Evaluation of Bio-Fog Sealants for Pavement Preservation

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June 2016

Research Project
Final Report 2016-20

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Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.
MN/RC 2016-20		

4. Title and Subtitle	5. Report Date
Evaluation of Bio-Fog Sealants for Pavement Preservation	June 2016
	6.
7. Author(s) Debaroti Ghosh, Mugur Turos, Mihai Marasteanu	8. Performing Organization Report No.
9. Performing Organization Name and Address Civil, Environmental and Geo- Engineering University of Minnesota, Twin Cities 500 Pillsbury Drive, Minneapolis, MN	10. Project/Task/Work Unit No. 2015011 11. Contract (C) or Grant (G) No. (c) 99008 (wo) 148
12. Sponsoring Organization Name and Address Local Road Research Board Minnesota Department of Transportation Research Services & Library 395 John Ireland Boulevard, MS 330 St. Paul, Minnesota 55155-1899	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes
http://www.lrrb.org/PDF/201620.pdf

16. Abstract (Limit: 250 words)

Pavement preservation is playing an increasingly significant role in maintaining our aging pavement infrastructure. One important component is the application of sealants to the pavement surface. In a joint study between MnDOT and the University of Minnesota, the field performance and mechanical properties of asphalt mixtures from pavement sections treated with a number of new products, called bio sealants, is investigated. The objective of the study is to obtain relevant properties of treated asphalt materials to understand the mechanism by which sealants improve pavement performance. Laboratory testing was performed on treated asphalt binder and mixtures. For binders, a dynamic shear rheometer and a bending beam rheometer were used to obtain rheological properties of treated and untreated asphalt binders. Field cores from both untreated and treated sections were collected and thin beam specimens were prepared from the cores to compare the creep and strength properties of field-treated and laboratory-treated asphalt mixture. It is observed that the oil-based sealants have a significant softening effect on the control binder compared to the water-based sealants. For asphalt mixtures, different trends are observed for the field samples compared to the laboratory prepared samples. Similar to binder results, significant differences are observed between the asphalt mixtures treated with oil-based and water-based sealants, respectively. From the analysis performed on the bending creep and strength results at low temperature, it is concluded that the application of sealants in the field have no significant effect on these properties. Fourier transform infrared spectroscopy (FTIR) analysis showed that the sealant products could not be detected in mixture samples collected from the surface of the treated section.

17. Document Analysis/Descriptors	18. Availability Statement
pavement maintenance, sealing compounds, rheological properties, Fourier transforms, infrared spectroscopy	No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	86	

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June 2016

Published by:

Minnesota Department of Transportation
Research Services & Library
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

ACKNOWLEDGMENTS

The support provided by Minnesota Local Road Research Board and Minnesota Department of Transportation is gratefully acknowledged..

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EXECUTIVE SUMMARY

In this project, four sealant products were evaluated using experimental laboratory testing. The products were oil-based RePlay and Biorestor, and water-based Jointbond and CSS-1h. Cores were obtained from the control and treated sections of CSAH 75 in Wright County, Minnesota within the boundaries of State Aid Project 086-675-018.

The effect of the sealants on binder's performance grade was investigated by performing Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR) laboratory tests. To prepare the testing samples, two procedures were used for applying the sealant: simple-mixing and pipette method. The pipette method is a laboratory-developed brushing procedure in which the sealant is applied using a pipette in a controlled amount based on the field application rate. The performance grade (PG) of the virgin and treated binders was determined in accordance with AASHTO M320 and it was found that the simple mixing procedure results in significant softening of the treated binders. The brushing method produced results more consistent with field observations. The largest softening effect was noticed on the binder treated with oil-based RePlay and Biorestor, respectively.

BBR asphalt mixture beam specimens were prepared from the field cores from both the control and treated sections. The beams were then tested using a BBR Pro device to obtain creep and strength properties of field-treated and laboratory-treated asphalt mixtures. The laboratory treated samples were prepared using the pipette method used for binder testing, an application process that mimics the spraying of sealant in actual field conditions. The field-treated samples were tested after one year of sealant application, whereas the laboratory treated samples were tested after one month of sealant application in the laboratory.

Analysis of the results showed that the application of sealants in the field had no significant effect on most of the material properties evaluated in this project. For the laboratory treated samples, significant differences were observed for almost all material properties. FTIR analysis on samples from the surface of the cores supported the laboratory findings. No measurable traces of sealant were detected in field-treated samples, while the presence of sealants was detected in the laboratory-treated samples.

Due to the limited set of materials evaluated in this project, more research is needed to understand why the application of these products in field conditions does not appear to significantly affect the properties of the asphalt materials at the surface of the pavement.

CHAPTER 1: INTRODUCTION

1.1 Background

Pavement preservation is playing an increasingly significant role in maintaining our aging pavement infrastructure under severe budget constraints. One important component is the use of surface treatments based on application of sealants. Recently, a number of new products, called bio sealants, have been used to treat pavement surfaces. A number of field studies were conducted to evaluate if the application of these products improve pavement performance and the conclusions were mixed with regard to the usefulness of these products. At this time, there are no published studies focused on investigating how the application of these new sealants affect relevant properties of materials at the surface of asphalt pavements.

1.2 Objective

The aim of this study is to evaluate relevant properties of asphalt materials treated with sealant products to better understand the mechanism by which sealants improve pavement performance. This information is critical in performing life cycle analyses of these products to help city and county engineers make informed decisions about the use of sealants for their road network.

The proposed research consists of developing laboratory sample preparation method that can simulate the application procedure of sealants in the field and performing experimental investigation on field samples obtained from cores and on laboratory prepared samples. For asphalt binders, rheological and fracture properties are obtained using Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR) testing methods. For asphalt mixtures, BBR creep and strength test are performed at low temperature. Statistical analyses of the experimental results are used to evaluate the effect of applying different types of sealants to the control asphalt binder and asphalt mixture. Investigating the feasibility of using semi-empirical methods to predict mixture properties from binder properties is also included in this research.

1.3 Organization of the Report

The objective and motivation towards this study were presented in Chapter 1. Chapter 2 provides a literature review of current efforts in the area of pavement preservation. Chapter 3 describes the materials used in the investigation and the testing protocols used to obtain rheological and strength properties of the investigated materials. The results of asphalt binder testing are presented in Chapter 4, and the results of asphalt mixture testing are presented in Chapter 5. Analyses of the results from the previous two chapters, as well as the application of Hirsch model to the data, are presented in Chapter 6. Chapter 7 contains the study conclusions and recommendations for future work.

CHAPTER 2: LITERATURE REVIEW

Recently, a number of new products have been introduced as alternative surface sealant for streets, highways, shoulders, and recreation trails. Asphalt-based fog sealants have been successfully used for surface treatments for many years. However, harmful sealants, such as coal tar-based products, have been banned by the Minnesota Legislature since January 1, 2014. These sealants contain high concentrations of chemicals called polycyclic aromatic hydrocarbons (PAHs), and environmental mixtures of PAHs are generally carcinogenic. A study by Minnesota Pollution Control Agency revealed that about 67% of total PAHs in the sediments of 15 metro-area storm-water ponds were from coal tar-based sealants. An overview of current practice for preventive maintenance activities using fog seal and new type of sealants or rejuvenators are presented below.

Pennsylvania department of transportation conducted a research project on evaluating a new soy-based sealer named RePLAY, developed by BioSpan Technologies *(1)*. RePLAY, an Agricultural Oil Seal & Preservation Agent is an asphalt sealant which is 88% biobased and 40% of which is sourced from soybean oil *(2)*. This product was reported to be very effective in drastically reducing the presence of air (for oxidation) and water into the pavement. The oil increases the flexibility of the aged, brittle pavements penetrating deep into the surface of the pavement with an average of 0.75 to 1.25 inches, and thus adding lost oil to the asphalt *(1)*. This results in adding years to the service life of asphalt surfaces, filling cracks, and reducing the oxidation process of the roadway, when applied every 3-5 years. According to the manufacturer, the process of introducing new SBS and SBBS polymers to the mix has made RePLAY exceptional from other conventional surface sealants. It is claimed by the BioSpan Technology that the product contains approximately 15% polymers, which increase the resistance to raveling, rutting, and cracking and thus strengthen the pavements *(2)*. The objective of the research project by PennDOT was to evaluate RePLAY's effectiveness at reducing permeability without reducing durability or skid resistance to unacceptable level *(1)*. As a result, a series of skid tests, field observations and a permeability test were planned in order to evaluate and determine the performance of the RePLAY. The RePLAY was applied by the company representatives using their own equipment following the manufacturer's specifications. The product smelled like citrus degreaser and developed a glossy and slippery surface to walk on. The effect of application of the product was noticeable within minutes, softening the asphalt surface and the joint seals and with the changes in color. Only some coarse aggregates were observed to be wet after 15 minutes. The researchers drove over the treated asphalt surface and braked aggressively several times after 35 minutes. The road was open just after an hour and five minutes later of the application of the BioSpan-RePLAY. Similar type of observations were also made in a similar project of evaluating treated pavements using RePLAY which was funded by Minnesota Local Road Research Board (LRRB) and conducted in 2011 *(3)*.

Three cores were taken in the treated lane with BioSpan-RePLAY, and three cores were taken from the adjacent untreated lane for the project conducted by PennDOT *(1)*. Permeability tests were performed on both types of cores to determine the change. Skid testing values were obtained prior to the application of the product, two weeks after the application and at the end of the project. The permeability tests were conducted as per ASTM PS 129 method *(4)*. Permeability was found not to be an issue, because both the treated and untreated cores were found to be impermeable. The coefficient of the water permeability was determined to be the same for both experimental and control sections. A significant loss in friction and reflectivity of pavement markings were observed in the treated pavement even after two weeks of the application of the product. There was no visible evidence of the application of BioSpan-RePLAY after 18 months of the application. Same deterioration was observed in winter for both the treated and untreated sections. The BioSpan Technologies claimed that the use of RePLAY for 3-5 years substantially saves the high cost of repaving *(2)*. However, PennDOT concluded that safety concerns associated with the use of RePLAY as pavement sealers, along with inconclusive evidence of having a benefit to extend pavement life, outweighed the benefits of its use.

Two sections of very different pavement conditions were selected for the Minnesota LRRB project *(3)*. One of the sections was a fifteen years old, cracked and raveled bicycle/pedestrian trail, and the other was a driveway without any distresses constructed within the last five years. The application of the RePLAY followed the same procedure, as mentioned before, according to the manufactures specification. A significant difference was observed in the behavior of water when applied to both newer and older pavement, respectively, before and after application of RePLAY *(3)*. The water was more prone to penetrate in to the older bicycle/pedestrian trail than in to the newer driveway before application of RePLAY. Once the RePLAY was applied, water ran off the paved surfaces at a high rate of speed without wicking in to the surface, for both new and old pavements. This observation contradicts the observation from the PennDOT project that equal permeability was measured in the pavements before and after the application of RePLAY *(2)*. The authors of the LRRB report mentioned that visual inspections of pavements prior to and after application of RePLAY also confirmed about the top layer of asphalt getting sealed after the application *(3)*. This was a helpful observation for the pavements experiencing high foot/ pedestrian traffic all year long, especially in hottest weather. The conventional sealants were observed to have the problems of becoming soft and sticky during hot weather periods and thus affecting pedestrian traffic negatively. The equipment needed to apply the RePLAY included a sprayer and a flatbed truck. The truck is very common for most agencies and the sprayer would cost between $15,000 and $20,000. The application of the product can be performed by only two people and requires very little traffic control. As restriping pavement is not mandatory after the application of RePLAY, it makes the process less expensive than applying chip seal coating where there are pavement markings. The application cost of RePLAY using contract labor results has an equivalent cost of applying a chip seal coat and it appears to be more cost-effective in some cases.

Recently, BioBasedNews.com published an article on the benefits of using RePLAY at Tyndall Air Force Base in Florida *(2)*. The manufacturer stated that airports are extremely environmentally sensitive because of jet fuels, vehicle exhausts, and the demand for electrical power and heating and cooling puts a tremendous stress on the environment *(2)*. RePLAY is considered as an environment friendly surface sealant.

The Flexible Pavement Division of the Central Road Research Institute (CRRI) of New Delhi, India released a report from April 2010 on their research evaluating BioSpan premier asphalt product, RePLAY, Agricultural Oil Seal and Preservation Agent *(2)*. As described in the report, field tests were conducted by CRRI team on a six-lane toll road in July 2009, and after allowing eight weeks for RePLAY to fully penetrate, 24 core samples, 12 unmodified and 12 modified with RePLAY were collected. Through the analysis of the collected samples using ASTM International standards, RePLAY was proved to be a sealant that improves the properties of bitumen present in the road surface and bituminous mix *(2)*.

A project by Maine DOT was carried out to determine if JOINTBOND® extends the useful life of the construction joint by reducing permeability at the joint *(5)*. JOINTBOND, manufactured by D&D Emulsion, Inc., and distributed by Pavement Technology, Inc., is a post-applied polymerized maltene-based emulsion product composed of a petroleum resin oil base and SBR copolymer uniformly emulsified with water *(6)*. This product penetrates the pavement's surface and affects the chemistry of the in-place asphalt binder to help prevent joint deterioration and separation. JOINTBOND was designed to help minimize asphalt maintenance by penetrating newly placed asphalt pavement and stabilizing the critical area surrounding the longitudinal construction joint *(5)*. A total of 11 miles were treated in this project. The treated area appeared as a darkened stain on the centerline joint at this point, the day after treatment. According to the manufacturer, the pavement should show little sign of the treatment and no damage to the pavement markings. The product/ installation is expected to be evaluated by the Transportation Research Division over a two-year period for effectiveness through being monitored for signs of joint degradation and permeability at the centerline joint. The investigation initially reported that the JOINTBOND product changed the white lines to a more yellow color.

A similar study was conducted by University of Arkansas on HMA longitudinal joint evaluation and construction in 2011 *(6)*. The authors of the study used field core density and field permeability, as well as infiltration, as reasonable indicators of joint quality. The study investigated a number of joint construction techniques, to generate a recommendation for appropriate methods that can be used to improve longitudinal joint quality, which can be easily implemented within an existing quality control/quality assurance (QC/QA) program. Among eight construction joint techniques, only the JOINTBOND product appeared to both increase density and decrease permeability, though the method of application did not intuitively cause the anticipation of an increase in density *(6)*.

Zubeck et al. (2012) found that crack sealing and patching represent the most extensively used applications in pavement preservation treatments, followed by chip seals, fog seals, and slurry seals *(7)*. If the aggregate is not properly embedded into the substrate, snow plough damage may occur during the winter months. As a solution for mitigation of winter pavement damage, Croteau et al. (2005) suggested the use of multi-layer systems with fine aggregate or use of premium binder *(8)*. Wood and Olson (2007) presented a history of the chip seal program at Minnesota Department of Transportation (MnDOT) that resulted in significant improvements and a successful implementation *(9)*. MnDOT currently uses chip seals for both high and low traffic roads. On an existing road, they can be used to seal cracks, provide a new wearing course, and provide protection from sunlight and moisture. The average service life was noticed to increase in the 1990's from 5-7 years to 8-10 years *(9)*.

Gransberg (2005) summarized a survey of U.S. public highway and road agencies that use chip seals as a part of their roadway maintenance program *(10)*. A total of 72 individual responses from 42 U.S. states and 12 U.S. cities and counties were received as mentioned in the study *(10)*. A single layer of asphalt binder covered by embedded aggregate (one stone thick) is generally referred to as a chip seal (also called a “seal coat”). The primary purpose of the chip seal is to seal the fine cracks in the underlying pavement’s surface and prevent water intrusion into the base and sub-grade. Bleeding was the major problem reported as long-term distress that appears in chip-sealed roads *(10)*. Bleeding can best be controlled by rigorous quality control testing and monitoring of construction procedures. From the survey, it was found that the major cause of early failure after construction is weather related (e.g., rain or an unexpected temperature drop). It was also found that damage caused by loose stone is the major public or user complaint *(10)*. Eleven of 14 programs describe the pavement ride of their roads as either good or excellent after sealing. Finally, these programs also follow up their seals with routine crack sealing and some-times fog sealing to maintain the integrity of the asphalt membrane for the life of the seal *(10)*. The survey concluded that the chip seal can be successfully used on high-volume roads if it is installed before pavement distress becomes severe or the structural integrity of the underlying pavement is breached *(10)*.

James (2006) described the components and characteristics of some sealers *(11)*. He mentioned that aggregate reactivity is mostly associated with the very finest-size fractions which make the highest contribution to surface area. As a consequence, a reactive rapid-setting emulsion is used with the low-surface area unreactive aggregates used in chip seal.

Simpson (2006) presented an overview of the application of asphalt emulsion which includes the description of various conventional sealants which are used in North America for pavement maintenance, such as scrub seals, chip seals and slurry seals *(12)*. Scrub seals, an effective surface treatment for oxidized or distressed pavements, function by sealing fine cracks prior to application of surface chips or by creating a mastic seal on distressed pavements *(12)*. Chip seals, an effective maintenance tool for restoring a wearing course to a pavement, prevent ingress of moisture into a pavement or base course and can prevent deterioration due to oxidative aging of a pavement. Slurry seals, which represent fine aggregate emulsion mixes, provide a smooth to moderately textured surface for low-speed, low-traffic volume streets and roads. Slurry seals cure quickly and have the advantage over chip seals of being water-based systems that produce no dust or loose chip during resurfacing as stated by Simpson (2006) *(12)*. Cape seals and cape scrub seals were designated as multiple application surface treatments. Multiple application surface treatments are new construction sealing in rural areas that include double and triple chip seals. Cape seals consist of an application of slurry seal or micro-surfacing placed over a chip sealed surface as described in the study *(12)*. The chip seal is placed to ensure sealing and waterproofing of the existing surface, whereas, the slurry or micro-seal is placed over the chip seal to eliminate the risks associated with loose chips as well as to establish the desired surface texture. Fog seals are low-cost and are used to restore “flexibility” to an existing HMA pavement surface *(12)*. The need for a surface treatment or non-structural overlay can be postponed due to the use of fog seals. The author mentioned that fog seals are the most cost-effective preventive maintenance tool and should be considered for routine maintenance programs *(12)*. Lee and Shields (2010) stated that crack sealing should not be performed on wet surfaces due to problems with adhesion between the crack face and seal or fill material *(13)*. They recommended an operation temperature of close to 4.5°C. Fog seals, scrub seals, flush seals, chip seals and Ultrathin Bonded Wearing Course (UBWC) need to be applied at temperatures > 15°C.

Mogawer et al. (2013) focused on the use of asphalt rejuvenators in high RAP and RAS mixtures to offset the stiffness effects of the aged binder from RAP and RAS without negatively impacting the performance of the mixtures *(14)*. These rejuvenators may help the hardened binder from the RAP/RAS comingle with the virgin binder. In the study, three locally used rejuvenators, with different chemical compositions, were added to a PG 58-28 virgin binder and performance grading and viscosity tests were conducted. The three rejuvenators are BituTech RAP, SonneWarmix RJT and Sonne Warmix RJ. A decrease in viscosity of the virgin binder was observed from the study with addition of rejuvenators *(14)*. The rheological properties obtained from generating master curves along with the results from LAS and MSCR tests confirmed that the rejuvenators had a softening effect on the virgin binders and reduced the stiffness of the binders. For example, the results from the MSCR test showed a decrease in rutting resistance with addition of rejuvenators. The results from Hamburg Wheel Tracking Device (HWTD) also indicated that the rejuvenators increased the rutting and moisture susceptibility of the 40% RAP and 5% RAS as well *(14)*.

A similar type of study was performed by Lin et al. (2013) who investigated the influence of using rejuvenator sealer materials on aged asphalt binder *(15)*. The effect of two different types of rejuvenators composed of a petroleum solvent and a rejuvenator available in China was studied. Asphalt was aged using the rolling thin-film oven test (RTFOT) and ultraviolet (UV) light. The performances of both aged binder and rejuvenator treated binder were evaluated by means of viscosity, temperature sweep, creep recovery, fatigue and modulus of aged asphalt binder *(15)*. These authors also concluded that rejuvenators lower the viscosity and soften asphalt binder. Moreover, MSCR test results of this study showed that asphalt binders with rejuvenators have higher creep recovery than control binder, which may help asphalt binder to heal faster under traffic loading. Since aged asphalt can be efficiently softened by adding rejuvenator sealer materials, these materials can be used in maintenance activities to improve the performance of existing pavements *(15)*. Zaumanis et al. also evaluated the effectiveness of rejuvenators in terms of penetration for production of very high (40% to 100%) reclaimed asphalt pavement (RAP) content mixtures *(16)*. The study used penetration index (PI) and the penetration–viscosity number (PVN) as the indicators of oxidative hardening and cracking. A report by NCAT in 2012 concluded that adding a recycling agent (i.e., a rejuvenator) can be helpful to restore the performance properties of recycled binder to offset the higher binder stiffness and improve the mixture resistance to cracking when high RAP/RAS contents are used *(16)*.

The diffusion and mixing of binders in a blend depends upon a number of factors, including compatibility of binders, temperature of mixing, performance grade of virgin and recycled binder, and the percentage of recycled binder in the blended binder *(17)*. Ali and Sobhan analyzed several factors which are important to determine the amount of rejuvenator to be added to the mix *(18)*. These include hardness of the existing binder and the reaction between the binder and rejuvenator. Boyer concluded that it is better to apply two or more low-rate applications of the emulsion to achieve the proper rate of application than to make only one pass and have it be too heavy *(19)*.

Hugener et al. (2013) investigated the idea of reactivating the old binder in reclaimed asphalt pavement (RAP) using vegetable oil-based rejuvenator *(20)*. RAP was produced on-site from old pavements and then was sprayed with water and rejuvenator before it was mixed thoroughly and immediately compacted. The preparation was done by mixing RAP, rejuvenator and water using a 30-kg asphalt mixer at room temperature. They investigated different curing condition (temperature and humidity), compaction effort, and changing the mixture procedure. Uniaxial compression tests were performed as a screening process for those various options. The water content of the cold mixtures was set to 5.6% by mass, to which 0.35% of rejuvenator was added, except for the rejuvenator enriched with bitumen, for which 0.64% was added. The homogeneity of the rejuvenator was not investigated in this study due to lack of suitable simple method. The authors concluded that rejuvenators are not suited for uncoated minerals, because they can only activate the old binder, but not act as a binder by themselves *(20)*. Nahar et al. (2014) focused on the rheological and microstructural assessment of rejuvenated asphalt. Virgin binder was aged in the laboratory using an accelerated procedure based on the rotational cylinder ageing tester, RCAT, in order to consistently mimic RAP binder *(21)*. Two distinct rejuvenators were selected for this study. They which were mixed with the laboratory aged binders for 15 minutes at 150°C. Three mixtures were prepared using 10%, 20% and 25% rejuvenators with the aged binder. Rheological measurements were conducted at 30, 40, 50 and 60°C using a Dynamic Shear Rheometer (AR 2000ex rheometer from TA Instruments), and the results were shifted to a reference temperature of 30°C using the time-temperature superposition principle *(21)*.

There has been always some challenges regarding surface treatments in cold region. The selection of sealant for use in a cold climate has remained a difficult task. Cold urban conditions can significantly limit the number of sealant materials that perform well over many years *(22)*. Zukbec and Mullin (2012) also mentioned about a number of challenges of cold regions which may prevent the use of certain pavement preservation treatments *(7)*. These challenges include issues with construction as well as issues while the treated road is in service. In-service challenges include usage of studded tires for winter traction, snow and ice removal operations and exposure to cold and moisture. Boyer (2000) mentioned that applying the rejuvenator at periodic intervals can restore the asphaltene-maltene balance to maintain a ductile, pliable pavement which is particularly applicable to pavements in the hot, dry southwestern section of the country *(19)*. As an explanation he stated the established fact that the greatest change in composition of an asphalt binder takes place during the manufacture of the hot mix asphalt (HMA). Applying a rejuvenator/ sealant to a new surface a few months or years after it has been laid may not help the pavement. Brownridge (2010) mentioned that in order for a rejuvenator to penetrate it cannot be retarded by blending with asphalt binder because that stops the absorption which might result in loss of the rejuvenation effectiveness *(23)*. Viscosity of the sealant is also an important issue which is temperature-susceptible. A study by Al-Qadi et al. (2006) described that the sealant with an appropriate consistency at the recommended installation temperature would provide a better effectiveness and would ensure appropriate bond strength *(24)*.

A number of conclusions can be drawn from the literature search. Some of the products investigated were defined as sealants and others were defined as rejuvenators, or a combination of the two. It is not clear what rules were used for attributing these different roles to the products investigated. It was also found that currently, there are no laboratory procedures to simulate the application process of sealants to pavement surfaces, a critical step in designing effective products in laboratory conditions rather than conducting expensive field testing. This represents one of the research objectives of this current study.

CHAPTER 3: MATERIAL AND TESTING

The materials used in this investigation and the testing methodology used to evaluate the properties of these materials are presented in the next sections.

3.1 Materials

The materials used in this study come from a field project conducted by MnDOT on CSAH 75 in Wright County, Minnesota. The road and shoulder was paved full width in 2013 using a MnDOT type SPWEB340C mix design. Treatments were installed between August and October of the 2014 construction season as follows:

1. CSS-1h (CSS-1h) is a slow set cationic emulsion with relatively low viscosity that is made using relatively hard base asphalt. In July 2014, a 1:1 dilution of CSS-1h was applied to 1000-ft of Wright CSAH 75 as a bituminous fog seal at a rate of 0.1 gallons per square yard in the westbound shoulder.
2. RePlay (Re) is a polymer-bearing, proprietary fog treatment product for bituminous pavement. RePlay was applied as a fog treatment over 2680-ft of the bituminous shoulder at a rate of 0.020 gallons per square yard.
3. Biorestor (Bio) is a proprietary fog treatment product for bituminous pavement. Biorestor was applied as a fog treatment over 1338-ft of the bituminous shoulder at a rate of 0.015 gallons per square yard (Bio1) and at a rate of 0.020 (Bio2) gallons per square yard to another 1326 ft.
4. Jointbond (Jo) is a proprietary product that is designed for stabilizing the area surrounding longitudinal construction joints. Jointbond was applied as a fog seal over 3000 ft of bituminous shoulder at a rate of 0.073 gallons per square yard.

Four field cores from each type of treated section along with the control section were collected. Three cores were taken from the control and the treated sections a few days after treatments were applied, and one core was taken 8 months later. The earlier three cores received a random core numbering of 1, 2, and 3 for each treatment type. Core number 4, from all treated section, was collected eight months later. A summary is shown in Table 3.1.

TABLE 3.1 Cores used in the study

Type	Number of cores	Rate of Application (gallon/sy)
Control Section	3+1	
Control Section + Emulsion (CSS-1H)	3+1	.1
Control Section + Biorestor (0.015)	3+1	.015
Control Section + Biorestor (0.02)	3+1	.02
Control Section + RePLAY	3+1	.015
Control Section + Jointbond CSAH 75	3+1	.073

3.2 **Experimental Testing**

The following paragraphs provide a short description of the test methods used to obtain rheological and strength properties of the asphalt binders and mixtures investigated in this study.

3.2.1 Asphalt Binder

For asphalt binder testing, the current test methods used to obtain the performance grade of asphalt binders were used. A Dynamic Shear Rheometer (DSR) was used to obtain binder properties at intermediate and high temperatures.

Low temperature stiffness and relaxation properties of binder were determined using a bending beam rheometer (BBR).

Dynamic Shear Rheometer Testing

Characterization of viscous and elastic behavior of binder at intermediate to high temperatures was done in accordance with the AASHTO T 31 5 (*Determination of rutting and fatigue factors using a Dynamic Shear Rheometer (DSR)*) test method *(25)*. The AASHTO T 315 test method helps determine the high temperature rutting factors of unaged and RTFO-aged binders as well as the intermediate temperature fatigue factor of PAV-aged binders. The un-aged and RTFO-aged samples were tested using 25-mm diameter parallel plates, while and PAV-aged samples were tested using 8-mm diameter parallel plates. The DSR test was performed at a loading frequency of 10 rad/s. The complex modulus (G*) and phase angle (δ) are calculated automatically as part of the operation of the rheometer using a proprietary computer software supplied by the instrument manufacturer.

Bending Beam Rheometer Test

The BBR is used to perform low-temperature creep tests on thin beams of asphalt binders conditioned at the desired temperature for one hour *(26)*. The asphalt beam (101.6x12.5x6.25mm) is tested in a three-point bending configuration. A constant load is applied instantaneously and maintained for all the duration of the test (240s) while the deflection at the mid span of the beam is continuously recorded (Figure 3.1).

FIGURE 3.1 BBR Testing Setup for Binders.

Correspondence principle and elastic solution for a simply supported beam are used to obtain the creep compliance. The creep stiffness, *S(t)*, equal to the inverse of the creep compliance, *D(t)*, is calculated as:

$$S(t) = \frac{\sigma}{\varepsilon(t)} = \frac{P \cdot l^3}{4 \cdot b \cdot h^3 \cdot \delta(t)} \qquad (1)$$

where

S(t)	flexural creep stiffness, function of time,
σ	maximum bending stress in the beam, MPa,
ε(t)	bending strain (mm/mm), function of time,
P	constant load = 980±50mN ,
l	length of specimen (101.6mm),
b	width of specimen (12.7mm),
h	height of specimen (6.35mm),
δ(t)	deflection at the midspan of the beam at time t, and
t	time.

The m-value which is the slope of log stiffness versus log time curve is computed according to:

$$m(t) = \left| \frac{d \log S(t)}{d \log(t)} \right| \qquad [2]$$

Both stiffness and the m-value are used to determine the critical temperature.

3.2.2 Asphalt Mixture

Low temperature creep and strength properties of asphalt mixtures are generally obtained using the Indirect Tension Tester (IDT) performed on cylindrical specimens loaded in compression along the diameter *(27)*. Due to the localized effect of the sealant at the surface of the pavement, in this study a BBR-Pro device was used to obtain the creep and strength properties of asphalt mixtures, which allows testing of miniature mixture beams of different layers, see Figure 1. This approach is based on two testing methods developed by Marasteanu et al. *(28, 29)* using a modified Bending Beam Rheometer (BBR) called BBR Pro. This approach is more suitable to check the level of penetration and effect of sealant by testing beams from various depth of the obtained cores. The testing procedures are described in detail elsewhere *(29, 30)*. An example of a BBR asphalt mixture beam is shown in Figure 3.2, while Figure 3.3 shows the steps required to prepare mixture beams from a cylindrical specimen or core.

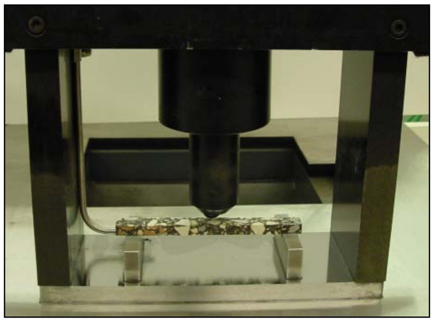


FIGURE 3.2 Bending Beam Rheometer with thin asphalt mixture (28).

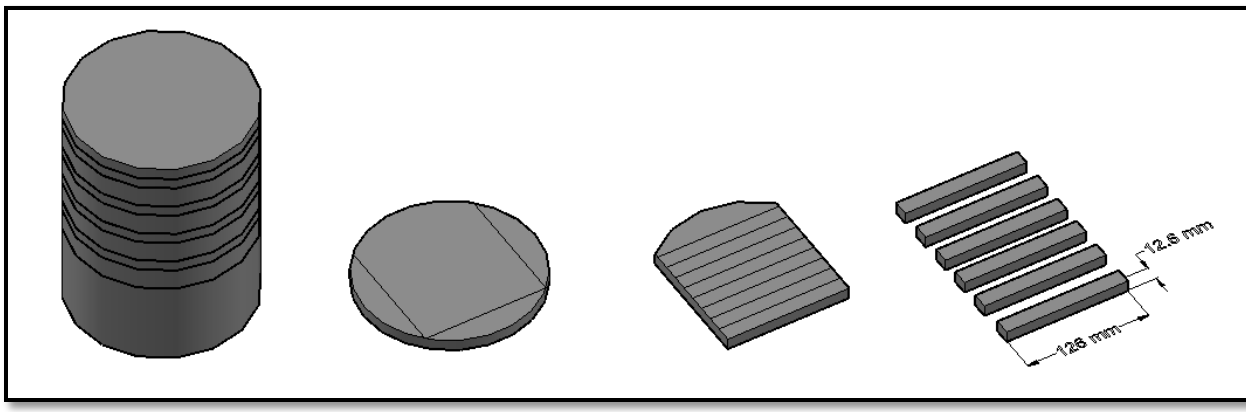


FIGURE 3.3 Asphalt Mixture Beam Preparation (28).

BBR creep tests with duration of 500 sec followed by a recovery period of 500 sec were performed on all samples. For samples undergoing both creep and strength test, at the end of the recovery period, ramp loading at a constant loading rate was applied until the beams broke. The rate was chosen such that a load of 43N was obtained in 150 sec. Since asphalt mixtures are less temperature susceptible than asphalt binder, all testing was done in chilled air in the BBR bath at -24ºC and -12ºC. A total of 576 beams were tested using 3 replicates from each layer for each core of each treated and control sections.

CHAPTER 4: ASPHALT BINDER TESTING

4.1 Introduction

In this chapter, the asphalt binders sample preparation methods are discussed and the results of the rheological testing are presented. One asphalt binder, a PG58-28, was used as control and the four types of sealants were applied using different methods and rates.

4.2 Asphalt Binder Sample Preparation

For laboratory testing, it is important to identify the amount of sealant applied to the binder. This is necessary to be able to simulate actual field conditions in which the sealant is applied on the surface of the pavement. Two key parameters are needed to determine this amount. The first one is the application rate used in the field, and the second one is the penetration depth of the seal into the asphalt layer.

4.2.1 Determination of Application Rate

Two methods are used to determine the application rate of bio-seal treatments. In one method, nonwoven geotextile pads are used to measure the application rates. In this method, 2ft by 2ft square pads were weighed before and after the seal application. The application rate was converted to gallons per square yard using the measured specific gravity from field samples. In the other method, gallons applied to the treated area are determined by measuring the size of the treated section with a foot meter, and obtaining the volume of the treatment from the distributor truck metering system. In this research effort, this latter method was used since the information provided by MnDOT followed this method.

To obtain the penetration depth, a literature search was conducted. It was found that according to the manufacturers of the products BioSeal's product Biorestor adds agricultural oils and polymers to the asphalt cement in the top 1/2" of the pavement and RePlay Penetrates deep into asphalt (2-3 cm) *(31, 32)*.

Based on the application rates provided by MnDOT and penetration information from literature, the amount of seal to be added to the asphalt binder was calculated as follows. In all calculations, it was assumed that the asphalt mixture contained 5% binder (by weight) and 95% aggregates. The specific gravity of aggregates was assumed to be 2400kg/m3. Based on the penetration amount from literature, the weight of aggregate affected by sealant per surface area was calculated followed by the calculation of affected binder-weight (Column 7 and 8 of Table 4.1). The results are presented in Table 4.1 and the calculation steps are presented in Table 4.2.

TABLE 4.1 Calculation of Seal Amount as a Percent of Binder Weight

1	2			3	4	5	6	7	8	9
Section (Target Rate)	Gallons	Area (ft^2)	Gallons/ yd^2	Penetration depth (from literature) inch	Spraying Rate liter/m^2	Sealant Density kg/liter	Sealant Weight kg/m^2	Aggregate Weight kg/m^2	Binder Weight kg/m^2	Percent Sealant (by weight)
RePlay A (0.020) RePlay B (0.020)	35.4	16080	0.01998	1.18	0.09	0.80	0.07	71.93	3.60	2.0
Biorestor A (0.015) Biorestor B (0.015)	37.78 x 42.9%	9366	0.01557	0.5	0.07	0.80	0.06	30.48	1.52	3.7
Biorestor C (0.020) Biorestor D (0.020)	37.78 x 57.1%	9282	0.02092	0.5	0.09	0.80	0.08	30.48	1.52	5.0
CSS-1h (0.10)	77.8	7000	0.1	unknown	0.45	0.9	0.41	Depends on penetration		
Jointbond A (0.08) Jointbond B (0.08)	180	22193	0.073	unknown	0.33	0.95	0.31	Depends on penetration		

TABLE 4.2 Calculation Steps of Table 4.1

Calculation Steps of Table 4.1	
Column 3=	obtained from literature
Column 4=	Column 7 * 4.52731481 (to convert from Gallon/sq. y to Liter/sq. m)
Column 5=	Density of sealants was measured in lab
Column 6=	Column 4*Column 5
Column 7=	Density of Aggregate (assumed 2400kg/m^3) * Column 3 * 0.025 (to convert inch to m)
Column 8=	Column 7 * 5% binder(binder % from mix design)
Column 9=	Column 6/ Column 8

4.2.2 Application Procedure

There is no specific method to add sealants to a binder. A number of methods were developed in this investigation ranging from direct mixing of hot binder and sealant to application of sealants to the surface of testing specimens. After the trial procedures of sample preparation described below, the sealants were applied to both RTFOT and PAV aged binder using two methods: simple mixing, and a laboratory-developed pipette method.

Mixing with heated binder

In this method, the RTFO-aged and PAV-aged, respectively, binders were heated at 150˚C and mixed with the four sealant products that were kept at room temperature. After 5 minutes of mixing, the samples were left at room temperature until the next day, when they were tested. Some literatures mentioned about this mixing procedure as a way of their laboratory investigation of rejuvenated binder *(21)*. As a result this procedure was considered to use in this investigation by mixing sealant of 4% by binder weight. The amount 4% of sealant by binder weight was fixed based on Table 4.1. The mixing percent amount was observed to vary from 2% to 5% for RePlay and Biorestor to match the field application rate (Table 4.1). The amount for Jointbond and CSS_1h was not possible to calculate due to lack of information on their penetration from literature (Table 4.1). As a consequence an intermediate amount of 4% was selected for all sealants to maintain consistency. Boiling liquid was observed forming when the Jointbond was added to the heated binder, see Figure 4.1. The addition of RePlay resulted in a very sticky and odorous mixture.

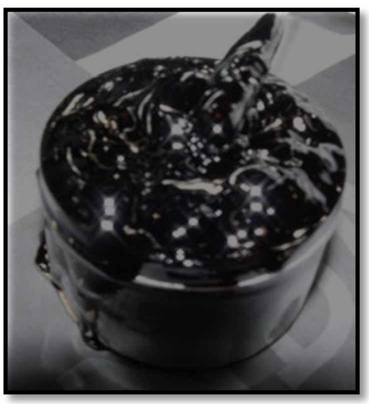


FIGURE 4.1 Mixing Jointbond and Heated Binder.

In this mixing procedure the exact amount of the applied seal is known. However, this procedure does not simulate actual field conditions. As a consequence, besides using this procedure, it was necessary to develop another method of sample preparation which can closely mimic the field application. The pipette method was developed and considered another way of sample preparation for this study after going through some trial procedures like spraying and brushing. The detail description is given below.

Spraying

In the actual field the sealants were applied using a spraying truck. To simulate the spraying, in this method, the sealant was applied to the DSR and BBR testing specimens using a small spraying bottle. The weight of one spray was calculated to be approximately 0.015gm. This was done by weighing the bottle before and after one spray. The specimens were kept for 72 hours at room temperature (Figure 4.2), and tested. Spraying allows the seal to disperse on the surface of the specimen, which damages the surface. As a result, the method was found unsuitable to use for further investigation.

FIGURE 4.2 DSR large plate specimen after 72 hours from spraying the sealant.

Brushing

When the spraying method didn’t work, brush was thought to be used as an alternative medium to apply sealant. In this method, the sealant was applied using a brush. The amount of sealant to be applied was determined using sealant weight (kg/m2) from Table 4.1 and multiplying by the DSR sample surface area. In case of brushing, it is impossible to control the amount applied since the absorbing capacity of the brush was unknown. The condition of the DSR specimen 72 hours after brushing is shown in the Figure 4.3. In this procedure, it is difficult to control the amount of seal applied to the surface since the brush absorbs some seal as well and the sample surface gets distorted.

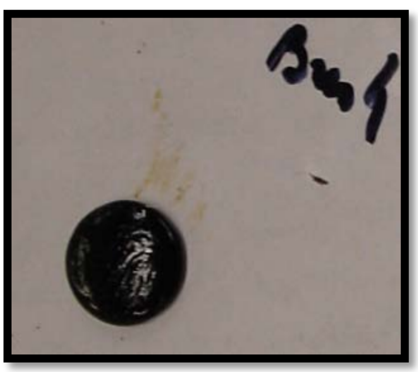


FIGURE 4.3 DSR_large plate specimen after 72 hours from brushing.

After failing to use spraying and brushing methods, pipette method was introduced overcoming the issues of inability of controlling exact amount of sealant application and sample surface distortion.

Pipette Method

In the pipette procedure, the sealant is applied with a measuring pipette to control the number of drops and then spread on the surface of the DSR and BBR specimens using a plastic non-absorbent strip (Figure 4.4). The density for all sealants was calculated to be around 0.80 kg/liter. The measuring dropper counts 0.5 ml for 25 drops. Therefore, each drop measures 0.016 gm.

FIGURE 4.4 Sample Preparation Using Pipette Method.

Based on the field application rate (provided in Table 4.1) and laboratory sample surface area, the number of drops to be applied were calculated. Table 4.3 contains detailed information on the number of drops to be applied on binder sample based on surface area for both 2% and 4% sealant by binder weight. The detail calculation step is provided in Table 4.4.

TABLE 4.3 Calculation of Number of Drops for Binder Sample

1	2	3	4	5	6	7	8	9	10	11
Test	Sample surface area	Binder Weight Table 4.1	Binder Weight	Weight per drop	Weight Sealant per sample	Drops per sample (calc.)	Drops per sample (applied)	Weight Sealant per sample	Drops per sample (calc.)	Drops per sample (applied)
					2% Sealant (Binder Weight)			4% Sealant (Binder Weight)		
	mm^2	kg/m^2	kg	gm	gm			gm		
DSR large pl.	254.47	3.60	0.0009	0.016	0.018	1.15	2	0.037	2.29	2
DSR small pl.	78.54		0.0003		0.006	0.35	1	0.011	0.71	1
BBR Beam	1587.50		0.0057		0.114	7.14	8	0.229	14.29	16

TABLE 4.4 Calculation Steps of Table 4.3

Column 3=	Binder weight per surface area affected by sealant application in the field, calculated in Table 4.1.
Column 4=	Column 2*Column 3/1000000
Column 5 =	Measured in the laboratory
Column 6=	Column 4 *1000* 2% (RePlay) (from Table 4.1 column 9)
Column 7=	Column 6/ Column 5
Column 8=	rounding up Column 7 to nearest number
Column 9=	Column 4 * 1000*4% (Biorestor) (from Table 4.1 column 9)
Column 10=	Column 9/ Column 5
Column 11=	rounding up Column 10 to nearest number

Two drops were applied to the DSR large plate and one drop to the DSR small plate specimen, respectively based on the calculation described in Table 4.3 for both application rate of 2% and 4% sealant of binder weight. The number of drops used to treat the beams were 8 for 2% sealant by binder weight which simulates the spraying rate of 0.02 gallon/sy in the field. Since the BBR beam sample has significant surface area compared to DSR sample, the number of drops calculated for 4% sealant by binder weight is 15 which simulates the spraying rate of 0.045 gallon/sy. Sixteen drops were used instead of 15 drops as the double of 8 drops. PAV-aged binder beams were tested using only 8 drops. Since the asphalt mixtures in the field sections were less than 2 years old at the time the cores were collected, additional BBR testing was performed on RTFO-aged binder, treated using 8, 16 and 32 drops. This was done to try and better match the aging condition of the binders and mixtures. The DSR samples were tested after 3 days and 48 days from the application of the sealant, whereas, the BBR samples were tested after 3 days of sealant application. The DSR samples were stored in the freezer at 4ºC for being tested after 48 days. For testing after 3 days, the DSR samples and BBR samples were kept in the room temperature. This pipette method was observed to be the most suitable method since it can closely mimic the field application procedure and thus this method was used for further investigation.

A flow chart of the testing plan of the proposed study is presented in Figure 4.5.

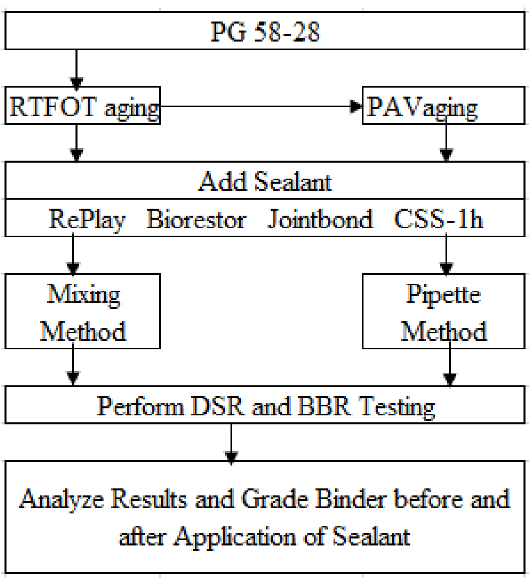


FIGURE 4.5 Testing Plan of Asphalt Binder.

4.3 Rheological Master Curves

Frequency sweeps were performed in 6°C increments from 4°C to 70°C using Dynamic Shear Rheometer. Small plate geometry was used for tests performed from 4°C to 34°C, and large plate geometry was used for testing from 34°C to 70°C.

Examples of |G*| master curves generated at a reference temperature of 22°C are shown in Figures 4.6 to 4.10. A number of trends can be observed by visual inspection. In RTFOT case, Biorestor produces the most significant changes (softening) of the original binder. These changes are more significant when the simple mixing procedure is used, as expected. Replay comes in as second. However, for PAV binder, Replay produces the most significant softening when simple mixing is used. For brushing, both Replay and Biorestor produce the most softening effect.

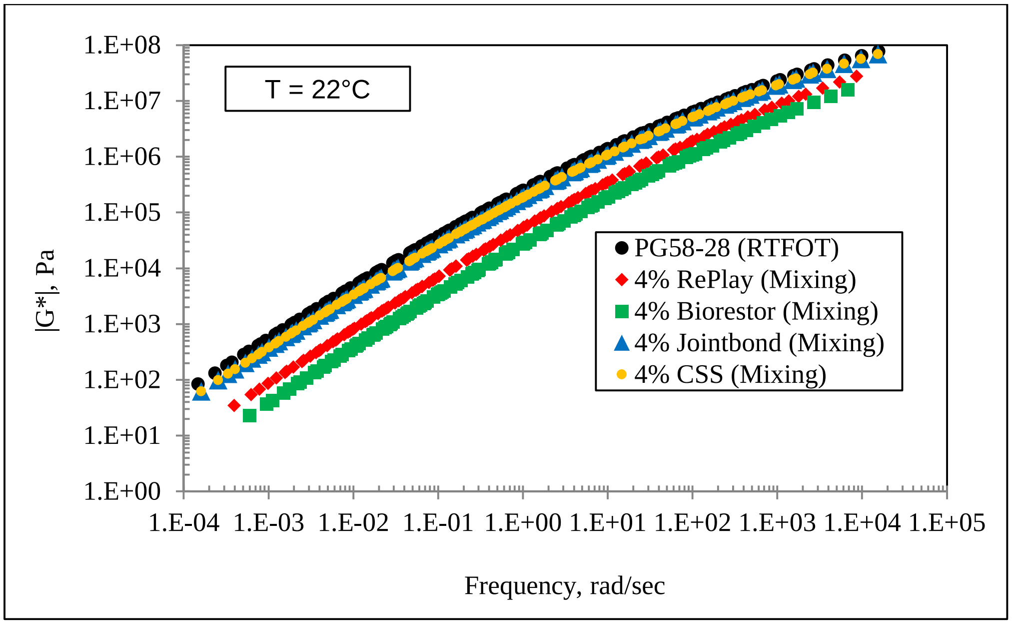


FIGURE 4.6 |G| Master Curves for RTFOT and Simple Mixing Procedure.*

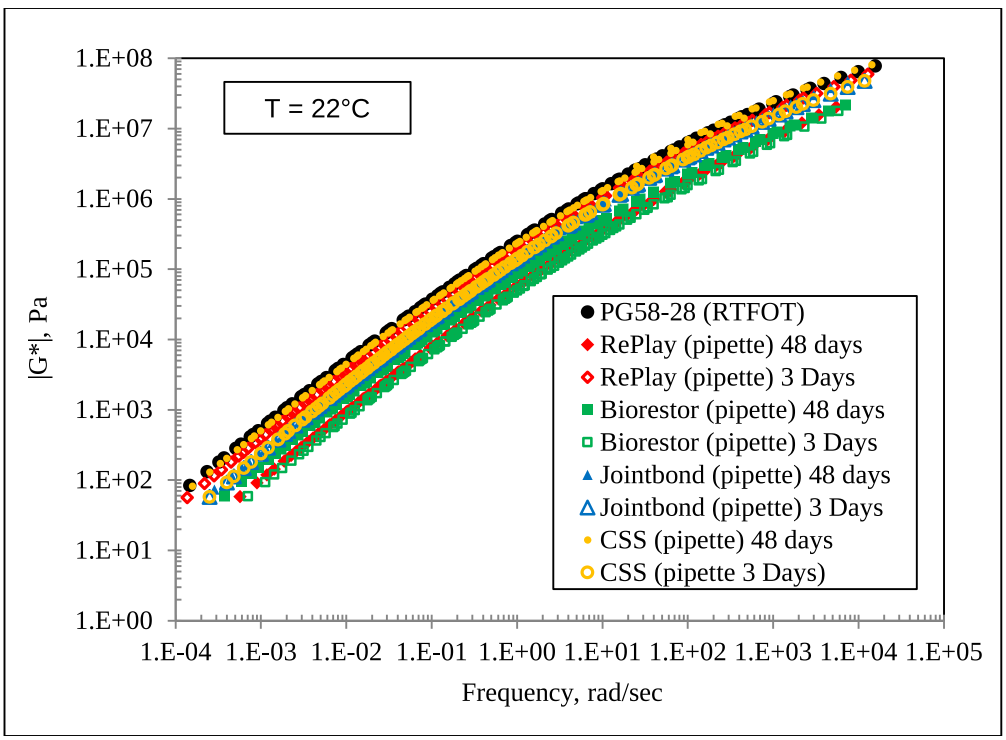


FIGURE 4.7 |G| Master Curves for RTFOT and Pipette Method.*

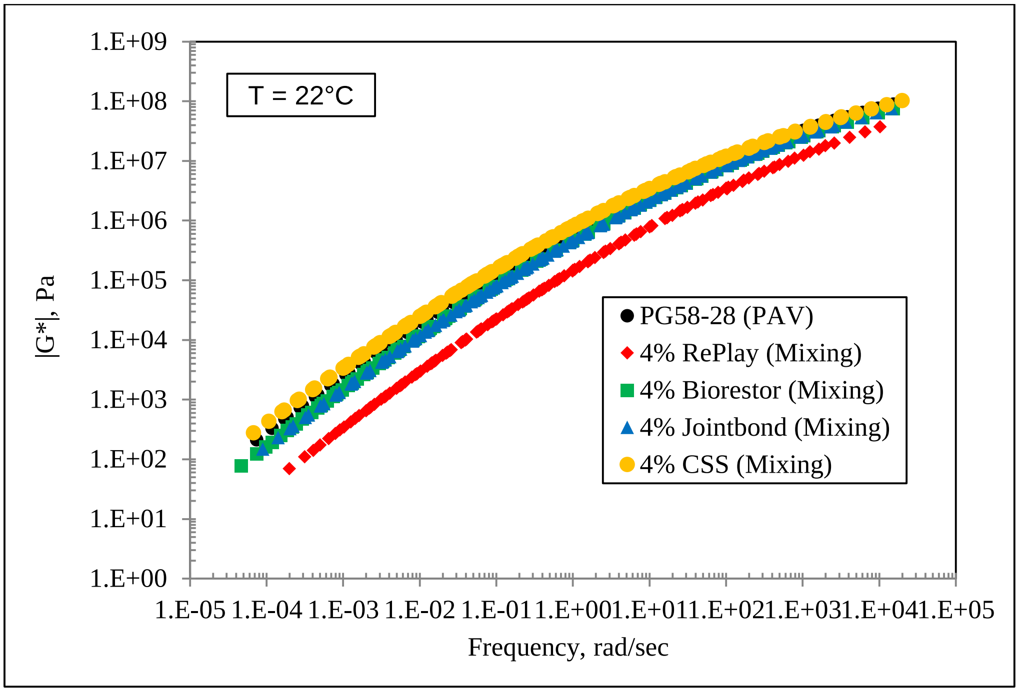


FIGURE 4.8 |G*| Master Curves for PAV and Simple Mixing Procedure.

FIGURE 4.9 |G*| Master Curves for PAV and Pipette Method.

The results of applying the seal by brushing and by spraying on the surface of a prepared DSR large plate sample of PAV-aged binder are presented in Figure 4.10.These two methods were abandoned due to poor control of application weight.

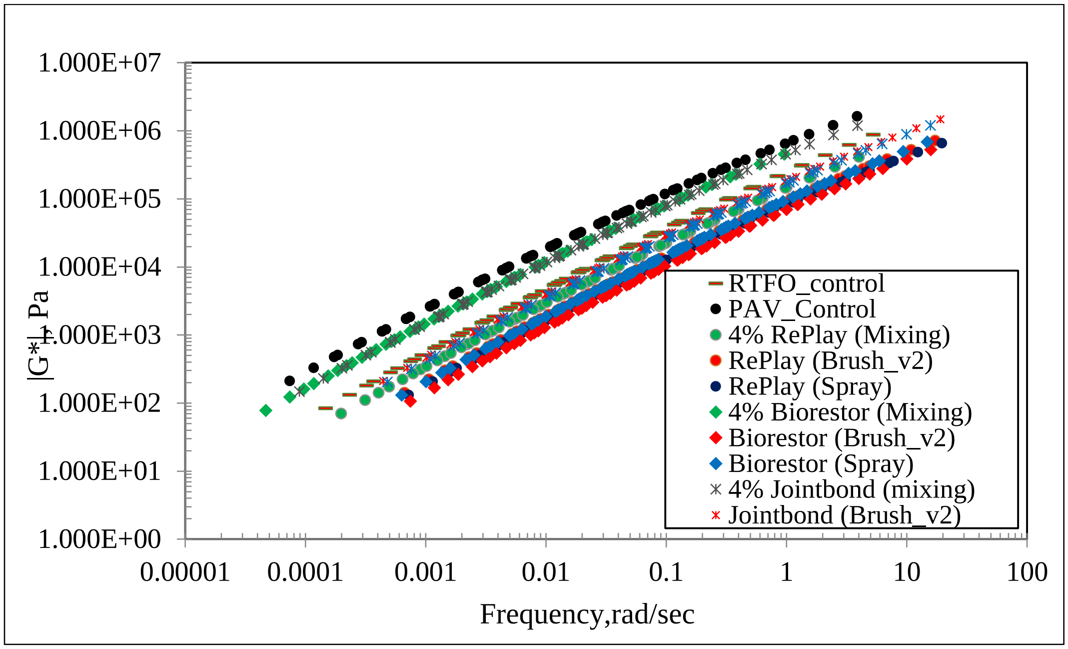


FIGURE 4.10 DSR Master Curve (Large Plate) of PAV-aged PG 58-28 for Three Different Procedures.

4.4 **Performance Grade Specification Criteria**

To better understand the effect of sealants to the properties of the PG58-28 asphalt binder, calculations were performed to determine the specific changes in the low, intermediate, and high temperature criteria used to obtain the performance grade of the binder.

4.4.1 <u>Rutting Factor</u>

Figure 4.11 shows the comparison of the RTFOT $|G^*|/\sin\delta$ values at 58°C. It can be observed that the largest change occurs for the Replay and Biorestor sealants when simple mixing is used. The reduction in the rutting factor is almost three fold. It can also be observed that mixing procedure results in more significant changes compared to the brushing procedure. The 3-day and 48-day results also appear to indicate that the softening effect of the sealant application decreases with time. The results are also shown in Table 4.5.

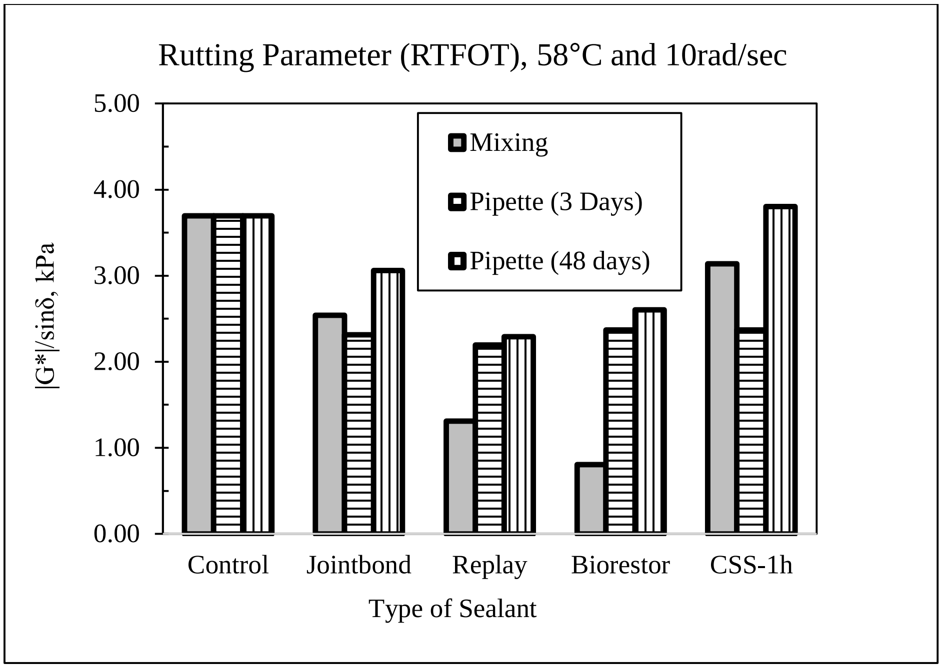


FIGURE 4.11 RTFOT |G*|/sinδ Results at 58°C.

TABLE 4.5 RTFOT Rutting Factor, |G*| and Phase Angle at 58ºC and 10rad/s

Specimen	Application Procedure	Rutting Factor (|G*|/sin δ), kPa	|G*| kPa	Phase Angle degrees
Control		3.70	3673	83.49
RePlay	Mixing	1.31	1308	85.85
	Pipette(3 days)	2.19	2182	83.96
	Pipette(48 days)	2.29	2281	84.44
Biorestor	Mixing	0.80	802.2	86.60
	Pipette(3 days)	2.37	2360	84.44
	Pipette(48 days)	2.60	2590	84.19
Jointbond	Mixing	2.54	2539	84.40
	Pipette(3 days)	2.31	2304	84.77
	Pipette(48 days)	3.06	3042	83.95
CSS-1h	Mixing	3.14	3119	83.96
	Pipette(3 days)	2.37	3596	84.44
	Pipette(48 days)	3.80	3776	83.12

4.4.2 Fatigue Factor

According to Superpave performance grading criteria, for PG 58-28 it is important to determine the fatigue factor at 19ºC. The following Table 4.6 and Figure 4.12 show the fatigue properties at two different temperatures obtained from DSR testing, which are need for interpolating the fatigue factor at 19ºC.

TABLE 4.6 Fatigue Factor, |G*| and Phase Angle at 10rad/s

		16˚ C			22˚ C		
Specimen	Application Procedure	Fatigue Factor (|G*| x sin δ) kPa	|G*|, kPa	Phase Angle	Fatigue Factor (|G*| x sin δ) kPa	|G*|, kPa	Phase Angle
Control	No sealant	5614	7384	49.49	2418	2944	55.2
Jointbond	Mixing	4353	5554	51.6	1830	2175	57.29
	Pipette(3 days)	4927	6060	54.39	1994	2320	59.25
	Pipette(48 days)	4551	5787	51.86	1971	2347	57.1
RePaly	Mixing	1717	2038	57.41	683.1	774.2	61.92
	Pipette(3 days)	1694	2005	57.65	751.8	853.1	61.79
	Pipette(48 days)	2225	2648	57.17	890.1	1015	61.29
Biorestor	Mixing	1683	2006	57.04	670.8	763.8	61.43
	Pipette(3 days)	1564	1884	56.13	647.2	746	60.18
	Pipette(48 days)	1922	2425	52.42	846.3	1013	56.64
CSS-1h	Mixing	6520	8863	47.36	2739	3428	53.04
	Pipette(3 days)	5728	7662	48.39	2603	3211	54.13
	Pipette(48 days)	6362	8468	48.71	2634	3238	54.45
Fatigue Criteria: |G*| x sin δ = maximum 5000 kPa at 19˚C for PG 58-28							

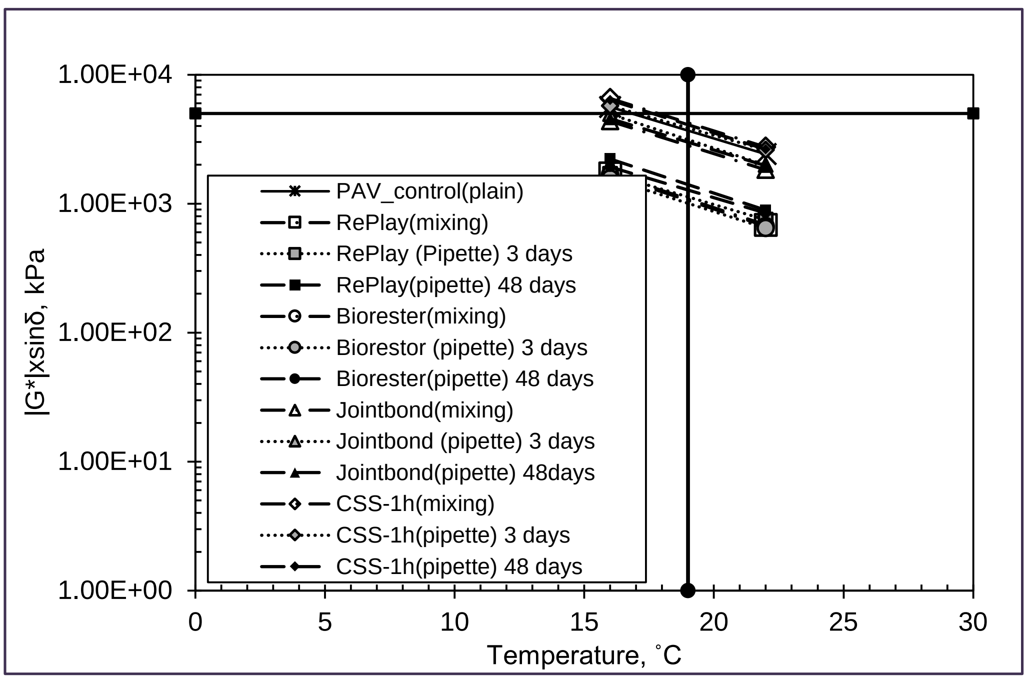


FIGURE 4.12 PAV |G*|sinδ Results at 19°C.

Figure 4.13 shows the changes in the fatigue PAV |G*|sin δ values at 19°C. The largest softening effect is again observed when Replay and Biorestor are simply mixed with the PAV binder. Less pronounced differences are observed between the different application procedures and the 3-day and 48-day results indicate only a minimal reduction in the softening effect with time.

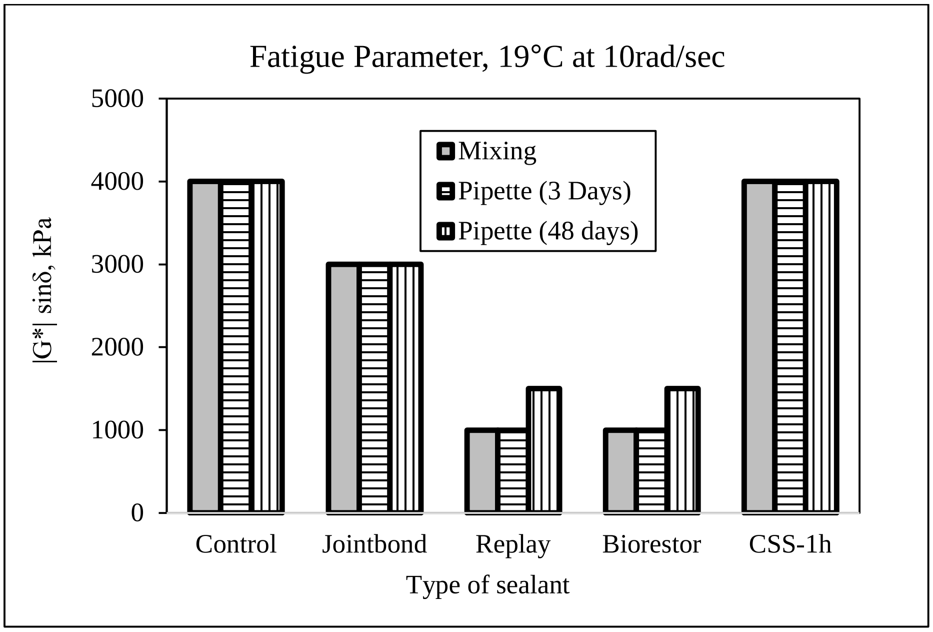


FIGURE 4.13 PAV |G*|sinδ Results at 19°C.

4.4.3 Creep Stiffness and m-value

For low temperature characterization, all beams were tested first at -24°C. Based on the m-value and S results obtained at -24°C, some materials were tested at -30ºC and some at -18ºC. As a consequence, the beams treated with RePlay and Biorestor were eligible to be tested at -30ºC whereas, beams treated with Jointbond and CSS-1h were tested at -18ºC.

Figures 4.14-4.16 show the changes in the PAV BBR parameters S(60s) and m(60s), where S represents the creep stiffness, which is the inverse of creep compliance, and m represents slope of the creep stiffness versus time curve on a double logarithmic scale. The BBR tests were performed after 3 days from sealant application. Lack of materials did not allow testing samples after 48 days. Also, it was quite challenging to store BBR samples for 48 days. The creep stiffness and m-value at 60 sec using two different methods are presented in Table 4.7 and 4.8 for two different temperatures.

TABLE 4.7 Creep Stiffness and m-value at 60 sec using Pipette Method

Stiffness and m-value at 60 sec (Pipette_3 days)							
PAV-aged PG 58-28 with Sealants	Temperature	Stiffness,S (Mpa)			m-value		
	℃	Sample 1	Sample 2	avg	Sample 1	Sample 2	avg
Control	-18	187.266	185.225	186.245	0.378	0.356	0.367
	-24	435.763	456.624	446.193	0.301	0.296	0.298
Jointbond	-18	232.594	232.399	232.496	0.347	0.348	0.348
	-24	448.192	457.955	453.074	0.281	0.286	0.284
RePlay	-18	170.856	154.677	162.767	0.339	0.316	0.327
	-24	303.874	334.584	319.229	0.277	0.285	0.281
Biorestor	-18	163.244	195.252	179.248	0.363	0.358	0.361
	-24	348.731	359.935	354.333	0.286	0.289	0.287
CSS-1h	-18	240.021	243.932	241.977	0.354	0.368	0.361
	-24	438.362	479.234	458.798	0.243	0.283	0.263

TABLE 4.8 Creep Stiffness and m-value at 60 sec Using Mixing Method

Stiffness and m-value at 60 sec (Mixing)							
PG 58-28 (PAV-aged)	Temperature	Stiffness,S (Mpa)			m-value		
	℃	Sample 1	Sample 2	avg	Sample 1	Sample 2	avg
Control	-24	436.000	457.000	446.500	0.301	0.296	0.299
	-18	187.266	185.225	186.245	0.378	0.356	0.367
Jointbond	-24	409.000	410.000	409.500	0.308	0.320	0.314
	-18	160.818	158.652	159.735	0.394	0.396	0.395
RePlay	-24	129.325	123.488	126.406	0.431	0.421	0.426
	-30	376.555	397.623	387.089	0.341	0.326	0.333
Biorestor	-24	158.009	134.424	146.216	0.406	0.398	0.402
	-30	399.788	318.413	359.100	0.314	0.276	0.295
CSS-1h	-18	247.654	243.038	245.346	0.293	0.360	0.327
	-24	524.469	524.469	524.469	0.293	0.293	0.293

The Figure 4.14 below shows the significant softening effect of oil-based RePlay and Biorestor when using mixing procedure. Mixing procedure ensures a very good blending of hot binder and the sealant which results in large drop in stiffness.

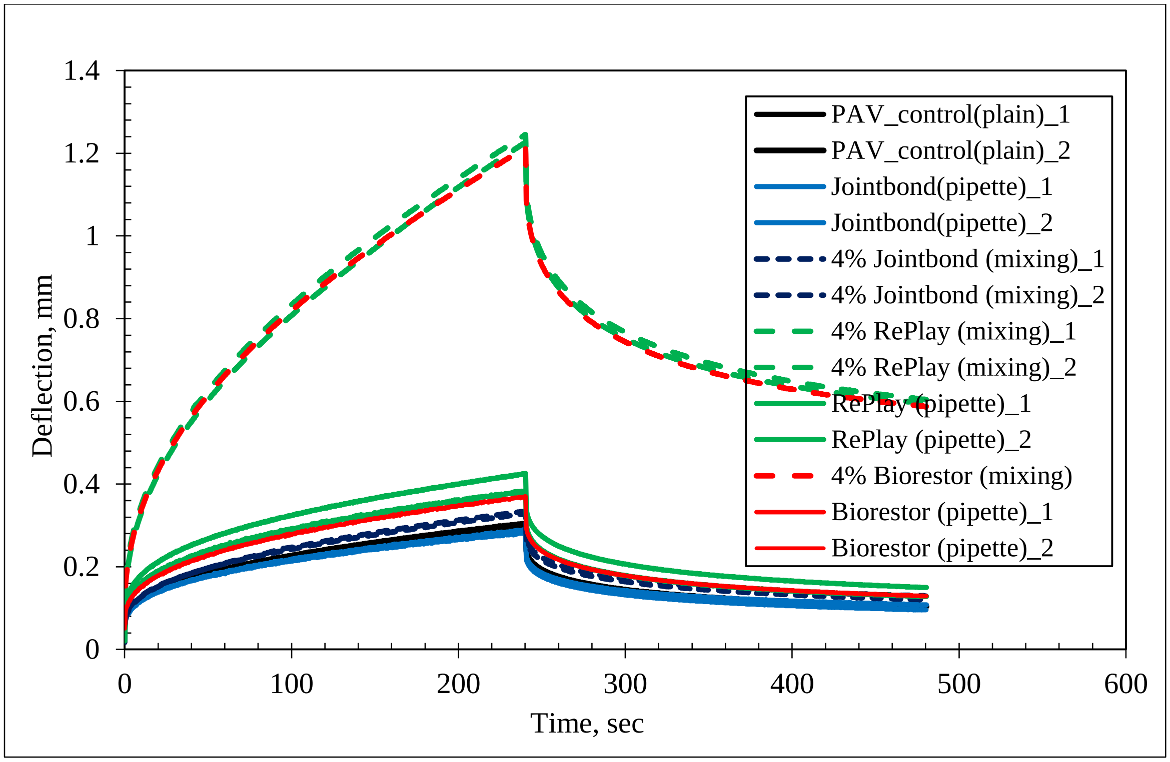


FIGURE 4.14 Deflection vs Time for PAV-aged PG 58-28 at -24ºC.

FIGURE 4.15 PAV S(60s) Results at -18°C.

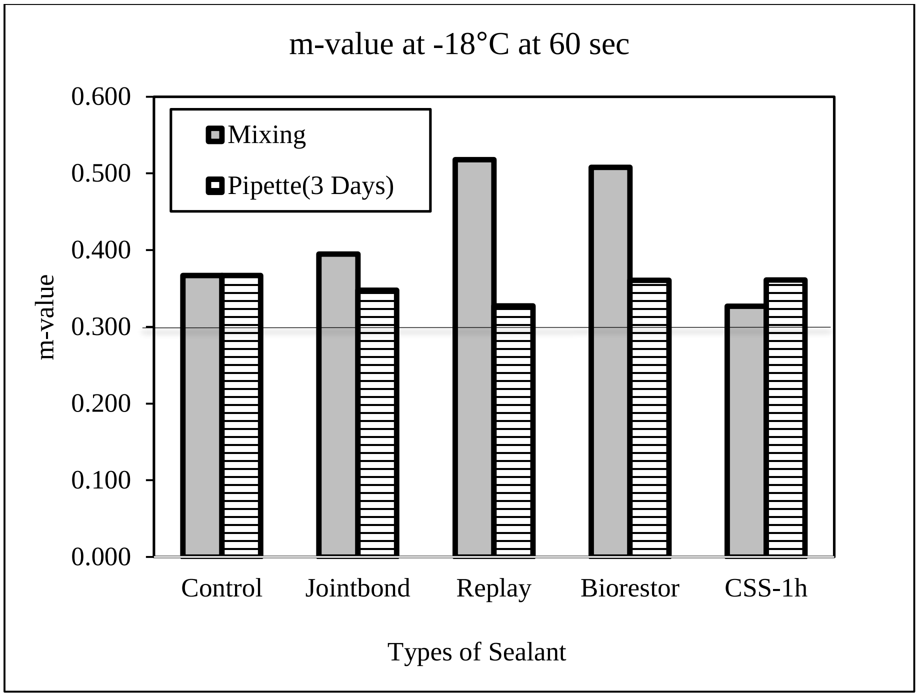


FIGURE 4.16 PAV m(60s) Results at -18°C.

The most significant reduction in creep stiffness is again observed for Replay and Biorestor and the simple mixing procedure. This change is accompanied, as expected by a significant increase in m-value. It is however noted that for the brushing method the changes are much less pronounced for both S and m-value. It is also interesting to observe the increase in stiffness achieved by the application of the emulsion, without a major decrease in m-value.

4.5 Additional Binder Testing

Since low temperature cracking is a phenomena observed in long-term aged pavement, the BBR test was performed on PAV-aged binders. However, in this project the asphalt mixtures in the field sections were less than 2 years old at the time the cores were collected. As a consequence, additional BBR testing was performed on RTFO-aged binder at -24ºC, treated using the pipette method and three application rates (Figures 4.17 and 4.18). This was done to try and better match the aging condition of the binders and mixtures. Four replicates were tested for each case and the average value discarding the outliers was reported. In all cases, increasing the application rate increased the stiffness of the treated binder, which is contrary to expectations for the oil based sealants. Surprisingly, the increase in stiffness is accompanied by increase the m-value, which is also contrary to expectations with an exception for CSS-1h with 32 drops.

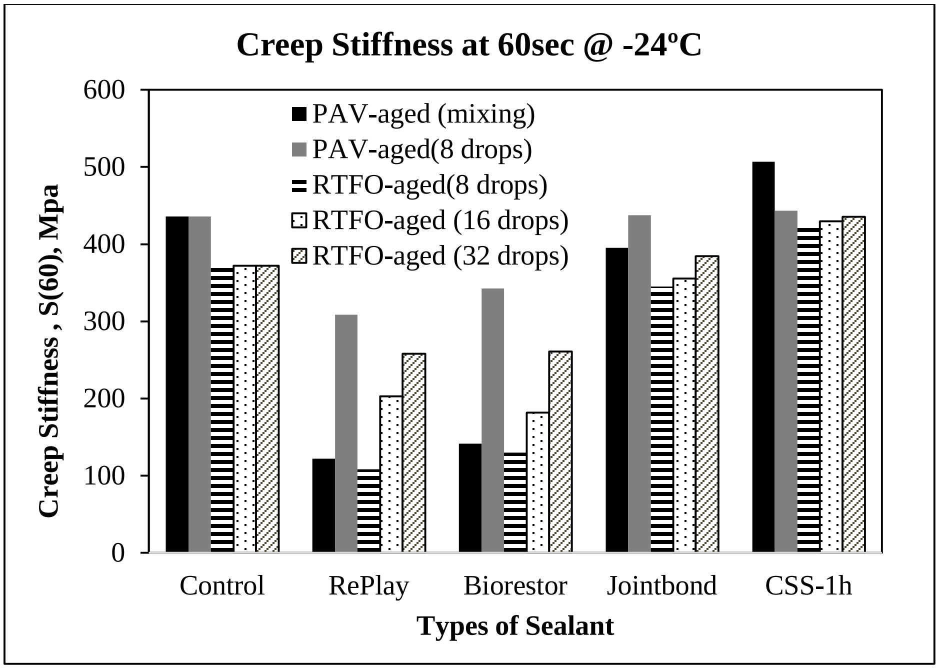


FIGURE 4.17 Change in Creep Stiffness due to PAV-aging, RTFOT-aging and Different Application Rate of the Sealant.

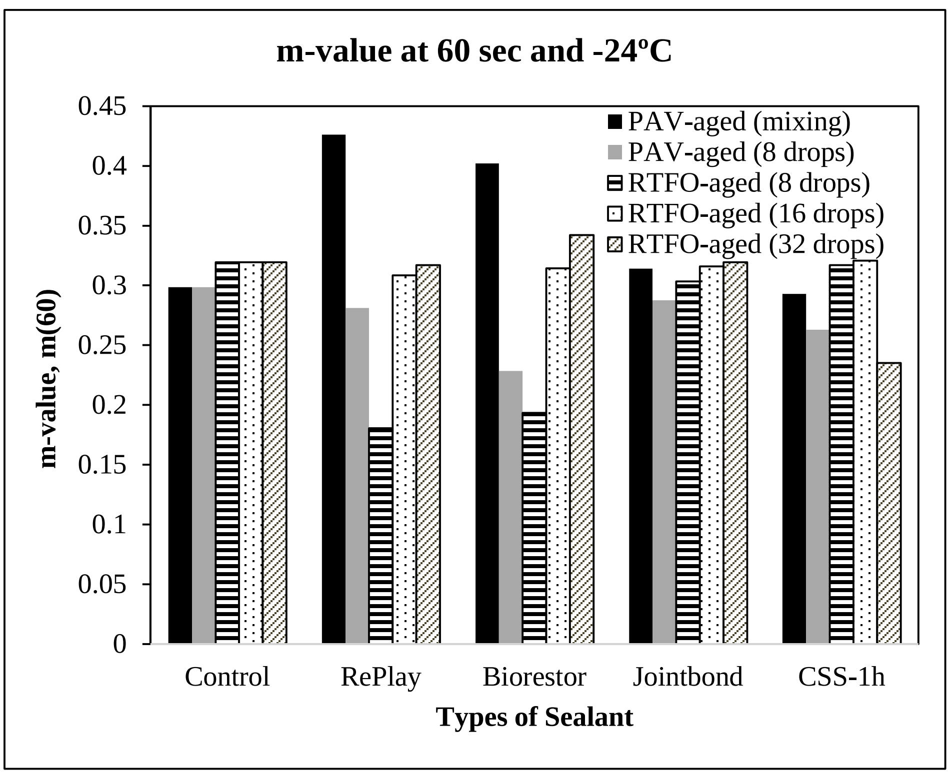


FIGURE 4.18 Change in m-value due to PAV-aging, RTFOT-aging and Different Application Rate of the Sealant.

4.6 Summary

The rheological properties of aged-asphalt binder before and after treatment were obtained by performing DSR and BBR tests in the laboratory. Two types of application process were used for applying sealant: simple-mixing and a laboratory-developed pipette method. The simple mixing method resulted in significant softening effect, whereas the pipette method was found to be more realistic and close to field observation. However, detail analysis is presented in Chapter 6 to investigate the final outcome.

CHAPTER 5: ASPHALT MIXTURE TESTING

5.1 Introduction

The sample preparation, testing plan and results obtained on asphalt mixture samples are discussed to evaluate the effectiveness of sealant application on asphalt mixture.

5.2 Asphalt Mixture Sample Preparation

Asphalt mixture beams were prepared according to the method presented in Chapter 3. This method includes several cutting steps from a gyratory compacted cylinder or field core to the actual BBR beams. In the 1st step, each core receives four horizontal cuts resulting in four layers of around 6 mm each, called top, bottom, middle, and last. Each layer is then cut into six beams with the dimensions of approximately l =125.0mm, b=12.5mm, D=6.25mm.

Four field cores from each type of treated section along with the control section were collected. Initially, the cores were labeled according to the treatment they received with a random core numbering of 1, 2, and 3 for each type. The fourth core from all type of treated section was collected eight months later. The top 3 mm was removed from Core No. 1, 2 and 4 to obtain a smooth surface. However, for Core No. 3 the original top surface was not removed to compare the properties of the shaved and unshaved cores.

Four cores from each type were cut into 4 layers, horizontally. Each horizontal layer was then cut vertically to obtain 6 beams. As a result, a total of 576 small mixture beams were obtained from all the cores. The beams were measured after the cutting process. The width and thickness of the beams were measured in three different points using a standard laboratory caliper. The thickness measured ranged from 4.14 to 7.29 mm with a 6.69% of coefficient of variation and was plotted in Figure 5.1. A normal distribution of the measured values is observed.

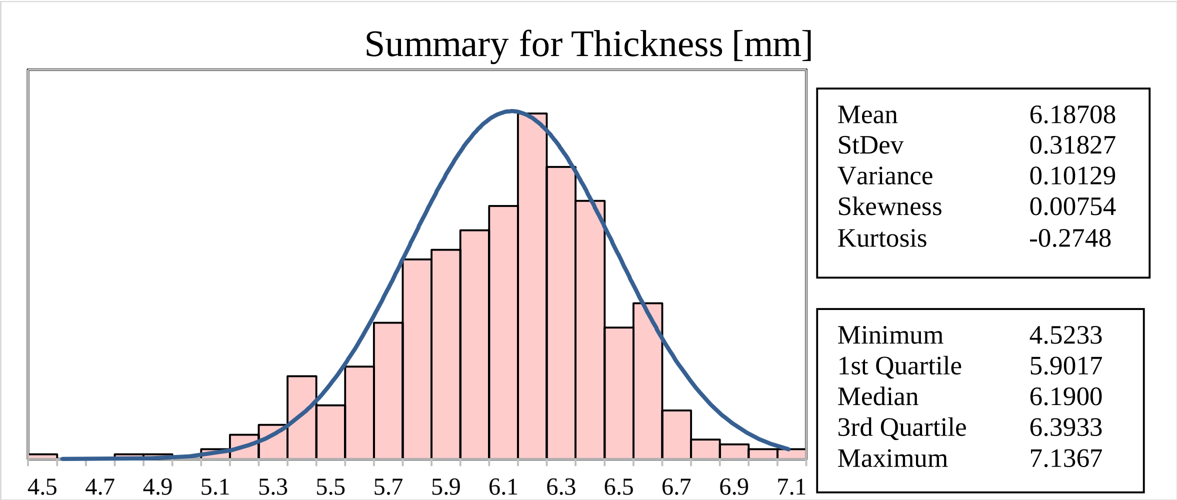
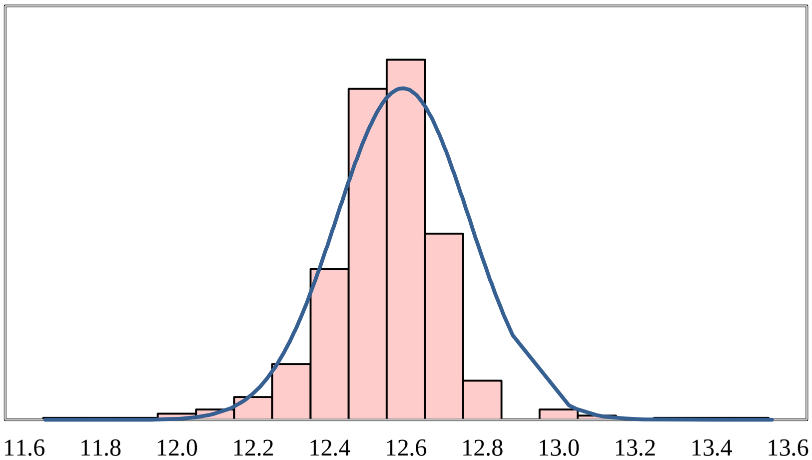


FIGURE 5.1 Statistics for BBR Mixture Beams Thickness.

The width of the beams had a low coefficient of variation of 1.32%. Width measured values ranged from 11.70 to 13.51 mm showing the consistency of the values and how normally distributed they were (Figure 5.2).



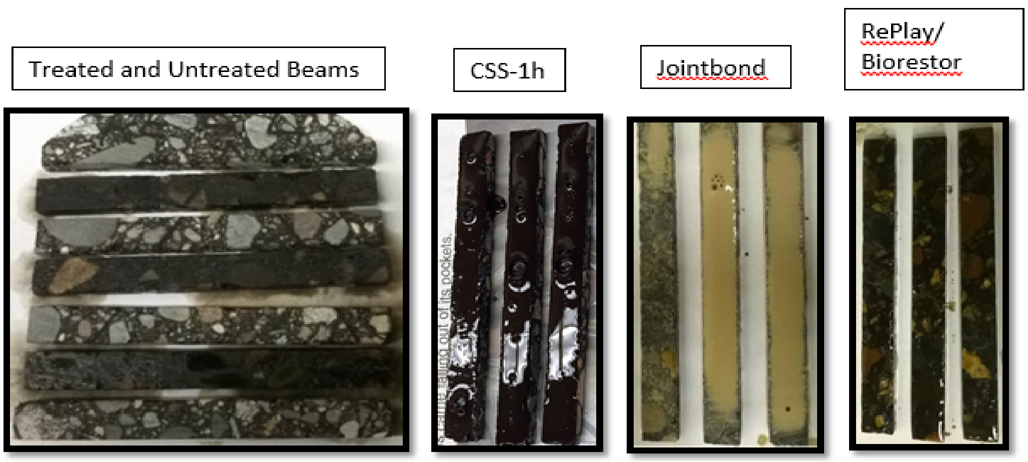
Mean	12.5922
StDev	0.16603
Variance	0.02756
Skewness	0.01616
Kurtosis	6.36516

Minimum	11.7000
1st Quartile	12.5100
Median	12.6033
3rd Quartile	12.6850
Maximum	13.5133

FIGURE 5.2 Statistics for BBR Mixture Beams Width.

The pipette method, developed for binder sample preparation to simulate the application of sealant in the field was also used for mixture sample preparation. The lower part of the cores is not affected by the application of the sealants that occurs at the surface since it is highly improbable that the sealants applied in the field penetrate more than 29 mm, as indicated by some of the manufacturers. As a consequence, the beams cut from the bottom layer (4^{th} layer) of the cores were used in this experiment. In this procedure, the sealant is applied with a measuring pipette to control the number of drops as described in the previous section 4.2 and then spread on the surface of the BBR specimens using a plastic non-absorbent strip (Figure 5.3a). The number of drops to be applied is calculated in Table 5.1 based on spraying rate of sealant in the field. The spraying rate used in Table 5.1 is based on the column 6 of Table 4.1. Due to lack of materials, the beams were treated using 8 drops only. The detail calculation step is provided in Table 5.2. The condition of beams before and after treatment in the laboratory is presented in Figure 5.4b. The number of drops used to treat the beams in the laboratory were 8 which simulates the spraying rate of 0.02 gallon/sy in the field. The spraying rate of Jointbond and CSS-1h was about 0.09 gallon/sy, which resulted in around 30 drops (Table 5.1). However, due to lack of mixture specimens and to perform analysis based on consistent sample preparation procedure for all the sealants, the mixture beams were treated with 8 drops of sealants.

(a)



(b)

FIGURE 5.3 Preparation of Laboratory Treated Mixture Beams.

TABLE 5.1 Calculation of no. of Drops for Mixture Beams

Calculation of Number of Drops of Sealant for Mixture Beams						
1	2	3	4	5	6	7
Sample type	BBR Sample Surface Area	Spraying Rate of Sealant.	Weight of Sealant. per Sample	Weight of one drop of Sealant	No. of Drops of Sealant per sample	Drops applied per sample
		by weight				
	mm^2	kg/m^2	gm	gm		
BBR Beam_Re	1587.50	0.07	0.111	0.016	6.95	7
BBR Beam_Bio1	1587.50	0.06	0.095	0.016	5.95	6
BBR Beam_Bio2	1587.50	0.08	0.127	0.016	7.94	8
BBR Beam_Jo	1587.50	0.31	0.492	0.016	30.76	31
BBR Beam_CSS-1h	1587.50	0.41	0.651	0.016	40.68	41

TABLE 5.2 Calculation Steps in Table 5.1

Column 3=	Column 6 From Table 4.1
Column 4=	Column 2 * Column 3*1000
Column 5 =	Measured in Laboratory
Column 6=	Column 4 / Column 5

A flow chart of the testing plan of the study is presented in Figure 5.4.

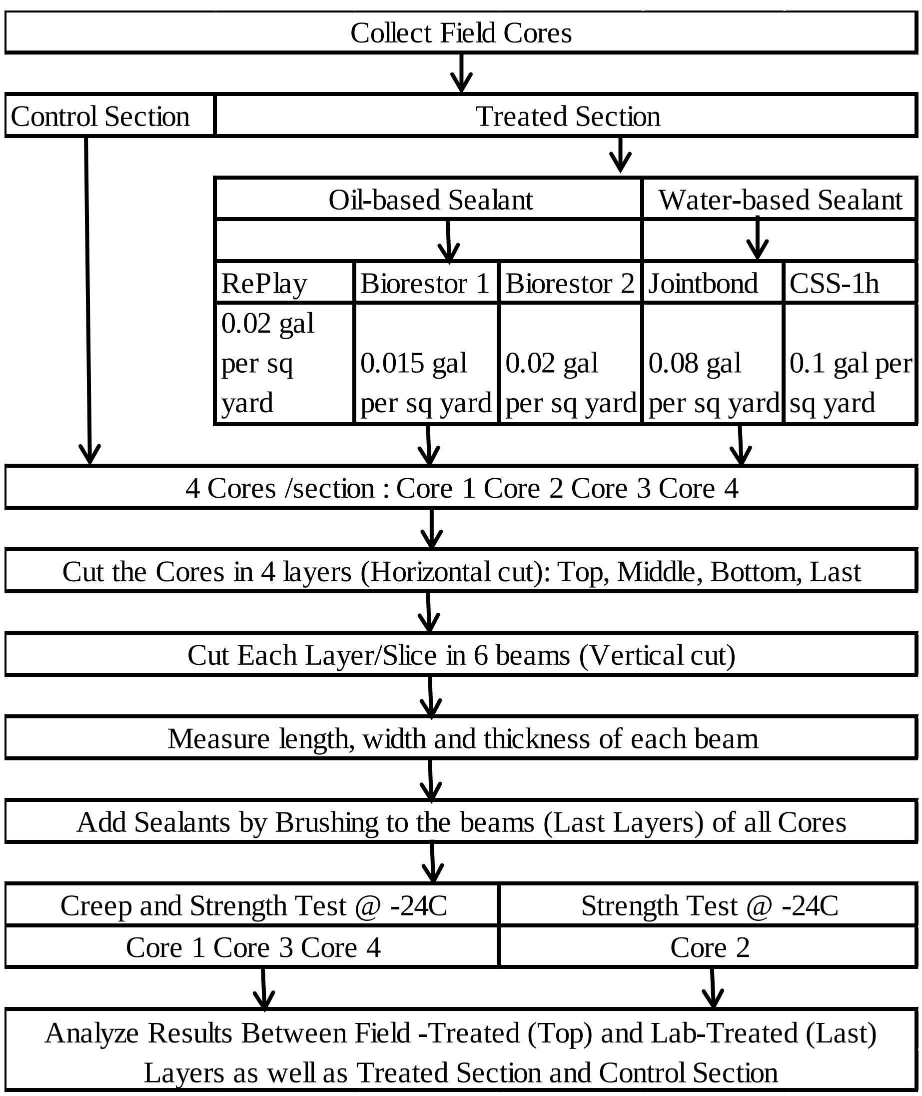


FIGURE 5.4 Testing Plan of the Study.

5.2.1 Testing Method

The laboratory treated mixture beams were tested after 1 month of sealant application in the laboratory, whereas the beams from the surface of the field cores were tested after about 9 months of sealant application in the field. Both creep and strength tests were performed on the beams cut from Core No. 1, 3 and 4. Only strength test was performed on the beams from Core No. 2. All tests were performed using BBR Pro.

In this strength test, a constant loading rate was applied, such that a load of 43N was obtained in 150 sec, until the beams broke. BBR creep tests with duration of 500 sec followed by a recovery period of 500 sec were performed on all samples from Core No. 1, 3 and 4 along with the strength test at the end of the recovery period. A total of 576 beams were tested in air, 288 beams at -24ºC and 288 beams at -12ºC; 3 replicates from each layer for each core of each treated and control sections.

5.3 Experimental Result

5.3.1 Creep Stiffness

Three replicates were tested for each case and the average value was reported discarding the outliers. Figures 5.5 to 5.8 show the creep stiffness average values for the field treated and laboratory treated at -24ºC and -12ºC, respectively.

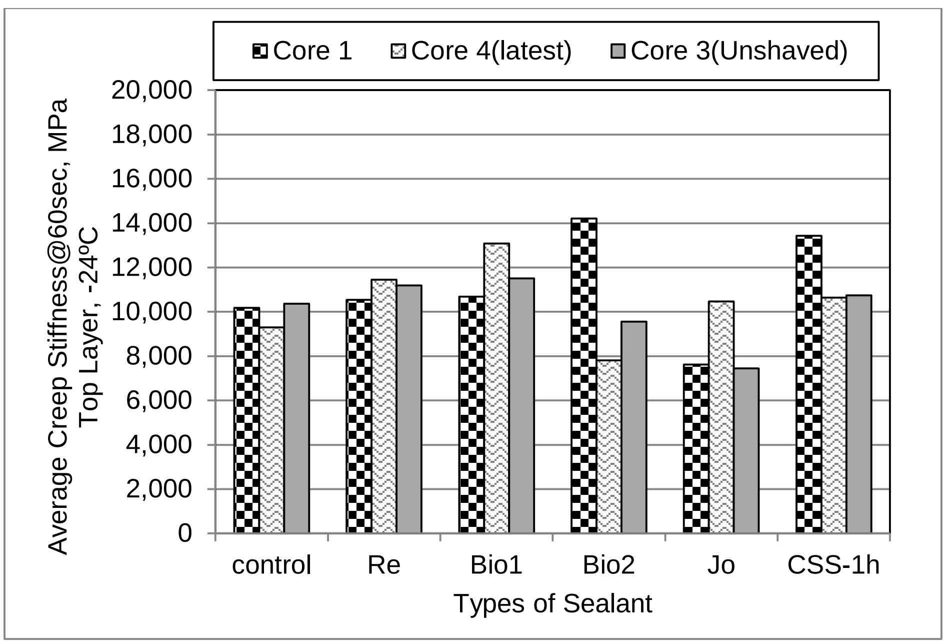


FIGURE 5.5 S(60s) Results at -24ºC of Mixture Beams from Field Treated/Top Layer.

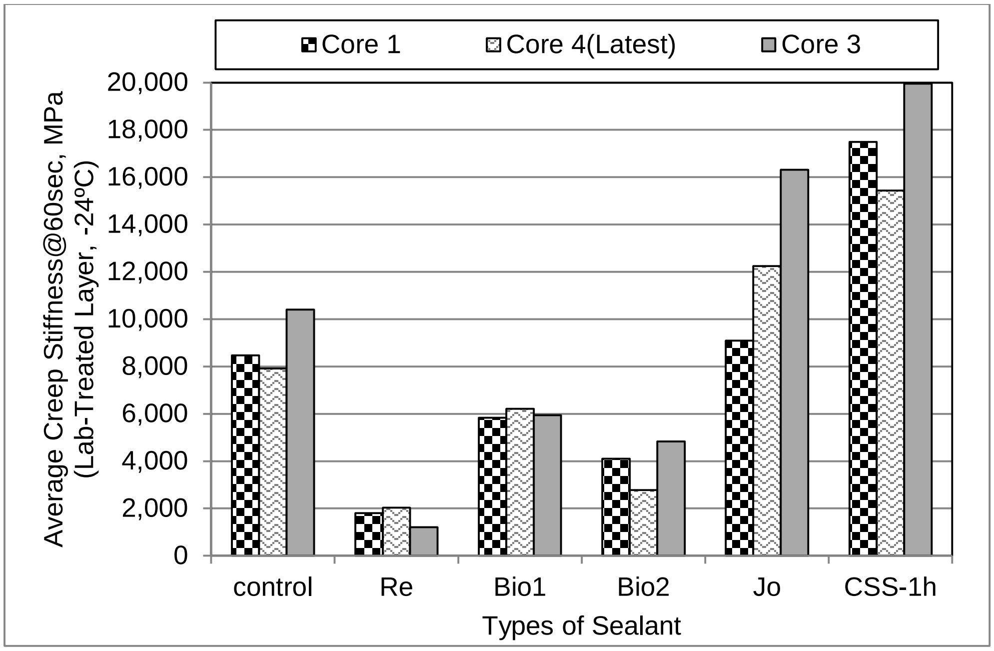


FIGURE 5.6 S(60s) Results at -24ºC of Mixture Beams from Lab-Treated Layer.

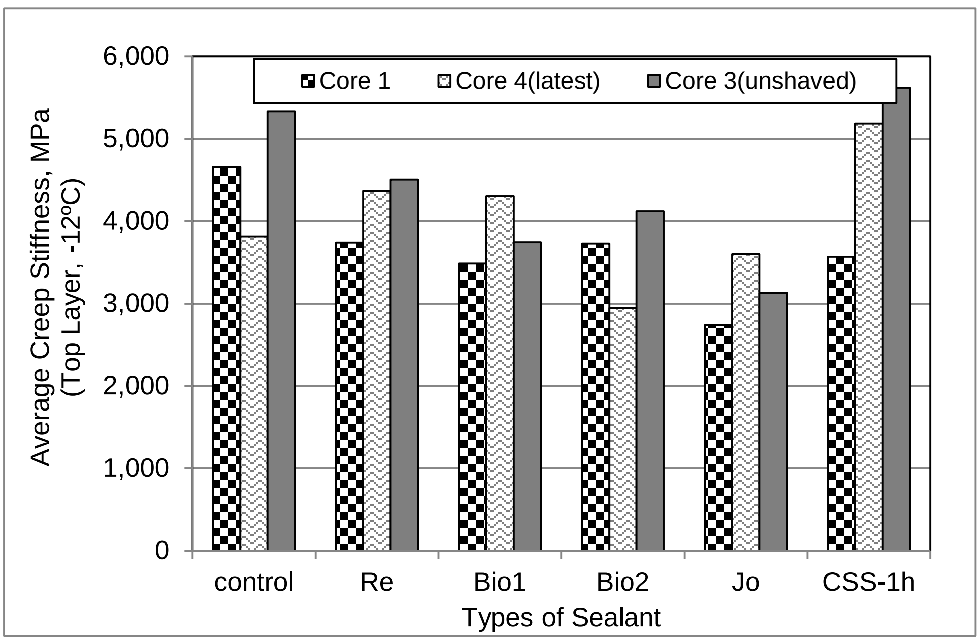


FIGURE 5.7 S(60s) Results at -12ºC of Mixture Beams from Field Treated/Top Layer.

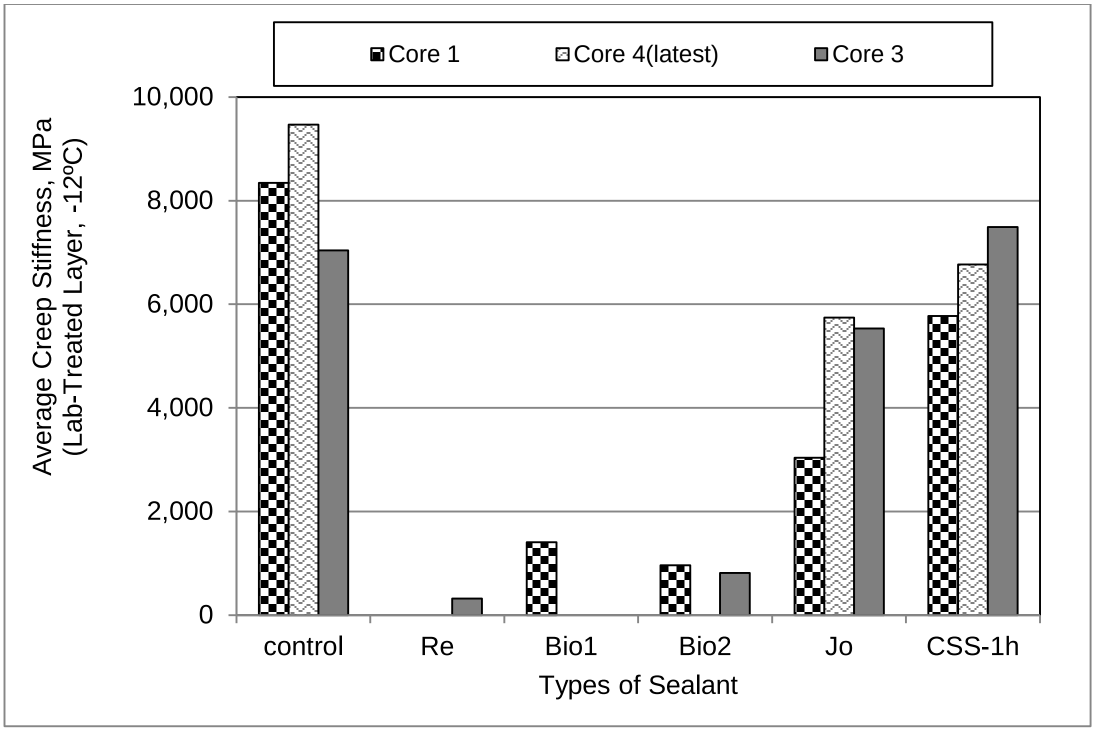


FIGURE 5.8 S(60s) Results at -12ºC of Mixture Beams from Lab-Treated Layer.

A number of observations can be made. The beams from the top layer of the control section (Figures 5.5 and 5.7) have similar stiffness values for all cores, while the beams from the bottom layer (Figures 5.6 and 5.8) were less stiff and the values were scattered. Oil-based sealants, RePlay (Re) and Biorestor (Bio1 and Bio2) increased the stiffness of the control for the field treated samples. However, a significant decrease is observed for the laboratory treated samples, similar to the results reported in many other studies.

5.3.2 m-value

Figures 5.9 to 5.12 show the m-value averages for the field treated and laboratory treated samples at -24ºC and -12ºC, respectively. Very small changes can be observed in the field treated samples. On the contrary, significant increases in m-value averages can be noticed on the laboratory treated samples when using oil-based sealants.

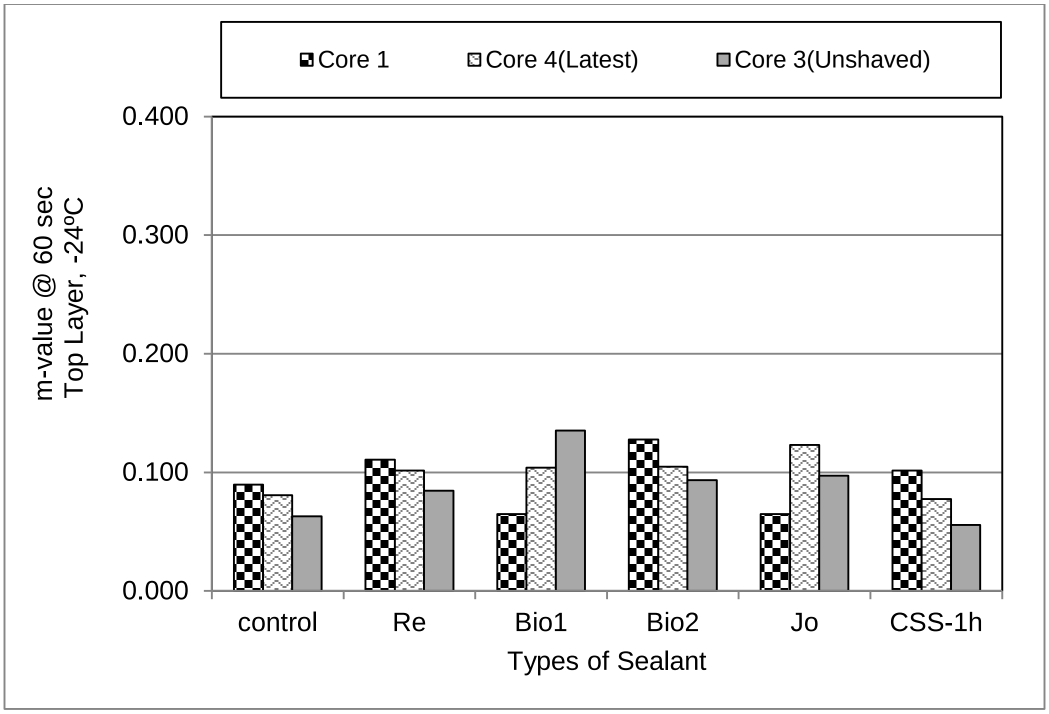


FIGURE 5.9 m-value(60s) Results at -24ºC of Mixture Beams from Field Treated/Top Layer.

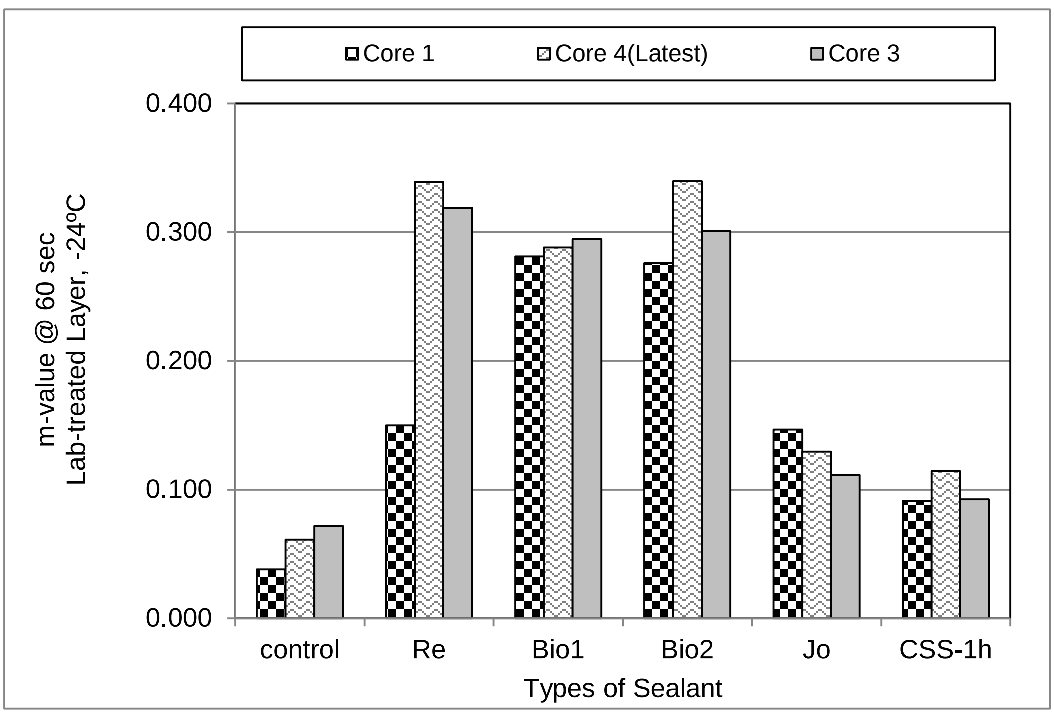


FIGURE 5.10 m-value(60s) Results at -24ºC of Mixture Beams from Lab-Treated Layer.

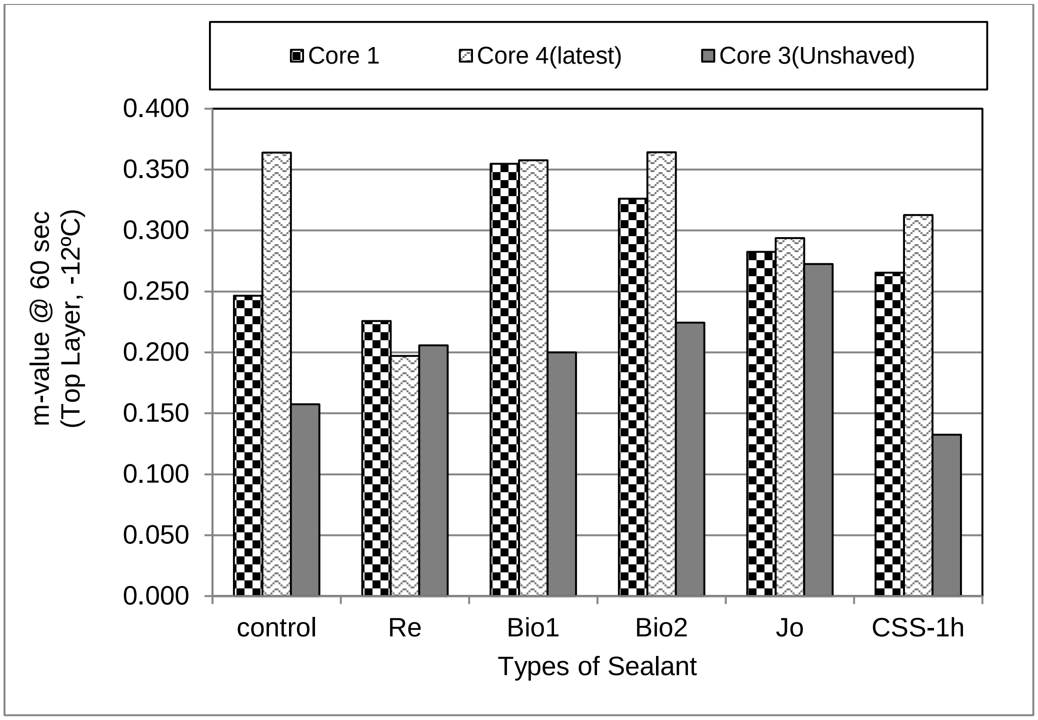


FIGURE 5.11 m-value(60s) Results at -12ºC of Mixture Beams from Field Treated/Top Layer.

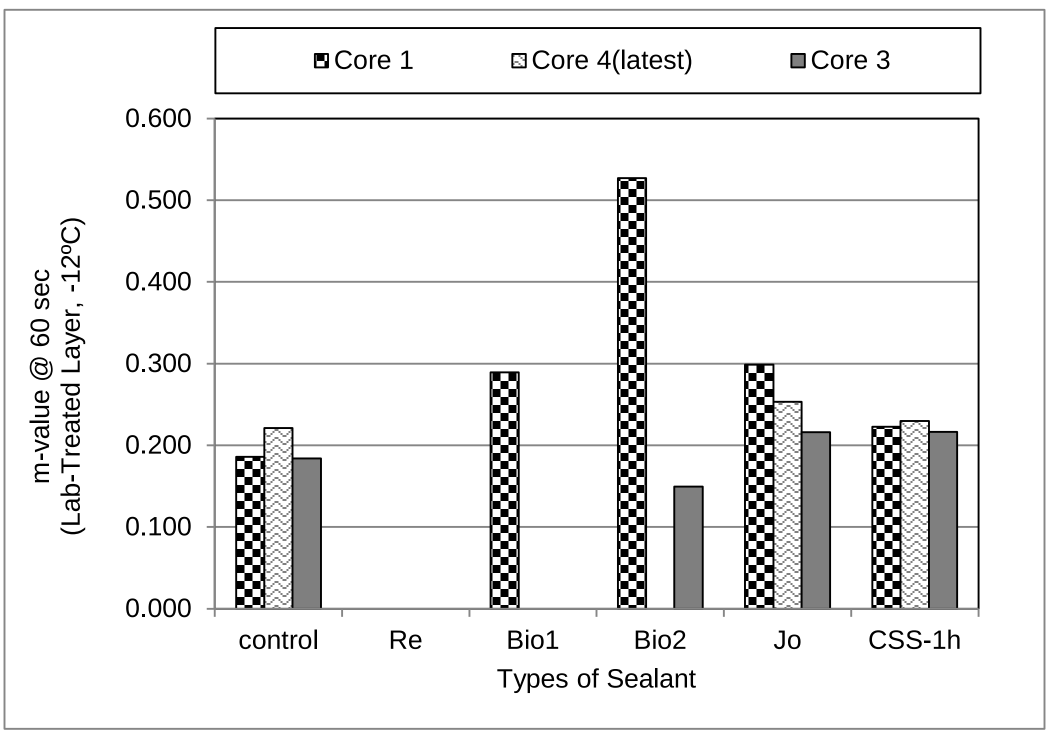


FIGURE 5.12 m-value(60s) Results at -12ºC of Mixture Beams from Lab-Treated Layer.

5.3.3 <u>Strength</u>

Strength tests were also performed on the mixture beams using BBR Pro, a modified BBR machine developed by Marasteanu et al. (2012) *(18).* Unlike the original BBR that applies constant loads, this BBR Pro can apply loads at different rates. The stress and failure strain results are shown in Figures 5.13 to 5.20 for two different temperatures. Small change in both strength and strain at failure are observed for the field-treated mixture beams (Figures 5.14, 5.16, 5.18 and 5.20). For the laboratory treated samples, no major changes in strength were observed, except a decrease in strength when RePlay/Biorestor was applied in the laboratory (Figures 15 and 17). Average strength and failure strain at -12ºC for the mixture beams treated with oil-based RePlay or Biorestor in the laboratory were not possible to obtain due to beam-breaking because of high softening issue (Figures 5.17 and 5.21). However, for the failure strain, 3 to 6 times higher values were observed for RePlay and Biorestor (Figures 5.19 and 5.21).

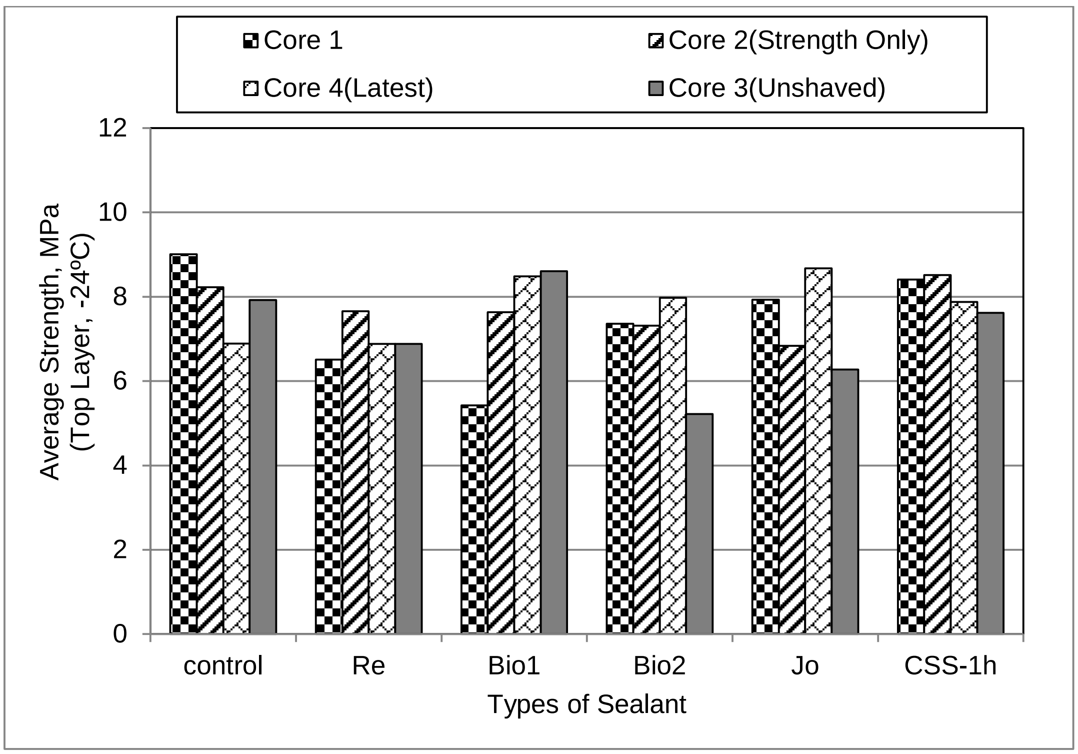


FIGURE 5.13 Strength at -24ºC of Mixture Beams from Field Treated/Top Layer.

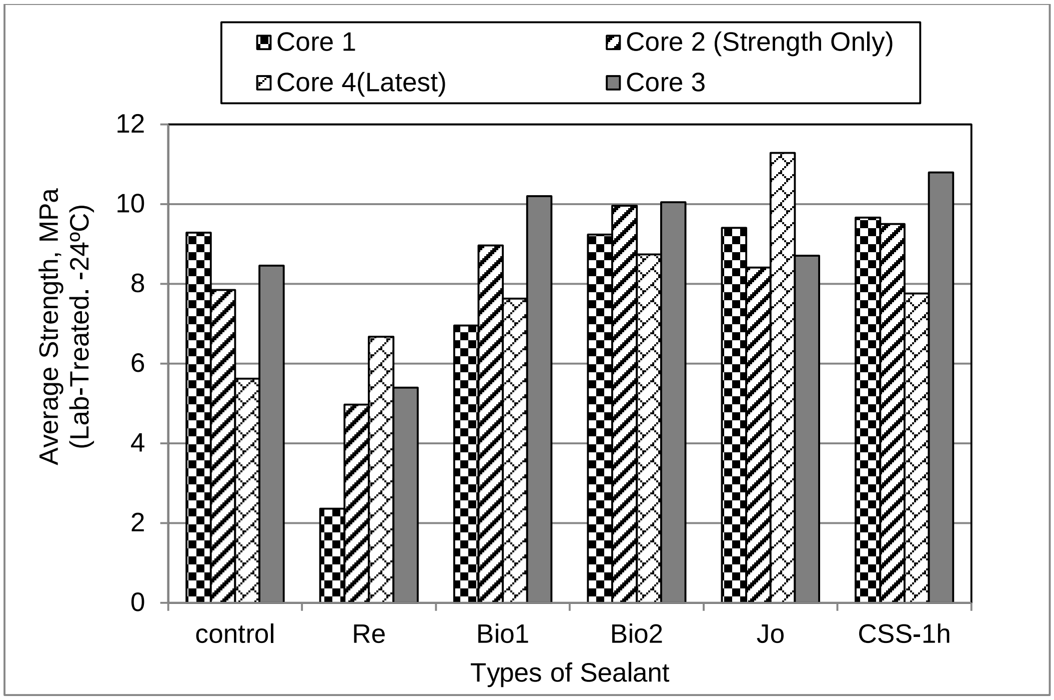


FIGURE 5.14 Strength at -24ºC of Mixture Beams from Lab-Treated Layer.

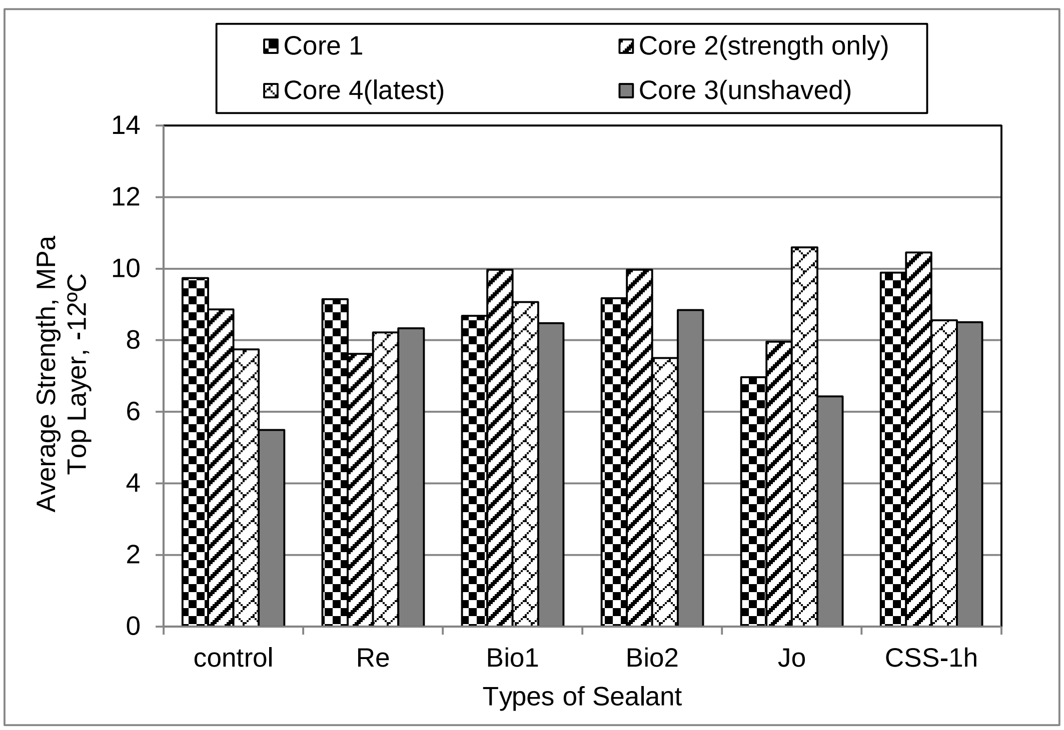


FIGURE 5.15 Strength at -12ºC of Mixture Beams from Field Treated/Top Layer.

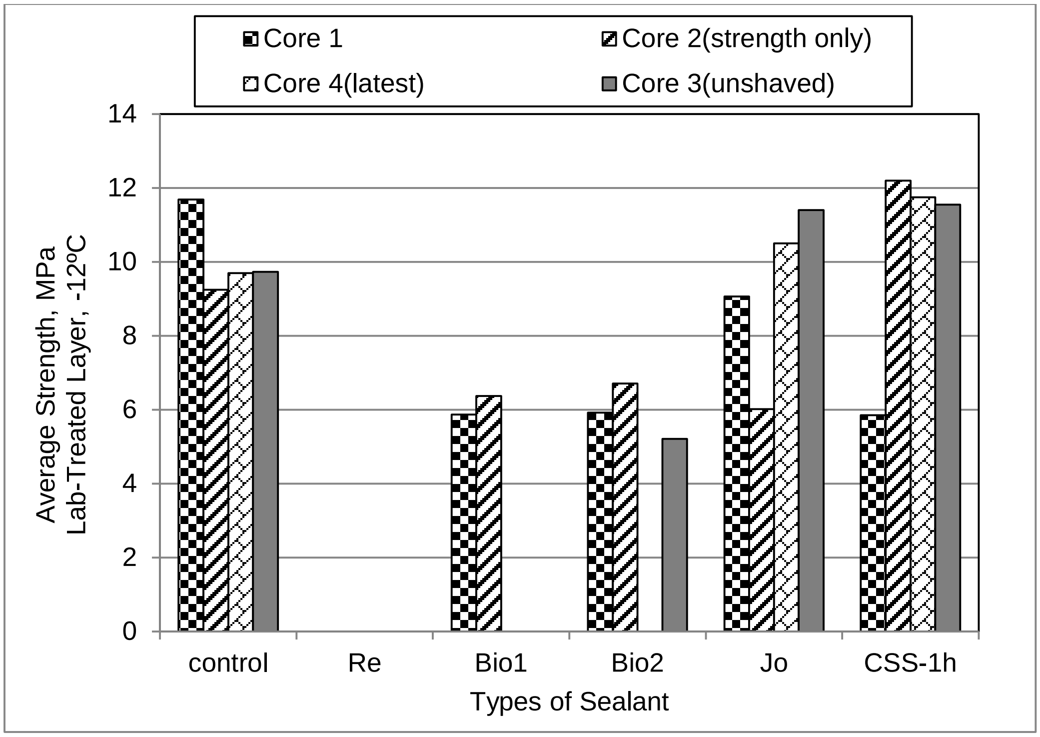


FIGURE 5.16 Strength at -12ºC of Mixture Beams from Lab-Treated Layer.

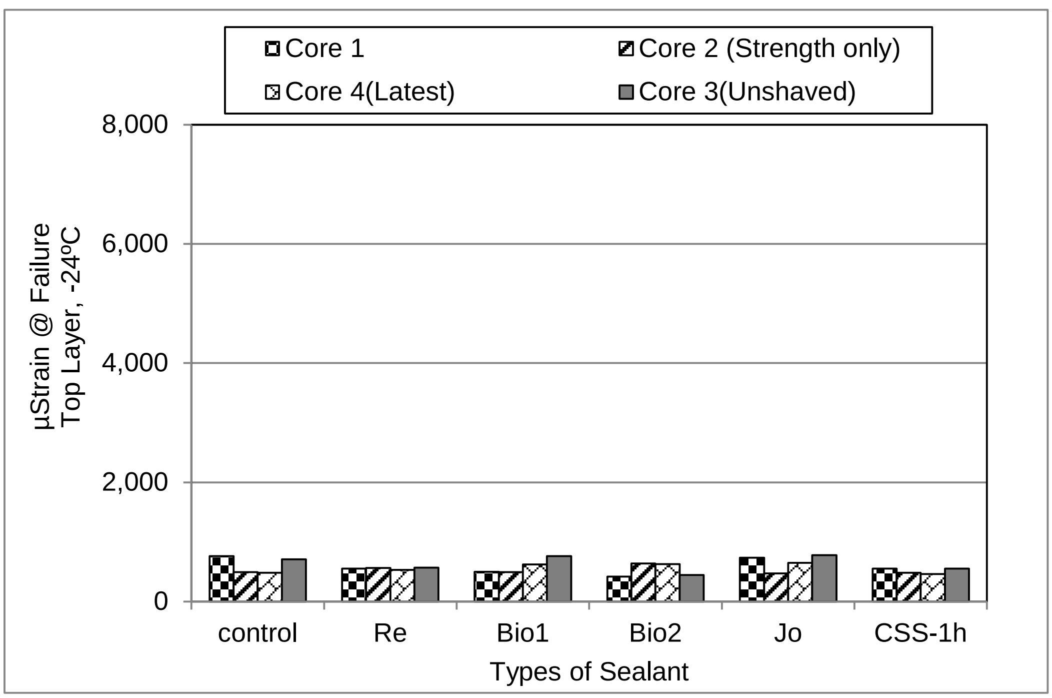


FIGURE 5.17 µStrain at Failure at -24ºC of Mixture Beams from Field Treated/Top Layer.

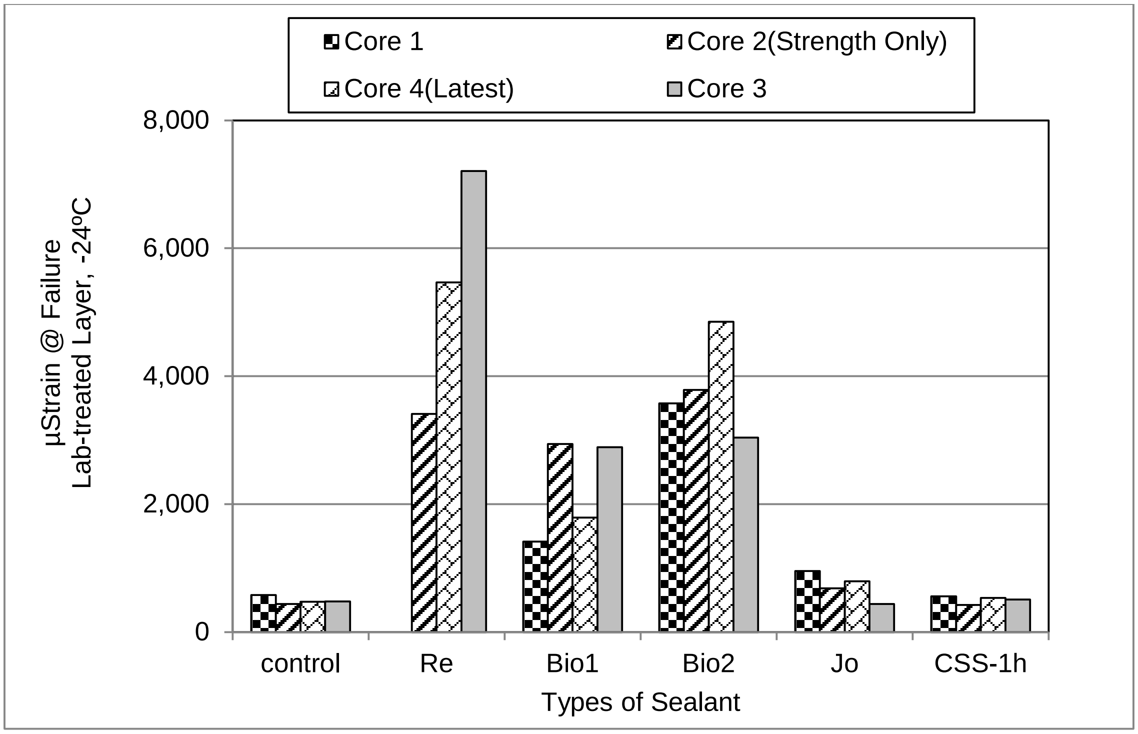


FIGURE 5.18 µStrain at Failure at -24ºC of Mixture Beams from Lab-Treated Layer.

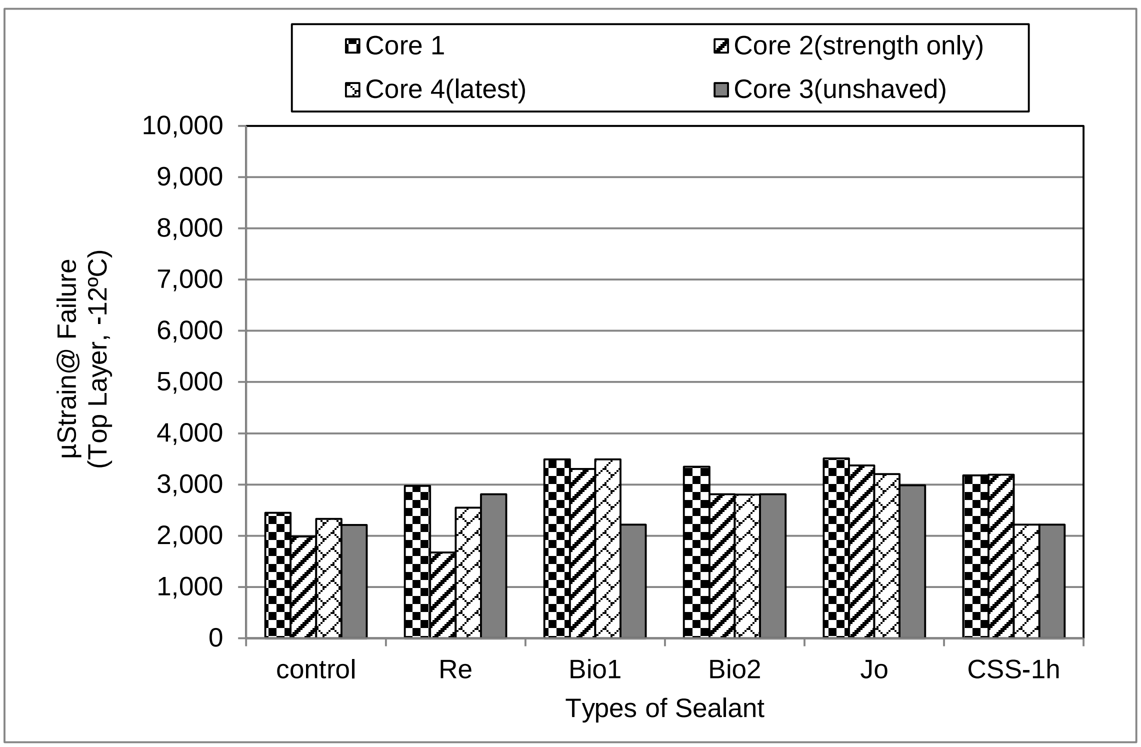


FIGURE 5.19 µStrain at Failure at -12ºC of Mixture Beams from Field Treated/Top Layer.

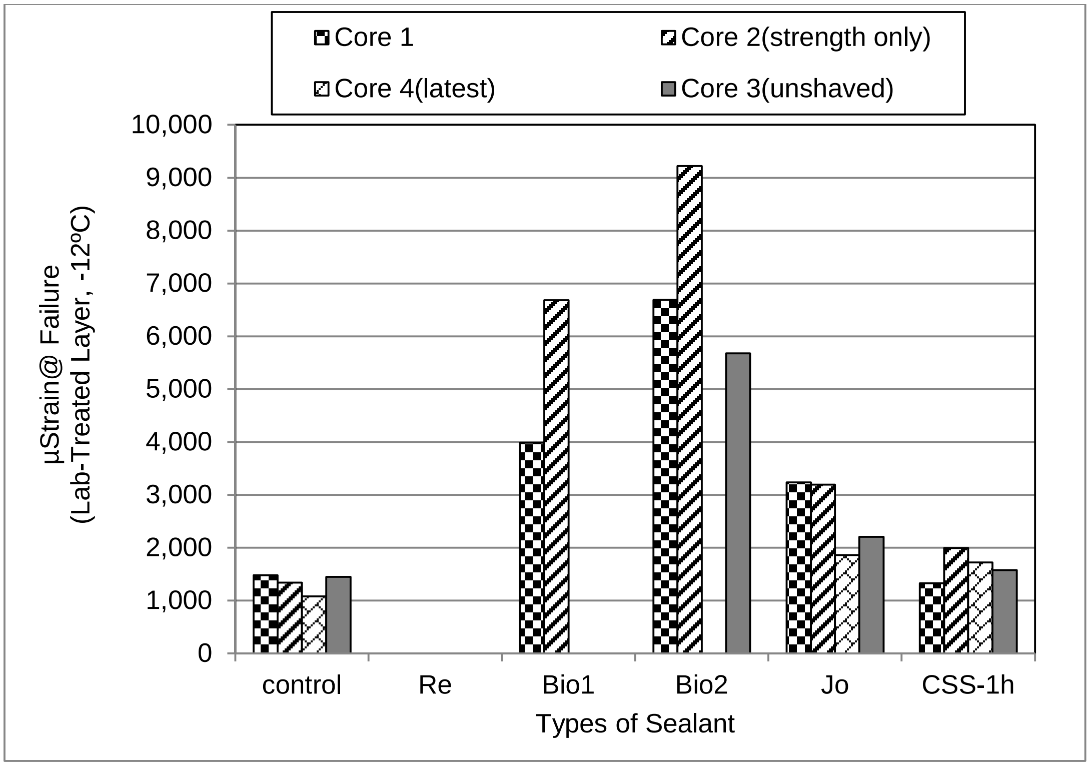


FIGURE 5.20 µStrain at Failure at -12ºC of Mixture Beams from Lab-Treated Layer.

5.4 Shaved vs Unshaved Top Surface

As described earlier, Core 1, 2 and 3 were received from the field few days after sealant application. Top 3mm was removed from Core 1 and 2 to obtain smooth surface. Since, the exact penetration of the sealant in the field is unknown, there might be a chance that removing top 3 mm surface will result in removing the treated surface. In this regard, Core 3 remained unshaved to run a comparison analysis between shaved and unshaved samples. The following plots represent low-temperature mixture properties at -12ºC and -24ºC. A fixed pattern was observed in all cases for the test temperature of -12ºC. The creep stiffness was reported to be higher for the unshaved surface (Core 3) than the shaved surface (Core 1) (Figure 5.22). As a consequence, m-value decreased for Core 3 comparing with Core 1 (Figure 5.24). Average strength and strain at failure at -12ºC were observed to be smaller for Core 3 than Core 1 (Figures 5.26 and 5.28). The obtained test results at -24ºC followed a fixed pattern only for the beams treated with water-based Jointbond and CSS-1h, with an exception for m-value (Figure 5.23, 5.25, 5.27 and 5.29). Creep stiffness and average strength were observed to be lower for Core 3 than Core 1 when tested at -24ºC (Figure 5.23 and 5.27). Figure 5.29 shows that micro-strain increases a very small amount for Core 3 comparing with Core 1 at -24ºC.

5.4.1 Creep Stiffness

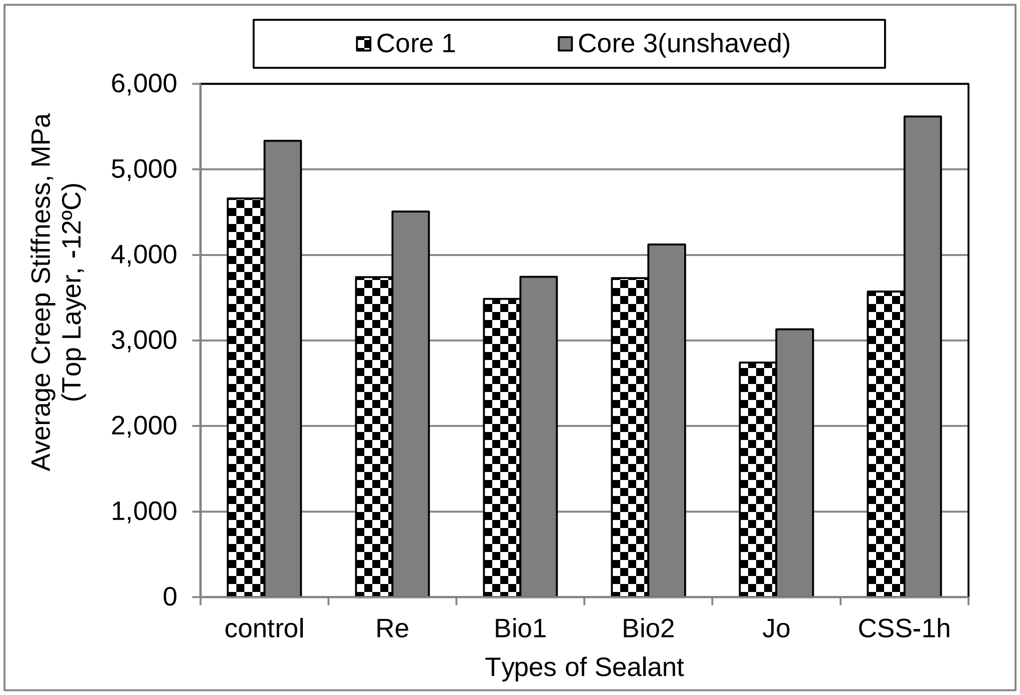


FIGURE 5.21 Creep Stiffness of Mixture Beams for Shaved and Unshaved Top Surface at -12ºC.

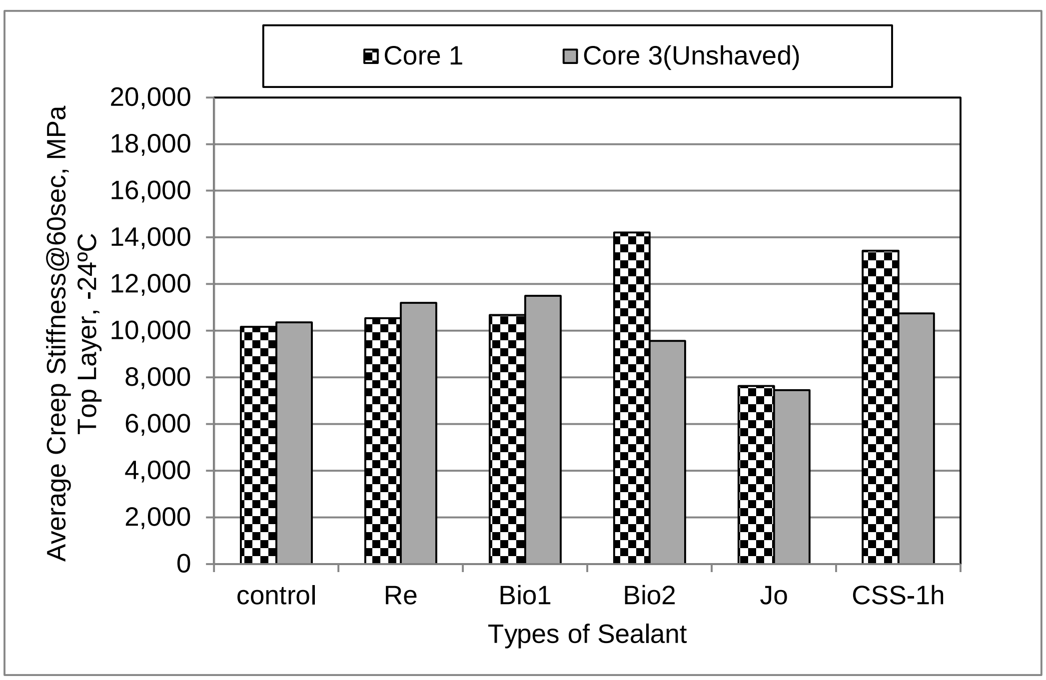


FIGURE 5.22 Creep Stiffness of Mixture Beams for Shaved and Unshaved Top Surface at -24ºC.

5.4.2 m-value

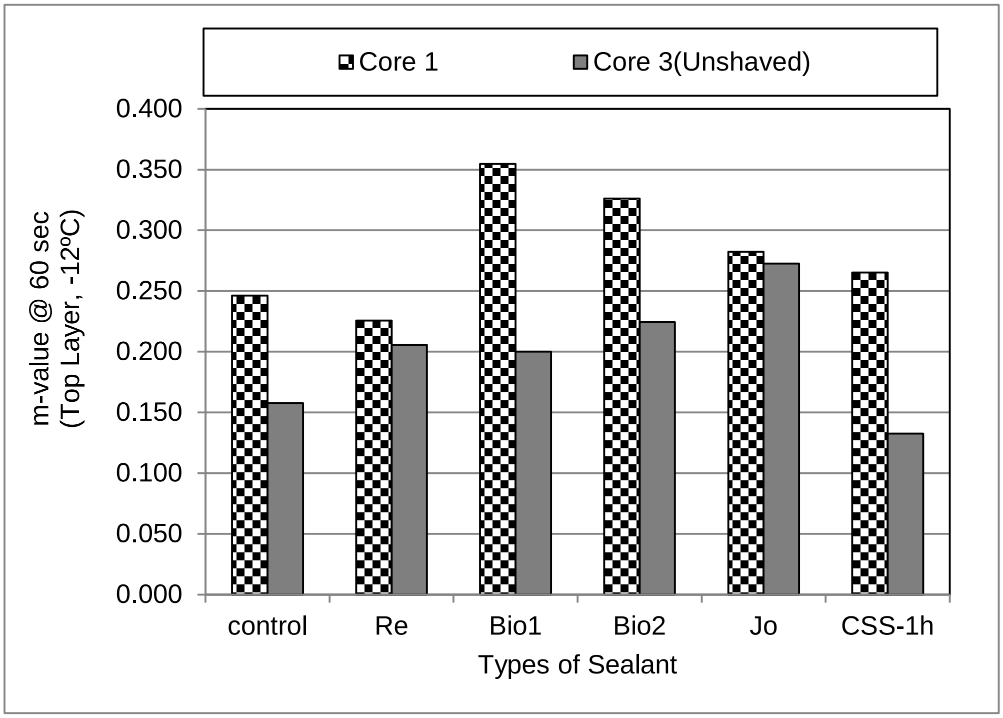


FIGURE 5.23 m-value of Mixture Beams for Shaved and Unshaved Top Surface at -12ºC.

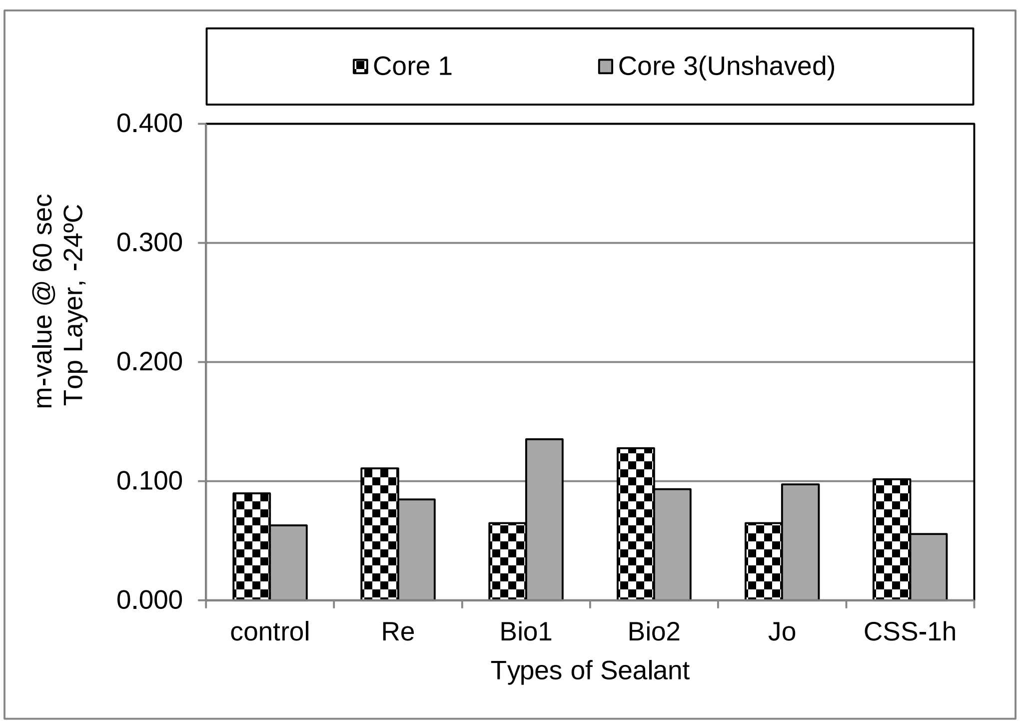


FIGURE 5.24 m-value of Mixture Beams for Shaved and Unshaved Top Surface at -24ºC.

5.4.3 Average Strength

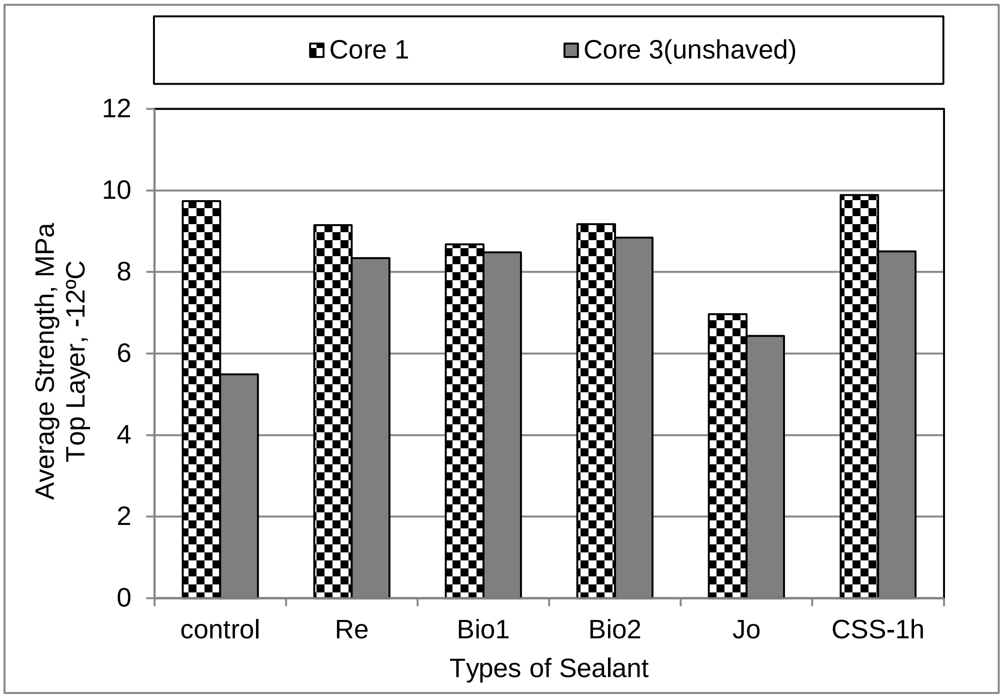


FIGURE 5.25 Average Strength of Mixture Beams for Shaved and Unshaved Top Surface at -12ºC.

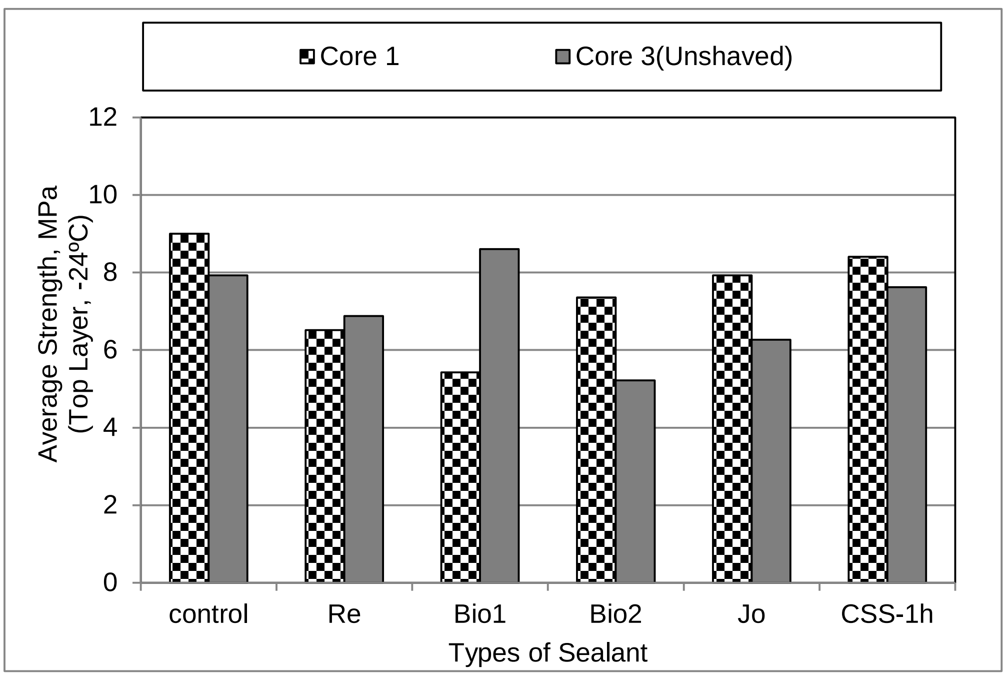


FIGURE 5.26 Average Strength of Mixture Beams for Shaved and Unshaved Top Surface at -24ºC.

5.4.4 Strain at Failure

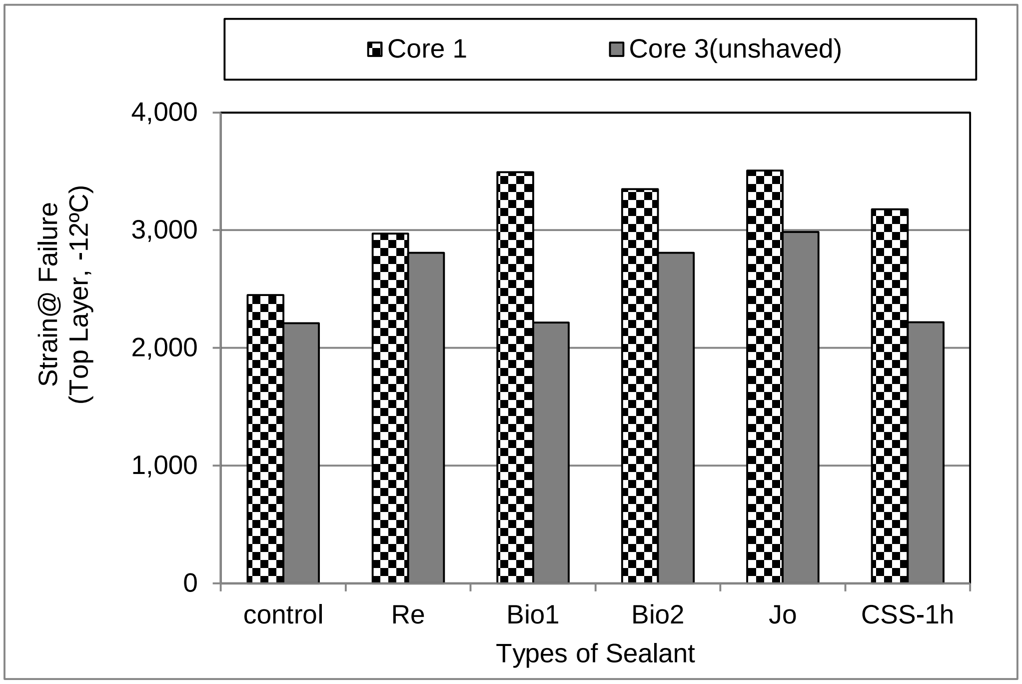


FIGURE 5.27 µStrain at Failure of Mixture Beams for Shaved and Unshaved Top Surface at -12ºC.

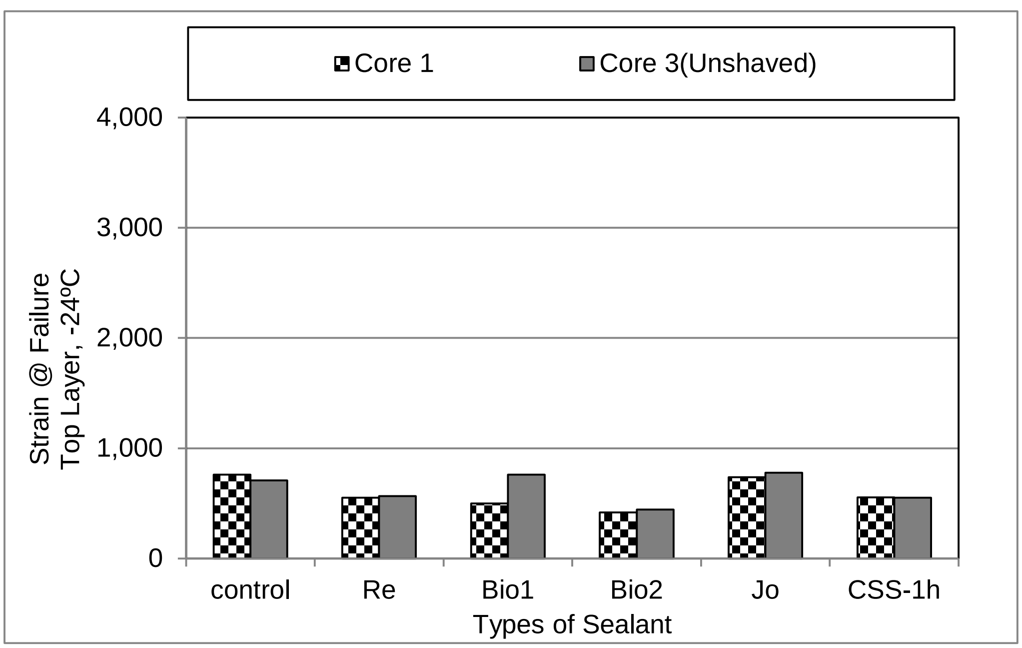


FIGURE 5.28 µStrain at Failure of Mixture Beams for Shaved and Unshaved Top Surface at -24ºC.

5.5 Summary

Creep and strength tests were performed on mixture beams prepared from field cores. The beams include both field-treated and laboratory treated. The pipette method was used to treat the beams in the laboratory and a comparison was run between the results obtain from field-treated beams and lab-treated beams. A significant softening effect was observed in case of lab-treated beams treated by oil-based RePlay and Biorestor. However, there was hardly any change in properties noticed in case of field-treated beams compared to the control section. A more detailed analysis of the mixture results is presented in the next chapter.

CHAPTER 6: ANALYSIS OF THE EXPERIMENTAL RESULTS

6.1 Introduction

In this chapter, further analysis of the experimental results obtained on the asphalt binder and mixture materials investigated in this study are presented. Statistical analyses are performed to investigate the effect of sealant on binder and mixture. A semi empirical model is used to evaluate the feasibility of relating asphalt binder and mixture properties to better understand the effect of sealant application rates to mixture properties.

6.2 Analysis of Asphalt Binder Experimental Results

The performance grade (PG) of the virgin and blended binders was determined in accordance with AASHTO M320. The following plots represent the change in rutting factor, fatigue factor, stiffness and m-value due to different application procedure as well as different storage time for different sealants (Figure 6.1-). The plots show that for the mixing procedure, oil-based RePlay and Biorestor have a very significant effect comparing with the control binder and binder treated with Jointbond or CSS-1h. The application of water-based Jointbond and CSS-1h don't bring any major changes in the rutting parameter comparing with the control binder.

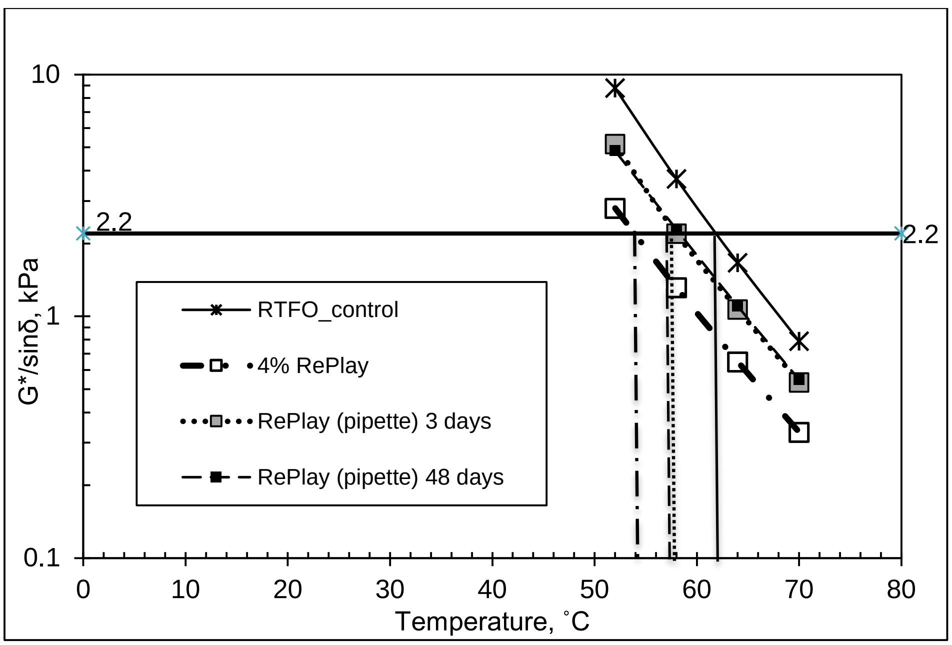


FIGURE 6.1 Change in Rutting Factor of Binder Treated with RePlay due to Different Application Process and Storage Time.

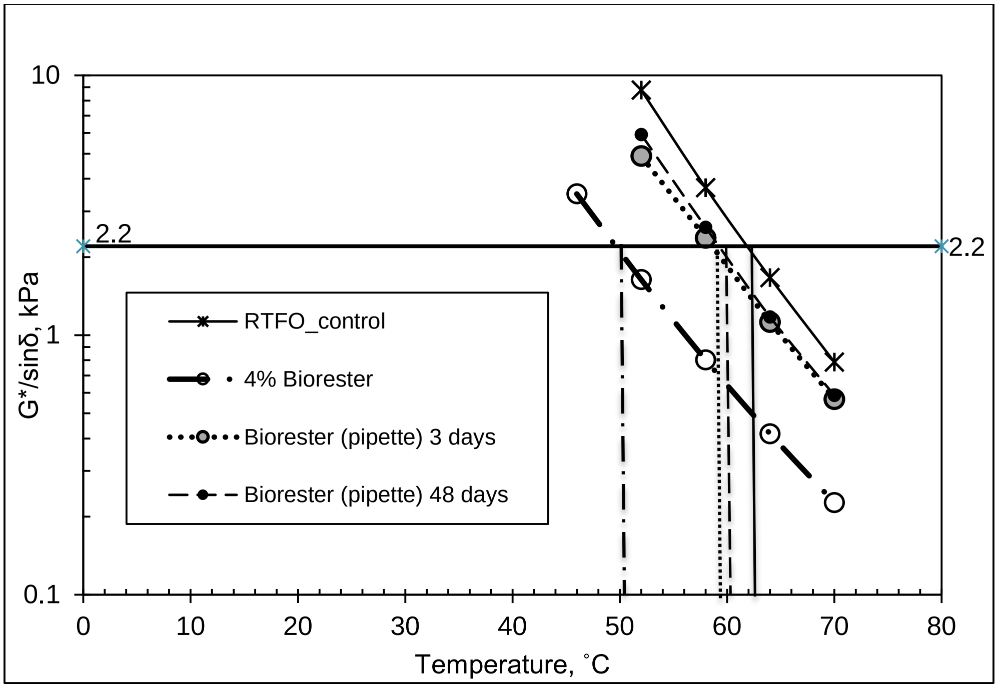


FIGURE 6.2 Change in Rutting Factor of Binder Treated with Biorestor due to Different Application Process and Storage Time.

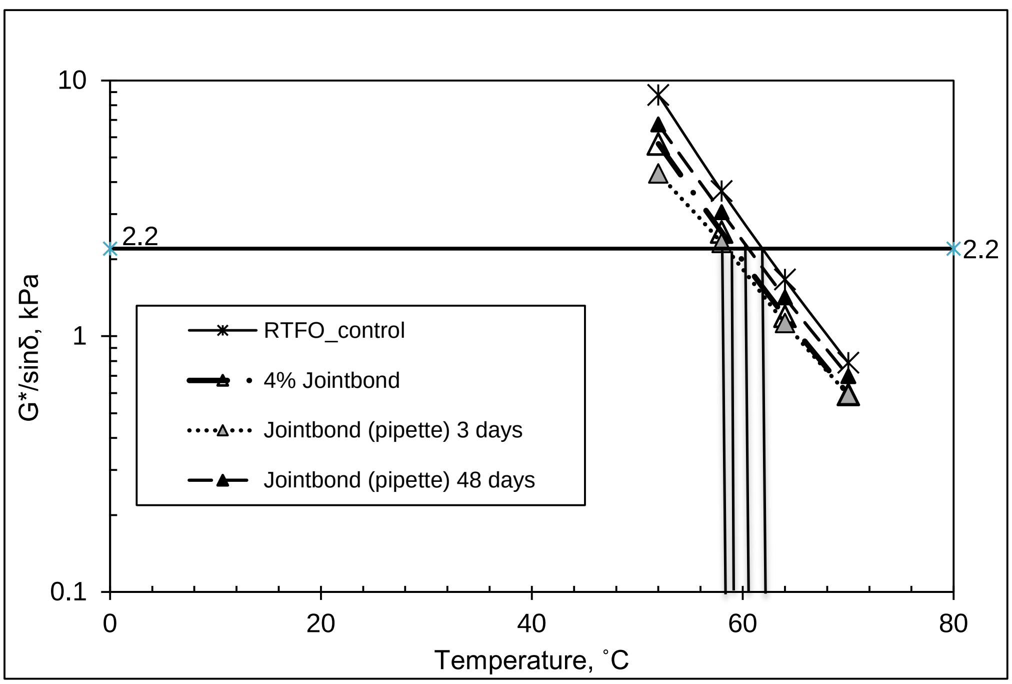


FIGURE 6.3 Change in Rutting Factor of Binder Treated with Jointbond due to Different Application Process and Storage Time.

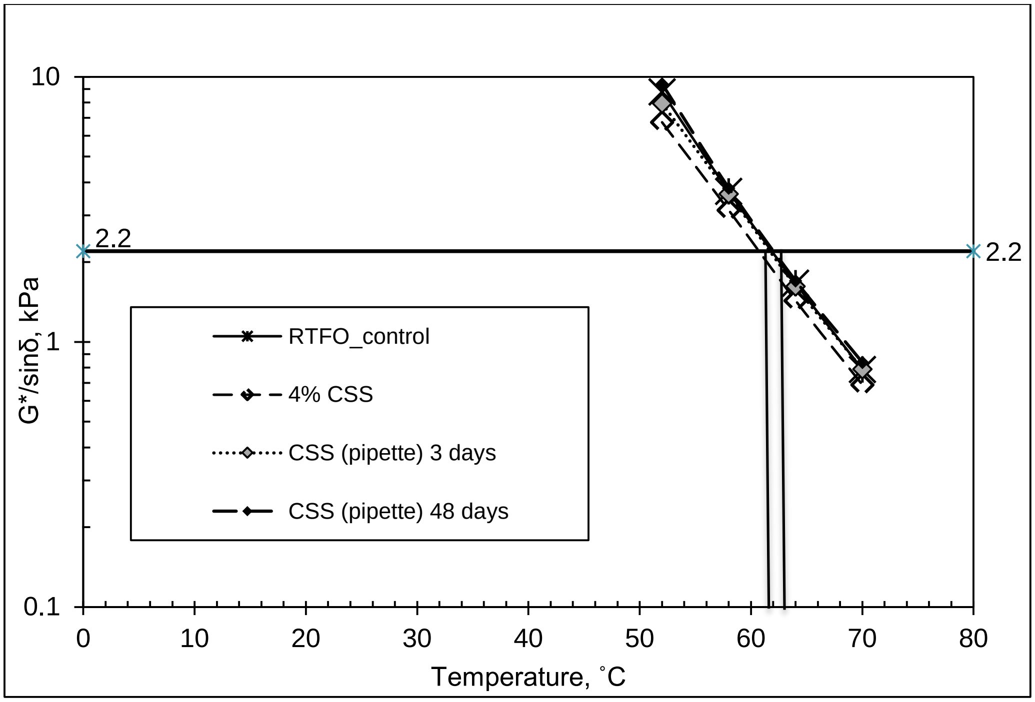


FIGURE 6.4 Change in Rutting Factor of Binder Treated with CSS-1h due to Different Application Process and Storage Time.

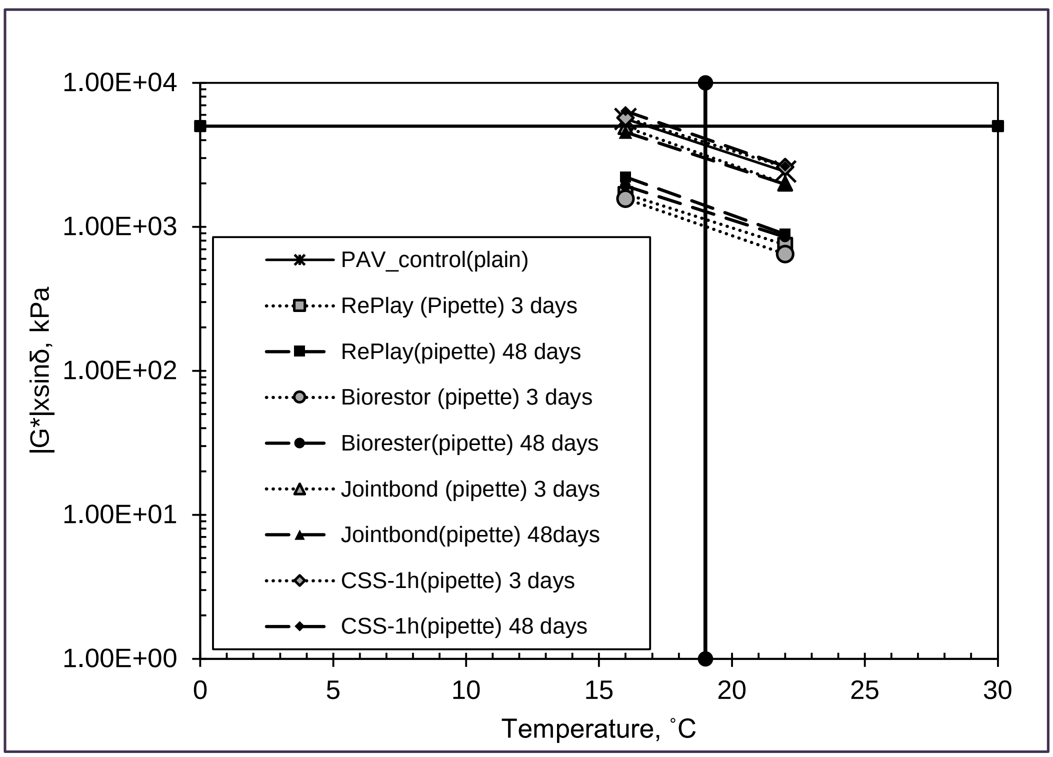


FIGURE 6.5 Change in Fatigue Factor due to Pipette method.

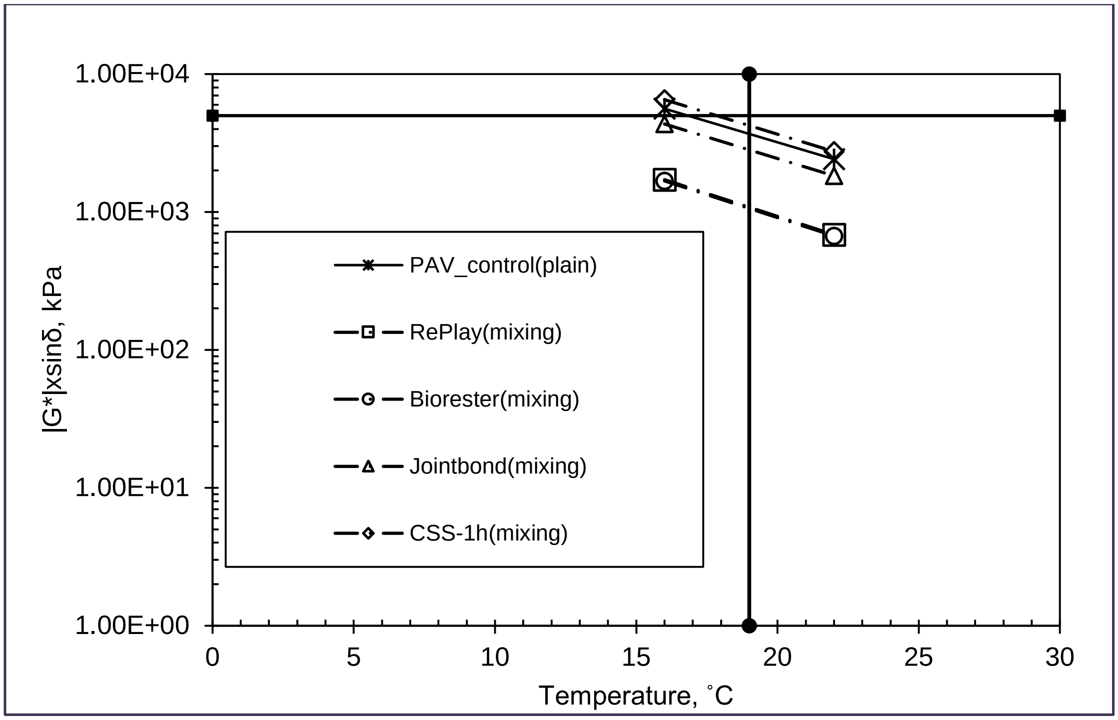


FIGURE 6.6 Change in Fatigue Factor due to Mixing Method.

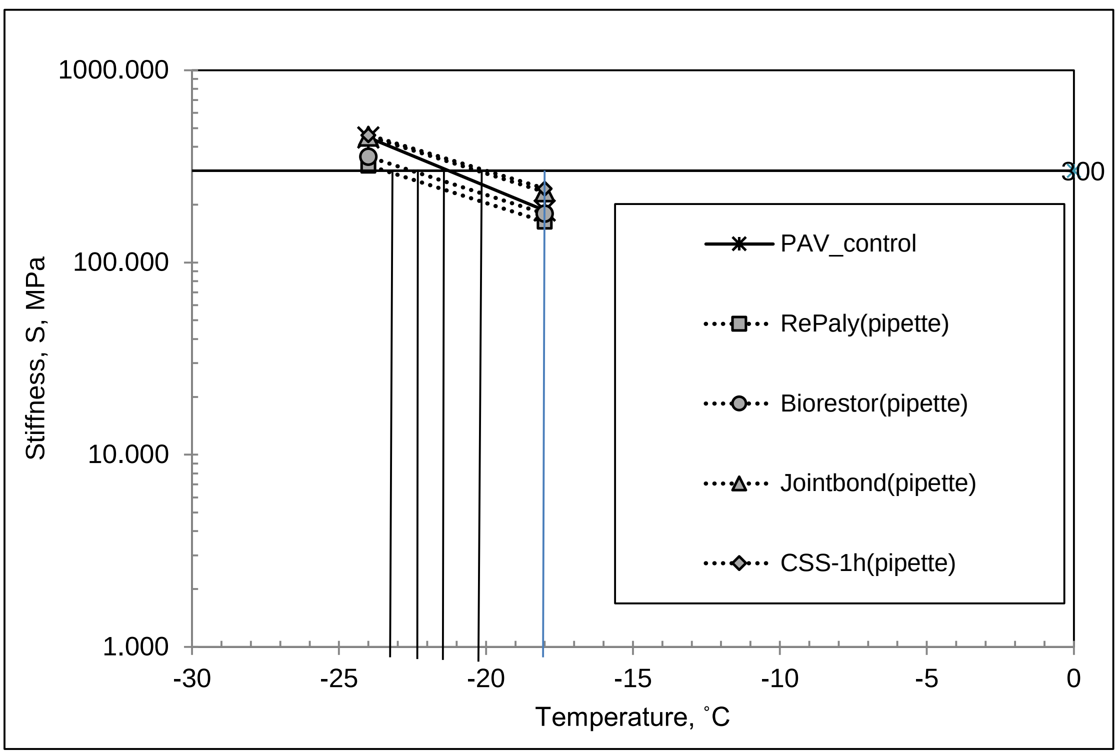


FIGURE 6.7 Change in Creep Stiffness due to Pipette Method.

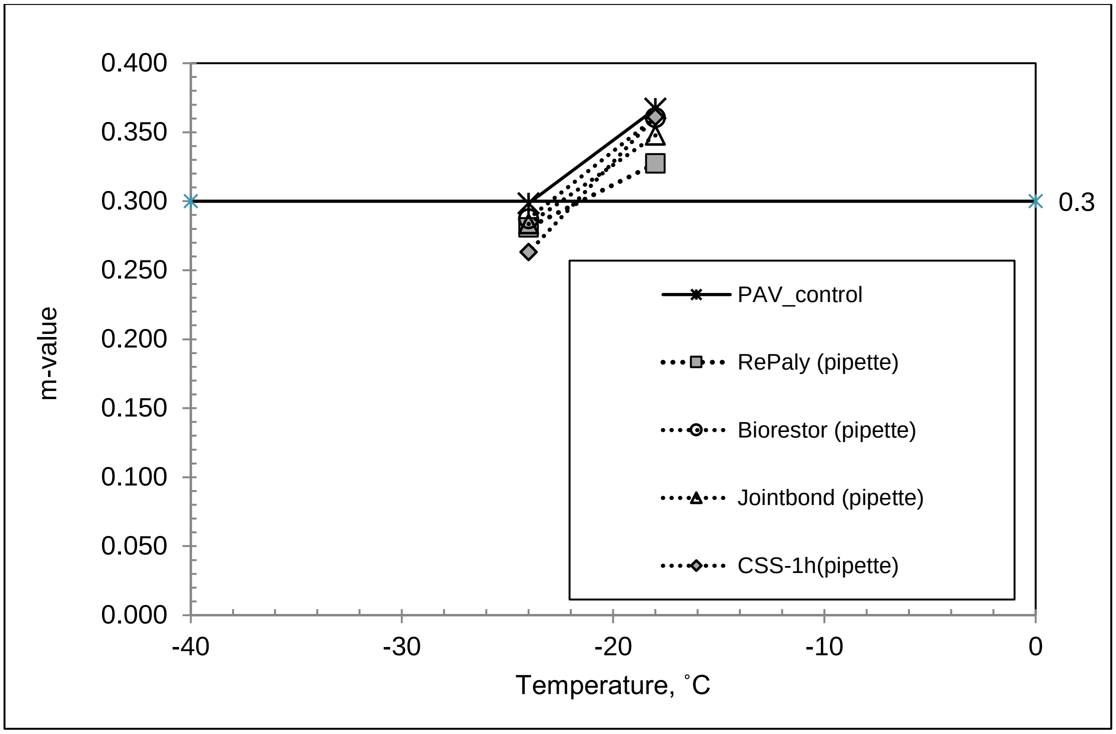


FIGURE 6.8 Change in m-value due to Pipette Method.

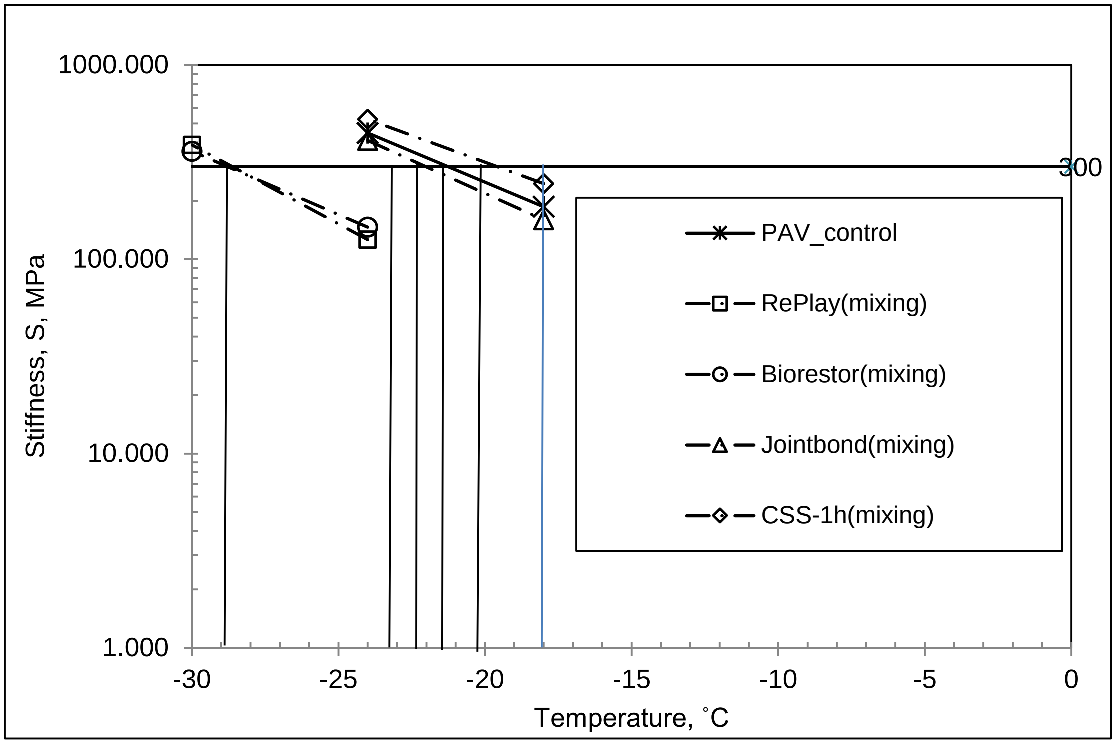


FIGURE 6.9 Change in Creep Stiffness due to Mixing Method.

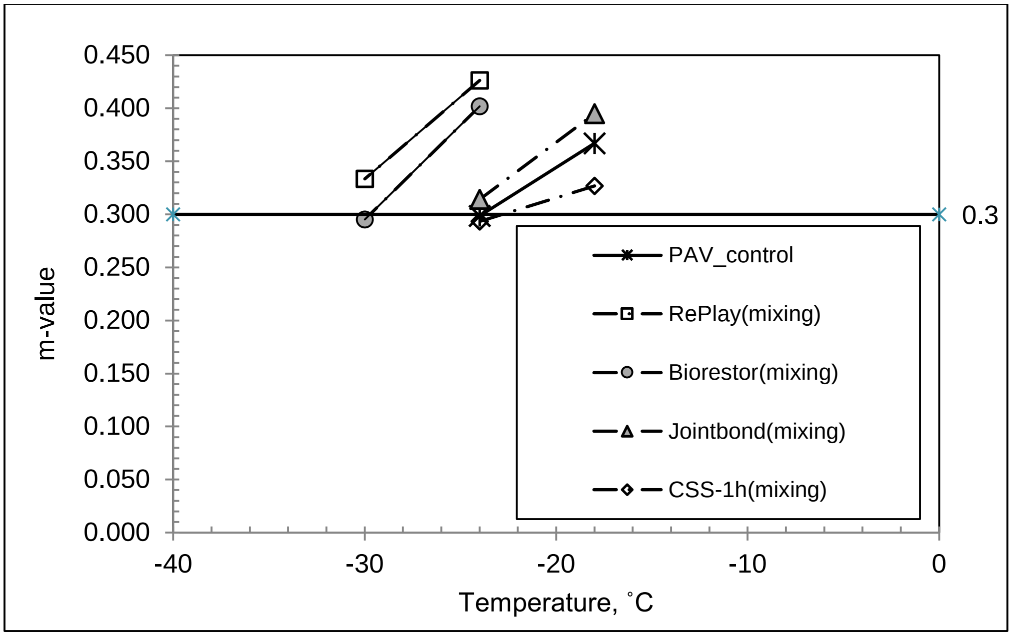


FIGURE 6.10 Change in m-value due to Mixing Method.

To better evaluate the changes produced by the application of sealants, the exact temperature values for the high and low failure criteria were tabulated rather than the specification temperatures (Table 6.1). The BBR tests were not conducted for 48 days due to difficulty in storing the beams.

TABLE 6.1 Change in Performance Grade

	Mixing 4%	**Pipette(3 days)**	**Pipette(48 days)**
Control PG 58-28	PG 62-31		
RePlay	PG 54-38	PG 58-33	PG 58-…
Biorestor	PG 50-38	PG 58-32.5	PG 59-…
Jointbond	PG 59-31	PG 58-30	PG 61-…
CSS-1h	PG 61-29	PG 62-30	PG 62…

A number of important observations can be made. The simple mixing procedure results in significant changes in the PG of the original binder, a clear indication that this procedure cannot simulate the blending mechanisms that occur in field conditions.

The pipette method appears to be a much better indicator of the effect of the sealant application in field conditions. The changes are consistent with the mild softening effects observed in sealant applications in the field.

A one-way ANOVA test for single factor was performed to determine the statistical significance of sealant application on the low temperature properties of treated binders. For binder testing, only two replicates were used. The results of the ANOVA test are presented in Table 6.2. For a significance level of 5%, the variables with *p*-values smaller than 0.05 are significant and presented in bold. In some cases, p-value is even less than 0.01 which indicates the probability of

99% that the bio-sealants have the effect on control binder. The positive and negative signs in Table 6.2 represents an increase and respectively, a decrease in properties compared to the control.

The statistical analysis verifies the findings of laboratory experiments. For the binder, the most significant effect is observed for the case when the hot binder and sealants were mixed together, as indicated by the very small p-values.

TABLE 6. 2 One-Way ANOVA Test for Binder at Low Temperature

Creep Stiffness Test of Binder @ -24ºC								
P-value from One-Way ANOVA Test								
	RTFO (8 drops)		RTFO (16 drops)		PAV (8 drops)		PAV(mixing)	
	Stiffness	m-value	Stiffness	m-value	Stiffness	m-value	Stiffness	m-value
RePlay	**(-)0**	**0.001**	**(-)0.0003**	0.277	**(-)0.02**	0.059	**(-)0.001**	**0.002**
Biorestor	**(-)0.003**	0.239	**(-)0.003**	0.487	**(-)0.02**	0.062	**(-)0.003**	**0.002**
Jointbond	(-)0.899	0.687	(-)0.073	0.727	**(+)0.07**	0.053	(-)0.63	0.139
CSS-1h	(+)0.051	0.766	**(+)0.015**	0.572	**(+)0.02**	0.222	(+)0.65	0.176

6.3 Analysis of Asphalt Mixture Experimental Results

A one-way ANOVA test for single factor was performed to determine the statistical significance of sealant application on the low temperature properties of treated mixtures. Mixture beams from respective layers of all cores were used as replicates in the analysis. For mixture creep-stiffness and m-value, a total of 9 replicates where used, whereas for strength and strain at failure, 12 replicates were used. The results of the ANOVA test are presented in Tables 6.3 and 6.4 for two different temperature, -24ºC and -12ºC, respectively. For a significance level of 5%, the variables with *p*-values smaller than 0.05 are significant and presented in bold. In some cases, p-value is even less than 0.01 which indicates the probability of 99% that the bio-sealants have the effect on control binder/mixture. The positive and negative signs in Tables 6.3 and 6.4 represent an increase and respectively, a decrease in properties compared to the control.

TABLE 6. 3 p-value from One-Way ANOVA Test for Mixture at -24ºC

Creep Stiffness and Strength Test of Mixture Beams @ -24ºC									
Sealants		**Stiffness, MPa**		**m-value**		**Strength, MPa**		**Strain @ Failure**	
		Field	Lab	Field	Lab	Field	Lab	Field	Lab
Oil-Based	Re	**0.040**	**(-)0.000**	0.210	**(+)0.000**	*0.059*	**(-)0.001**	*0.057*	**(+)0.000**
	Bio1	0.310	**(-)0.001**	**0.011**	**(+)0.000**	0.293	0.803	0.340	**(+)0.000**
	Bio2	0.740	**(-)0.000**	0.450	**(+)0.000**	**0.041**	**(+)0.016**	*0.060*	**(+)0.000**
Water-Based	Jo	0.250	0.170	*0.060*	**(+)0.002**	0.357	**(+)0.015**	0.473	*0.070*
	CSS-1h	0.230	**(-)0.004**	0.690	**(+)0.005**	0.327	0.432	0.170	0.222

TABLE 6. 4 p-value from One-Way ANOVA Test for Test Results @ -12ºC

Creep Stiffness and Strength Test of Mixture Beams @ -12ºC									
Sealants		**Stiffness, MPa**		**m-value**		**Strength, MPa**		**Strain @ Failure**	
		Field	Lab	Field	Lab	Field	Lab	Field	Lab
Oil-Based	Re	0.632	**5.02E-07**	0.972	**0.000**	0.534	**2.19E-13**	0.246	**1.06E-11**
	Bio1	0.474	**9.16E-08**	0.126	**0.000**	0.366	**0.0038**	**0.014**	**1.39E-05**
	Bio2	0.189	**4.79E-08**	0.064	**0.001**	0.812	**0.0059**	**0.027**	**2.34E-06**
Water-Based	Jo	**0.037**	**0.0126**	0.074	**0.000**	0.274	0.6757	**0.037**	**0.00037**
	CSS-1h	0.672	0.335	0.953	**0.007**	0.641	**0.0396**	0.277	**0.032**

The statistical analysis verifies the findings of laboratory experiments. For the mixtures, only a few significant effects are observed for the field mixtures, while significant changes in almost all properties investigated are observed for the laboratory treated mixtures.

6.4 FTIR Analysis

To better understand the results of the mechanical testing presented in the previous section, Fourier Transform Infrared absorption spectroscopy (FTIR) evaluations were performed on two sealants and on the corresponding extracted binders obtained from the mixture beams used in the experimental laboratory testing. This was done to detect the presence of these sealants on the surface of the field cores and in the laboratory treated asphalt mixture beams. The presence of the other two sealants could not be tested since their corresponding spectrum matched the asphalt binder spectrum. Test specimens were prepared by evaporating residue from liquid samples and then configuring them as Cap Film on NaCl Window specimens.

Stacked absorbance spectra are shown in Figures 6.11 and 6.12 for wavenumbers in the region between 455.13 and 3995.85 cm-1. In both cases, it is noticed that traces of the sealants were detected only on the laboratory treated samples and not on the field treated samples. It is not clear what the mechanism responsible for this difference is.

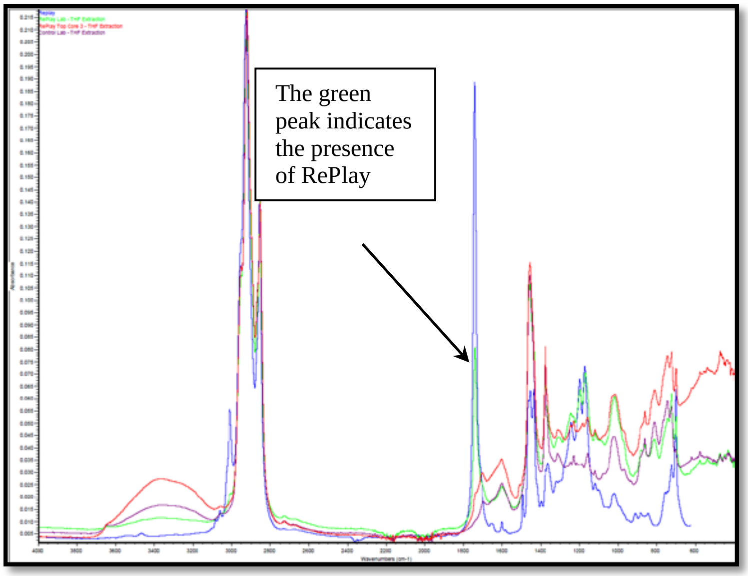


FIGURE 6.11 Stacked absorbance spectra for RePlay and RePlay treated samples.

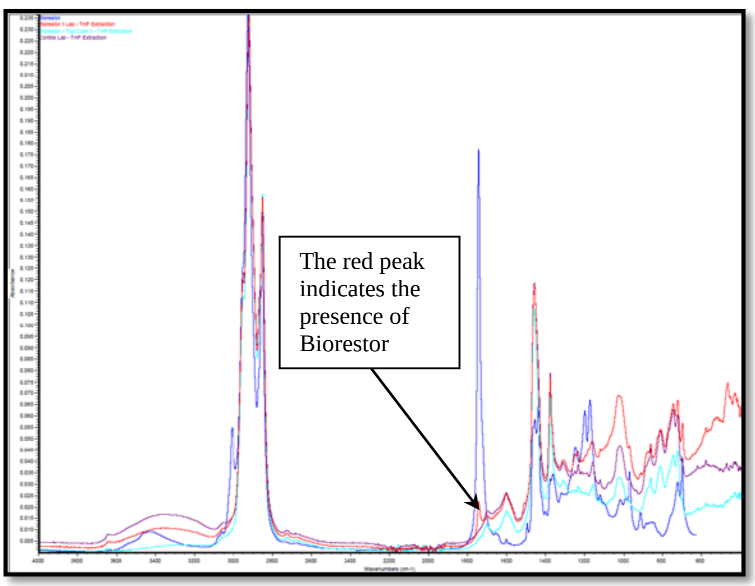


FIGURE 6.12 Stacked absorbance spectra for Biorestor and Biorestor treated samples.

6.5 Application of Hirsch Model to Experimental Binder and Mixture Data

In this analysis, Hirsch semi empirical model is used to relate binder and mixture properties and to investigate if it is possible to predict treated mixture properties from treated binder properties. The goal is to determine if changes in mixture behavior are due to the addition of sealant. In the calculations, only the creep stiffness results at -24ºC were used. After a number of iterations, it was decided to only use the experimental binder creep stiffness results obtained on samples treated in the laboratory using the pipette method. Both RTFO-aged and PAV-aged binder beams were treated with sealants to predict the mixture creep stiffness. The predicted mixture creep stiffness was then compared with the obtained experimental mixture creep stiffness data for Core 3 only, for both field treated (top layer) and lab-treated (bottom layer) samples. Core 3 results were used since it was the only core from which the top was not removed, and therefore was the closest to real field conditions.

6.6 Forward Problem

Christensen et al. (2003) proposed a semi-empirical model based on Hirsch model (Hirsch, 1962) which can estimate the extensional and shear dynamic modulus *(33)*. This model is used to solve the forward problem of predicting mixture stiffness from experimental binder stiffness. The general equation for the semi-empirical model is

$$S_{mix}=P_c[E_{agg}*V_{agg}+S_{binder}*V_{binder}]+(1-Pc)*[(V_{agg}/E_{agg})+(1-V_{agg})^2/(S_{binder}*V_{binder})]^{-1} \quad (2)$$

where:

S_{mix}= effective creep stiffness of the mixture,

E_{agg}, V_{agg}= modulus and volume fraction of the aggregate,

S_{binder}, V_{binder}= creep stiffness and volume fraction of binder and

P_c= contact volume is an empirical factor defined as:

$P_c=0.1*LN(E_{binder}/a)+0.609$; a= 1000 MPa.

Volume fraction of aggregate and binder were calculated from the information provided in the mix design data-sheet. The total binder was 4.8% of which 3.9% was the newly added fresh binder along with the rest of it coming from the RAP. The calculation was performed using both Pb=3.9% and Pb=4.8%, where Pb is the percent binder used. The observed difference was very negligible. Therefore, the plots obtained using Pb=4.8% are presented.

Since the modulus of aggregate is not known, based on a study by Zofka et al., both E_{agg}=19GPa and E_{agg}=29GPa were used. Zofka et al. (2005) used a value of aggregate modulus different from the original formulation, proposed by Christensen (2003) (19GPa instead of 29GPa) with better fitting results. As a result in this study both values were used (33, 34). The results are shown in Figures 6.13-6.22.

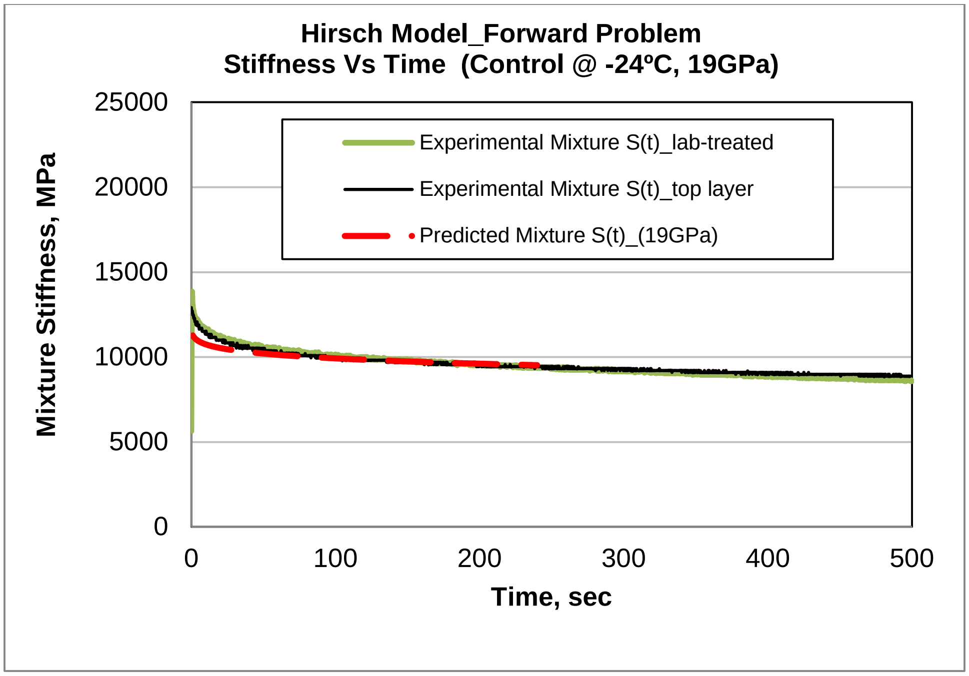


FIGURE 6.13 Hirsch Model using E_{agg}=19 GPa for Control RTFO-aged PG 58-28.

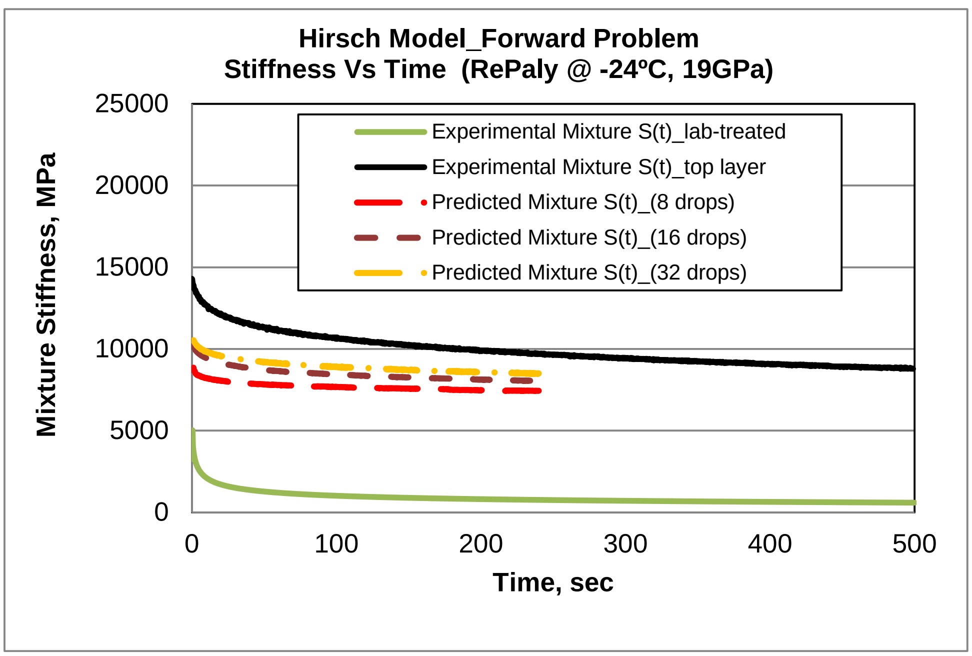


FIGURE 6.14 Hirsch Model Using E_{agg}=19 GPa for RTFO-aged PG 58-28 Treated with RePlay.

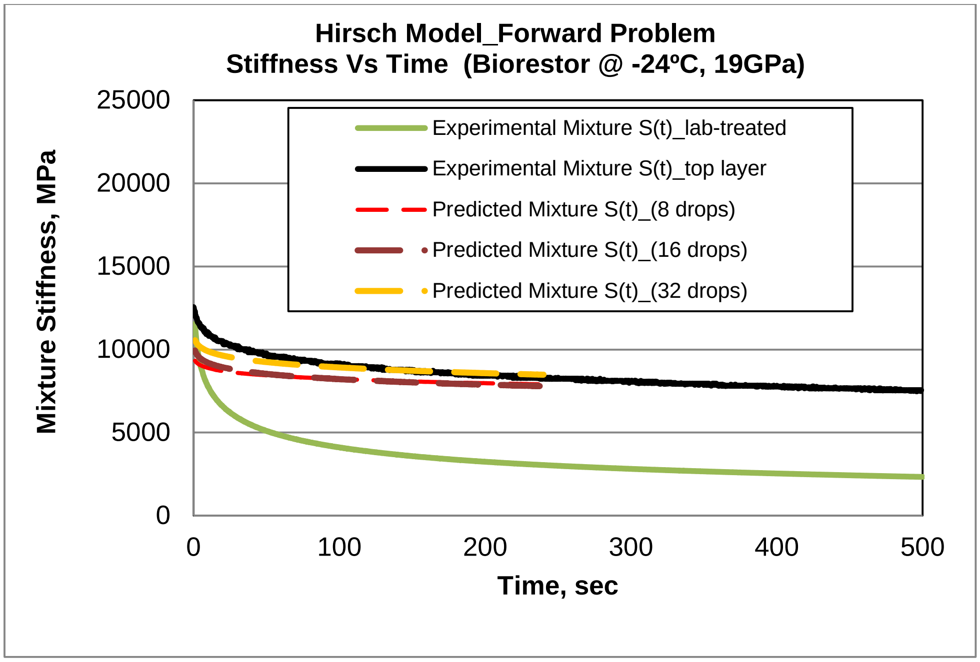


FIGURE 6.15 Hirsch Model Using E_{agg}=19 GPA for RTFO-aged PG 58-28 Treated with Biorestor.

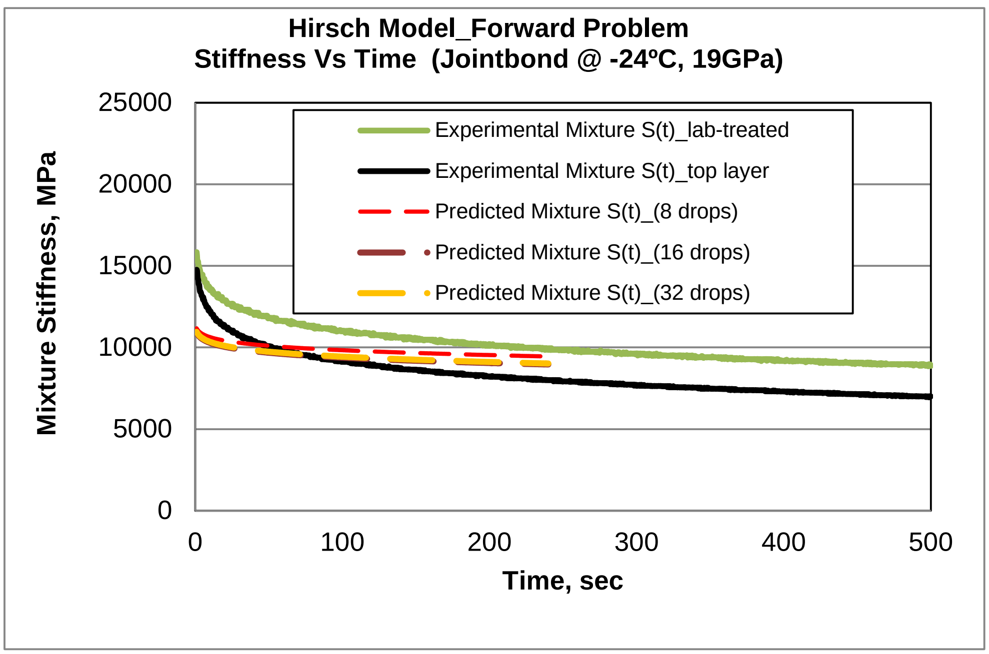


FIGURE 6.16 Hirsch Model Using E_{agg}=19 GPA for RTFO-aged PG 58-28 Treated with Jointbond.

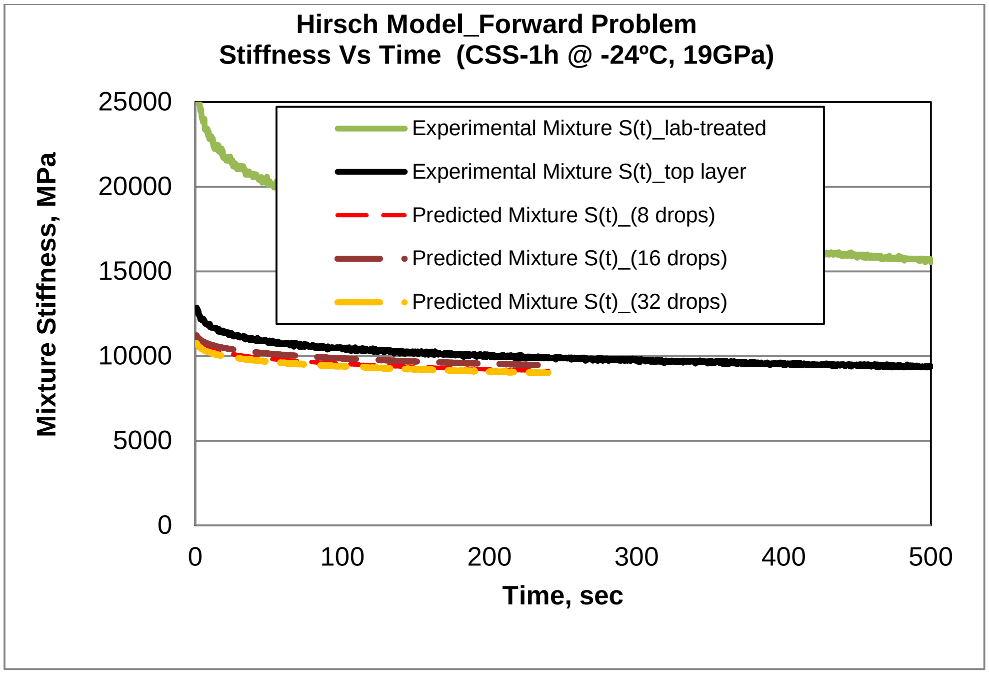


FIGURE 6.17 Hirsch Model Using E_{agg}=19 GPA for RTFO-aged PG 58-28 Treated with CSS-1h.

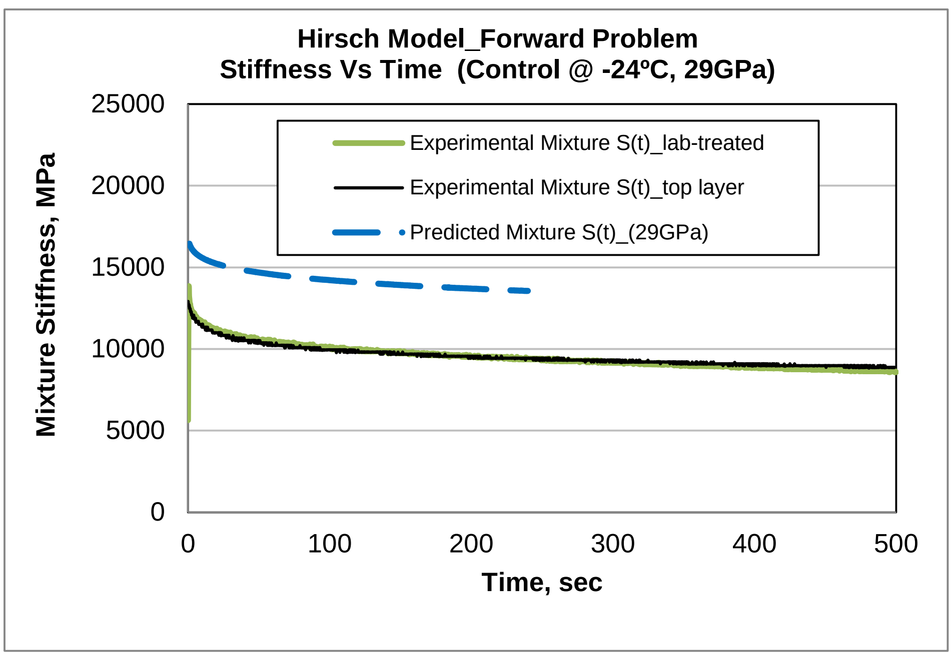


FIGURE 6.18 Hirsch Model using E_{agg}=29 GPa for control RTFO-aged PG 58-28.

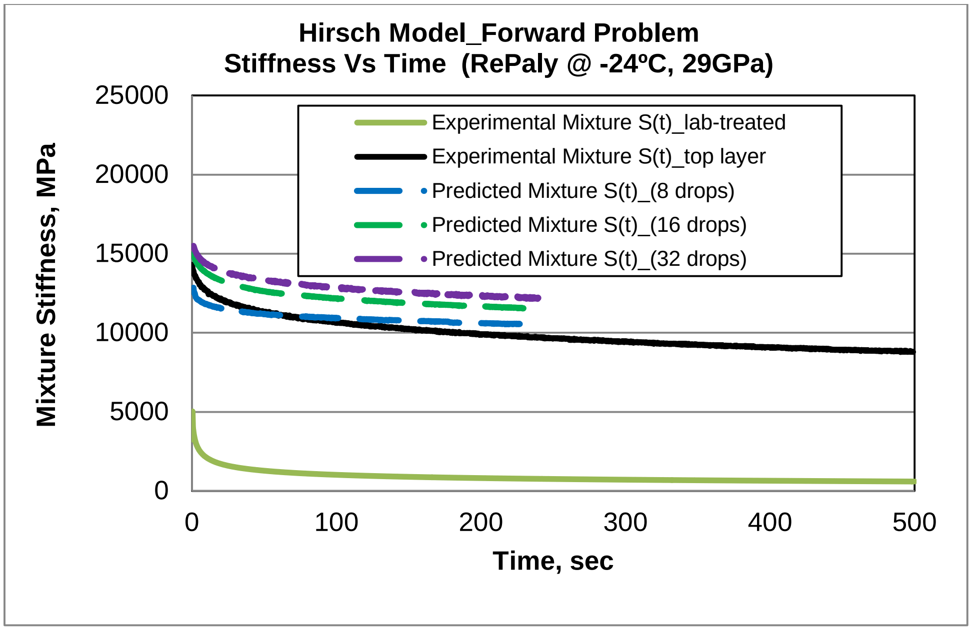


FIGURE 6.19 Hirsch Model Using E_{agg}=29 GPA for RTFO-aged PG 58-28 Treated with RePlay.

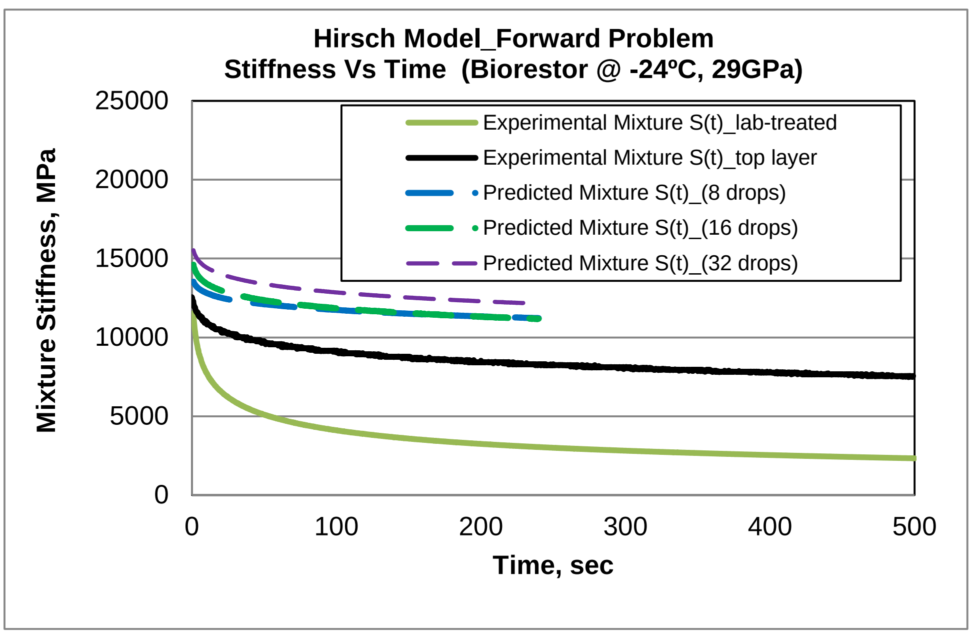


FIGURE 6.20 Hirsch Model Using E_{agg}=29 GPA for RTFO-aged PG 58-28 Treated with Biorestor.

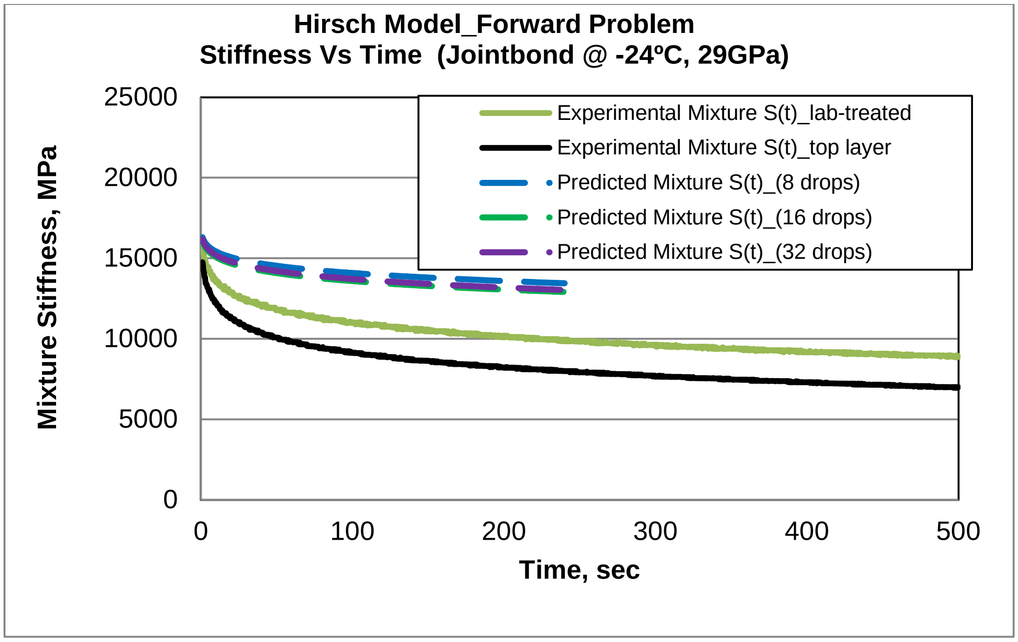


FIGURE 6.21 Hirsch Model Using E_{agg}=29 GPa for RTFO-aged PG 58-28 Treated with Jointbond.

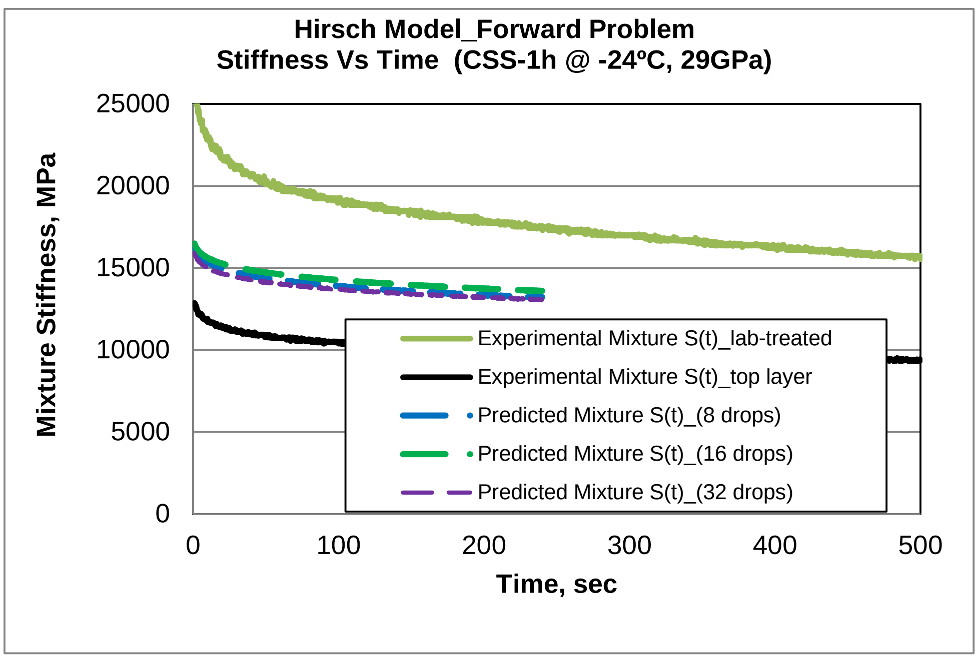


FIGURE 6.22 Hirsch Model Using E_{agg}=29 GPa for RTFO-aged PG 58-28 Treated with CSS-1h.

The Hirsch model using E_{agg} = 19GPa predicts reasonable well the field mixture properties for the control binder and binder treated with Jointbond and CSS-1h; the model under predicts the mixture stiffness for the oil based sealants. Hirsch model using E_{agg} = 29GPa over predicts the mixture stiffness for all four sealants. The opposite trend is also visible for two different aggregate modulus when increasing the application rate of the sealant. The predicted mixture stiffness using E_{agg} = 19GPa gets closer to the field-treated mixture stiffness with increase in no. of drops or application rate of sealant, while the predicted mixture using E_{agg} = 29GPa moves away from the field-treated mixture stiffness (Figures 6.14-6.22). In addition, it can be observed that the stiffness values for the laboratory treated mixture beams is much lower for the oil-based sealants and it is higher for the water based sealants, compared to the predicted values. These results may indicate some other changes in the mixture beams prepared in laboratory conditions.

6.7 Inverse Problem

For the inverse problem, in which binder creep stiffness is predicted from experimental mixture creep stiffness, a simplified procedure developed by Zofka et al. (2005) was used (30). In this procedure, binder stiffness values between 50 to 1000MPa are selected and corresponding mixture creep stiffness is obtained using Equation 1. Then, a simple function (Equation 3) is fitted to the plot obtained in this manner (Figure 6.23) and the function coefficients are obtained.

$$S_{mix} = a * \ln(S_{binder}) + b, \tag{3}$$

where a and b are regression parameters. The advantage of this simple equation is that S_{binder} can be easily calculated from S_{mix}, which could not be done using equation 1 directly. Examples of the inverse problem results are shown in Figures 6.24 to 6.26.

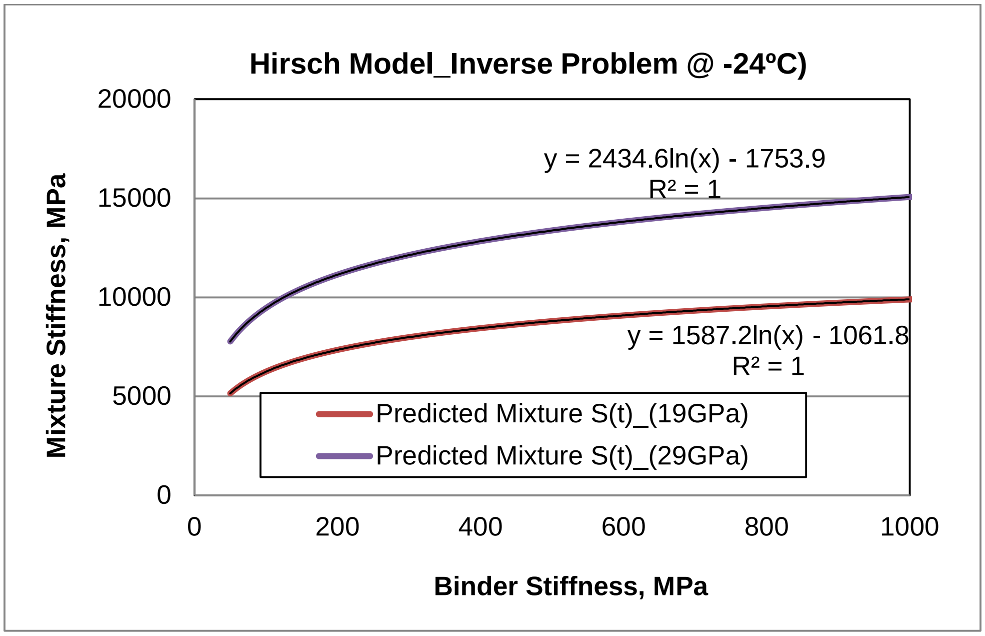


FIGURE 6.23 Simplified Mixture stiffness function.

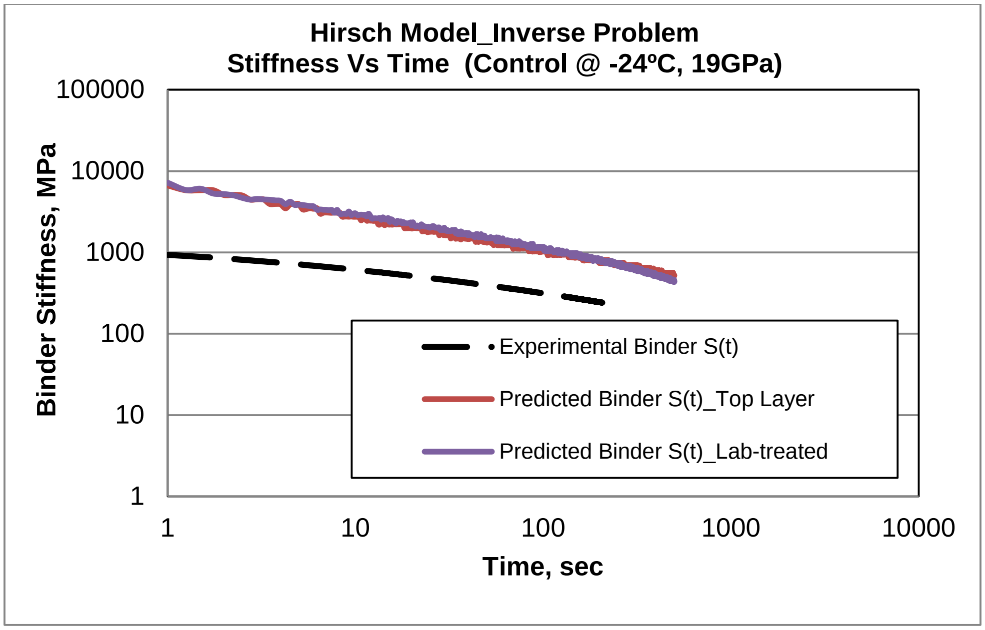


FIGURE 6. 24 Hirsch Model Using E_{agg}=19 GPa for Control Mixture Section.

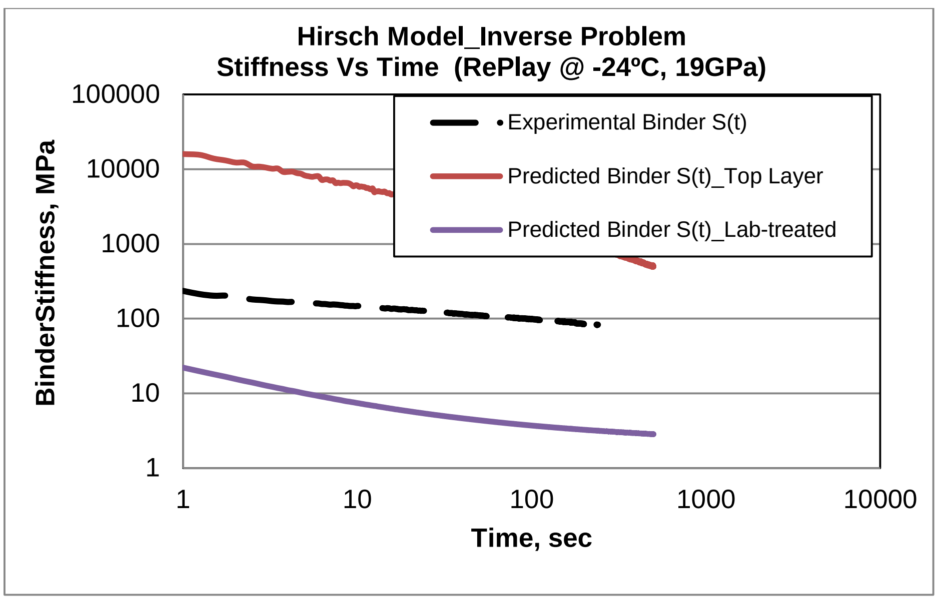


FIGURE 6.25 Hirsch Model Using E_{agg}=19 GPa for Mixture Treated with RePlay.

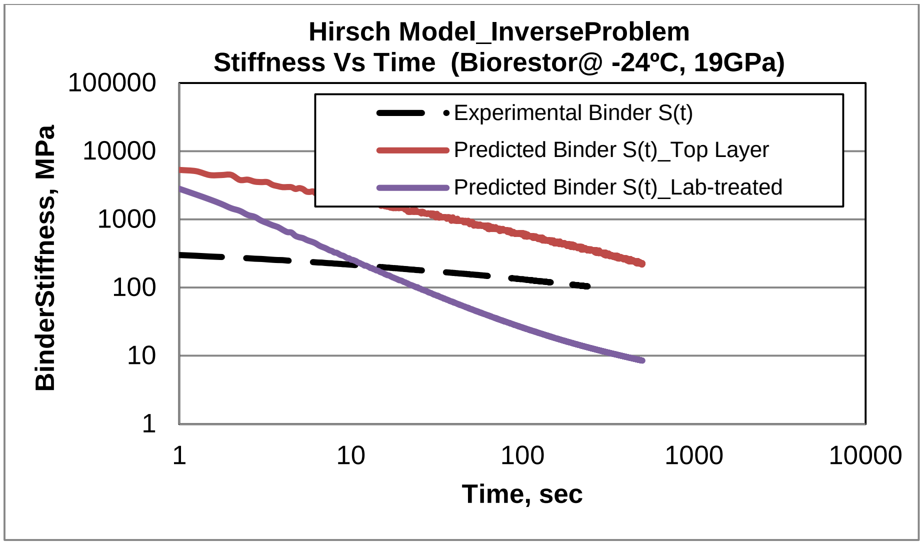


FIGURE 6. 26 Hirsch Model using E_{agg}=19 GPa for Mixture treated with Biorestor.

In general, the results of the inverse problems were not consistent and were very sensitive to small errors in the experimental data. As a result, the use of this method was not pursued further.

6.8 Summary

Statistical analyses, FTIR analysis and Hirsch model were used to analyze the obtained data from binder and mixture testing. It was observed that both statistical and FTIR analyses support the finding from mixture testing that there were no significant effects of sealant application in the field treated samples. The best Hirsch model prediction of field mixture creep stiffness from binder experimental data is observed when using RTFO-aged binder and the pipette method for sealant application, and E_{agg} = 19GPa.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

A number of conclusions can be drawn from the experimental work and statistical analyses performed in this investigation.

For asphalt binders, the oil-based RePlay and Biorestor had the highest softening effect whereas the water-based Jointbond and CSS-1h either increased the stiffness or showed similar stiffness values as the control. The simple-mixing procedure significantly changes the binder performance grade of the original binder, whereas the changes due to the laboratory-developed pipette method proved to be more realistic and a better indicator of the effect of field treatment.

For asphalt mixtures, the analysis performed on the bending creep and strength results at low temperature showed that the application of sealants in the field resulted in only a few statistically significant changes in the properties of the control section, while for the laboratory-treated samples, significant differences were observed in almost all cases. This was particularly true for the oil-based sealants that significantly affected all rheological and fracture properties of the mixtures treated in laboratory conditions. It can be hypothesized that the significant differences observed between the field-treated and the laboratory-treated samples are due to a number of factors:

- Field samples were tested 9 months after product application and it is possible that some of the sealant was absorbed by the aggregates or evaporated. Laboratory samples were tested after only 1 month in very stable environmental conditions.
- The application rate in the laboratory was very well controlled, while less control can be achieved in the field.
- Application of sealant on laboratory samples could produce localized damage that could influence the results significantly, as seen with some of the test specimens treated with the oil-based products.

FTIR analysis showed that no trace of sealants was detected in the field-treated mixture beams, which supports the above hypothesis. A field study by PennDOT on RePlay, described in the literature review, also concluded that there was no visible effect of sealant application after 18 months.

The Hirsch model analysis appears to indicate that the pipette method can replicate the sealant application procedure used in the field, which means that laboratory experiments could be performed to determine the amount of sealant required to obtain specific changes in mixture properties.

Due to the limited scope of this project, no clear recommendations can be made at this time. More research is needed to investigate additional materials and application rates before a definitive conclusion can be made regarding the benefit of the application of these products in terms of pavement performance improvements.

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APPENDIX A

ADDITIONAL EXPERIMENTAL RESULTS

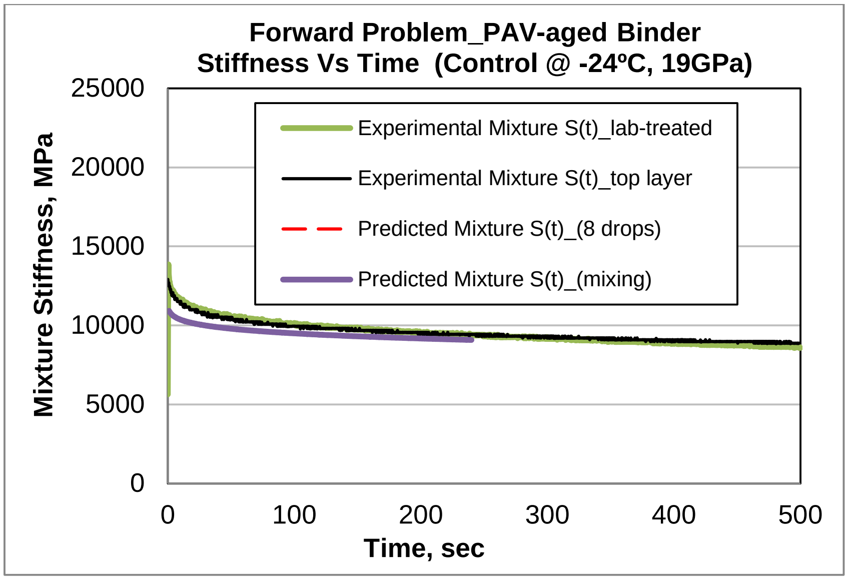

FIGURE A. 1 Hirsch Model using E_{agg}=19 GPa for Control PAV-aged PG 58-28.

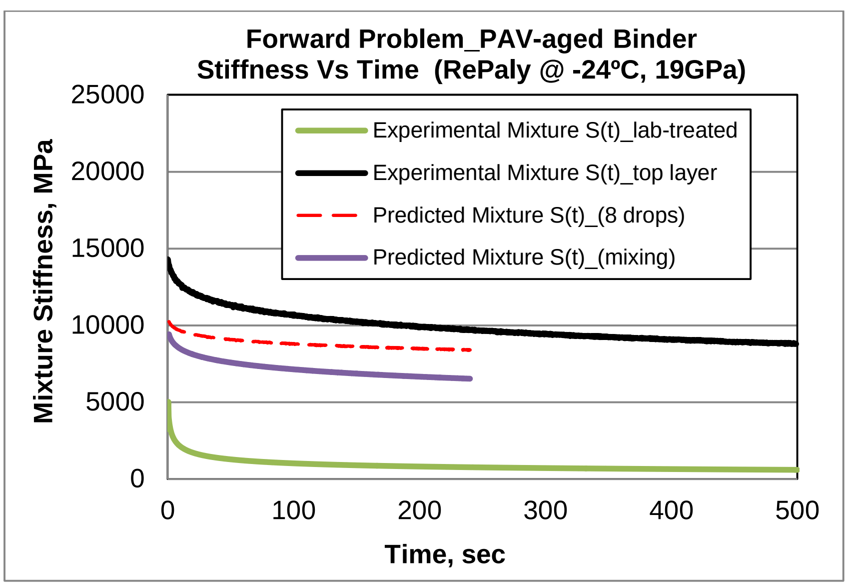

FIGURE A. 2 Hirsch Model using E_{agg}=19 GPa for PAV-aged PG 58-28 Treated with RePlay.

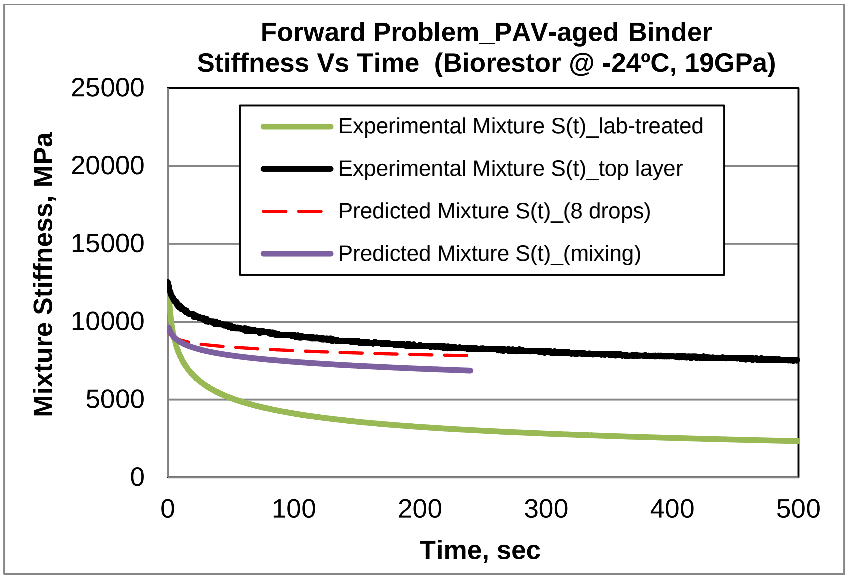

FIGURE A.3 Hirsch Model using E_{agg}=19 GPa for PAV-aged PG 58-28 Treated with Biorestor.

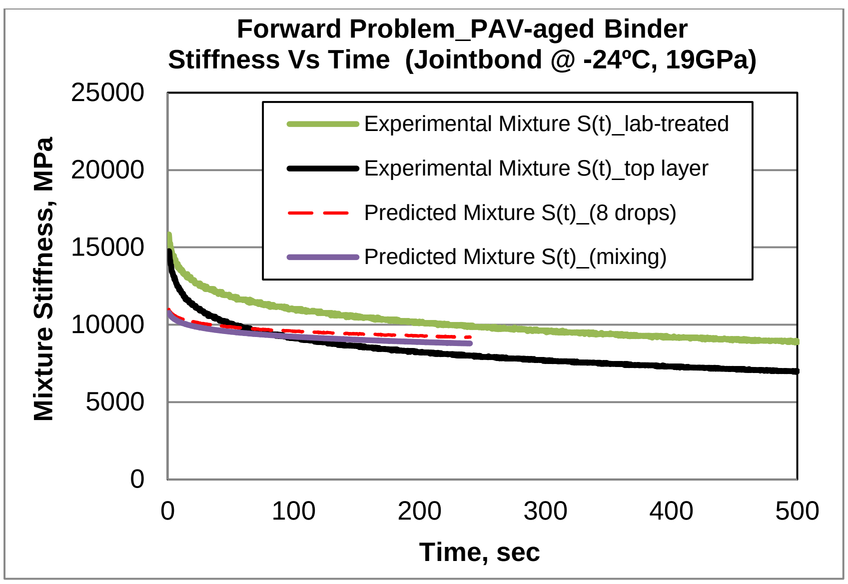

FIGURE A.4 Hirsch Model using E_{agg}=19 GPa for PAV-aged PG 58-28 Treated with JointBond.

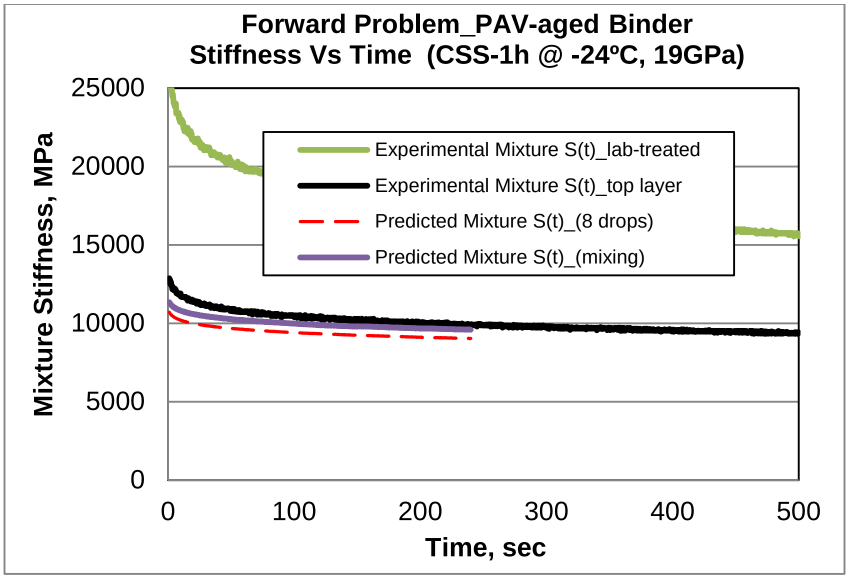

FIGURE A. 5 Hirsch Model using E_{agg}=19 GPa for PAV-aged PG 58-28 Treated with CSS-1h.

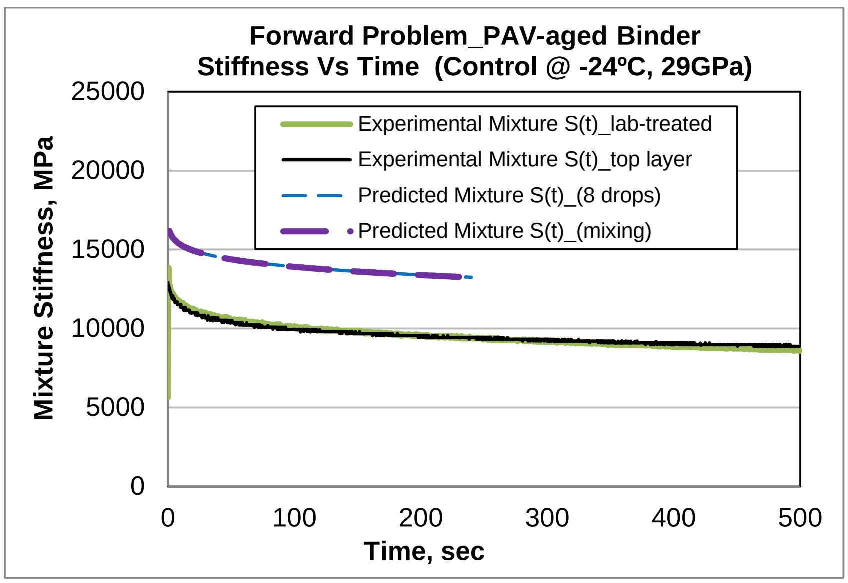

FIGURE A.6 Hirsch Model using E_{agg}=29 GPa for Control PAV-aged PG 58-28.

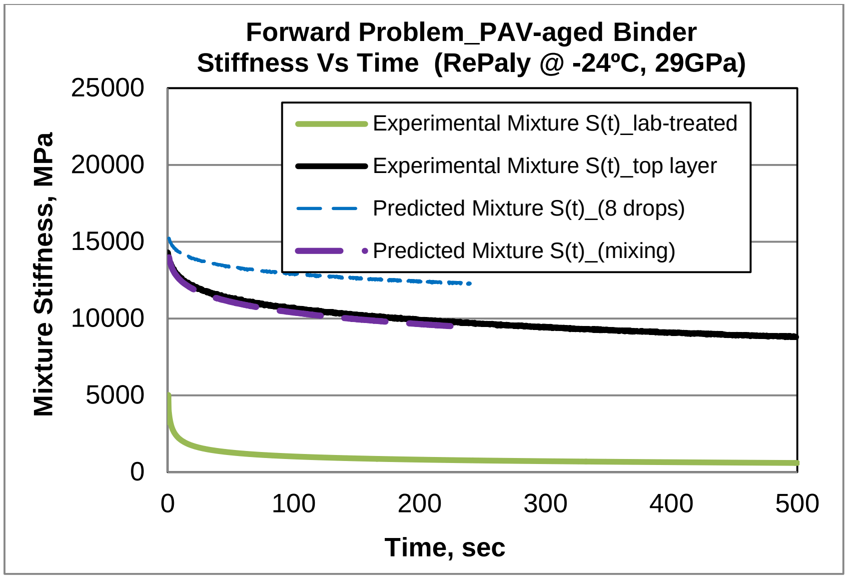

FIGURE A.7 Hirsch Model using E_{agg}=29 GPa for PAV-aged PG 58-28 Treated with RePlay.

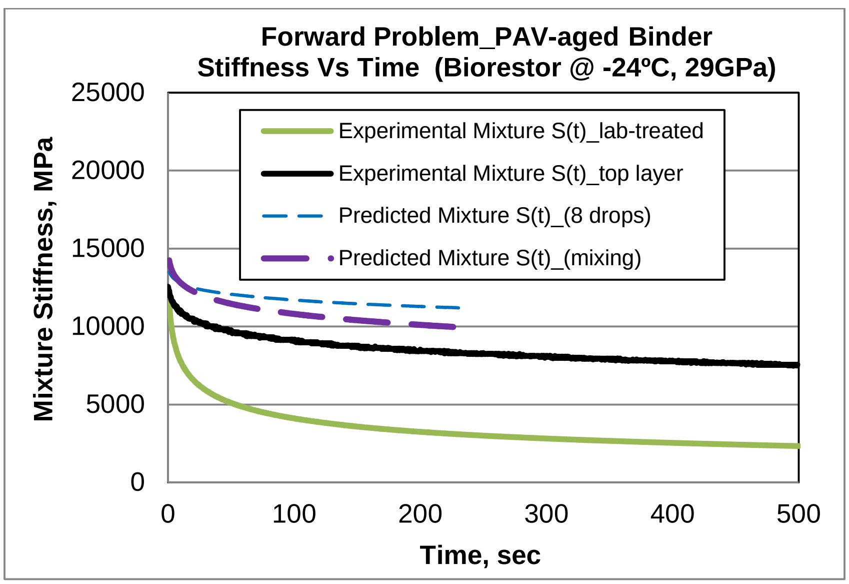

FIGURE A. 8 Hirsch Model using E_{agg}=29 GPa for PAV-aged PG 58-28 Treated with Biorestor.

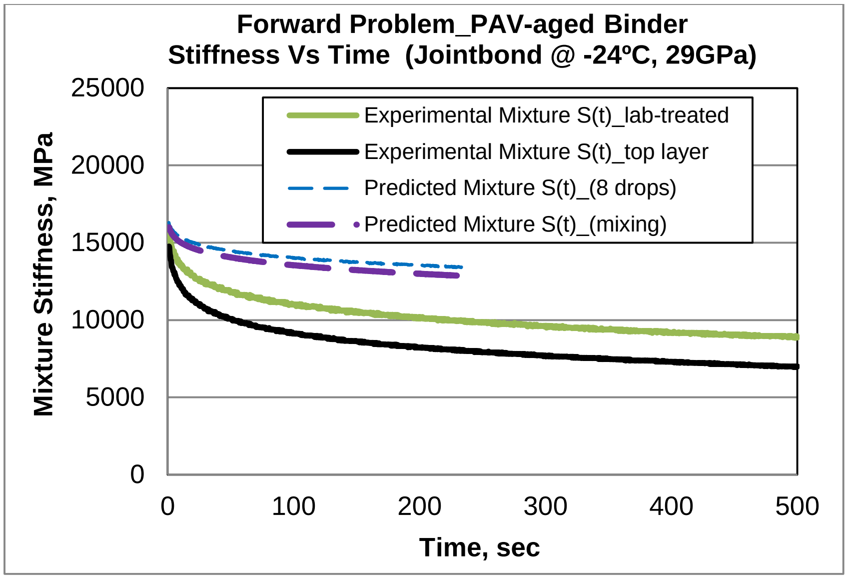

FIGURE A.9 Hirsch Model using E_{agg}=29 GPa for PAV-aged PG 58-28 Treated with Jointbond.

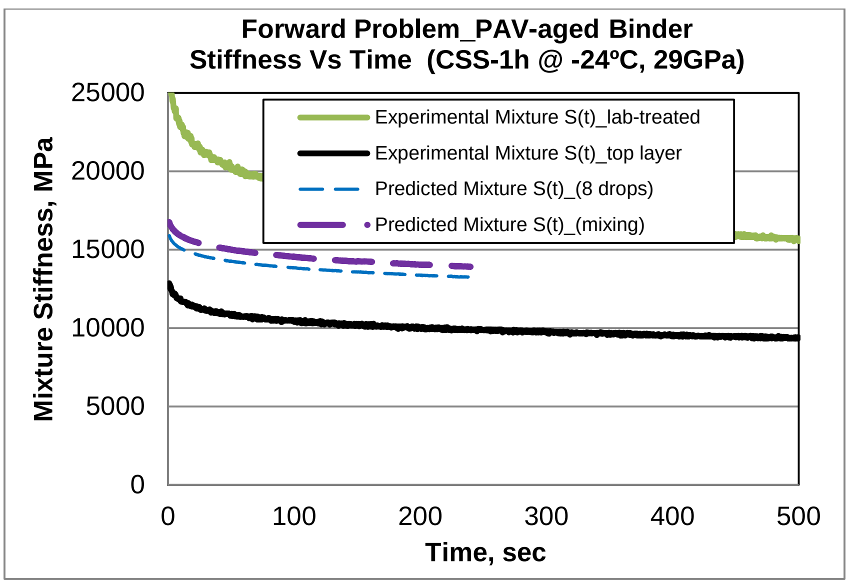

FIGURE A.10 Hirsch Model using E_{agg}=29 GPa for PAV-aged PG 58-28 Treated with CSS-1h.