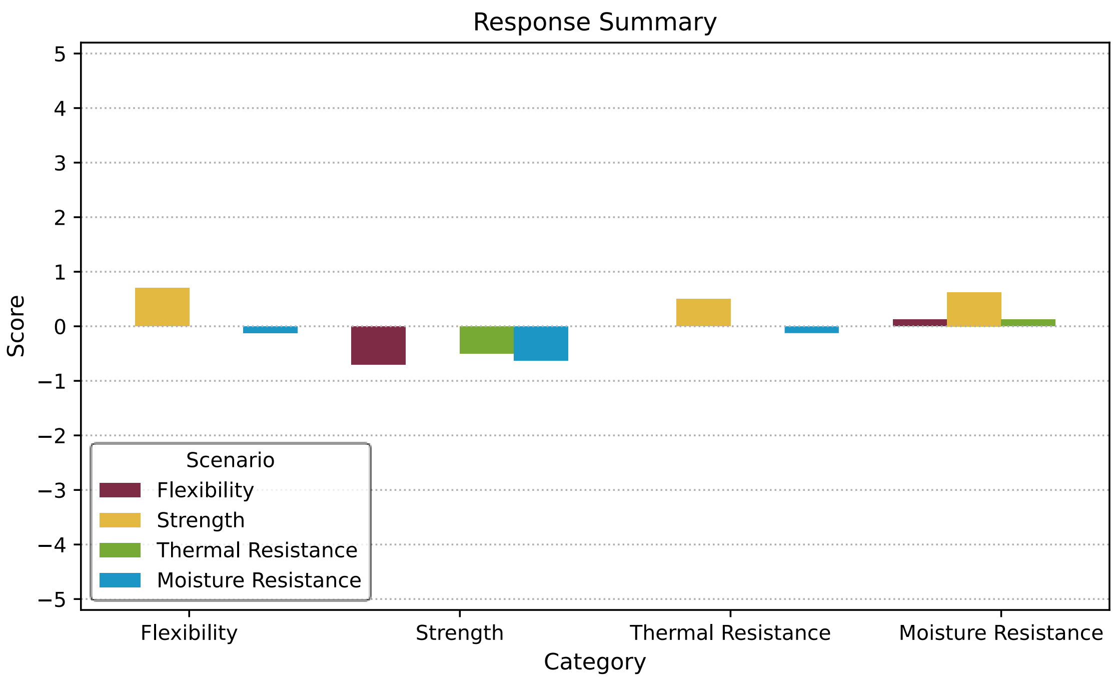
Please rate the importance of the following factors affecting crack sealant performance in roadways, where 1 is least important and 5 is extremely important:

	1	2	3	4	5
Flexibility	○	○	○	○	○
Strength	○	○	○	○	○
Thermal Resistance	○	○	○	○	○
Moisture Resistance	○	○	○	○	○

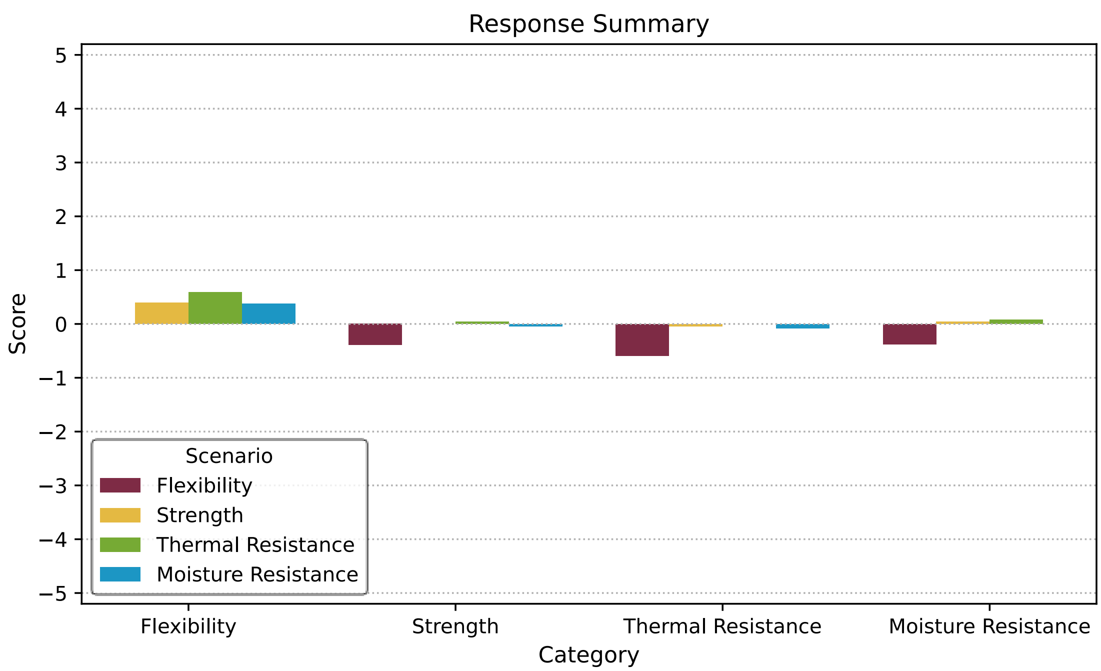
(c)

Figure 74- Survey to Understand the Importance of Factors Affecting Asphalt Crack Sealant Performance in the Field: (a) General Information, (b) Factor Importance for Scenario 1 and (c) Factor Importance for Scenario 2

The average difference of the scores between each criterion was then translated into intensities, ranging from 1 (as equal importance) to 4 (strong importance over the other). The final intensities were summarized for each scenario **Table 90** and **Table 91** in Chapter 10 for scenario 1 and 2 respectively.



(a)



(b)

Figure 75- Survey Results Average Difference Scores Between Each Criterion: (a) for Scenario 1 and (b) for Scenario 2

1.2. AHP Analysis

After assigning the intensities for the major criteria, the parameters within each criterion were then assigned individual intensities based on the two scenarios and climatic conditions: hot and cold. The final decision matrices for each scenario and climatic conditions were included at the end of this appendix in **Table 102**, **Table 103**, **Table 104** and **Table 105**.

The decision matrices were then used to find the corresponding weights for each parameter according to the AHP analysis. Those weights were obtained by finding the eigenvectors and eigenvalues of the pairwise comparison matrix. The eigenvectors corresponding to the largest eigenvalue represent the relative weights of the options in the decision-making process. Those weights were normalized to sum up to a value of 1 and summarized in **Table 88** in Chapter 10 of this document.

1.3. TOPSIS

After identifying the weights for each criterion and parameter within the criterion, the ideal positive and ideal negative solutions were found. Those translate into representing the best possible performance for each parameter. In other words, based on the climatic conditions, the parameters within each criterion were chosen to be either better at higher values or low values, depending on the scenario. For example, stiffness is better to increase in hot climates and decrease in cold conditions. A summary of those definitions is shown in **Table 99**:

Table 99- Category Definitions for Each Parameter

Parameters	Cold Climate	Hot Climate
	The More the Better	The More the Better
Tenacity	1	1
%Jnr Slope	0	0
m-value	1	1
Stiffness	0	1
Dry Bond	1	1
Toughness	1	1
Shear Thinning	1	1
k	0	0
Cp	1	1
CTE	0	0
VTSi	0	0
MISTI	0	0
Wet Bond	1	1
Pull-Out Moisture Susceptibility Index	1	1

The same procedure was followed for both Scenarios 1 and 2, for cold and hot climates. After obtaining the weights for each parameter, they were used to complete the TOPSIS analysis and obtain the final ranking.

The distances to the ideal solutions were then calculated for each alternative, based on the Euclidean distance to the ideal positive and ideal negative based on the weighted and normalized decision matrix. Finally, the relative closeness to the ideal positive solution divided by the relative closeness to the ideal negative solution was found.

The alternatives were finally ranked based on the relative closeness, referred to as Final score, with the highest indicating the best option.

Table 100- Parameters Included for Analysis with Values for Scenario 1, Parking Lot, Crack Filler

Material Type/ Parameters	VTSi	Shear Thinning	Toughness	Tenacity	Dry Bond	Wet Bond	Pull-Out Moisture Susceptibility Index	%Jnr Slope	Stiffness	m-value	k	Cp	CTE	MISTI
CF - Control	1.90	0.75	3124	1855	2337	1620	-0.31	1.19	247	0.39	0.22	1059	3.09E-05	1.28
CF - 2.5% EaMBx	1.87	0.84	3803	1607	3815	3298	-0.14	5.68	333	0.34	0.20	1384	2.35E-05	1.24
CF - 5% RaMBx	1.79	0.78	2915	1875	1954	1678	-0.14	2.26	285	0.39	0.13	1432	2.40E-05	1.07
CF - 5% RaC	1.72	0.85	1529	600	2068	1958	-0.05	5.95	185	0.35	0.21	1190	2.53E-05	1.27
CF - 5% PCR	2.30	0.82	3190	2073	1933	1149	-0.41	4.83	92	0.30	0.16	861	2.56E-05	1.65
CF - 0.5% SF	2.04	0.75	4225	2647	2149	3803	0.77	1.80	320	0.25	0.19	1121	2.90E-05	1.12

Table 101- Parameters Included for Analysis with Values for Scenario 2, Roadways, Crack Sealant

Material Type/ Parameters	VTSi	Shear Thinning	Toughness	Tenacity	Dry Bond	Wet Bond	Pull-Out Moisture Susceptibility Index	%Jnr Slope	Stiffness	m-value	k	Cp	CTE	MISTI
CS - Control	2.12	0.78	2531	1715	1011	919	-9%	7.11	57	0.36	0.11	1173	2.19E-05	1.09
CS - 2.5% EaMBx	2.09	0.79	3184	2131	1423	1184	-17%	6.39	43	0.34	0.06	1324	1.65E-05	1.09
CS - 5% RaMBx	2.03	0.79	1493	1275	925.1	890.2	-4%	1.34	65	0.42	0.07	1170	1.76E-05	1.02
CS - 5% RaC	1.85	0.79	1067	540	1344	1207	-10%	5.57	53	0.35	0.13	1374	1.70E-05	1.29
CS - 5% PCR	2.16	0.78	2117	3389	1023	1034	1%	4.99	69	0.37	0.11	1608	1.87E-05	1.66
CS - 0.5% SF	2.12	0.82	3341	2807	1133	1350	19%	3.23	76	0.33	0.11	1210	2.08E-05	1.06

Table 102- Pairwise Decision Matrix with Intensities for Scenario 1, Hot Conditions Using CF

Sc1, Hot Conditions, CF	Tenacity	%Jnr Slope	m-value	Stiffness	Dry Bond	Toughness	Shear Thinning	k	Cp	CTE	VTSi	MISTI	Wet Bond	Pull-Out Moisture Susceptibility Index
Tenacity	1	0.33	3	3	3	3	3	1	1	1	1	0.5	0.5	0.5
%Jnr Slope	3	1	3	3	3	3	3	1	1	1	1	0.5	0.5	0.5
m-value	0.33	0.33	1	0.33	3	3	3	1	1	1	1	0.5	0.5	0.5
Stiffness	0.33	0.33	3	1	3	3	3	1	1	1	1	0.5	0.5	0.5
Dry Bond	0.33	0.33	0.33	0.33	1	3	0.33	0.33	0.33	0.33	0.33	0.25	0.25	0.25
Toughness	0.33	0.33	0.33	0.33	0.33	1	0.33	0.33	0.33	0.33	0.33	0.25	0.25	0.25
Shear Thinning	0.33	0.33	0.33	0.33	3	3	1	0.33	0.33	0.33	0.33	0.25	0.25	0.25
k	1	1	1	1	3	3	3	1	0.33	0.33	0.33	0.5	0.5	0.5
Cp	1	1	1	1	3	3	3	3	1	0.33	0.33	0.5	0.5	0.5
CTE	1	1	1	1	3	3	3	3	3	1	0.33	0.5	0.5	0.5
VTSi	1	1	1	1	3	3	3	3	3	3	1	0.5	0.5	0.5
MISTI	2	2	2	2	4	4	4	2	2	2	2	1	0.33	0.33
Wet Bond	2	2	2	2	4	4	4	2	2	2	2	3	1	0.33
Pull-Out Moisture Susceptibility Index	2	2	2	2	4	4	4	2	2	2	2	3	3	1

Table 103- Pairwise Decision Matrix with Intensities for Scenario 1, Cold Conditions Using CF

Sc1, Cold Conditions, CF	Tenacity	%Jnr Slope	m-value	Stiffness	Dry Bond	Toughness	Shear Thinning	k	Cp	CTE	VTSi	MISTI	Wet Bond	Pull-Out Moisture Susceptibility Index
Tenacity	1	3	3	3	3	3	3	1	1	1	1	0.5	0.5	0.5
%Jnr Slope	0.33	1	0.33	0.33	3	3	3	1	1	1	1	0.5	0.5	0.5
m-value	0.33	3	1	3	3	3	3	1	1	1	1	0.5	0.5	0.5
Stiffness	0.33	3	0.33	1	3	3	3	1	1	1	1	0.5	0.5	0.5
Dry Bond	0.33	0.33	0.33	0.33	1	3	3	0.33	0.33	0.33	0.33	0.25	0.25	0.25
Toughness	0.33	0.33	0.33	0.33	0.33	1	3	0.33	0.33	0.33	0.33	0.25	0.25	0.25
Shear Thinning	0.33	0.33	0.33	0.33	0.33	0.33	1	0.33	0.33	0.33	0.33	0.25	0.25	0.25
k	1	1	1	1	3	3	3	1	1	0.33	0.33	0.5	0.5	0.5
Cp	1	1	1	1	3	3	3	1	1	1	1	0.5	0.5	0.5
CTE	1	1	1	1	3	3	3	3	1	1	1	0.5	0.5	0.5
VTSi	1	1	1	1	3	3	3	3	3	1	1	0.5	0.5	0.5
MISTI	2	2	2	2	4	4	4	2	2	2	2	1	0.33	1
Wet Bond	2	2	2	2	4	4	4	2	2	2	2	3	1	1
Pull-Out Moisture Susceptibility Index	2	2	2	2	4	4	4	2	2	2	2	1	1	1

Table 104- Pairwise Decision Matrix with Intensities for Scenario 2, Hot Conditions Using CS

Sc 2, Hot Conditions, CS	Tenacity	%Jnr Slope	m-value	Stiffness	Dry Bond	Toughness	Shear Thinning	k	Cp	CTE	VTSi	MISTI	Wet Bond	Pull-Out Moisture Susceptibility Index
Tenacity	1	0.33	3	3	3	3	3	4	4	4	4	3	3	3
%Jnr Slope	3	1	3	3	3	3	3	4	4	4	4	3	3	3
m-value	0.33	0.33	1	0.33	3	3	3	4	4	4	4	3	3	3
Stiffness	0.33	0.33	3	1	3	3	3	4	4	4	4	3	3	3
Dry Bond	0.33	0.33	0.33	0.33	1	3	0.33	1	1	1	1	1	1	1
Toughness	0.33	0.33	0.33	0.33	0.33	1	0.33	1	1	1	1	1	1	1
Shear Thinning	0.33	0.33	0.33	0.33	3	3	1	1	1	1	1	1	1	1
k	0.25	0.25	0.25	0.25	1	1	1	1	0.33	0.33	0.33	1	1	1
Cp	0.25	0.25	0.25	0.25	1	1	1	3	1	0.33	0.33	1	1	1
CTE	0.25	0.25	0.25	0.25	1	1	1	3	3	1	0. 0.33	1	1	1
VTSi	0.25	0.25	0.25	0.25	1	1	1	3	3	3	1	1	1	1
MISTI	0.33	0.33	0.33	0.33	1	1	1	1	1	1	1	1	0.33	0.33
Wet Bond	0.33	0.33	0.33	0.33	1	1	1	1	1	1	1	3	1	0.33
Pull-Out Moisture Susceptibility Index	0.33	0.33	0.33	0.33	1	1	1	1	1	1	1	3	3	1

Table 105- Pairwise Decision Matrix with Intensities for Scenario 2, Cold Conditions Using CS

Sc 2, Cold Conditions, CS	Tenacity	%Jnr Slope	m-value	Stiffness	Dry Bond	Toughness	Shear Thinning	k	Cp	CTE	VTSi	MISTI	Wet Bond	Pull-Out Moisture Susceptibility Index
Tenacity	1	3	3	3	3	3	3	4	4	4	4	3	3	3
%Jnr Slope	0.33	1	0.33	0.33	3	3	3	4	4	4	4	3	3	3
m-value	0.33	3	1	3	3	3	3	4	4	4	4	3	3	3
Stiffness	0.33	3	0.33	1	3	3	3	4	4	4	4	3	3	3
Dry Bond	0.33	0.33	0.33	0.33	1	3	3	1	1	1	1	1	1	1
Toughness	0.33	0.33	0.33	0.33	0.33	1	3	1	1	1	1	1	1	1
Shear Thinning	0.33	0.33	0.33	0.33	0.33	0.33	1	1	1	1	1	1	1	1
k	0.25	0.25	0.25	0.25	1	1	1	1	1	0.33	0.33	1	1	1
Cp	0.25	0.25	0.25	0.25	1	1	1	1	1	1	1	1	1	1
CTE	0.25	0.25	0.25	0.25	1	1	1	3	1	1	1	1	1	1
VTSi	0.25	0.25	0.25	0.25	1	1	1	3	3	1	1	1	1	1
MISTI	0.33	0.33	0.33	0.33	1	1	1	1	1	1	1	1	0.33	1
Wet Bond	0.33	0.33	0.33	0.33	1	1	1	1	1	1	1	3	1	1
Pull-Out Moisture Susceptibility Index	0.33	0.33	0.33	0.33	1	1	1	1	1	1	1	1	1	1