PERFORMANCE EVALUATION OF
ASPHALT MIXTURES SUBJECT TO
CLIMATIC EFFECT

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ABSTRACT

PERFORMANCE EVALUATION OF ASPHALT MIXTURES SUBJECT TO CLIMATIC EFFECT

AMAL ABDELAZIZ

As extreme and unpredicted weather events are increasing, considering climatic effect on civil engineering structures is becoming a primary concern. The transportation system is one of the most important Civil Engineering Infrastructures. Pavement is a fundamental element in the transportation system. Most of the models used in evaluating pavement designs are based on the applied traffic load repetitions. However, there are other factors affecting the service life of asphalt pavements, such as environment and climate conditions. Previous studies showed that the response of a pavement system is highly dependent on its temperature. Temperature of pavement surfaces can be affected by numerous factors, such as air temperature, precipitation, and speed of wind as well as solar radiations. Temperature data is important to determine the amount of stress acting on a pavement surface. Thus, the deflection of pavements is highly influenced by its temperature. Temperature is also a main contributor to multiple types of pavement distresses, resulting in a significant impact on the service life of the pavement.

The objective of this thesis is to investigate the effect of temperature variations on the performance of asphalt pavements. Four different climate factors will be considered. In part one, the behavior of asphalt mixtures in resisting low temperature cracking is evaluated. The study is done by comparing the low temperature properties of two types of asphalt binders: styrene-butadiene-styrene (SBS) modified asphalt binder and conventional asphalt binder, through laboratory tests and numerical analysis. In part two, the effect of freeze-thaw cycles on asphalt

mixtures is studied, by conducting numerical simulations and finite element analysis. In part three, the impact of extreme high temperatures on the behavior of asphalt mixtures is studied, through laboratory tests and numerical analysis. In part four, the influence of solar radiations on the performance of asphalt concrete pavements is investigated, through the performance of computer software analysis and solar radiation modeling. Based on the outcomes of the different case studies, conclusions and recommendations are presented for future research needs on evaluating the climate effect on the behavior of asphalt mixtures.

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CHAPTER 1

GENERAL INTRODUCTION AND LITERATURE REVIEW

1. Introduction

The increase in unpredicted extreme weather events around the globe, is rising many challenges that could significantly impact the performance of civil infrastructure systems. The transportation infrastructure is one of the main systems affected by the changes in weather patterns. The asphalt pavements constitute one of the most critical systems in the transportation infrastructure and contributes at least 94% of the paved roads and highways in the United States (Pavement facts, 2018). Climate factors such as temperature changes, solar radiations and freeze-thaw cycles have a significant impact on the behaviors of asphalt mixtures. The asphalt is a viscoelastic material that exhibits linear and nonlinear responses when subjected to loading. Since it is a viscoelastic material, the mechanical properties of the asphalt binder heavily depend on both the temperature and rate of loading. The viscoelastic material behaves differently under high and low temperatures. At high temperatures, the asphalt binder attains high viscosity and acts as a viscous fluid. On the other hand, at low temperatures, the stiffness of the asphalt binder increases and the binder acts as an elastic solid (Ng, 2008).

Due to the differences in climate conditions in different locations, a pavement design that works effectively in a certain area would not necessarily work in a different location. As a result, transportation agencies need to carefully design pavements based on their local traffic and climate data. The climate in Flagstaff is characterized by very dry, hot summers, and cold, snowy winters. The city receives a large amount of snowfall, approximately 77 inches annually. In addition, due to the high elevation of the city (7000 feet above the sea level), the temperature variations between the daytime and night are significant, resulting in a large number of freeze-thaw cycles each year (U.S. Climate Data, 2018).

During the design life of a pavement structure, the asphalt layer is exposed to oxidation, traffic load repetitions and environmental conditions. These factors can lead to the occurrence of severe pavement distresses on the pavement surface, if not maintained properly. The most common types of pavement distresses are fatigue cracking, thermal cracking and rutting. Fatigue cracking is one of the primary distress types that initially occurs at the bottom of the asphalt layer and propagates to the surface that would allow the moisture to infiltrate through the pavement layer causing the pavement to deteriorate (Gao et al. 2012). Rutting or permanent deformation occurs due to plastic deformation of the asphalt layer (Huber et al. 1987). Resistance to rutting is dependent on the compressive strength of the subgrade soil (Huang, 2004). The third pavement distress type covered in this thesis is thermal cracking, known as the low temperature cracking. Thermal induced cracking is a prevalent distress in the asphalt pavements in cold regions. Thermal cracking arises when the induced thermal stresses exceed the tensile strength of the pavement, causing transverse cracks along the surface (Akentuna et al.2016).

In this research project, the impacts of different climate conditions on fatigue cracking, rutting and low temperature cracking are evaluated. The climate conditions considered in this project are low temperatures, freeze-thaw cycles, extreme high temperatures and solar radiations. The low temperature properties of asphalt mixtures are studied by comparing two types of asphalt binders in resisting low temperature cracking which are, styrene-butadiene-styrene (SBS) polymer modified binder and conventional binder. Previous research projects showed that the addition of SBS modifiers to asphalt binders can improve the low temperature crack resistance (Sengoz and Isikyakar, 2008) (Hao etal.2017) (Klutz, 1997). Lu et al. (1998) investigated the low temperature properties of SBS polymer modified binder using a laboratory evaluation method. The study was done by performing dynamic mechanical analysis and low temperature creep tests. The results indicated that SBS polymer modification improves the low temperature properties of asphalt binders. In addition, it was found that there is a linear correlation between the low temperature parameters. Another research conducted by Lin et al. (2017) was to investigate the influence of factors on the low temperature properties of SBS modified binder using the thermal stress restrained specimen test (TSRST). The factors considered included the type of polymer, SBS content, sulfur content and rubber processing oil. The results revealed that the stiffness of SBS modified asphalt declined with the increase in the SBS content. The results also showed that the stiffness of the SBS binder are lower than the conventional binder, indicating that SBS polymer has a positive impact on the low temperature properties of the asphalt binder.

Another issue that arises in asphalt pavements due to low temperatures is the freeze-thaw cycles damage. The effect of freeze-thaw cycles was evaluated in this thesis using two types of asphalt mixtures: rubberized asphalt mixtures (RMA) and fiber reinforced asphalt mixtures (FRA). The freeze-thaw cycles effect was evaluated by predicting the fatigue and rutting lives of the asphalt mixtures at up to 300 cycles. In the past years, numerous research projects have been implemented to investigate the influence of freeze-thaw cycles on the service life of pavements (Guo et al. 2014) (Wasiuddin et al. 2014) (Feng et al. 2010). For example, a research done at the University of New Mexico was used to evaluate the effect of freeze-thaw cycles on the fatigue life of hot mix asphalt (Tarefder et al. 2018). The mechanical characteristics of the asphalt binders were characterized using bending beam rheometer (BBR) tests and samples were subjected for up to 20 cycles of freezing and thawing. The research outcomes showed that freeze-thaw cycles cause damage to asphalt binders, resulting in a reduction in the stiffness and fatigue life. Özgan and Serin (2013) also investigated the impact of freeze-thaw cycles on the performance of asphalt mixtures. Their study involved exposing asphalt binder specimens to freeze-thaw cycles for up to 24 days. The characteristics of the asphalt binders before and after the exposure to freeze-thaw cycles were compared. Based on the results, it was concluded that freeze-thaw cycles reduced the Marshall Stability value by 63.8% at the end of the 24 days of freezing and thawing, indicating that freezing-thawing cycles have negative effects on the engineering properties of the asphalt concrete.

Flexible pavements also experience issues when exposed to high temperatures or solar radiations. This thesis discusses the influence of the increase in temperatures due to climate change on the behavior of asphalt mixtures. The impact of high temperatures is evaluated based on the rutting life of the asphalt pavement. The thesis also evaluates the impacts of solar radiations on the performance of asphalt pavements. Many previous research projects reported that high temperatures and solar radiations have negative impacts on the properties of asphalt mixtures. Xu et al. (2015) studied the effect of ultraviolet aging on the properties of modified asphalt binders. Experimental analysis was conducted using the rotational viscometer test and dynamic shear modulus test to characterize the properties of the asphalt mixtures. The results showed that the increase in temperatures lead to an increase in the rutting factor. In addition, the results revealed that the ultraviolet aging of a binder increases its stiffness and its elastic behavior, making it more brittle, which could result in many types of failures.

2. Research Objectives

This thesis aims to characterize the performance of asphalt pavements under various climate conditions. The responses of asphalt pavements are evaluated based on four different climate conditions which are, low temperatures, freeze-thaw cycles, extreme high temperatures and solar radiations. The responses of asphalt mixtures are predicted through the performance of laboratory experiments, numerical analysis, software simulations and finite element analysis. The main goals of the thesis are:

- Evaluating the performance of styrene-butadiene-styrene (SBS) polymer modified asphalt binders in resisting low temperature cracking.
- Studying the impact of freeze-thaw cycles on the fatigue and rutting lives of asphalt pavements.
- Evaluating the effect of the increase in temperatures due to global warming on the performance of asphalt mixtures.
- Investigating the influence of solar radiations on the service life of asphalt pavements.

3. Methods and Materials

This section provides an overview of the testing methods and materials used in the research project. The research was completed through the performance of laboratory experiments followed by numerical and software analysis.

3.1 Laboratory Experiments

In this research, the mechanical properties of asphalt mixtures were evaluated using bending beam rheometer (BBR) tests. The BBR test is a common method used by many Highway agencies to evaluate the mechanical properties of asphalt binders such as, stiffness, m-values and creep compliances. The BBR apparatus used in testing procedures is provided in Figure 1. The beams are tested by first conditioning them in a bath of ethanol for 60 minutes, as shown in Figure 2. Then, after the beams are conditioned, a constant load of approximately 980 N is applied. The BBR test measures the deflection of small asphalt beams as a function of time, while the constant load is applied. The deflection as a function of time is recorded for a time period of 240 seconds. Figure 3 shows a simplified diagram of the setup of BBR tests. The test uses the beam theory to determine the stiffness of the asphalt mixture beams. The testing procedures are based on the AASHTO TP 125-16 standard for determining the Flexural Creep Stiffness of Asphalt Mixture Beams Using the Bending Beam Rheometer (AASHTO, 2016) with additional information provided by Ho and Romero (2011, 2012) and Ho et al. (2017). The stiffness values obtained from BBR tests at 60 seconds were used to characterize the behaviours of asphalt mixtures at low temperatures.

Figure 1. BBR apparatus

Figure 2. Conditioning of beams in BBR bath

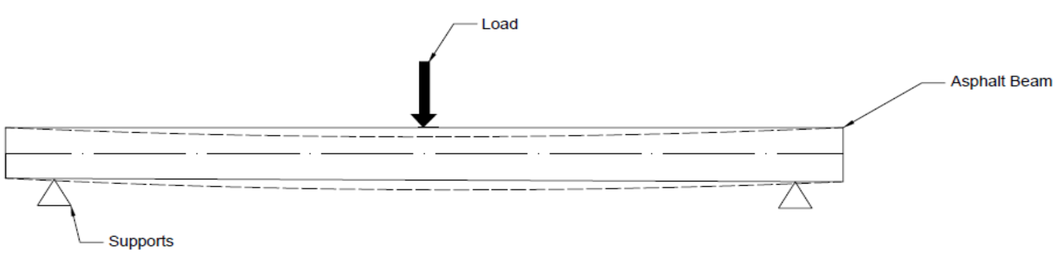

Figure 3. Bending Beam Rheometer (BBR) test set up

3.2 Data Analysis Methods

Three different types of pavement distress were analyzed in this research: fatigue cracking, rutting and low temperature cracking. The fatigue cracking and rutting were evaluated using software simulations and finite element analysis. While, the low temperature cracking was evaluated by performing viscoelastic analysis.

3.2.1 Modeling of Fatigue Cracking and Rutting

Numerical analysis was performed using KENLAYER, a pavement analysis and design software and ANSYS, a finite element analysis software, to determine the responses of the asphalt pavement. KENLAYER is a computer program that uses deterioration models to evaluate flexible pavements. The program evaluates the pavement by computing deflections, critical stresses and strains using viscoelasticity and damage analysis. The analysis can be done using linear, non-linear, viscoelastic layers or a combination of them (Huang, 2004). ANSYS is a finite element analysis software that was used to create a three-dimensional model of the pavement structure to compute the applied tensile and compressive strains based on the elastic modulus and the thicknesses of the pavement layers. As mentioned previously, fatigue cracking and rutting depend on the critical horizontal strain on the bottom of the asphalt layer and the critical compressive strain on the top of the subgrade layer, respectively. After the computation of critical strains using KENLAYER and ANSYS, the predicted critical strains were used to estimate the fatigue and rutting lives of the asphalt pavement and compare the traffic volumes (equivalent single axle load of 18-kips).

3.2.2 Modeling of Low Temperature Cracking

Viscoelastic analysis was performed to determine the low temperature properties of asphalt mixtures. The analysis was done by generating master curves of the creep compliances using the power law function that would be further used to predict relaxation moduli of asphalt mixtures. The relaxation modulus is one of the most important engineering properties of asphalt mixtures that represents the ability of the mixture to relax thermally induced cracks. After determining the relaxation moduli, thermal stress curves were generated to predict the thermal stress applied on the pavement at low temperatures, as well as predict when the asphalt pavement might be failed/cracked due to excessive thermal induced stresses within the pavement pavements.

4. Thesis Organization

This research is composed of different case studies conducted to evaluate the influence of climate effect on the performance of asphalt mixtures. The thesis uses different articles to address this issue. These articles have either been published or will be sent for review for publication in scientific journals or conference proceedings. The thesis is divided into eight different chapters. Chapters 2 to 8 are organized as follow:

- Chapter 2 introduces a method to evaluate the low temperature properties of polymer modified asphalt mixtures. The study is done by predicting the low temperature parameters of styrene-butadiene-styrene (SBS) polymer modified asphalt mixtures and non-SBS asphalt mixtures, through laboratory tests and numerical analysis. Parts of the contents of Chapter 2 will be sent for review for publication in the Annual Conference of the Transportation Research Board.
- Chapter 3 presents an experimental evaluation method to compare the relaxation properties of SBS polymer modified asphalt mixtures and non-SBS asphalt mixtures at low temperatures. The contents of Chapter 3 have been accepted for publication in the Journal of Procedia Engineering.

- Chapter 4 provides a method to determine the effect on freeze-thaw cycles on fatigue cracking and rutting of asphalt pavements. Chapter 4 has been published in the proceedings of the World Conference on Pavement Asset and Management.
- Chapter 5 discusses the differences between using KENLAYER (flexible pavement analysis software) and finite element analysis to characterize the performance of asphalt mixtures under freeze-thaw cycles. Parts of the contents of Chapter 5 will be sent for review for publication in the Annual Conference of the Transportation Research Board.
- Chapter 6 addresses the influence of the increase in temperatures due to climate changes on the behavior of asphalt mixtures. Parts of the contents of Chapter 6 have been published in the proceedings of the 9th European Nonlinear Dynamics Conference.
- Chapter 7 contains a study done on the influence of solar radiations on the performance of asphalt pavements. The research was completed by performing finite element analysis, using test sections located at downtown Flagstaff, Arizona. Chapter 7 has been accepted for publication in Sustainable Civil Infrastructures Series by Springer.
- Chapter 8 summarizes the overall results and conclusions obtained from the outcomes of the different study cases.

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CHAPTER 2

A MATERIAL TESTING APPROACH TO EVALUATE THE PERFORMANCE OF STYRENE-BUTADIENE-STYRENE POLYMER MODIFIED ASPHALT MIXTURES

Parts of the contents of this chapter will be sent for review for publication in the Annual Conference of the Transportation Research Board.

Abstract

Asphalt pavements in cold climates often experience cracking due to the thermal induced stresses. The selection of appropriate asphalt binder is one of the main factors that helps in mitigating low temperature cracking. The use of polymer modifiers has been a common practice to increase the durability of asphalt pavements in cold regions. This paper provides an experimental evaluation method to evaluate the low temperature properties of polymer modified asphalt mixtures. Two types of asphalt binders were used in the study: styrene-butadiene-styrene (SBS) modified binder and unmodified virgin binder (conventional binder). Asphalt mix samples were collected from the paving site and brought back to the laboratory where the mixtures were reheated and compacted using a Superpave Gyratory Compactor (SGC). A series of creep compliance tests were performed to determine the low temperature properties of both mixtures. The viscoelastic responses of asphalt mixtures were evaluated using Prony series function. In addition, the relaxation and thermal stress properties were investigated to determine the behavior of both mixtures at low temperatures. Based on the results of the study, it was concluded that the addition of SBS polymer in the asphalt mixtures can improve the relaxation properties of asphalt mixtures. The study outcomes also showed that the non-SBS mixtures would have experienced higher thermal stresses as compared to the SBS asphalt mixtures.

1. Introduction

Polymer modified asphalt binders have been used by many agencies in the United States to improve the performance of asphalt pavements. Polymers have the ability to reduce the stiffness of asphalt at low temperatures and increase it at high temperatures, which improves the ability of binders to resist fatigue cracking, thermal cracking and rutting distress. One of the most commonly polymer modifiers is styrene-butadiene-styrene (SBS) polymer. SBS polymers are classified as elastomers that derive their strength from the crosslinking of their molecules to increase the elasticity of binders. The use of proper concentration of SBS polymer can significantly improve the properties of base bitumen by increasing its strength and cracking resistance (Topal et al. 2011). In spite of numerous studies being focused on the influence of SBS polymer in enhancing the performance of asphalt pavements under high temperatures, limited research projects have been studied on the behaviours of SBS modified binders at low temperatures. This study aims to characterize the performance of SBS modified asphalt mixtures in resisting low temperature cracking by conducting laboratory tests, field visits and numerical analysis.

Low temperature cracking, also known as thermal cracking is one of the most dominant distress types in cold regions and in areas that experience large variations in daily temperatures. Low temperature cracking occurs when the thermal induced stress at low temperatures is higher than the tensile strength of the pavement structure (Isacsson and Zeng, 1998). Extensive efforts have been made to characterize thermal induced cracking in asphalt pavements. Several research projects showed that the addition of SBS polymers could enhance the performance of asphalt pavements in resisting low temperature cracking (Jutao et al. 2017) (Kluttz and Dongré, 1997) (Hesp et al.2000). On the other hand, other research studies proved that the addition of SBS polymers does not have a significant impact on the low temperature characteristics of asphalt pavements. A research done by Lin et al. (2017) investigated the influence of SBS polymer on the low temperature properties and relaxation capacity of asphalt binders. The study was conducted using a bending beam rheometer (BBR) tests associated with Burger's model. The characteristics of SBS asphalt mixtures were also evaluated using thermal stress restrained specimen test (TSRST). The results indicated that SBS modifier has a positive impact on the stiffness of asphalt binders at low temperatures. Moreover, the study outcomes indicated that the addition of SBS modifier promotes the relaxation capacity of asphalt binders. Another research conducted by Kim et al. (2013) on evaluating the influence of SBS modified asphalt mixtures in resisting fatigue cracking and low temperature cracking. The fatigue behaviors of the asphalt mixture were characterized using BBR tests and indirect strength tests. The results showed that SBS polymers enhance the mechanical properties of asphalt binders by reducing its stiffness after short and long-term oxidation, resulting in an improvement in low temperature cracking resistance and fatigue resistance at higher strain level.

Although, several research studies proved that SBS polymers have a positive impact on low temperature properties of asphalt mixtures, other studies adversely showed that this is not necessary true. For example, a research done by Lu et al. (2003) investigated the influence of polymer modification on the low temperature properties of asphalt binders. The study was conducted using SBS, styrene-ethylene-butylene-styrene (SEBS), ethylene vinyl acetate (EVA) and ethylene butyl acrylate (EBA) polymers. The asphalt mixtures were prepared using a gyratory compactor, and the low temperature properties were evaluated using BBR, TSRST and dynamic shear rheometer (DSR) tests. The results indicated that low temperature properties depend mainly on the base bitumen and that in most cases polymer modifications do not have a significant impact on low temperature performance. Another research performed at Cooper University evaluated the influence of adding SBS polymers on low temperature parameters of asphalt binders using BBR tests. The results of the research showed that polymer modified binders are more prone to low temperature cracking, compared to unmodified binders (Ng, 2008). Due to the insufficient research studies on the factors influencing the low temperature properties of SBS modified binders, it is essential to conduct further investigations on the benefits of SBS modifiers.

In this study, the bending beam Rheometer (BBR) test is used to characterize the low temperature properties of SBS asphalt mixtures. The benefits of using BBR testing methods include, the availability of equipment at reasonable costs, simple operation and staff familiarity (Ho and Romero, 2013). The BBR test is based on conditioning beams of asphalt binders in a BBR bath filled with ethanol at desired temperatures. The test evaluates the stiffness properties of asphalt binders by applying a constant load and determining deflections as a function of time. Currently, there are four testing methods used to characterize low temperature properties of asphalt mixtures including, the Indirect Tensile Test (IDT), the Thermal Stress Restraint Specimen Test (TSRST), Asphalt Concrete Cracking Device (ACCD), and the BBR test (Ho and Romero, 2013). The IDT test is the most common test used in characterizing thermal cracking properties of asphalt mixtures. The test evaluates low temperature properties by determining the resilient modulus, static creep and strength properties of the mixtures. Although IDT tests seemed to be effective in evaluating low temperature characteristics, the sample preparation procedures are time consuming, making it impractical for daily applications. The TSRST test evaluates low temperature properties using a closed loop system that measures the tensile stress in asphalt specimens as it cools down at a constant rate (Das et al. 2012). The ACCD method is considered a simpler testing alternative compared to the TSRST device. The test uses an Invar ring so that if there is a large difference in the coefficient of thermal expansion between the cored asphalt mixtures around the ring, the asphalt mixture shrinks and get subjected to tensile stresses, while the temperature of the ring is lowered. When the stress applied on the asphalt specimen exceeds its strength, the sample cracks (Akentuna et al. 2016).

This paper aims to characterize the influence of SBS modifiers on the low temperature properties of asphalt mixtures. A paving project was constructed along interstate I-40 located west of Williams and Flagstaff, Arizona. Two types of asphalt binders are mixed with asphalt mixtures: SBS polymer modified binder and unmodified virgin binder (non-SBS binder). The low temperature performance of both SBS and non-SBS asphalt mixtures was evaluated using BBR tests. The stiffness, creep compliance values and m-values of the SBS modified binder and the unmodified binder were evaluated. Viscoelastic analysis was performed using Prony series to determine the relaxation properties and thermal stresses of both types of asphalt binders.

2. Methodology

2.1 Material preparation

Four different asphalt samples were collected from the paving site, two of these samples are made of SBS modified asphalt binder and the other two samples are made of conventional binder. The samples were collected from four different paving lots to ensure that the results are representative of the whole paving project. All asphalt samples were made of PG 70-22 binder with a nominal material aggregate size of ¾ inches. The percentage of asphalt binder within the samples ranged from 5.43% to 5.59%. The mix design characteristics of the asphalt samples are summarized in Table 1. The asphalt samples were shipped to the materials laboratory of Arizona

Department of Transportation where mixtures were reheated and then compacted using a Superpave Gyratory Compactor (SGC). Then, the samples were cut into six faced blocks. After that, the asphalt blocks were trimmed into small specimens to get them prepared for BBR testing.

Table 1. Mix design characteristics

Mix Design	Non-SBS (Sample 1)	Non-SBS (Sample 2)	SBS (Sample 1)	SBS (Sample 2)
Nominal material aggregate size	¾ inches	¾ inches	¾ inches	¾ inches
Asphalt binder type	PG 70-22	PG 70-22	PG 70-22 SBS	PG 70-22 SBS
Percent of asphalt binder (%)	5.47	5.49	5.59	5.43
Bulk specific gravity (G_{mb})	2.385	2.385	2.379	2.379
Maximum theoretical gravity (G_{mm})	2.509	2.509	2.499	2.499
Percent of air void, %	5.1	4.45	4.7	4.9
Voids in mineral aggregate filled (VMA), %	14.15	13.9	14.4	13.6
Percent of void filled (VFA), %	74.7	78.9	77.2	74.7

2.2 Air voids assessment

The process of cutting the compacted asphalt samples into six faced blocks may lead to inconsistent changes in the amount of air voids, resulting in misleading BBR test results. Thus, it is essential to measure the changes in air voids of the compacted specimens and the asphalt blocks to ensure consistency in results. The percentage of air voids for the compacted SBS modified samples is equal to 4.8%. While, the percentage of air voids for the unmodified binder samples is equal to 5%. After the compacted samples were cut into blocks, the average percentage of air voids of the SBS modified binder blocks was reduced to 2.2% and for the unmodified binder it was reduced to 2.1%. The reduction in the percentage of air voids is due to cutting the rough surface of the compacted samples. The percentages of air voids were determined based on Equations 1 and 2. The values of bulk specific gravity and rice specific gravity were determined based on the mix design specifications. The differences in air voids between the compacted samples and the asphalt blocks are illustrated in Figure 1. The change in air voids was consistent among the different samples and it ranged from 2.1% to 3.1%. Due to the consistency in results, the effect of air voids can be neglected when analyzing results.

$$D = \frac{A}{B-C} \tag{1}$$

Where:

D = bulk specific gravity;

A = mass of dry sample;

B = mass of SSD sample;

C = mass of sample in water.

$$\text{Air voids (\%)} = (1- \frac{D}{E}) \times 100 \tag{2}$$

Where:

E = maximum rice specific gravity.

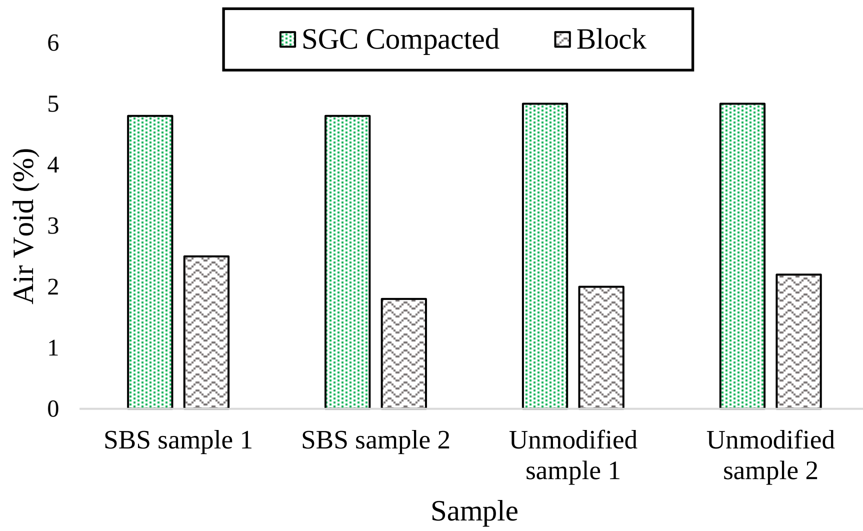


Figure 1. Air void change between compacted samples and blocks

2.3 Bending Beam Rheometer (BBR) test

Bending beam rheometer (BBR) tests were performed to determine the creep compliance, m-values and stiffness of both asphalt mixtures. Although BBR was initially developed to evaluate the low temperatures properties of asphalt binders not mixtures, numerous previous research projects proved that using thin asphalt mixture beams in BBR tests to determine low temperature properties of asphalt mixtures is a valid approach (Ho and Romero 2014) (Ki et al. 2017) (Marasteanu et al. 2007). A research conducted by Zofka at University of Minnesota replaced asphalt binder beams with asphalt mixture beams to determine the low temperature performance of asphalt mixtures. The results of the research concluded that the creep stiffness produced from BBR tests are very similar to the ones produced from Indirect Tensile Test (IDT) (Zofka, 2007). As a result, using small asphalt beams in BBR tests to compare the behavior of modified and unmodified asphalt mixtures at low temperatures is an effective approach. Although, both BBR and IDT methods produce comparable results, the BBR method has many benefits associated with it which includes, using less materials, less conditioning time, availability at most laboratories, and staff familiarity (Ho and Romero, 2013).

A BBR test measures the deflection of an asphalt beam as a function of time by applying a constant load at a specified constant temperature. To prepare the asphalt mixture beams, they were trimmed into rectangular shapes with dimensions of 12.7 x 6.35 x 127 mm. To ensure consistency in results, the variations in beam dimensions did not exceed a coefficient of variance (CV) of less than 20%. A summary of the measured beam width values and thickness values are illustrated in Figures 2 and 3, respectively. The graphs show that the dimensions of beams are normally distributed. Moreover, the CV value of the width distribution is less than 0.014 and for thickness distribution is less than 0.053. This indicates that the variations in beam dimensions is very small and the effect of the variation in dimensions on BBR results can be neglected. The asphalt beams were tested at temperatures of -6°C, -12°C and -18°C, based on binder specifications. For a valid BBR test, the number of replicates used at each testing temperature was 10 specimens (Ho and Romero, 2013). The testing procedure used to perform BBR tests is based on The American Association of State Highway and Transportation Officials (AASHTO) standard TP125: Determining the Flexural Creep Stiffness of Asphalt Mixtures Using the Bending Beam Rheometer (BBR) (AASHTO TP125, 2016). Some modifications to the testing procedures were made to be able to test the creep stiffness for thin asphalt beams (Ho and Romero, 2011 and 2012).

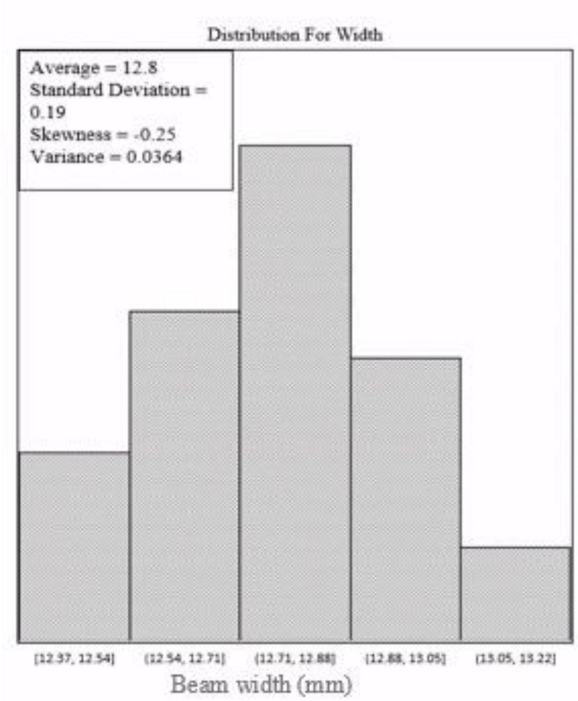


Figure 2. Summary of width distribution

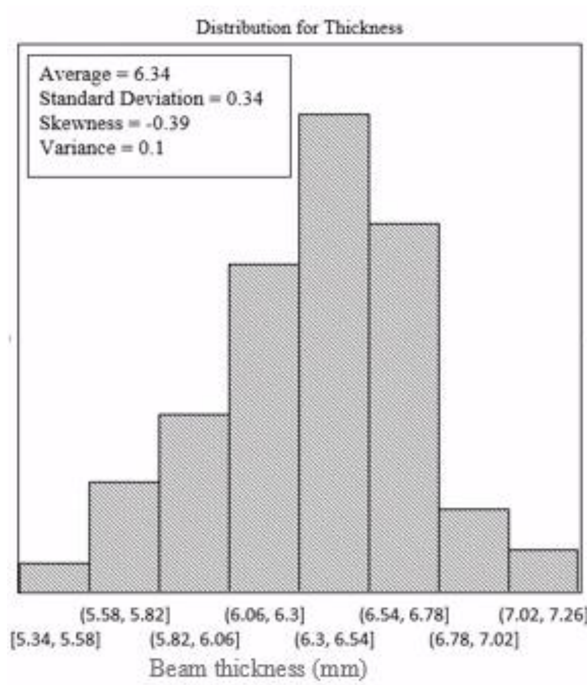


Figure 3. Summary of thickness distribution

2.4 Stiffness of asphalt mixtures

BBR calculates the stiffness of the asphalt beam based on the beam theory. Stiffness is recorded each 0.5 second during the whole 240 seconds testing period. Stiffness at 60 seconds are used as the representative stiffness of the asphalt mixture beams in accordance with AASHTO T313 Standard (AASHTO T313, 2008). The stiffness values of modified and conventional binders were graphed against the three different testing temperatures, as illustrated in Figure 4. SBS modified binder showed to have lower stiffness properties compared to the unmodified binder. The difference in stiffness values between the different asphalt specimens showed variability of less than 20%. A summary of the statistics for stiffness including the mean, standard deviation and CV values is provided in Table 2. In addition, the correlation between testing temperature and stiffness can be represented by an exponential function. The stiffness of the asphalt beam is computed with accordance to Equation 3:

$$S(t) = \frac{PL^3}{4bh3\delta(t)} \quad (3)$$

Where:

S(t) = the creep stiffness as a function of time in MPa;

P = constant load in N;

L= span length in mm;

b = beam width in mm;

h = beam thickness in mm; and

δ(t) = beam deflection in mm

Table 2. Statistical information on the stiffness of asphalt mixtures

Temperature	**-6˚C**			**-12˚C**			**-18˚C**		
Sample	AVG (MPa)	STD (MPa)	CV	AVG (MPa)	STD (MPa)	CV	AVG (MPa)	STD (MPa)	CV
Unmodified Sample 1	5387	486	0.09	9088	348	0.04	14679	1342	0.09
Unmodified Sample 2	6158	409	0.066	9624	1305	0.136	12396	2109	0.17
Modified Sample 1	4458	186	0.042	7059	189	0.027	10873	549	0.05
Modified Sample 2	4243	407	0.096	6138	190	0.03	9857	1237	0.13

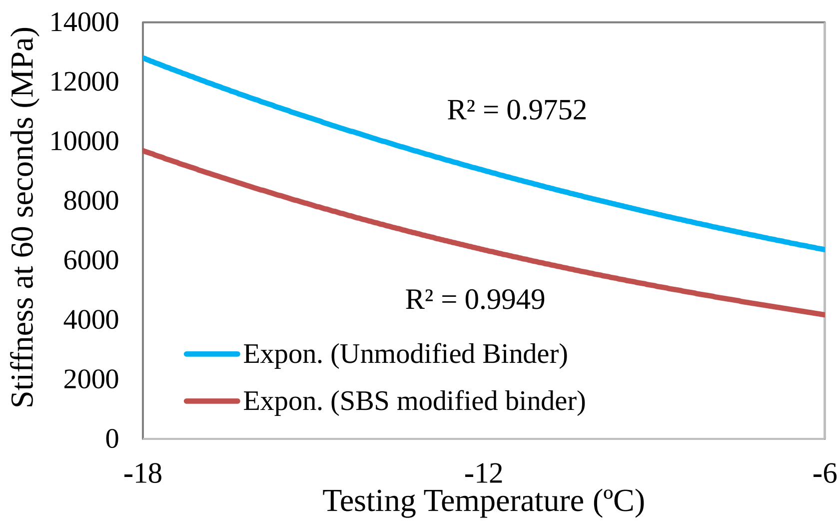


Figure 4. Stiffness of modified and unmodified asphalt binders versus temperature

The maximum stress and strain at the bottom of the thin asphalt beam were estimated using the deflections and the dimensions of the beam, based on Equations 4 and 5, respectively (Zofka, 2011).

$$\sigma_0 = \frac{3PL}{2bh^2} \tag{4}$$

$$\varepsilon = \frac{6\delta(t)h}{L^2} \tag{5}$$

2.5 Evaluation of m-values

The m-values obtained from BBR test results were analyzed for both asphalt binders. The m-value is defined as the slope of the curve of creep stiffness versus loading time, using log scales for both parameters (Tabatabaee et al. 2012). The m-value indicates the ability of the binder to resist stresses. The higher m-value is, the better the binder is in relaxing stresses. The m-values for both the SBS modified binder and unmodified binder were graphed against the different temperatures, as shown in Figure 5. As the temperature decreased, the m-values decreased as well. This is expected because at lower temperatures, stiffness of asphalt increases. In addition, the m-values for SBS binder were found to be higher than those of the unmodified binder at the three testing temperatures. Thus, it is expected that the SBS binder has a better ability in resisting thermal induced stress.

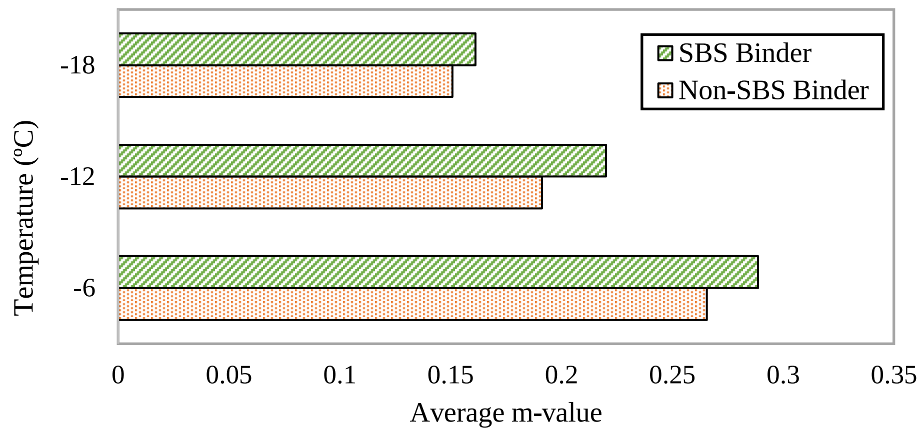


Figure 5. Average m-values of modified and unmodified asphalt binders versus temperature

2.6 Modeling of Viscoelastic Analysis

Linear viscoelastic modeling was performed to determine the relaxation moduli and thermal stresses applied on the pavement for the unmodified and polymer modified asphalt binders. The analysis was performed using the creep compliance responses obtained from BBR tests at the different temperatures (Ho, 2009). The response of creep compliance was represented using a power law function, as illustrated in Equation 7:

$$D(t) = D_0 + D_1 t^n \tag{7}$$

Where:

D(t) = creep compliance values in (1/MPa);

t= reduced time in seconds; and

D_0, D_1 and n are power function parameters.

The three power function parameters were determined by minimizing the sum of square error of the raw data values and the fitted curve values.

The relationship between creep compliance and relaxation modulus can be expressed using Equation 8:

$$\widehat{D}(s)\widehat{E}(s) = \frac{1}{s^2} \tag{8}$$

Where:

s = Laplace transform parameter;

$\widehat{D}(s)$ = creep compliance;

$\widehat{E}(s)$ = relaxation modulus;

^ = means that the relaxation modulus and creep compliance quantities are a function of Laplace transform parameter.

To determine the relaxation modulus in the Laplace domain, Laplace transform of Equation 7 was taken and substituted in Equation 8, the outcome of this substitution is shown in Equation 9:

$$\widehat{E}(s) = \frac{1}{\widehat{D}(s)s^2} = \frac{1}{s\,D_0 + D_1\,\Gamma(n+1)s^{1-n}} \tag{9}$$

Where:

Γ = gamma function

To determine the relaxation modulus, the Laplace transform in Equation 9 has to be inversed. But, the inverse of Equation 9 cannot be solved. As a result, an approximate formula provided in Equation 10 was used to determine the relaxation modulus.

$$E(t) = \frac{1}{D_0 + D_1\,\Gamma(n+1)(1.73t)^n} \tag{10}$$

Finally, the calculated relaxation moduli values were used to determine the thermal stresses exerted on the pavement structure at the different temperatures using Equation 11:

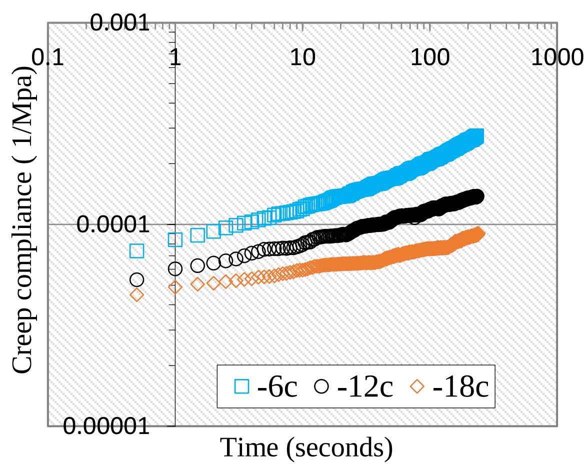
$$\sigma(T) = \int_0^T E(T - T')\frac{\partial\varepsilon(T)}{\partial T'}\,dT' \tag{11}$$

3. Results and Discussion

3.1 Viscoelastic Analysis

3.1.1 Generation of Master Curves

The creep compliance values for both asphalt binders were graphed against time at the three different temperatures, as shown in Figures 6 through 9. The creep compliance curves for the 2 unmodified samples are represented in Figures 6 and 7. While, the graphs for the SBS modified samples are provided in Figures 8 and 9. Based on the results, it can be observed that SBS samples have higher creep compliance values at the three different temperatures compared to the unmodified binder samples. This is expected because the SBS modified binders showed to have lower elastic modulus values compared to unmodified binder.



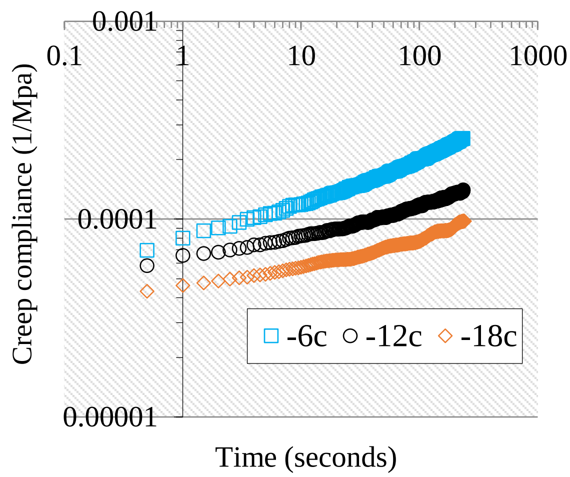


Figure 6. Creep Compliance (NonSBS, sample 1) **Figure 7. Creep Compliance (NonSBS, sample 2)**

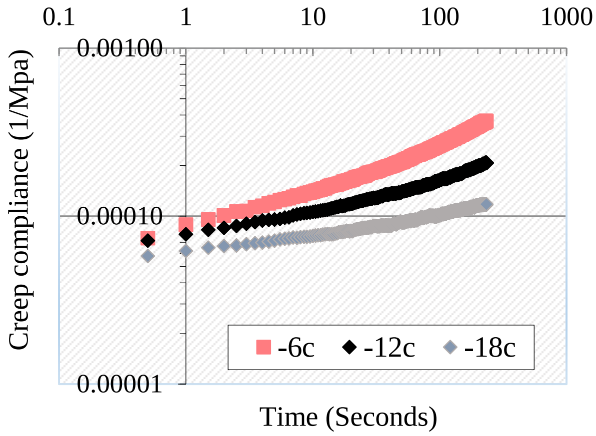


Figure 8. Creep Compliance (SBS, sample 1)

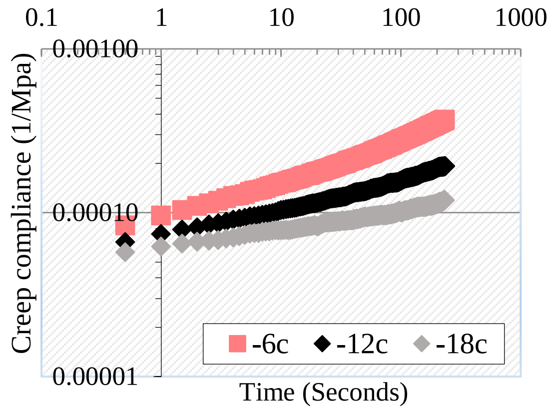


Figure 9. Creep Compliance (SBS, sample 2)

Since the creep compliances curves are almost parallel to each other for the three different temperatures, master curves were created using the Time Temperature Superposition Principle (TTPST). To generate the master curves -12ºC was selected to be the reference temperature for each group. In addition, the influence of temperature on the properties of asphalt mixtures was evaluated using the shift of the log time scale illustrated in Equation 12:

$$\xi = \frac{T}{a_T(T)} \quad (12)$$

Where:

T = time in seconds;

$a_T(T)$ = shift factor; and

$\xi =$ Reduced time in seconds.

The shift factors $a_T(T)$ in the previous equation were determined with accordance to an Arrhenius function (Christensen and Anderson, 1992). The function relates the shifts factors and temperatures using the selected reference temperature. The expression for Arrhenius function is provided in Equation 13:

$$\log[\ a_T(T)] = 2.303\frac{E_a}{R}\cdot(\frac{1}{T_R} - \frac{1}{T}) \quad (13)$$

Where:

Ea= the activation energy for flow below T_R, 261 kJ/mol.;

R= the ideal gas constant, 8.34J/mol-°K;

T_R = reference temperature, °C or °K;

T= selected temperature, °C or °K.

The correlation between the shift factors and the three different testing temperatures for the four different samples used in the study are illustrated in Figures 10 through 13. The shift factors were used to develop the master curves, as shown in Figures 14 through 17.

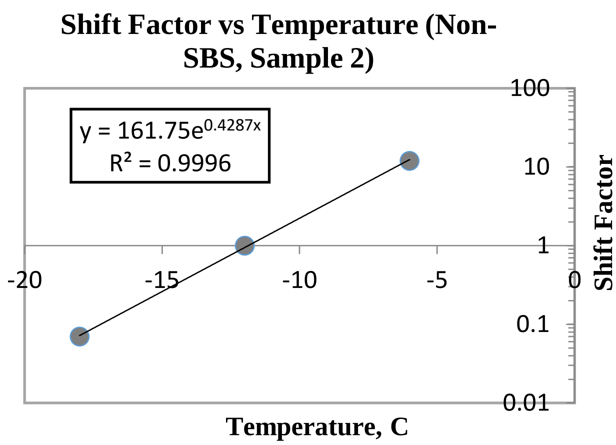


Figure 10. Shift Factors (Non-SBS, sample 1)

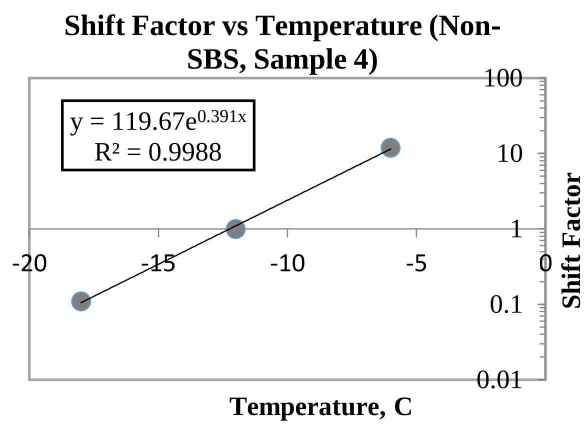


Figure 11. Shift Factors (Non-SBS, sample 2)

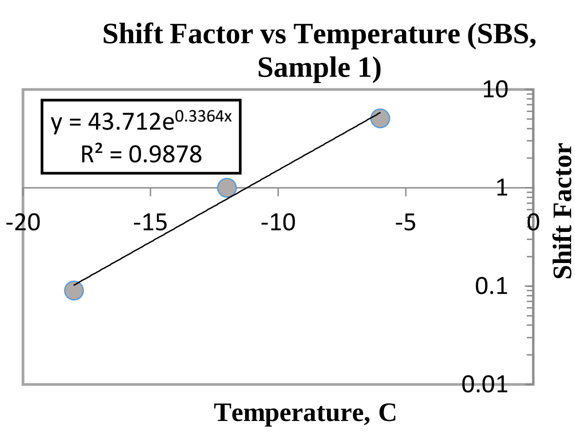


Figure 12. Shift Factors (SBS, sample 1)

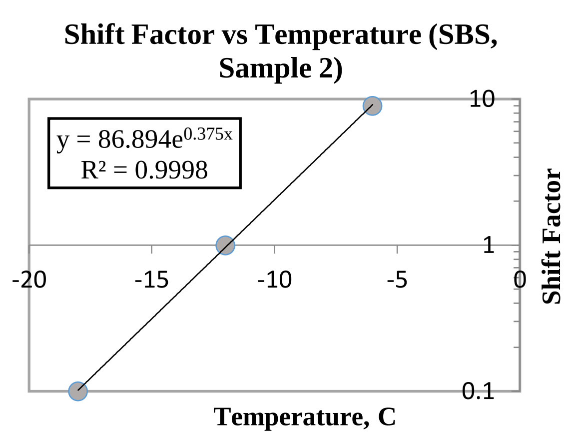
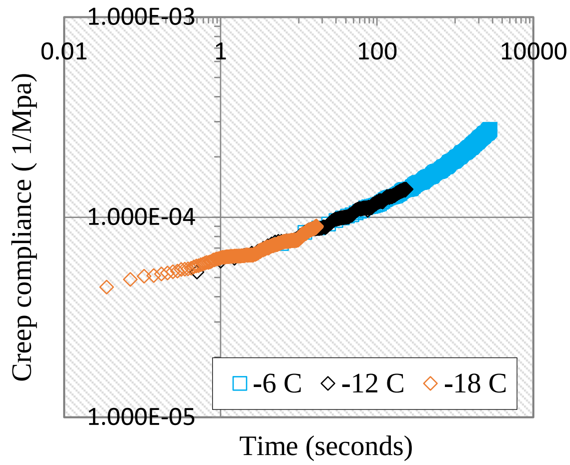


Figure 13. Shift Factors (SBS, sample 2)



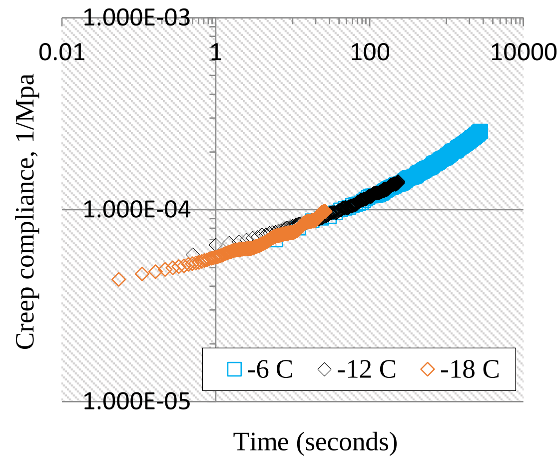
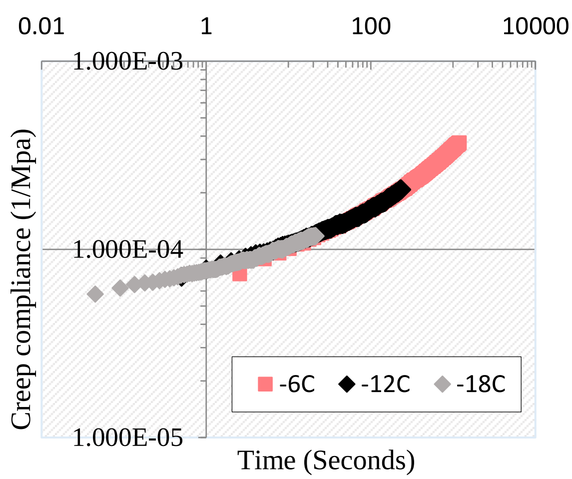


Figure 14. Master curve of Non-SBS sample1 **Figure 15. Master curve of Non-SBS sample 2**



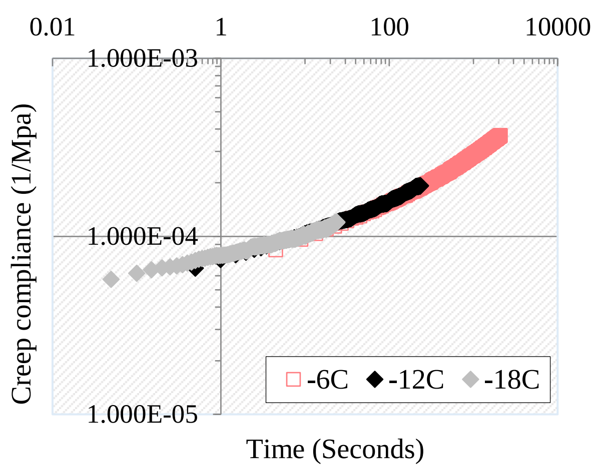


Figure 16. Master curve of SBS sample 1 **Figure 17. Master curve of SBS sample 2**

3.1.2Pre-somoothing Techniques

After the generation of the master curves, the power law function was implemented using pre-smoothing techniques of nonlinear regression models to determine the linear viscoelastic responses of the asphalt mixtures. Pre-Smoothing is a process that uses Prony series function and power law function to fit experimental creep compliance data. The pre-smoothing techniques involved minimizing the sum of squared errors between the raw data and fitted curves, as presented in Equation 14. The results of the power law function are represented in Figures 18 through 21. The fitted experimental data of unmodified binder samples are shown in Figures 18 and 19. While, the results of the power law function for the SBS modified binder samples are illustrated in Figures 20 and 21. Based on the results, it can be concluded that power law functions are capable of fitting the experimental creep compliance values. The power function parameters used to generate the fitting curves are represented in Table 3. These parameters were used to determine the relaxation and thermal properties of the asphalt mixtures.

$$\text{Minimize } \sum \left| D_p(\xi) - D(\xi) \right|^2 \tag{14}$$

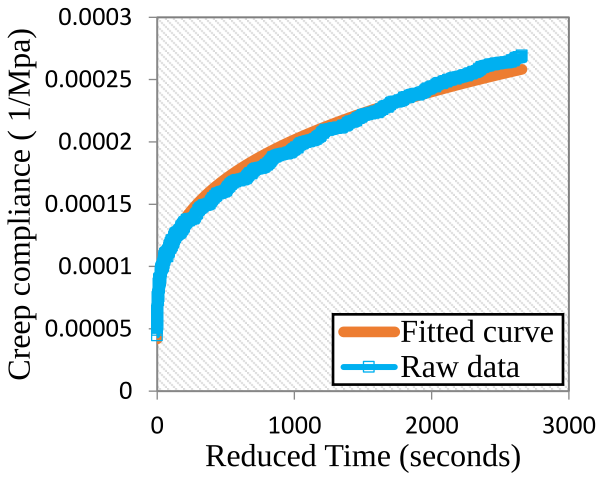
Where:

$D_p(\xi)$ = fitted power law response at reduced time ξ;

$D(\xi)$ = raw experimental data at reduced time, ξ.

Table 3. Power function parameters

Asphalt Binder	D_0 (1/MPa)	D_1 (1/MPa)	n
Non-SBS (sample 1)	3.38818E-05	2.16934E-05	0.29628455
Non-SBS (sample 2)	1.98625E-05	3.16999E-05	0.247305208
SBS (sample 1)	4.49E-05	2.25112E-05	0.369987689
SBS (sample 2)	4.74E-05	2.32461E-05	0.339735738



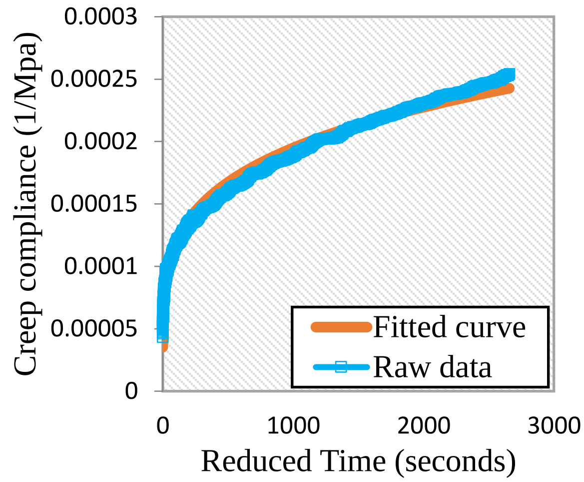
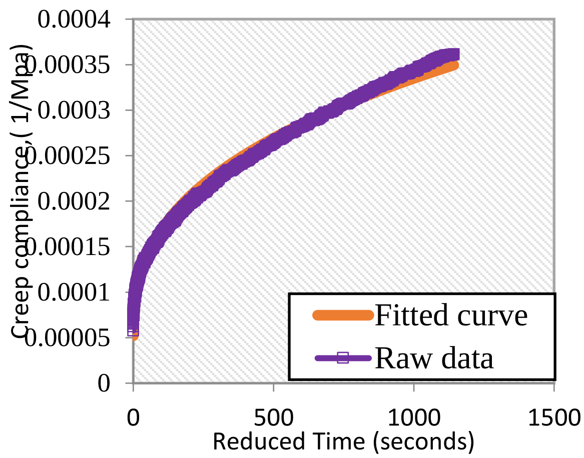


Figure 18. Power function for NonSBS sample 1 **Figure 19. Power function for NonSBS sample 2**



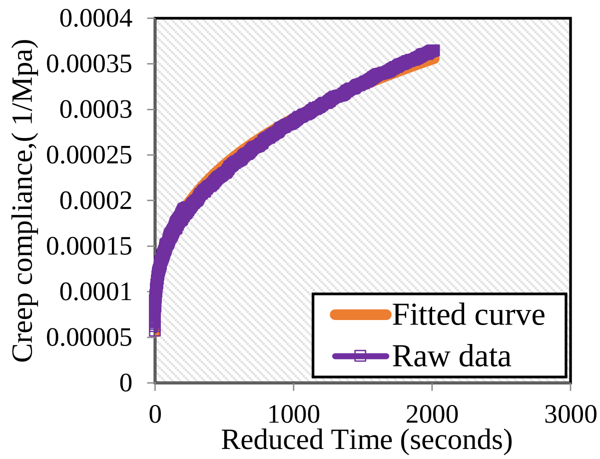


Figure 20. Power function for SBS sample 1 **Figure 21. Power function for SBS sample 2**

3.1.3 Thermal properties of asphalt binders

The thermal properties of the asphalt binders were determined through the generation of relaxation modulus curves and thermal stress curves. Relaxation modulus is a fundamental engineering property of asphalt mixtures that represents the ability of asphalt to relax when subjected to thermal induced stress. The relaxation modulus of the polymer modified, and unmodified asphalt binders were graphed against the reduced time, as shown in Figure 22. Then, the average creep compliances of the modified and unmodified binders were determined and used to generate relaxation modulus curves of the averages of the SBS modified binders and conventional binder samples. The relaxation modulus curves showed that SBS modified asphalt binder have higher relaxation capabilities compared to the unmodified asphalt binder. Thus, indicating that the SBS asphalt mixture have better abilities in relaxing thermal induced stress, compared to the unmodified binder.

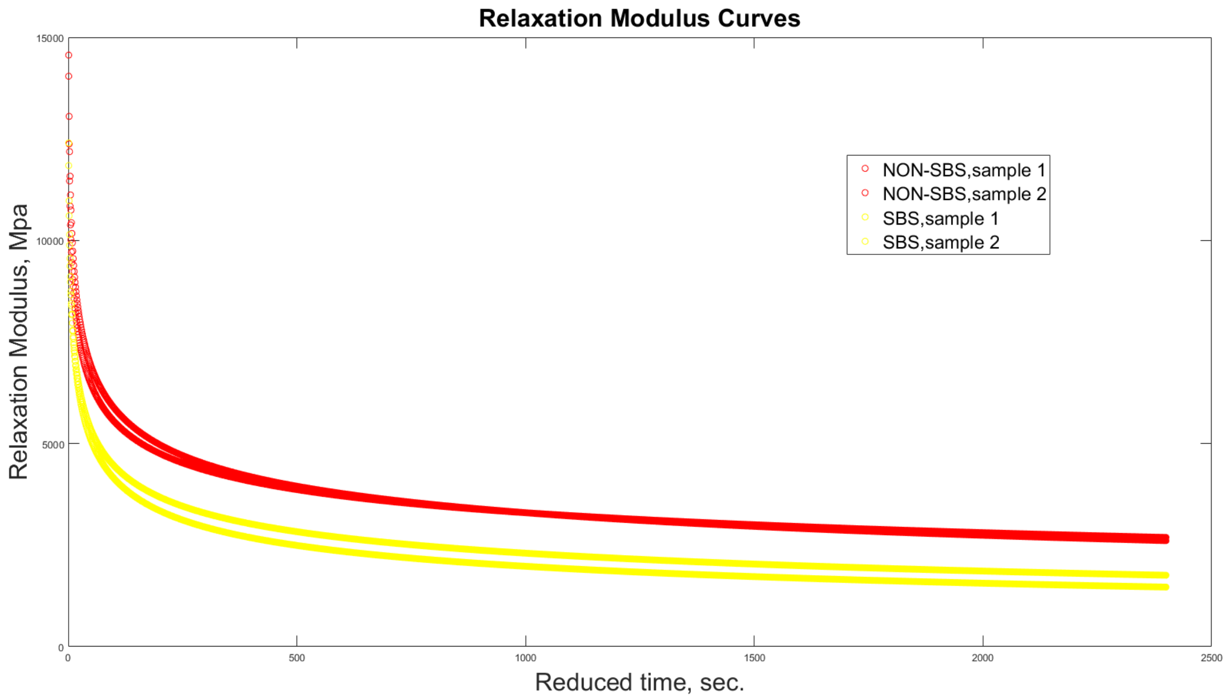


Figure 22. Relaxation curves of all samples

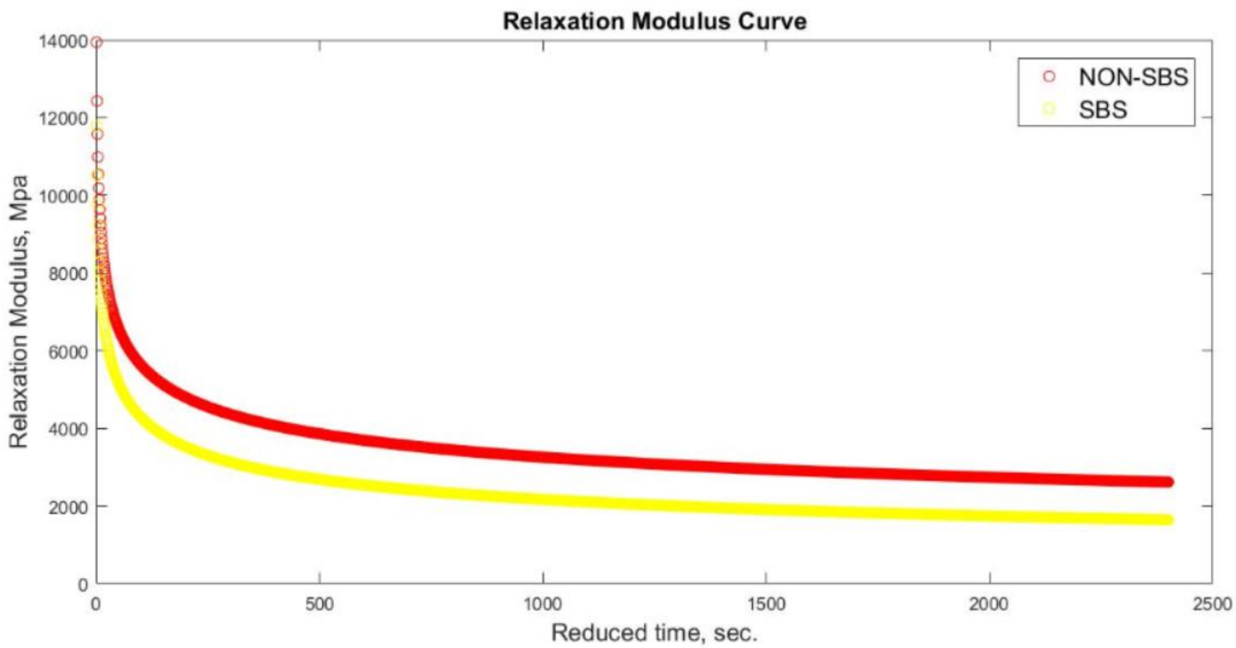


Figure 23. Relaxation curves of the averages of SBS modified and unmodified samples

After the determination of relaxation moduli curves, the thermal stresses applied on the pavement at different temperatures were predicted for SBS modified binders and unmodified binders. As shown in Figures 24 and 25, the SBS modified binders have lower thermal stress compared to the unmodified binder, meaning that at low temperatures the unmodified binder is expected to crack first as it has lower abilities in relaxing thermal induced stress. When the pavement surface temperature is -40°C, the thermal stress on the unmodified binder is predicted to be 5 MPa, while for the polymer modified binder the thermal stress is only 3.5 MPa. It can also be noted that when the pavement temperature is higher than -15°C both types of asphalt binders are expected to behave the same in terms of resisting thermal induced cracking.

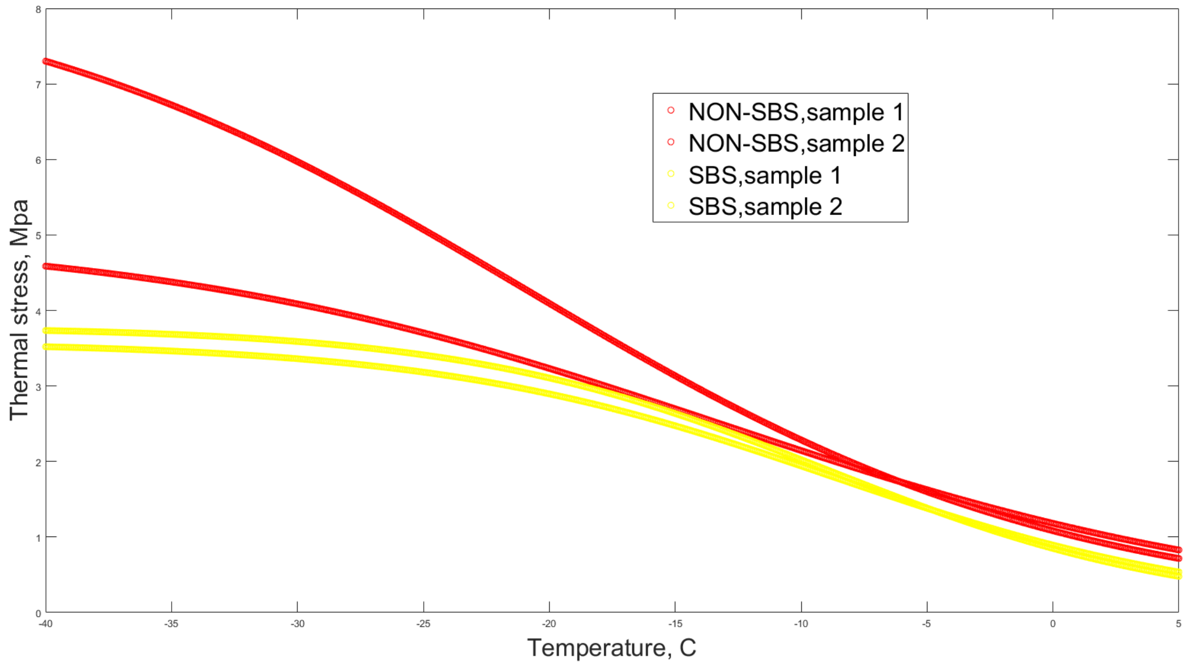


Figure 24. Thermal stress curves of all samples

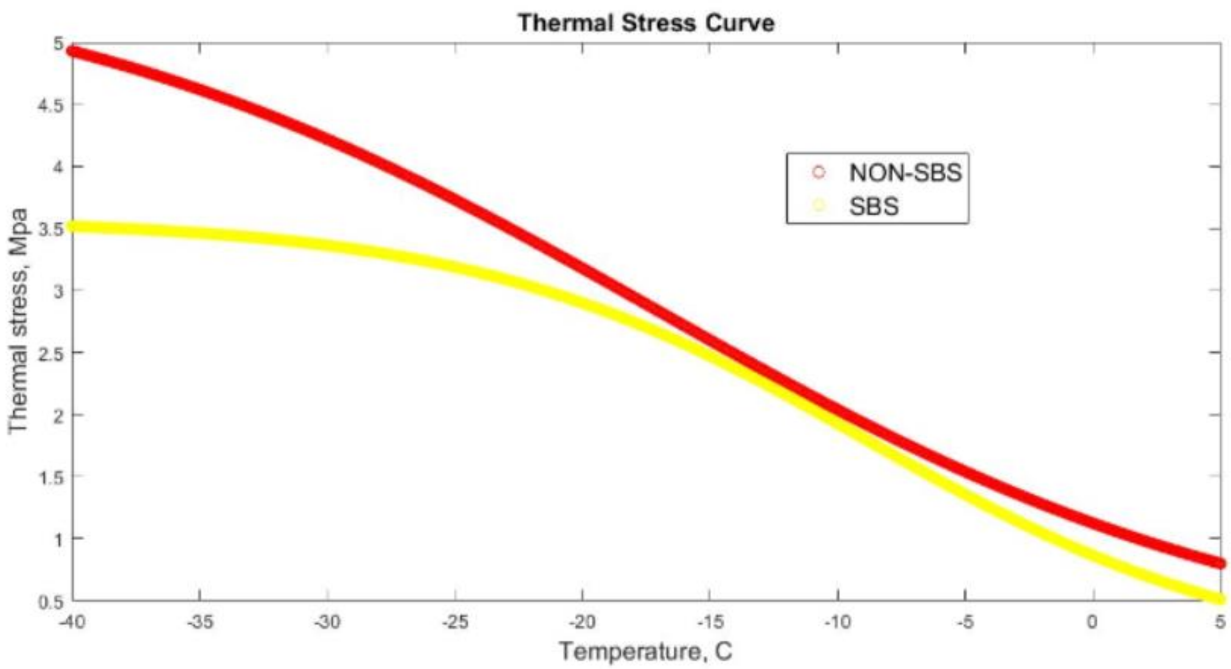


Figure 25. Thermal stress curves of the averages of SBS modified and unmodified samples

4. Conclusions

In this study, the behavior of SBS modified asphalt binders in resisting low temperature cracking was studied. The study was conducted by comparing the behavior of SBS modified binder to conventional binder. The mechanical properties of the asphalt binders were evaluated using BBR tests. Viscoelastic analysis was performed to determine the relaxation and thermal stress properties of both types of asphalt binders. Based on the study outcomes the following was concluded:

- SBS modified binder has lower stiffness values compared to the unmodified binder. The polymer modified binder also showed to have higher m-values compared to the unmodified binder, indicating that SBS polymer has a better ability in resisting thermal induced stress.
- The addition of SBS polymer modifier improved the low temperature crack resistance of the asphalt binder.
- The SBS modified bitumen showed to have better relaxation capabilities in resisting thermal stress.
- The thermal stress curves showed that the unmodified binder is predicted to experience higher level of thermal stress at low temperatures.
- Future field visits need to be conducted to verify laboratory testing results.

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CHAPTER 3

EVALUATING THE INFLUENCE OF POLYMER MODIFIED ASPHALT BINDERS ON LOW TEMPERATURE PROPERTIES

This Chapter has been accepted for publication in the Journal of Procedia Engineering

Abstract

Low temperature cracking is one of the most common distress types in asphalt concrete pavements, particularly in cold regions. Many factors influence the behaviour of asphalt concrete pavements at low temperatures, such as the applied traffic load, environmental conditions and material characteristics. Asphalt binders are one of the primary factors that influence material properties. The purpose of this study is to compare the performance of two types of asphalt binders: styrene-butadiene-styrene (SBS) modified asphalt binder and unmodified virgin binder (conventional binder) in resisting low temperature cracking. The study is conducted in Flagstaff, located at the area of Northern Arizona, in the United States. Asphalt samples were collected from the paving site and were compacted and trimmed into small beams. Bending Beam Rheometer tests were performed using the trimmed specimens at temperatures of -6°C, -12°C and -18°C. Based on the results of the study, it was concluded that, SBS modified asphalt binder performs better in resisting low temperature cracking, compared to the unmodified binder. Based on the study outcomes, it is recommended to use SBS polymer modified mixtures in areas subjected to severe cold weather events to maximize the life span of asphalt concrete pavements.

1. Introduction

Low temperature cracking or thermally induced cracking of asphalt pavements is one of the most predominant distress types in cold regions, particularly in Canada and northern United States (Marasteanu et al. 2004) (Li and Marasteanu, 2010). This problem leads to the early deterioration of asphalt concrete pavements, due to the inability of pavement to dissipate the stress from excessive thermal contraction (Liu et al. 2017). Previous research showed that the addition of polymers to asphalt mixtures enhances its performance, by increasing the ability of pavement to resist thermal cracking, fatigue distress and rutting. Moreover, the addition of polymers has shown to improve the performance of asphalt binders by increasing the characteristics of elastic recovery, viscosity, cohesive strength and ductility (Yildirim, 2007). The research on the behaviour of polymer modified bitumen can be found in extensive studies since the 90s. The concept of modifying virgin bitumen is based on increasing the viscoelastic range of the virgin asphalt to improve its flexibility at low temperatures (Wardlaw and Shuler, 1992).

Styrene-butadiene-styrene (SBS) polymer is one of the most common modifiers used in asphalt mixtures around the world. Most of the current research is focused on the impact of SBS polymers on the high temperature properties of asphalt mixtures. However, the factors affecting low temperature properties have not been well studied yet. Some of the previous research showed that SBS polymers could improve the low temperature cracking properties of asphalt mixtures. For example, a research done at Tongji University showed that the addition of SBS polymer reduces the stiffness of asphalt mixtures at low temperatures, indicating that SBS modifiers have a positive influence on the performance of asphalt pavements at low temperatures

(Lin et al. 2017). On the other hand, other research projects showed that the addition of SBS polymer does not have a significant impact on the stiffness of asphalt mixtures. For example, a research performed at Cooper Union University on evaluating the influence of adding SBS polymer to asphalt binders, showed that modified SBS polymers are more prone to low temperature cracking, compared to unmodified asphalt binders (Ng 2008). Thus, due to the inconsistent research results, it is necessary to conduct further investigations to better understand the influence of SBS modified asphalt binders on the low temperature cracking properties.

Currently, there are multiple testing methods used to determine the low temperature properties of asphalt mixtures which include, the Indirect Tensile Test (IDT), the Thermal Stress Restraint Specimen Test (TSRST), and the Bending Beam Rheometer (BBR) test. The IDT method is a common test used in evaluating thermal cracking. The method is a combination of three tests which are, the static creep, resilient and modulus and strength tests (Das et al. 2012). While, the TRST method characterizes low temperature cracking taking into account the thermal and mechanical effects. The test is performed by maintaining a constant axial strain as the temperature decreases, to allow the specimen to contract, while the servo-hydraulic press in the device prevents it. This process increases the thermal stress in the specimen until it fractures (Tapsoba et al. 2016). The Bending Beam Rheometer (BBR) test, also known as the standard test for binder at low temperatures, is a simple and cost-effective method used to determine the creep behaviour of asphalt mixtures. The results of BBR tests showed to be comparable to those of the IDT test (Gong et al. 2017). The test measures the deflection of thin asphalt beams at a constant load and constant temperature. The advantages of using BBR test over the other testing methods include the equipment availability at reasonable costs, and the reduced specimen size, as the dimensions of the beams tested in the BBR machine are only 12.5 x 6.75 x 127 mm (Romero, 2016).

The purpose of this study is to provide a laboratory investigation method using BBR test, to study the impact of adding SBS polymer on the low temperature properties of asphalt mixtures. A paving project was implemented in the area of Northern Arizona, in the United States. Two types of asphalt mixtures were used in the project which are: unmodified asphalt binder and SBS modified binder. BBR tests were performed to determine the low temperature cracking properties of both asphalt types of both asphalt mixtures. In addition, viscoelastic analysis was conducted to evaluate and compare the relaxation modulus of both binders. Based on the laboratory results and viscoelastic analysis, conclusions and recommendations for future research needs are provided.

2. Methodology

2.1 Sample Preparation

The study was completed using two types of asphalt mixtures: SBS polymer modified asphalt mixture and unmodified asphalt mixture. A PG 70-22 asphalt binder was used for both asphalt mixtures. A ¾ inches nominal material aggregate size was used for the unmodified and modified asphalt binders. The characteristics of the mix design used for asphalt mixtures are summarized in Table 1.

Table 1. Mix design characteristics

Mix Design	**Unmodified Binder**	**SBS Modified Binder**
Nominal material aggregate size	¾ inches	¾ inches
Asphalt binder type	PG 70-22	PG 70-22 SBS
Percent of asphalt binder (%)	5.7	5.7

Bulk specific gravity (G_{mb})	2.385	2.379
Maximum theoretical gravity (G_{mm})	2.509	2.499
Percent of air void, %	5	4.8
Voids in mineral aggregate filled (VMA), %	15.4	15.5
Percent of void filled (VFA), %	67.8	69

To study the low temperature cracking properties, asphalt samples were collected from the paving project and were reheated and compacted at the Materials Laboratory of Arizona Department of Transportation (ADOT), using a Superpave gyratory compactor (SGC). Then, asphalt samples were cut into six faced blocks. After that, the asphalt blocks were trimmed into small specimens to get them prepared for BBR testing. The testing procedures used to perform the BBR tests are based on The American Association of State Highway and Transportation Officials (AASHTO) standard TP125: Determining the Flexural Creep Stiffness of Asphalt Mixtures Using the Bending Beam Rheometer (BBR) (AASHTO TP125, 2016). Figures 1 through 9 illustrate the process of obtaining the asphalt samples from the paving site until they were tested in the BBR machine.

Figure 1. Getting samples

Figure 2. Asphalt samples

Figure 3. Transporting samples to lab

Figure 4. Six faced asphalt block

Figure 5. Asphalt trimming

Figure 6. Trimmed flat beams

Figure 7. Thin asphalt beams

Figure 8. Beams were conditioned

Figure 9. BBR test

2.2 Determination of Air Void Ratio

Measuring the air void ratio of the asphalt blocks is necessary, to ensure that the percentage of air voids did not significantly change when the SGC samples were cut into six faced asphalt blocks. Because, inconsistency in the percentage of air voids could lead to misleading BBR test results. The percentage of air voids were calculated based on Equation 1:

$$\% \text{ air voids} = (1- D/E) * 100 \quad (1)$$

Where:

D = the bulk specific gravity; and

E= the maximum rice specific gravity.

The calculated air voids percentages for the asphalt blocks were approximately 2% to 3% less than the percent of air voids for the SGC asphalt samples. The consistent reduction in air voids among the different asphalt blocks, indicates that the effect of the change in air voids on BBR tests is negligible.

2.3 Bending Beam Rheometer (BBR) Tests

Thin asphalt beams were tested in the BBR machine at three different temperatures: -6˚C, -12 ˚C and -18 ˚C, based on the used binder and in accordance with AASHTO T313 Standard (AASHTO T313, 2008). A minimum of 5 beams from each asphalt mixture were used to run BBR tests at the desired temperatures (Romero et al. 2011) (Ho and Romero, 2011). The BBR test measure the deflection and the stiffness of the beams at time increments of 0.5 seconds. The linear viscoelastic stiffness modulus obtained from the BBR tests can be calculated using Equation 2:

$$S(t) = PL^3/4bh^3\delta(t) \quad (2)$$

Where:

$S(t)$ = the creep stiffness as a function of time in MPa;

P = constant applied load in N;

L= span length in mm;

b = beam width in mm;

h = beam thickness in mm; and

$\delta(t)$ = beam deflection in mm

The measured stiffness values obtained from the BBR tests for both asphalt mixtures at a time of 60 seconds are summarized in Table 2. The calculated coefficients of variances (CV) of the stiffness values were found to be below 20%, indicating low variability among the different beams (Nielsen et al. 2007). As illustrated Figure 10, the average elastic modulus values of the unmodified asphalt binder are higher than the elastic moduli of the SBS modified binder, demonstrating that unmodified binders have higher stiffness and strength compared to the modified asphalt binder.

Table 2. Statistical information on the stiffness of asphalt mixtures

Temperature		**-6˚C**			**-12˚C**			**-18˚C**	
Binder Type	AVG (MPa)	STD (MPa)	CV	AVG (MPa)	STD (MPa)	CV	AVG (MPa)	STD (MPa)	CV
Unmodified binder	6158	409	0.066	9624	1305	0.136	12396	2109	0.17
SBS modified binder	4243	407	0.096	6138	190	0.03	9857	1237	0.13

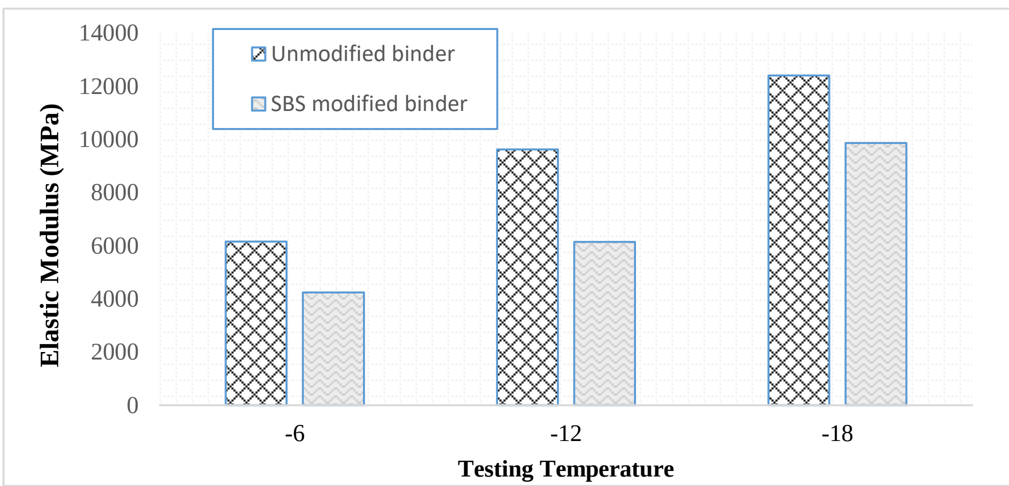


Figure 10. Elastic Modulus at 60 seconds for non-SBS and SBS mixtures

3. Results and Discussion

Viscoelastic analysis was performed to determine creep compliance values of the unmodified asphalt binder and SBS modified binder at the three different temperatures: -6˚C, -12 ˚C and -18 ˚C. The time-temperature superposition principle (TTSP) was used to shift the creep compliance curves at the three temperatures for both asphalt mixtures, as shown in

Figures 11 through 14. The shift factor used in the adopted TTSP model was calculated using an exponential function of time. The viscoelastic analysis showed that SBS modified asphalt binder has higher creep compliance values compared to the unmodified binder.

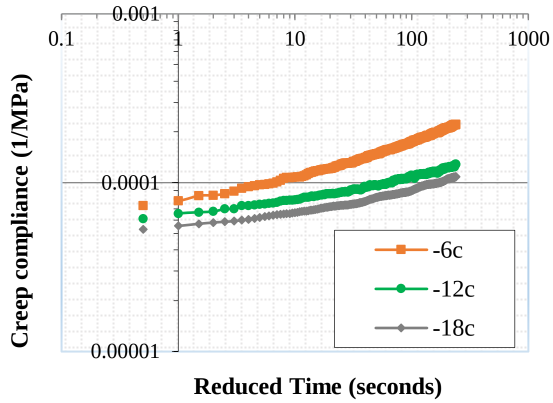


Figure 11. Creep Compliance Curves (Non-SBS)

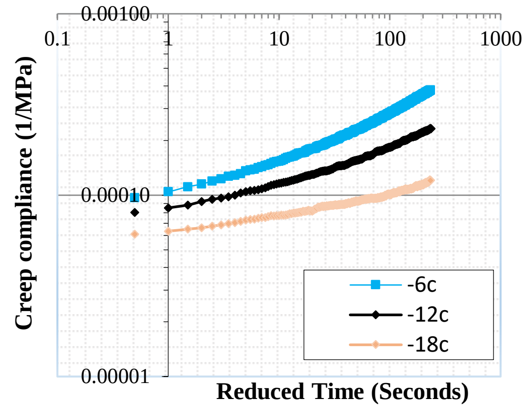


Figure 12. Creep Compliance Curves (SBS)

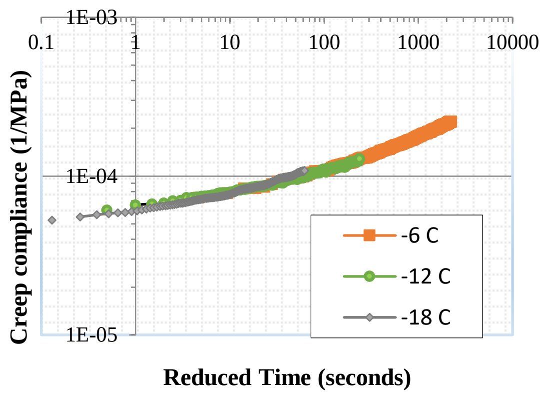


Figure 13. Master Curve (Non-SBS)

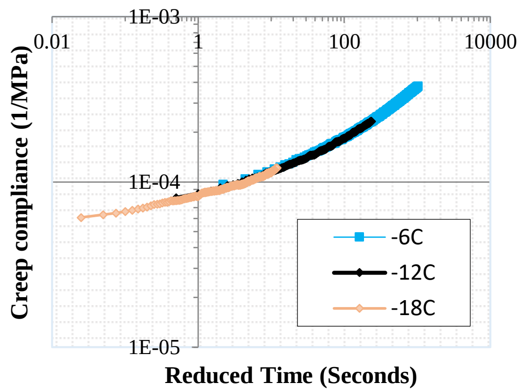


Figure 14. Master Curve (SBS)

The power law function, provided in Equation 3, was used to generate a fitting curve for the master curves of both asphalt mixtures, as shown in Figures 15 and 16. A reference temperature of -12°C was used to run the analysis. The parameters of the power function were determined using the fitting curves, and are summarized in Table 3.

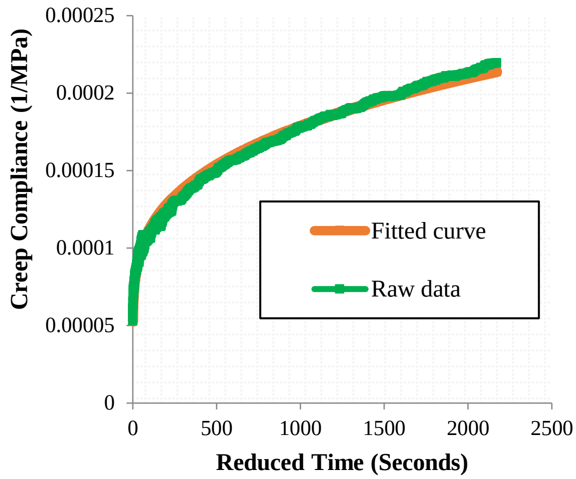
$$D(t) = D_0 + D_1 t^n \qquad (3)$$

Where:

D(t) = creep compliance values in 1/MPa at reduced time;

t= reduced time in seconds; and

D_0 , D_1 and n are power law parameters.



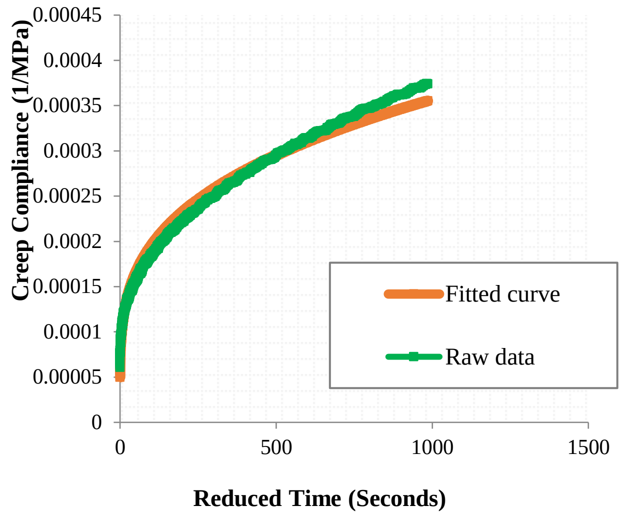


Figure 15. Power Law function (non-SBS) **Figure 16. Power Law function (SBS)**

Table 3. Power law function parameters

Asphalt Binder	D_0 (1/MPa)	D_1 (1/MPa)	n
Unmodified asphalt binder	4.3461E-05	1.69881E-05	0.299999998
SBS modified binder	3.8132E-05	3.7428E-05	0.310000515

The relaxation modulus curves of the unmodified binder and the SBS modified binder are provided in Figure 17. The SBS modified asphalt binder showed to have higher relaxation capabilities compared to the unmodified binder. Thus, indicating that the SBS asphalt mixture have better abilities in relaxing thermal induced stress.

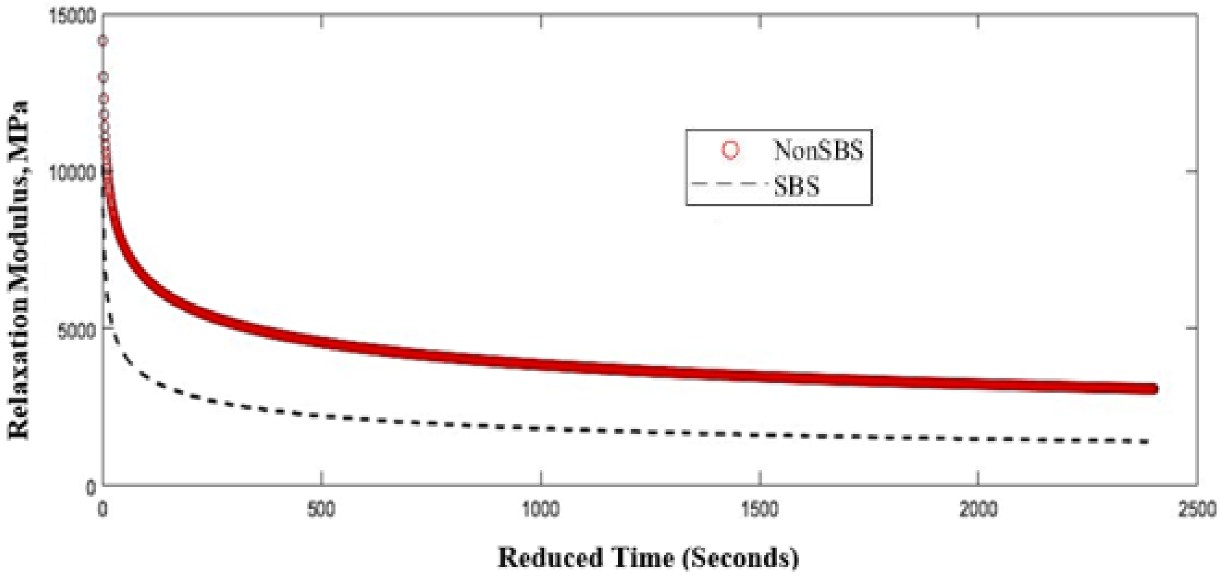


Figure 17. Relaxation modulus curves

4. Conclusions and Recommendations

In this study the influence of adding SBS polymer on the low temperature properties of asphalt mixtures was investigated. The study was completed by comparing the thermal cracking resisting properties of unmodified asphalt mixtures and SBS modified mixtures, through laboratory tests and viscoelastic analysis. Based on the outcomes of the study the following can be concluded:

- The Bending Beam Rheometer (BBR) test is capable of evaluating the low temperature properties of asphalt mixtures efficiently, with a minimum variability among different asphalt beams.
- The unmodified asphalt binder showed to have higher stiffness values compared to the SBS modified binder at the three testing temperatures: -6 ˚C, -12 ˚C and -18˚C.
- The relaxation capabilities of the SBS modified asphalt binder were found to be higher than the unmodified binder, indicating that the SBS modified binder has better abilities in

resisting induced thermal stress.

- The addition of the SBS modifier to the asphalt binder lead to an improvement in the low temperature cracking properties of the asphalt mixture.
- Field visits need to be done to further verify the results obtained from the laboratory methods and viscoelastic analysis.

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CHAPTER 4

EFFECT OF FREEZE-THAW CYCLES ON FATIGUE AND RUTTING CRACKING OF ASPHALT PAVEMENTS

This Chapter has been published in the proceedings of the World Conference on Pavement and Asset Management

Abstract

The purpose of this project is to evaluate the effect of freeze-thaw (F-T) cycles on fatigue and rutting cracking of asphalt pavements using numerical analysis and lab experiments. The effect of F-T cycles on the performance of asphalt pavements has not been well studied in support of understanding of fatigue and rutting cracking resistance. In association with local governments and consulting firms, an asphalt overlay project was constructed at Northern Arizona University (NAU) located in Flagstaff, Arizona, USA. Two types of asphalt mixtures were used for this study: rubberized asphalt mixtures and fiber reinforced asphalt mixtures. All mixtures were reheated and compacted to specimens in the Construction Materials lab of NAU. A series of creep compliance tests using a bending beam rheometer (BBR) were performed. KENPAVE, a computer software for pavement analysis, was used to analyze critical tensile stresses of the asphalt layer based on different overlaid thickness. Based on test findings and analysis results, the paper concluded that F-T cycles lead to early deterioration of asphalt pavement due to fatigue and rutting cracking.

1. Introduction

Pavement is a critical element in the transportation's infrastructure, and to the nation's economy. Several factors can affect the performance of pavements, such as the applied traffic load, soil, and environmental factors. Studies showed that there is a relationship between the distress of pavements, and the surrounding climate. Temperature and moisture can significantly affect the performance of pavements (Huang, 2004). Cold climates are sometimes associated with freeze- thaw (F-T) cycles. F-T cycles lead to early damage of asphaltic concrete pavements, creating economical and operational problems, and could potentially result in pavement failure (Amini and Tehrani, 2014). F-T cycles cause low temperature cracking, resulting in a reduction in the lifespan of the pavements. Low temperature cracking in asphalt concrete pavements has been an issue for many decades, particularly in cold climate regions (Gong et al. 2016). Fatigue and rutting cracking are two types of major asphalt cracking. Fatigue cracking is a part of pavements distresses that occurs in flexible pavements. Fatigue distress causes early deterioration of the pavement, by allowing the moisture to infiltrate through the cracks (Gao et al. 2012). Rutting cracking occurs due to the plastic deformation of the asphaltic concrete layer, or the layers below it, along the wheel path (Wen et al. 2013). Evaluating the performance of pavements in resisting fatigue and rutting cracking is essential to maximize the lifespan of pavements.

2. Background

The test section for this study is located in the City of Flagstaff, Arizona. Flagstaff is in Northern Arizona area at an elevation of 7000 ft. Due to the high elevation of the city, and the arid climate, there is a significant difference between the temperature in the morning, and at night. This difference leads to high frequency of F-T cycles. The number of F-T cycles in Flagstaff during the winter season exceeds the national average significantly, resulting in faster pavement deterioration, and high maintenance cost. The pavement structure of the section consists of the overlaid layer, existing asphalt concrete layer, aggregate base layer and subgrade layer as shown in figure 1. The overlay layer was constructed using two types of asphalt concrete mixtures, which are rubberized asphalt mixtures (RMA) and fiber reinforced asphalt mixtures (FRA). The two asphalt mixtures were used to determine the impact of F-T cycles on the performance of asphalt pavements.

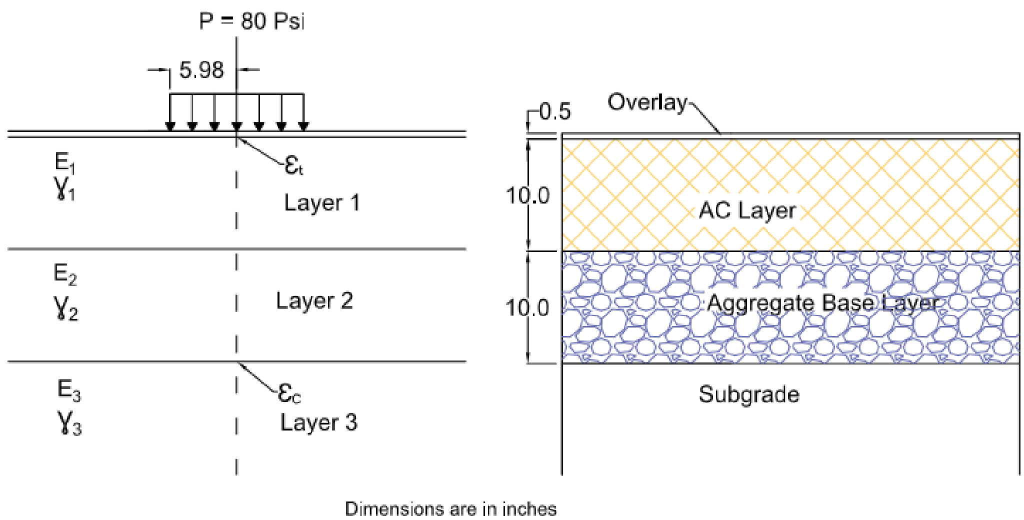


Figure 1. The pavement structure

3. Study Methodology

KENPAVE is a computer software for pavement design and analysis that can be applied to flexible and rigid pavements. The software is based on solving elastic multilayer systems under areas with circular loading (Huang, 2004). The software was used to determine the horizontal tensile strain (ε_t) at the bottom of the overlay layer responsible for fatigue cracking, and the vertical compressive strain (ε_c) at the top of the subgrade layer responsible for causing permanent deformation to the pavement. To determine the horizontal and compressive strains, the properties of mixtures including the creep compliances, and relaxation modulus were determined at different F-T cycles.

3.1 Creep compliances and Stiffness

The creep compliances and stiffness values were obtained from the bending beam rheometer (BBR) tests obtained at 0, 100, 150, 200, 250, and 300 F-T cycles. The BBR test measures the properties of asphalt mixtures including the stiffness, and the relaxation properties at low temperatures. These properties indicate the performance of asphalt pavement in resisting low temperature cracking such as, fatigue and rutting cracking. The BBR test measures the load applied on the beam, and its corresponding deflection as a function of time. Using the results obtained from the BBR test, and the dimensions of the tested beams, the stiffness, and creep compliances values were determined.

The testing procedure was based on AASHTO T313 standard for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (AASHTO, 2009) with modifications to be able to test stiffness values of asphalt thin beams (Ho and Romero, 2011 and 2012). Thin beams of FRA, and RMA mixtures were tested at -12˚C, -18˚C, and -24˚C and the stiffness values of both mixture beams at 60s were obtained and used to evaluate the effect of F-T cycles on performance of the two asphalt mixtures. The stiffness was plotted against the F-T cycles at the three temperatures for the two asphalt mixtures Figures 2, 3, and 4. According to the test results, it was found that stiffness decreased with the increase in the number of F-T cycles. A significant decrease in stiffness occurred mainly at the 100^{th}, and 150^{th} cycles.

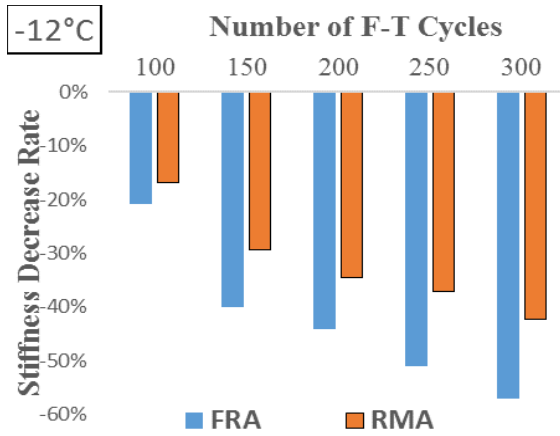


Figure 2. F-T cycles vs stiffness at -12°C

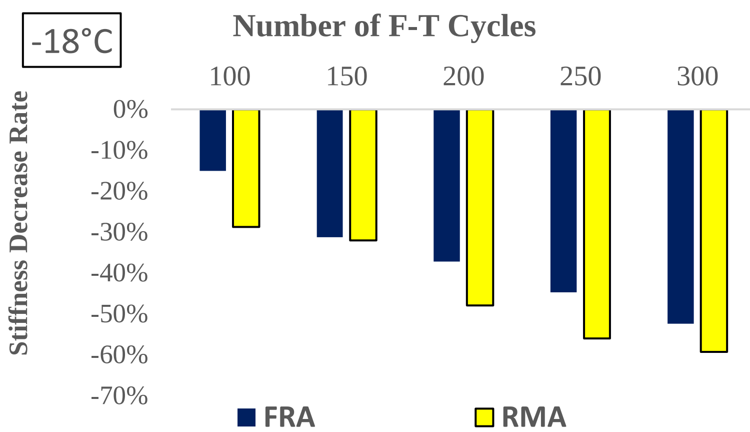


Figure 3. F-T cycles vs stiffness at -18°C

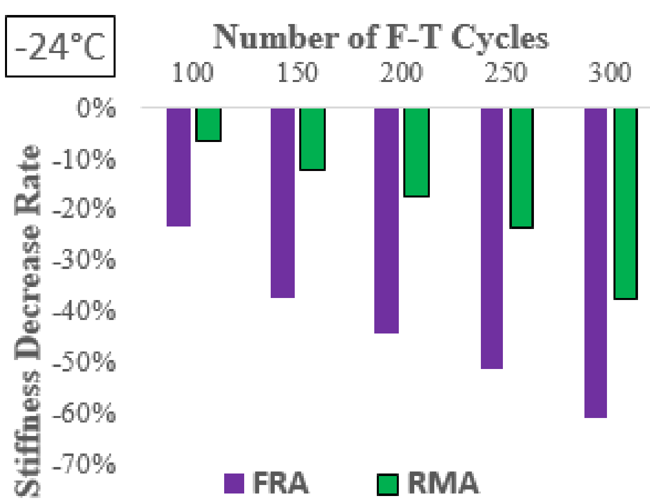


Figure 4. F-T cycles vs stiffness at -24°C

3.2 Creep Compliance Master Curve

BBR test measures the creep compliances using a time increment of 0.5 s. Because KENPAVE requires the creep compliances of viscoelastic layers starting from time 0.001s, so a master curve of the asphalt mixture is needed to complete KENPAVE analysis. The Power law function (Eq. 1) was used to generate a master compliance curve associated with the Time Temperature Superposition.

$$D(t) = D_0 + D_1 * t^n \quad (1)$$

Where:

D(t) = creep compliance at reduced time;

D_o, D_1 and n = power function parameters; and

t = reduced times.

The entire process of generating a master curve is beyond the scope of the paper so the calculations were neglected. The details were followed by Ho and Romero (2013).

3.3 Modeling in KENPAVE

Creep compliances and stiffness values from the master curves and BBR tests of both mixtures were used as input values for the overlay and base layers. The material properties of the pavement used in KENPAVE are summarized in Table 1. The responses of the pavement were evaluated using 18 kips of single axle load and tire pressure of 80 psi. KENPAVE analysis was performed for each of the two asphalt mixtures at 0, 100, 150, 200, 250, and 300 cycles.

Table 1. Material properties of the pavement

Layer Number	Material	Thickness (in)	Poisson ratio (υ)	Unit weight (lb/ft^3)
[1]	AC Overlay	5	0.3	152.7
[2]	AC Base	10	0.3	151.1
[3]	Aggregate base	10	0.4	125
[4]	Subgrade soil	-	0.45	101

3.4 Pavement Damage Analysis

The critical horizontal and compressive strains obtained from KENPAVE were used to perform damage analysis for fatigue and rutting cracking based on the following models:

3.4.1 Fatigue model

Fatigue damage was predicted using the following criteria:

$$N_f = f_1(\varepsilon_t)^{-f2} (E_1)^{-f3} \quad (2)$$

Where:

N_f = the allowable number of load repetitions to prevent fatigue cracking, and it depends on the tangential strain at the bottom of the overlay layer.

f_1, f_2, and f_3 = constants obtained from fatigue tests.

E_1 = the stiffness of the asphalt overlay layer, and it varied for each of the two asphalt mixtures at different F-T cycles.

3.4.2 Rutting model

Damage due to rutting depends on the vertical strain at the top of the subgrade soil, and it can be expressed as follows:

$$N_d = f_4 (\varepsilon_c)^{-f5} \quad (3)$$

where:

N_d = the allowable number of load repetitions to prevent rutting cracking.

f_4 and f_5 = constants that are determined from road tests.

The Asphalt institute method uses the following values for f_1, f_2, f_3, f_4 and f_5 coefficients in their design procedure:

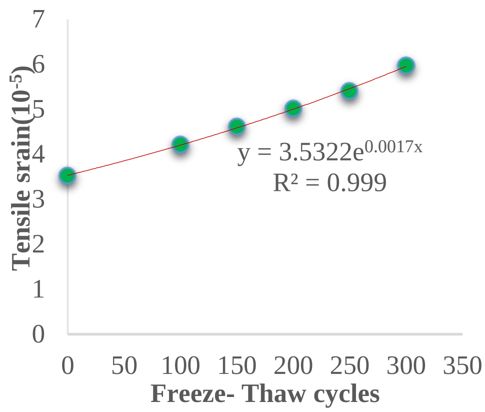
Table 2. Coefficients of Fatigue and Rutting Models

Coefficient	f_1	f_2	f_3	f_4	f_5
Value	0.0796	3.291	0.854	1.365×10^{-9}	4.477

4. Results and Discussion

4.1 Effect of Freeze-Thaw cycles on critical strains

To determine the relationship between F-T cycles and critical strains for fiber reinforced pavement mixtures and rubberized modified asphalt mixtures, the number of F-T cycles were plotted against tensile and compressive strains as shown in Figure 5 through Figure 8. Obviously, tensile and compressive strains increased with the increase in number of F-T cycles. The results demonstrate that the compressive strain at the top of the subgrade layer was higher than the tensile strain at the bottom of the overlay layer. The relationship between the critical strains and F-T cycles can be expressed as an exponential function as exhibited in Figure 5 through Figure 8.



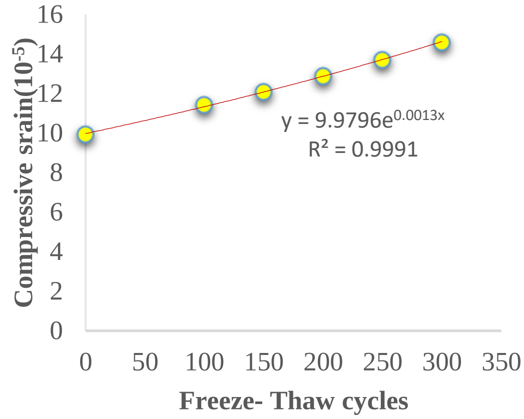
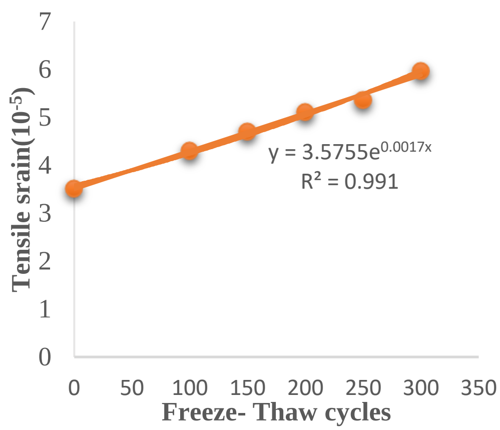


Figure 5. F-T cycles vs ε_t for FRA **Figure 6. F-T cycles vs ε_c for FRA**



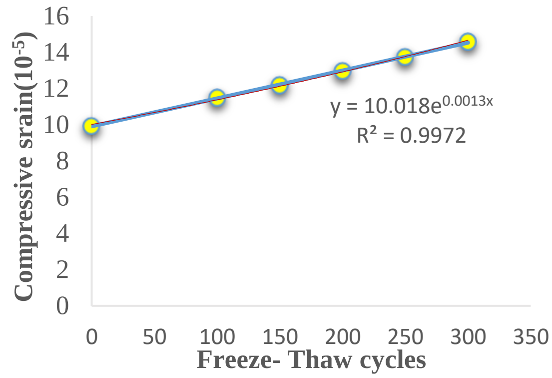


Figure 7. F-T cycles vs ε_t for RMA **Figure 8. F-T cycles vs ε_c for RMA**

4.2 Effect of Freeze- Thaw Cycles on Fatigue cracking and Rutting

The allowable numbers of load repetitions to prevent fatigue (N_f) and rutting (N_d) cracking of both FRA, and RMA asphalt mixtures were calculated for the 6 different F-T cycles. N_f and N_d were plotted against the number of F-T cycles to determine the impact of F-T cycles on the pavement's service life, and to determine the controlling failure criterion.

4.2.1 Effect of Freeze- Thaw Cycles on FRA Mixture

Figures 9 and 10 represent the number of load repetitions to prevent fatigue and rutting cracking against Freeze- Thaw cycles for the fiber reinforced asphalt mixture. The increase in the

F-T cycles significantly impacted the life cycle of the pavement. The fatigue life of the pavement is shorter than rutting life. Thus, the pavement's lifespan is controlled by fatigue distress, and the structure is predicted to fail due to fatigue cracking on the surface. A significant reduction in fatigue and rutting lives is observed at the 100th cycle where N_f was reduced by around 46% from its original value, and N_d was reduced by 37%.

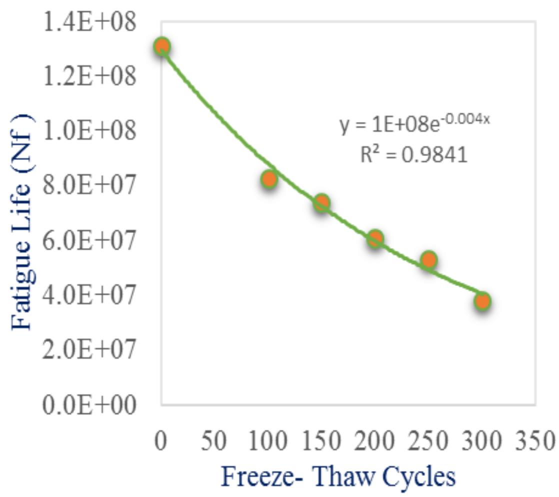


Figure 9. N_f vs F-T cycles for FRA

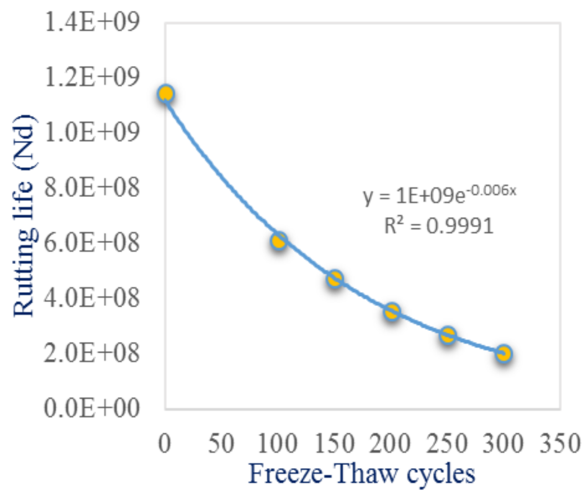


Figure 10. N_d vs F-T cycles for FRA

4.2.2 Effect of Freeze- Thaw Cycles on RMA Mixture

To evaluate the effect of Freeze-Thaw cycles on the lifespan rubberized asphalt mixtures, the number of load repetitions due to fatigue, and rutting distresses were plotted against the number of F-T cycles as shown in Figures 11 and 12. Based on the results, fatigue cracking is also the controlling parameter in case of RMA mixtures, as fatigue life is shorter than rutting life. The reductions in fatigue and rutting resistance at the 100th cycle were substantial where N_f was reduced approximately by 48% from its original value, and N_d was reduced by 31%.

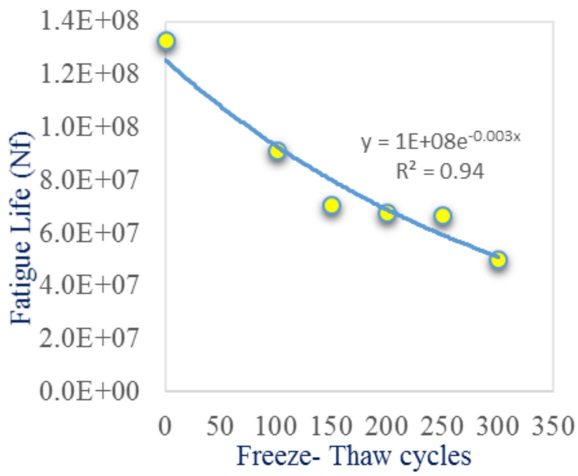


Figure 11. N_f vs F-T cycles for RMA

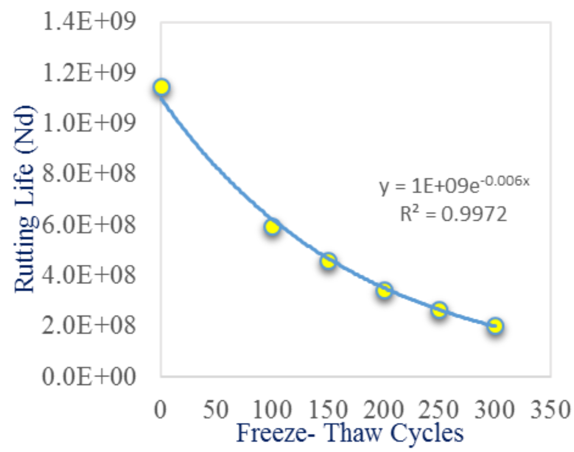


Figure 12. N_d vs F-T cycles for RMA

5. Conclusions

This study evaluated the effect of F-T cycles on fatigue and rutting cracking resistance of fiber reinforced asphalt, and rubberized modified asphalt mixtures. Based on the results obtained from the study the followings were concluded:

- Stiffness of FRA and RMA asphalt mixtures decrease with the increase in F-T cycles. A significant reduction of stiffness occurred at the 100^{th} and 150^{th} cycles.
- The correlation between critical strains and the increase in freeze- thaw cycles can be represented by an exponential function.
- Compressive strain at the top of the subgrade layer was higher than the tensile strain at the bottom of the overlay asphalt layer.
- Freeze- thaw cycles substantially impacted the service life of the asphalt pavement structure due to the reductions in fatigue and rutting cracking resistance.
- Fatigue cracking was the controlling parameter of asphalt pavement's failure mode for both asphalt mixtures.

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CHAPTER 5

THE USE OF ANSYS AND KENPAVE TO EVALUATE THE EFFECT OF FREEZE-THAW CYCLES ON THE PERFORMANCE OF ASPHALT MIXTURES

Parts of the contents of Chapter 5 will be sent for review for publication in the Annual Conference of the Transportation Research Board.

Abstract

Freeze- thaw (F-T) cycles are one of the main issues causing damages in Asphalt Concrete (AC) pavements in cold regions. Several research projects have been conducted to study the influence of freeze-thaw cycles on the fatigue and rutting distress of asphalt pavements, however, the effectiveness of these studies has not been considered satisfactory. The purpose of this paper is to use numerical methods and lab experiments to evaluate the impact of freeze-thaw cycles on fatigue and rutting lives of asphalt pavements. Numerical analysis was performed using finite element analysis and KENLAYER, a computer software used for pavement design and analysis. An asphalt overlay project was implemented on the campus of Northern Arizona University, in the United States, using two types of asphalt mixtures: rubberized asphalt mixtures (RMA) and fiber reinforced asphalt (FRA) mixtures. Asphalt samples of both mixtures were collected, reheated and compacted to small specimens in the Construction Materials lab. All specimens underwent a number of F-T cycles in accordance with the American Society of Testing and Materials (ASTM) C666 standards (2015), followed by bending beam rheometer (BBR) tests to determine the creep compliance values and stiffness of the asphalt specimens. Critical tensile and compressive strains of the pavement layers were predicted to determine the fatigue and rutting life cycles of the pavement structure. The outcomes of the paper conclude that the increase in the number of F-T cycles leads to a significant reduction in the fatigue and rutting

lives of AC pavements. In addition, the paper showed that the results obtained from both KENLAYER and the finite element method are relatively similar, but KENLAYER provides an easier and a more user-friendly approach to evaluate the mechanical responses of asphalt pavements.

1. Introduction

The temperature plays an important role in controlling the performance of Asphalt Concrete (AC) pavements. Fatigue cracking and rutting are two main modes of pavement distress that get affected by the surrounding environmental conditions. Fatigue distress typically occurs due to fatigue failure in the Hot Mix Asphalt (HMA) layer. Fatigue cracking results in the early deterioration of pavements, by allowing moisture to infiltrate through the cracks, which eventually result in potholes if not well maintained (Gao et al. 2012). Rutting distress is a linear depression that occurs due to the plastic deformation of the AC layer, or the layers below it, along the wheel path (Wen et al.2013). Rutting leads to a reduction in the lateral stability of vehicles, and can lead to moisture accumulation, resulting in vehicle hydroplaning (Wang et al. 2017). Characterizing the fatigue cracking and rutting performance of AC pavements is essential to predict the long-term performance of pavements.

Freeze-thaw (F-T) cycles are considered one of the primary reasons for damages in AC pavements in cold regions (Xu et al. 2016). Repeated F-T cycles results in changes in the voids in asphalt mixtures, making the pavement more prone to distresses such as rutting and fatigue cracking (Xu et al. 2015). Several previous research projects evaluated the impact of F-T cycles on the performance of asphalt mixtures (Xu et al. 2016) (Xu et al. 2015) (Si et al. 2014) (Gong et al. 2016) (Yi et al. 2014) (Ho et al. 2017). Özgan and Serin researched on the impact of F-T cycles on the characteristics of asphalt mixtures by exposing asphalt samples to 6, 12, 18 and 30 cycles (Özgan and Serin, 2013). Their study evaluated the influence of F-T cycles by comparing the characteristics of asphalt binder specimens before and after exposure to F-T cycles. The results revealed that F-T cycles have negative effects on the engineering properties of asphalt binders. Another research conducted by Si et al. (2014) evaluated the degradation of resilient modulus of AC mixtures due to F-T cycles, using the American Association of State Highway and Transportation Officials (AASHTO) T283 testing Procedure. Although, AASHTO T283 standard can be used to simulate F-T cycles, there are some issues associated with it. The testing procedure showed difficulty in maintaining constant F-T cycling temperature and can only simulate limited number of cycles, between 30 and 50 cycles (Ho et al. 2017). Due to the limitations of AASHTO T283 standard, in this project the influence of F-T cycles on asphalt mixtures was tested using ASTM C666 (Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, compatible apparatus) procedure with modifications. Although, the ASTM C666 apparatus is commonly used to test the impact of F-T cycles on previous concrete mixtures, a research conducted by Ho et al. (2017) showed that it is feasible to use ASTM C666 in testing the resistance of asphalt mixtures to F-T cycles. The advantage of using ASTM C666 is its ability to simulate a large number of F-T cycles. Thus, the ASTM C666 standard was adopted to operate F-T cycles of asphalt specimens up to 300 cycles.

Although, many research projects were performed to investigate the influence of F-T cycles on asphalt mixtures using laboratory tests, the impact of F-T cycles on fatigue cracking and rutting has not been well studied. In this research the influence of F-T cycles on fatigue cracking and rutting is predicted using mechanistic-empirical (M-E) design models. In M-E methods, the stresses, strains and deflections are computed using layered elastic models. Three main assumptions are made when using a layered elastic model which include, assuming that all pavement layers extend infinitely in the horizontal direction, the subgrade layer extends infinitely in the downward direction, and that materials cannot get stressed beyond their elastic limit (Muniandy, 2013). M-E design solutions predict the fatigue and rutting lives based on the estimated number of traffic load repetitions during the design period. Fatigue cracking is related to the horizontal tensile strain exerted on the bottom of the asphalt layer. While, rutting is related to the vertical compressive strain on the top of the subgrade layer (Huang, 2004). Excessive vertical strain lead to the formation of permanent deformation along the surface of the pavement structure. Thus, determining the amount of horizontal and vertical strains exerted on the AC pavement structure is essential to estimate its fatigue and rutting lives.

In this paper, two different computer programs were used to determine the critical strains applied on the pavement structure. First, KENLAYER a pavement analysis and design software was used to model the flexible pavement. The program allows for performing linear, non-linear and viscoelastic modeling of AC pavements (Huang, 2004). In addition to using KENLAYER, a finite element method was used to analyze the flexible pavement. In recent years, finite element models are gaining acceptance in analyzing pavement responses due to their ability of dealing with complex geometries, boundary conditions and material characteristics (Hadi and Bodhinayake, 2003). ANSYS, a finite element program, was used to create a three dimensional (3D) model to determine the critical strains withinthe AC pavement. The model computes the tensile and compressive strains based on the elastic modulus and the thickness of the pavement layers.

This paper evaluates the effect of F-T cycles on asphalt concrete pavements using numerical analysis and lab methods. In association with local governments and consulting firms, an asphalt overlay project was constructed at Northern Arizona University (NAU) located in Flagstaff, Arizona, USA. Two types of asphalt mixtures were used for this study: rubberized asphalt mixtures and fiber reinforced asphalt mixtures. A series of creep compliance tests using a bending beam rheometer (BBR) were performed. KENLAYER and ANSYS, two computer programs were used to analyze the flexible pavement and evaluate the influence of F-T cycles on the performance of AC pavements. Based on the study outcomes, a comparison between the significance of using ANSYS and KENLAYER is provided.

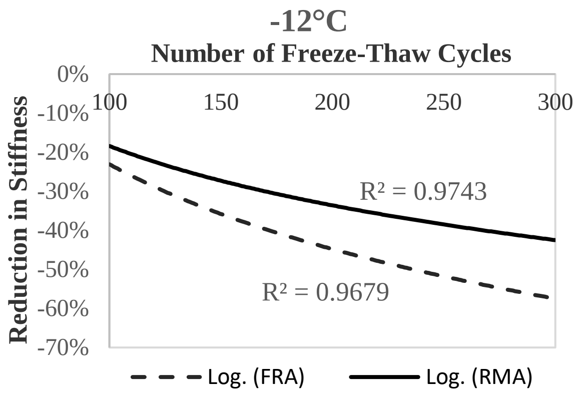
2. Material and methods

2.1 Material Preparation

An overlay paving project was implemented in the City of Flagstaff, Arizona. Flagstaff is located at an elevation of approximately 7000 ft. Due to the high elevation of the city and the arid climate, temperature varies significantly between the daytime and night. This difference in temperature results in a large annual number of F-T cycles. The pavement structure is composed of a 0.5 inches overlay layer on top of 10 inches Asphalt Concrete layer, followed by 10 inches of aggregate base layer over the subgrade layer. Two different asphalt mixtures were used to construct the overlay including rubberized modified asphalt (RMA) and fiber reinforced asphalt (FRA). To determine the influence of F-T cycles on the performance of both mixtures, asphalt samples were collected from the paving site, and brought back to the Materials Laboratory of Northern Arizona University where samples were reheated and compacted using a Superpave Gyratory compactor (SGC). A F-T apparatus was used to simulate F-T cycles of the asphalt mixtures in accordance to ASTM C666 standards. Asphalt specimens were subjected to six different F-T cycles including 0, 100, 150, 200, 250 and 300 cycles. After specimens reached the anticipated number of F-T cycles, they were taken from the apparatus to measure their air voids to ensure consistency in results and to avoid misleading results. Then, asphalt samples were cut into thin beams with dimensions of approximately 12.7 mm x 6.35 mm x 127 mm to prepare them for bending beam rheometer (BBR) testing.

2.2 Bending Beam Rheometer (BBR) test

To determine the low temperature properties of asphalt mixtures, BBR tests were performed. A BBR test uses thin asphalt beams to determine the deflection of the beam as a function of time. Creep compliance and stiffness values were obtained to evaluate the viscoelastic responses of asphalt mixtures. The testing procedure was based on AASHTO TP125 -16 standard for Flexural Creep Stiffness of Asphalt Mixtures Using the Bending Beam Rheometer Determining the (AASHTO, 2016) (Ho et al. 2017). BBR testing was conducted using thin asphalt beams made of FRA and RMA mixtures, at the three temperatures of -12˚C, -18˚C, and -24˚C. To determine the influence of F-T cycles on the performance of asphalt mixtures, the stiffness of both mixtures was plotted against the number of F-T cycles at the three temperatures, as shown in Figures 1 through 3. According to the results, the stiffness of asphalt mixtures decreased with the increase in the number of F-T cycles. The relationship between the reduction in stiffness and the number of F-T cycles is represented using a logarithmic function. Based on the results, it was observed that most the reduction in stiffness occurred between the 100^{th} and the 150^{th} cycles.



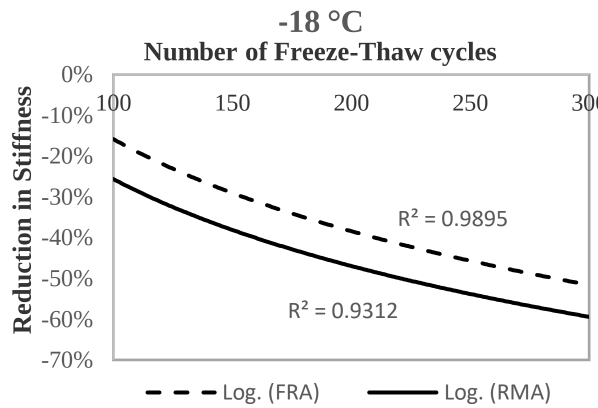


Figure 1. Stiffness vs F-T cycles at -12˚C

Figure 2. Stiffness vs F-T cycles at -18˚C

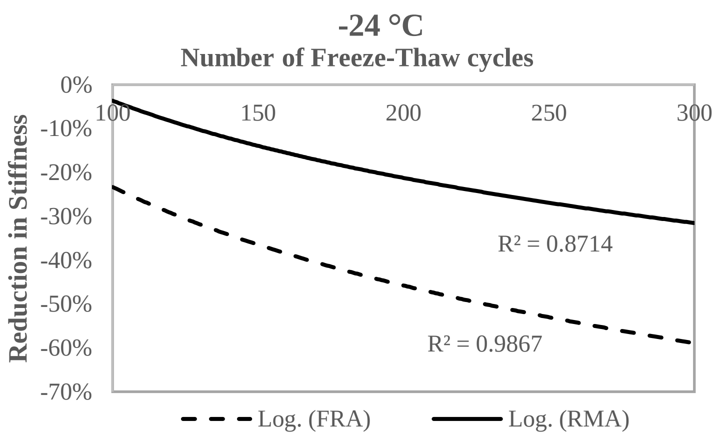


Figure 3. Stiffness vs F-T cycles at -24˚C

The creep compliance data at the reference temperature (18˚C) was used to run viscoelastic analysis. The use of creep compliance curve to characterize viscoelastic materials is completed by assuming that only the elastic modulus is considered to be elastic and time dependent (Huang, 2004). The creep compliance values can be expressed using Equation 1:

$$D\ (t) = \frac{\epsilon(t)}{\sigma} \quad (1)$$

Where, σ = stress and $\in (t)$ = time dependent strain under a constant load.

The master compliance curves were generated based on the Time Temperature Superposition Principle and the power law function, as shown in Equation 2:

$$D\ (t) = D_0 + D_1 * t^n \quad (2)$$

Where, D (t) = creep compliance at reduced time, D_o, D_1 and n = power function parameters, and t = reduced times.

2.3 Determining Critical Strains

To determine the critical compressive and tensile strains of the pavement structure due to the action of F-T cycles, two different computer programs were used: KENLAYER and ANSYS. Both programs predict critical strains based on the geometry and material properties of pavement structure. The stiffness of asphalt mixtures obtained from BBR tests at 60 seconds were used to run the analysis. The vertical compressive strain occurs on the top of the subgrade layer and it depends mainly on the stiffness or the elastic modulus of the soil layer. While, the tensile strain is determined on the bottom of the asphalt layer and it depends on the horizontal normal and shear stresses applied on the layer. The compressive strain is used to determine rutting distress or permanent deformation, and the tensile strain is used to evaluate fatigue cracking along the surface of the pavement.

2.3.1 KENLAYER

KENLAYER is a pavement design and analysis software, designed for analyzing flexible pavements. The program uses deterioration models in evaluating the performance of pavements in terms of stresses, strains and deflections. The program is capable of performing damage analysis for linear, non-linear and viscoelastic layers by applying single, dual, dual-tandem or dual-tridem wheels (Huang, 2004). In this study, the asphalt concrete layer and the overlay layer were modeled as viscoelastic systems, while the aggregate base and subgrade layers were modeled as linearly elastic systems. To run viscoelastic analysis in KENLAYER, the creep compliance values were obtained from BBR tests were inputted in the program. The responses of the pavement were evaluated using a stationary single axle load of 18 kips, tire pressure of 80 psi and a contact circular radius of 5.98 inches. The material and geometric properties of the pavement section used to run the model are summarized in Table 1. KENLAYER analysis was run for both the FRA and RMA asphalt mixtures at 0, 100, 150, 200, 250 and 300 cycles, respectively. Critical vertical compressive strains and horizontal strains were determined for each one of the 6 designated F-T cycles.

Table 1. Material properties of the pavement

Layer	Thickness (in)	Poisson ratio (υ)	Unit weight (lb/ft^3)
AC Overlay	0.5	0.3	152.7
AC Base	10	0.3	151.1
Aggregate base	10	0.4	125
Subgrade soil	-	0.45	101

2.3.2 Finite Element Analysis

A three-dimensional finite element model was developed using ANSYS to determine the critical stresses and strains of the pavement structure. The model was analyzed by assigning the geometric properties, materials and boundary conditions of the pavement section. The material properties of the pavement layers are provided in Table 2. The model was meshed using 10410 nodes and 1764 elements. The pavement layers were modeled assuming linear elastic behavior. The boundary conditions were assigned by restricting the displacement of the top two layers in all directions, except the vertical component. While, the subgrade layer was modeled by assigning horizontal and vertical constraints. Similar to the analysis done in KENLAYER, a constant tire pressure of 80 psi was applied at the top asphalt layer. The structure of the pavement and the mesh used to run the model are illustrated in Figure 4. The tensile and compressive strains of the pavement were determined by visualizing the normal strains in the x and y directions. To further validate the results, the solutions of the finite element model were compared to the results obtained from KENLAYER.

Table 2. Material properties of the pavement structure in ANSYS

Layer Name	Density (Kg/m^3)	Elastic Modulus (MPa)	Bulk Modulus (MPa)	Shear Modulus (MPa)
AC Overlay layer	2446	6505 - 16164	5421 - 13470	2502 - 6217
AC Layer	2420	345	287.5	133
Base layer	2002	34.5	57.5	12.3
Subgrade	1618	40	133	13.8

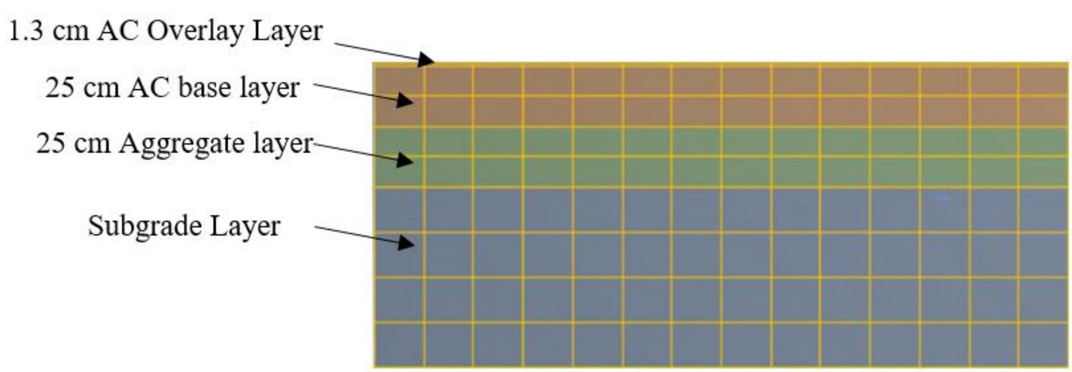


Figure 4. Side view of pavement structure and mesh refinement

2.4 Pavement Damage Analysis

The critical compressive and tensile strains obtained from KENLAYER and ANSYS were used along with the elastic modulus values from BBR tests to determine the fatigue and rutting lives of the pavement structure at different F-T cycles. Generally, pavements that have small loads applied on them are governed by fatigue failures. While, pavements with higher axle load are controlled by rutting failure (Behiry, 2012). In the study, the fatigue and rutting lives were calculated based on the Asphalt Institute method (Huang, 2004).

2.4.1 Fatigue life modeling

The reduction in the serviceability of the pavement due to fatigue distress was computed using Equation 3. The fatigue life of a pavement structure depends on the horizontal tensile strain (ε_t) applied on the bottom of the asphalt concrete based layer and the stiffness of the asphalt layer.

$$N_f = f_1(\varepsilon_t)^{-f2} (E_1)^{-f3} \quad (3)$$

Where:

N_f = the allowable number of load repetitions to prevent fatigue cracking.

f_1, f_2, and f_3 = constants obtained from fatigue tests. The Asphalt Institute method uses values 0.0796, 3.291 and 0.854 for f_1, f_2 and f_3, respectively.

E_1 = the stiffness of the asphalt overlay layer, and it varied for the RMA and FRA asphalt mixtures at the different F-T cycles.

2.4.2 Rutting life modeling

The rutting life depends on the vertical compressive strain applied on the subgrade layer, and it was determined using Equation 4.

$$N_d = f_4 (\varepsilon_c)^{-f5} \quad (4)$$

N_d = the allowable number of load repetitions to prevent rutting.

f_4 and f_5 = constants that are determined from road tests. The Asphalt Institute method uses values of 1.365×10^{-9} and 4.477 for f_4 and f_5, respectively.

3. Results and Discussion

3.1 The Effect of F-T cycles on Critical Strains

To evaluate the effect of F-T cycles on the critical strains, the compressive and tensile strains obtained from the finite element analysis method and KENLAYER were graphed against the number of cycles, as shown in Figures 6 through 9. The increase in the number of F-T cycles resulted in a significant increase in the level of critical strains. The relationship between the number of F-T cycles and the critical strains can be expressed using an exponential function, as illustrated in Figures 5 through 8. The predicted compressive strain on the top of the subgrade layer was found to be higher than the tensile strain on the bottom of the AC layer for both asphalt mixtures. The critical strains obtained from the finite element method were greater than those computed using KENLAYER. In addition, the computed critical strains applied on the pavement section with FRA asphalt mixture were found to be lower than the critical strains on the pavement constructed with the RMA mixture. Thus, the addition of fibers to asphalt mixtures could lead to the enhancement of the low temperature properties of asphalt mixtures.

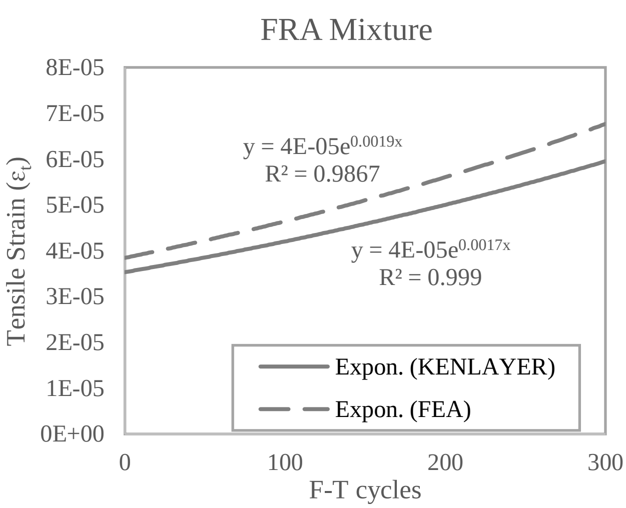


Figure 5. F-T cycles vs ε_t for FRA mixture

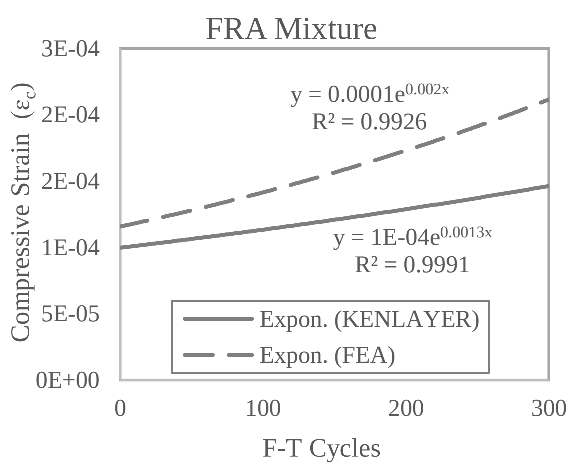
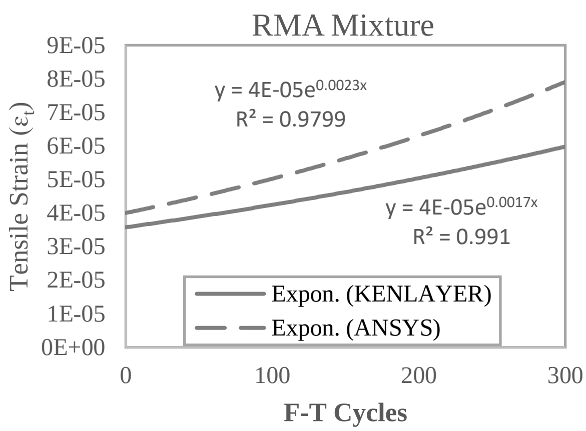


Figure 6. F-T cycles vs ε_t for FRA mixture



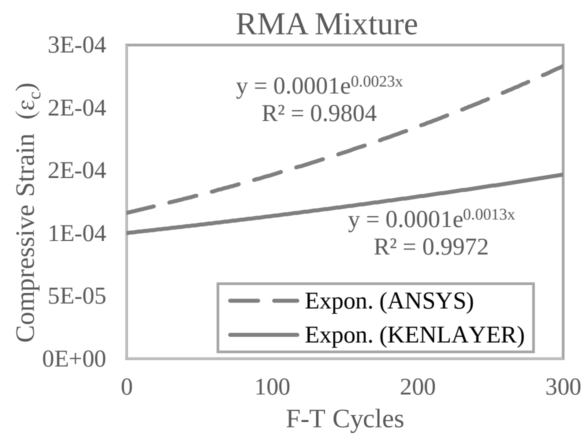


Figure 7. F-T cycles vs ε_t for RMA mixture

Figure 8. F-T cycles vs ε_t for RMA mixture

3.2 The Effect of F-T cycles on Fatigue and Rutting Distress

The number of F-T cycles were graphed against the number of load repetitions to evaluate fatigue cracking (N_f) and rutting (N_d) for both types of asphalt mixtures, as exhibited in Figures 9 through 12. It is noticed that both fatigue and rutting life cycles decrease as the number of F-T cycles increase. Most of the reduction in fatigue and rutting lives occurred at the 150 cycle The relationship between the increase in F-T cycles and fatigue and rutting lives can be represented as an exponential function.The predicted N_f values were found to be lower than the values N_d, thus fatigue failure is the controlling parameter of the asphalt pavement failure mode. Generally, the FRA mixtures have a better performance in terms o f resisting fatigue cracking and rutting, as compared to the RMA mixtures. In addition, the predicted fatigue and rutting lives obtained from the FEA model were found to be lower than the results obtained from KENLAYER.

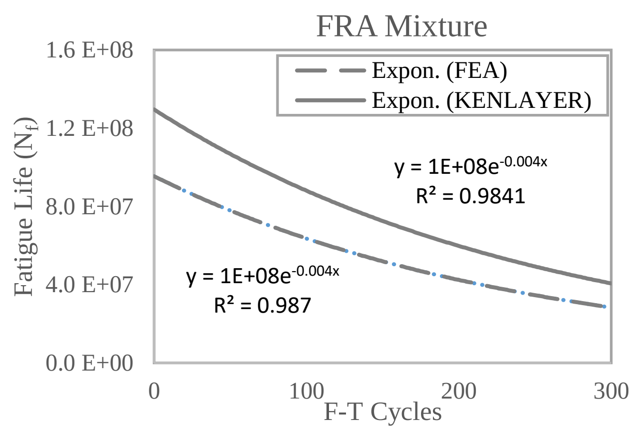


Figure 9. F-T cycles vs N_f for FRA mixture

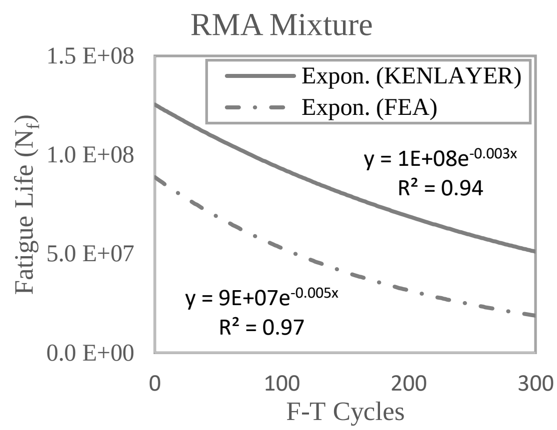


Figure 10. F-T cycles vs N_f for FRA mixture

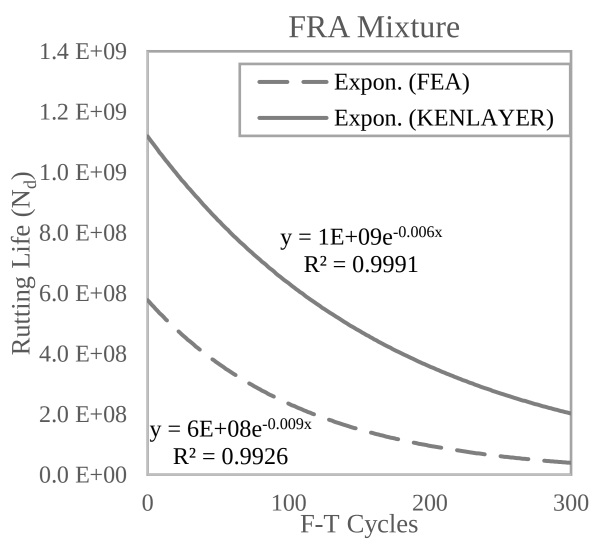


Figure 11. F-T cycles vs N_d for RMA mixture

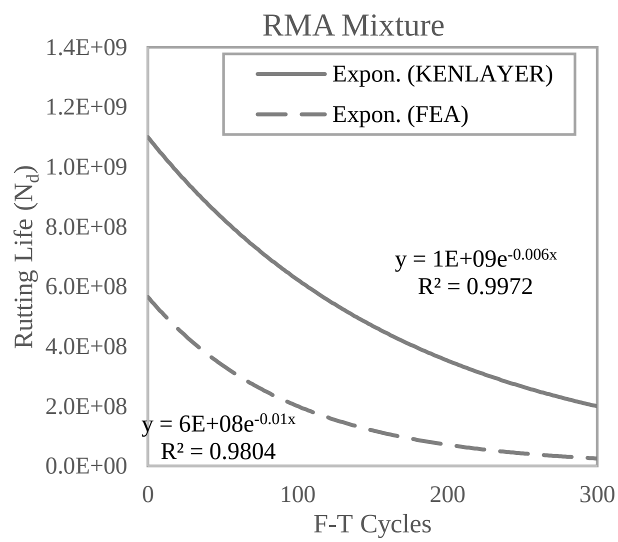


Figure 12. F-T cycles vs N_d for RMA mixture

3.3 Statistical Analysis

A one-way analysis of variances (ANOVA) was performed to determine if the effect of F-T cycles on the reduction of fatigue and rutting lives is significant or not. The analysis was performed using the N_f and N_d values of the RMA and FRA asphalt mixtures obtained from both the FEA method and KENLAYER software. The results of the ANOVA analysis are summarized in Table 3 and Table 4. The statistical p-values computed for the effect of F-T cycles on the decrease of fatigue lives using the results of KENLAYER and ANSYS for both asphalt mixtures are 0.0007677, 0.0004503, 0.003795 and 0.001695, respectively. In addition, the p-values computed for the influence of F-T cycles on the reduction of rutting lives are 0.00242, 0.008905, 0.00336 and 0.01202. Given all the p-values, it can be concluded that the influence of F-T on the reduction of fatigue and rutting lives of both RMA and FRA is significant.

Table 3. ANOVA analysis for the relationship between F-T cycles and fatigue life (Nf)

ANOVA: N_f of FRA mixture obtained from KENLAYER					
Source of Variation	SS	df	MS	F	P-value
Between Groups	4.9963e+15	1	4.9963e+15	85.08	0.0007677
Within Groups	2.3490e+14	4	5.8725e+13		
Total		5			
ANOVA: N_f of FRA mixture obtained from ANSYS					
Source of Variation	SS	df	MS	F	P-value
Between Groups	2.8082e+15	1	2.8082e+15	112.1	0.0004503
Within Groups	1.0020e+14	4	2.5050e+13		
Total		5			
ANOVA: N_f of RMA mixture obtained from KENLAYER					
Source of Variation	SS	df	MS	F	P-value
Between Groups	3.8323e+15	1	3.8323e+15	36.453	0.003795
Within Groups	4.2052e+14	4	1.0513e+14		
Total		5			
ANOVA: N_f of RMA mixture obtained from ANSYS					
Source of Variation	SS	df	MS	F	P-value
Between Groups	3.0885e+15	1	3.0885e+15	56.185	0.001695
Within Groups	2.1988e+14	4	5.4970e+13		
Total		5			

Table 4. ANOVA analysis for the relationship between F-T cycles and rutting life (N_d)

ANOVA: N_d of FRA mixture obtained from KENLAYER					
Source of Variation	SS	df	MS	F	P-value
Between Groups	5.4234e+17	1	5.4234e+17	46.478	0.00242
Within Groups	4.6675e+16	4	1.1669e+16		
Total		5			
ANOVA: N_d of FRA mixture obtained from ANSYS					
Source of Variation	SS	df	MS	F	P-value
Between Groups	1.8628e+17	1	1.8628e+17	22.658	0.008905
Within Groups	3.2885e+16	4	8.2213e+15		
Total		5			
ANOVA: N_d of RMA mixture obtained from KENLAYER					
Source of Variation	SS	df	MS	F	P-value
Between Groups	5.4193e+17	1	5.4193e+17	38.946	0.00336
Within Groups	5.5660e+16	4	1.3915e+16		
Total		5			
ANOVA: N_d of RMA mixture obtained from ANSYS					
Source of Variation	SS	df	MS	F	P-value
Between Groups	1.7460e+17	1	1.7460e+17	19.05	0.01202
Within Groups	3.6662e+16	4	9.1655e+15		
Total		5			

4. Conclusions

This paper evaluated the influence of F-T cycles on the performance of AC pavements in terms of fatigue cracking and rutting. The study investigated the performance of two types of asphalt mixtures FRA and RMA mixtures. Based on the analysis results the following conclusions were drawn:

- The stiffness of the asphalt mixtures significantly decreased with the increase in the number of F-T cycles. Most of the reduction in stiffness occurred at the 150^{th} cycle.
- The correlation between the critical compressive and tensile strains and the increase in freeze- thaw cycles can be represented using an exponential function.
- Compressive strain at the top of the subgrade layer that is used to determine rutting or permanent deformation was found to be higher than the tensile strain at the bottom of the overlay asphalt layer.
- Generally, the FRA mixtures have higher fatigue and rutting lives as compared to the RMA mixtures.
- The rutting and fatigue lives predicted using the finite element model were found to be lower than the results obtained from KENLAYER.
- KENLAYER is a simple and more user-friendly approach to determine critical strain applied on pavement compared to the finite element analysis approach.

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CHAPTER 6

ANALYSIS OF THE EFFECT OF EXTREME HIGH TEMPERATURES ON THE BEHAVIOR OF ASPHALT CONCRETE PAVEMENTS

Parts of the Contents of this Chapter have been published in the Proceedings of the 9th European Nonlinear Dynamics Conference.

Abstract

The increase in temperatures around the globe due to climate change could potentially impact the performance of asphalt pavements. This paper presents a method to evaluate the nonlinear behavior of asphalt concrete pavements under high temperatures. Extreme high temperatures could significantly reduce the service life of flexible pavements, causing the pavement to exhibit permanent deformation or rutting. Although, most of the pavement analysis models assume linear behavior of pavement layers, however, the nonlinear behavior of pavements would be more accurate for analysis at high stress levels. To determine the nonlinear behavior of the asphalt pavements under the action of extreme heat, KENLAYER, a pavement analysis and design software, was used to analyze the responses of the pavements. The study outcomes revealed that as the heat increases, the compressive strain of the pavement increases and the pavement becomes more prone to permanent deformation. The study also showed that relying on historical climate data to design pavements, is no longer an effective approach, due to the recent temperature changes.

1. Introduction

The objective of this paper is to investigate the non-linear responses of flexible pavements under high temperatures. Flexible pavements are constructed of multiple bituminous layers. The top layer consists of asphalt concrete, followed by granular base and subgrade layers. Asphalt is a viscoelastic material that represents both linear and non-linear behaviors. The linear behavior of asphalt occurs at low stress levels, while at high stress asphalt exhibits non-linear behavior (Delgadillo et al. 2012). Most of the existing models for pavement analysis assume linear behavior of layers in asphalt concrete pavements to reduce the complexity of computations. However, previous studies showed that flexible pavements exhibit nonlinear behaviors (Hadi and Bodhinayake, 2003). Thus, it is essential to study the nonlinear responses of a flexible pavements to predict its performance with more accuracy.

Several factors can affect the performance of hot mix asphalt concrete pavements such as, the traffic loads, soil, environmental and climatic conditions. Several studies showed that the response of a pavement system is highly dependent on its temperature. Temperature of pavement surfaces can be affected by numerous factors, such as air temperature, precipitation, and speed of wind as well as solar radiation. Temperature data is important to determine the amount of stress acting on a pavement surface, as well as the calculation of deflection of the pavements (Wang and Roseler, 2014). Temperature is also a main contributor to multiple types of pavement distresses such as thermal cracking, fatigue cracking and rutting, resulting in a significant impact on the service life of pavements (MATIĆ et al. 2013).

High temperatures could substantially influence the properties of asphalt mixtures by increasing the rate of distress, thus reducing the stiffness of the asphalt layer. The reduction in asphalt stiffness increases the critical stresses applied on pavement layers and makes the pavement more exposed to deterioration, such as rutting. Rutting or permanent deformation is one of the most common types of pavement distress that influence the service life of pavements, particularly during warm climates (Hossain and Zaman, 2012). Rutting is also a critical issue as it can affect the safety of road users by increasing the potential of vehicle hydroplaning (Yu and Shen, 2014).

To study the impact of high temperatures on asphalt concrete pavements, a test section was constructed at Northern Arizona University in Flagstaff, Arizona. The weather in Flagstaff varies significantly along the year. The temperature during the winter season is as low as -10ºC, while the average temperature in the summer is approximately 25 ºC. The pavement is made of an 0.5" (1.27 cm) overlay layer using rubberized modified asphalt mixtures (RMA), followed by 10 inches (25.4 cm) of asphalt concrete base layer, 10 inches (25.4 cm) of aggregate subbase layer, and a subgrade layer, as the cross-sectional view of the pavement structure is illustrated in Figure 1. This section was used to analyze the performance of asphalt concrete pavements under different temperatures.

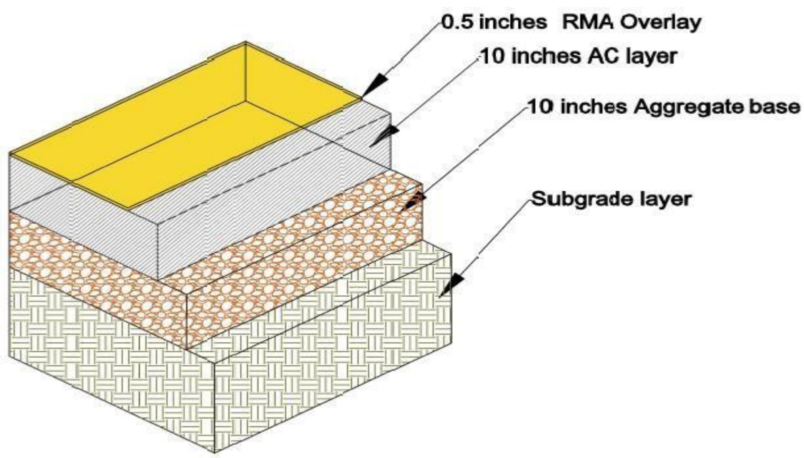

Figure 1. The pavement structure

2. Methodology

2.1 Climate Data

Historical climate data of the state of Arizona was obtained from UA Spatial Data Explorer Geoportal (2018). The annual mean maximum daily temperature and the annual mean number of days in which temperature exceed 90ºF (32°C) between the years of 1961 and 1990 are analyzed using geographic information system (GIS). The distributions of annual mean maximum temperature and annual mean number of days across the state of Arizona are shown in Figure 2 and Figure 3. The annual maximum daily temperature in Arizona ranged from 60 ºF (15°C) to higher than 85 ºF (30°C). During the years of 1961 to 1990, the city of Flagstaff had a mean of maximum daily temperature of approximately 18°C, with around 15 days each year in which the temperature exceeded 32°C.

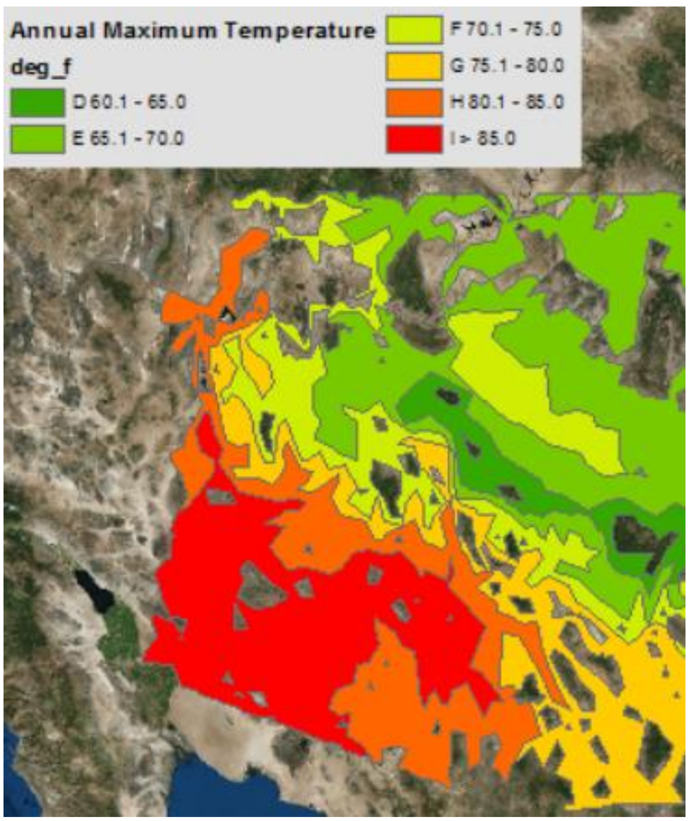

Figure 2. Annual mean maximum daily temperature

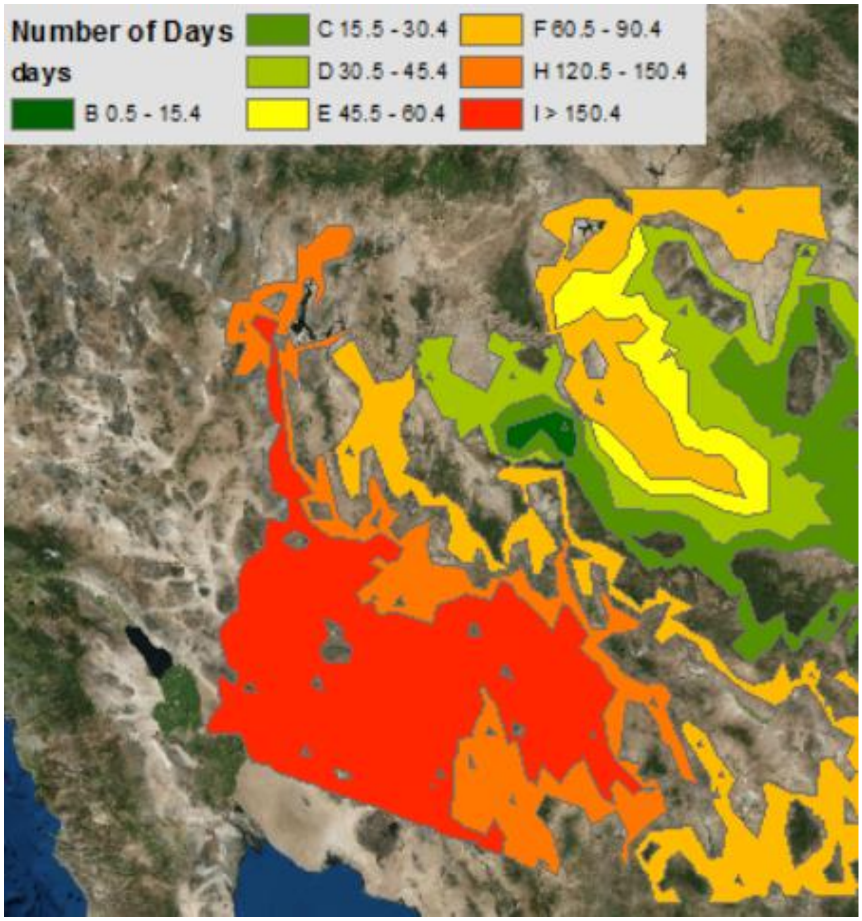

Figure 3. Annual mean number of days when temperature exceeded 32°C

Moreover, the average annual air temperature in the City of Flagstaff was analyzed to understand the changes in temperature during the last 20 years. Figures 4 and 5 represent the average annual air temperature and the maximum annual temperature values, respectively. The temperatures were recorded during a 20-year period (1997 -2017), as the design life for most asphalt concrete pavements is 20 years. Based on the data, it can be noted that temperatures tended to increase during the last few years of the study period.

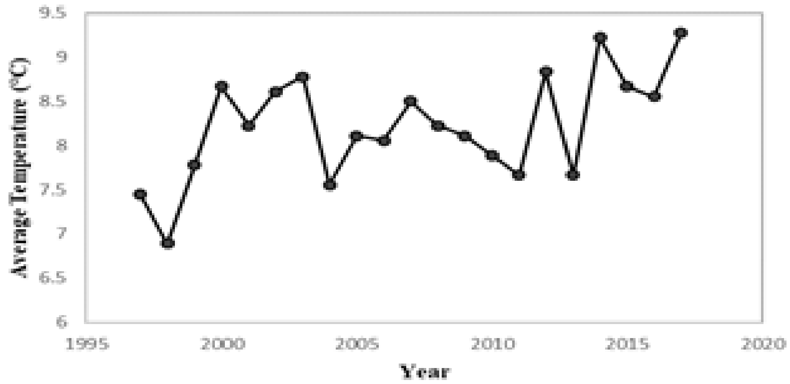

Figure 4. Average annual air temperature

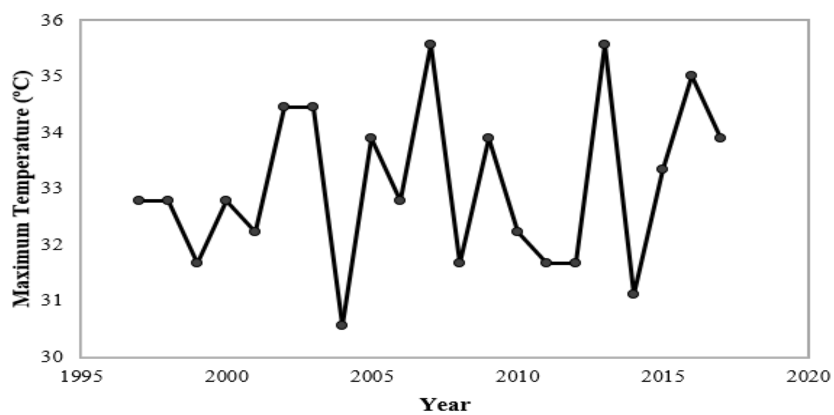

Figure 5. Maximum annual air temperature

2.2 Prediction of Pavement Temperature

The temperature of the pavement was predicted based on the Strategic Highway Research Program (SHRP) method (Ho and Romero, 2009) as shown in Equation 1:

$$T_{pav} = T_{air} + 0.051D - 0.000063\ D^2 \qquad (1)$$

Where:

T_{pav} = Pavement temperature at calculated depth, °C

T_{air} = air temperature, °C

D =Depth, mm

The pavement performance was evaluated at four different air temperatures: 21 ºC, 26 ºC, 31 ºC and 35ºC. These temperatures were selected based on the maximum annual air temperature in Flagstaff. To conduct the analysis, the temperature at the overlay layer and the aggregate base layer were obtained. The pavement response was evaluated at a depth of 20.5 inches, where the critical compressive strain is located. The calculated pavement temperatures obtained from the SHRP model were used in KENLAYER software to analyze the influence of temperature variations on asphalt concrete pavements by determining the compressive strain values at different temperatures.

2.3 Bending Beam Rheometer (BBR) Testing

Bending Beam Rheometer (BBR) tests were performed to obtain the stiffness and creep compliances of the asphalt mixture under different temperatures. The BBR testing procedure was based on AASHTO TP 125-16 standard for determining the Flexural Creep Stiffness of Asphalt Mixture Beams Using the Bending Beam Rheometer (AASHTO, 2016), with modifications to be able to test stiffness values of asphalt thin beams (Ho and Romero, 2011 and 2012). Thin beams of the rubberized modified asphalt (RMA) mixture were tested at three different temperatures: -12˚C, -18˚C, and -24˚C. The test was conducted by applying constant load on asphalt specimens, where the deflection was recorded as a function of time. Then, stiffness values were obtained at 60 seconds and used for the analysis. The BBR tests showed that the stiffness of the asphalt mixture decreased as the testing temperature increased. As shown in Figure 6, the average elastic modulus values for asphalt specimens at a testing temperature of -24ºC is equal to 2.6×10^6 PSI, while at -12ºC the average elastic modulus was reduced to approximately 1.4×10^6 PSI.

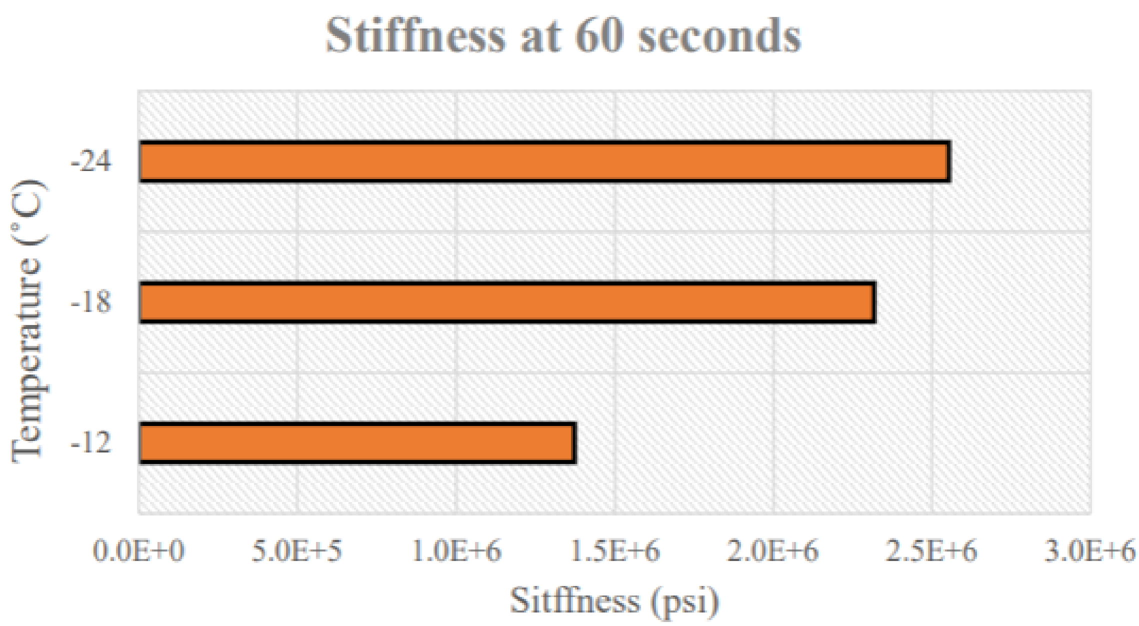

Figure 6. Stiffness of asphalt mixture at different temperatures using BBR tests

2.4 Modeling the Non-linear Behavior of the Pavement

After obtaining the stiffness and creep compliances values from the BBR tests, KENLAYER was used to evaluate the viscoelastic performance of the asphalt mixture including its non-linear behaviors. KENLAYER is a pavement design and analysis software for flexible pavements. The model can be used to compute the critical strains at the bottom of asphalt layer and top of subgrade layer. Granular materials have nonlinear resilient behavior that increases with the increase in critical stresses. The results obtained for the modulus of critical strains from the software can be reasonably compared with finite element analysis models. The procedure used in KENLAYER to generate nonlinear analysis consists mainly of the following four steps:

- First, the characteristics of the structure of the pavement were entered along with the nonlinear model characteristics.
- Granular layers were divided into number of sub-layers, where the stress was chosen to be at the middle depth of the layer.

- The modulus of elasticity for each layer was determined at the middle of the layers.
- The material properties of the pavement structure were entered in KENLAYER, as illustrated in Table 2. Finally, nonlinear modelling was performed, and pavement responses were analyzed.

Table 1. Material properties of the pavement structure

Layer Number	Material	Thickness (in)	Poisson ratio (υ)	Elastic Modulus (psi)
[1]	AC Overlay	0.5	0.3	2000000
[2]	AC Base	10	0.3	50000
[3]	Aggregate base	10	0.4	5000
[4]	Subgrade soil	-	0.45	5918

3. Results and Discussion

3.1 The Influence of Temperature Increase on Asphalt Stiffness

To determine the impact of temperature increase on the strength of the asphalt mixture, the stiffness values were graphed against air temperature, as shown in Figure 7. It is noticed that high temperatures have a negative impact on the stiffness of asphalt mixtures. As the temperature increases, the stiffness values decrease. The relationship between the air temperature and the stiffness can be represented using a power function with a correlation factor of 0.9946.

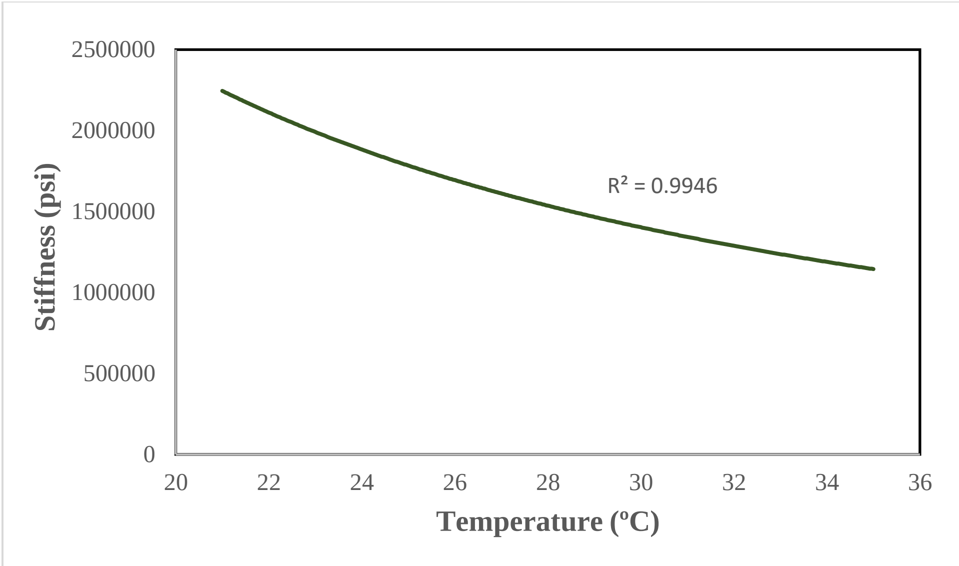

Figure 7. Elastic Modulus of Asphalt versus Temperature

3.2 The Effect of Temperature Increase on Compressive Strain

The values of compressive strain on the top of the subgrade layer at different elastic modulus values were determined using KENLAYER. The relationship between compressive strain and temperature is illustrated in Figure 8. As shown in Figure 8, the compressive strain increased with the increase in temperature. As mentioned previously, the compressive strain at the top of the subgrade layer affects rutting distress along the pavement surface. The relationship between compressive stress and temperature variations can be represented using an exponential function.

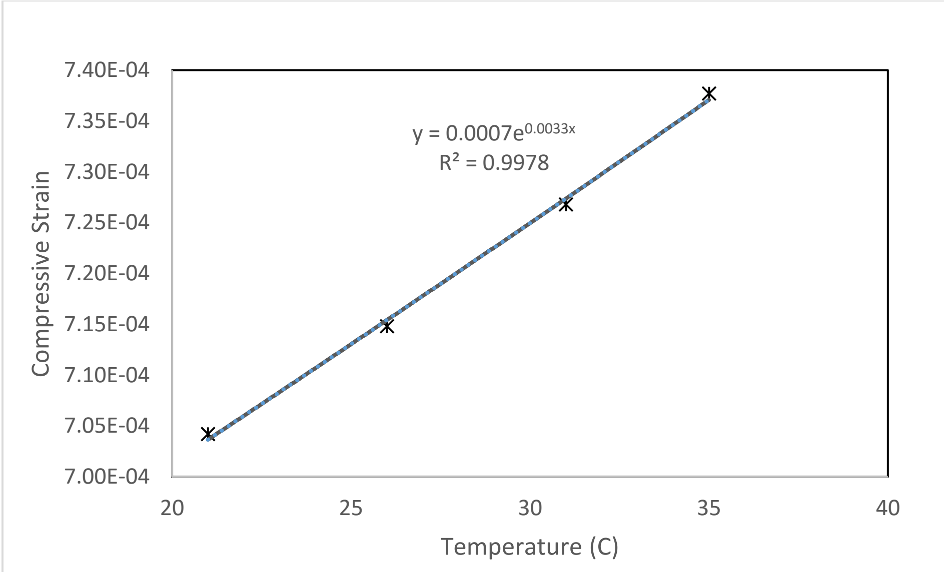

Figure 8. Effect of temperature on compressive strain

3.3 Statistical Analysis: Influence of Temperature Variations on Compressive Strain

The significance of the relationship between compressive strain and temperature variations was evaluated using R statistical analysis and the one-way ANOVA approach. The null hypothesis is that there is no relationship between compressive strain and temperature. Through R and ANOVA analyses, the results are summarized in Table 2.

Table 2. Statistical Analysis for temperature variations and tangential strain

	df	Sum of squares	Mean Squares	F-value	p-value
Compressive Strain	1	1323.4	1323.4	14.324	0.005352
Residuals	8	738.1	92.39		

As illustrated in Table 2, the p-value obtained for the relationship between temperature variations and compressive strain is approximately 0.005, which is a very significant value. Therefore, the hypothesis is rejected and it can be concluded that there is a substantial relationship between the increase in temperature and the amount of compressive strain exerted on the soil layer.

3.4 Influence of Temperature variations on the lifecycle of pavement

Pavement damage due to rutting depends on the compressive strain obtained from the analysis. The rutting lifecycles of the pavement structure were modeled using Equation 2:

$$N_d = f_4 \, (\varepsilon c)^{-f5} \qquad (2)$$

Where:

N_d is the allowable number of load repetitions to prevent rutting cracking. f_4 and f_5 are constants that are determined from road tests

After the calculation of the rutting lives for the pavement section using the model, N_d values were plotted against different temperature values, as illustrated in Figure 9.

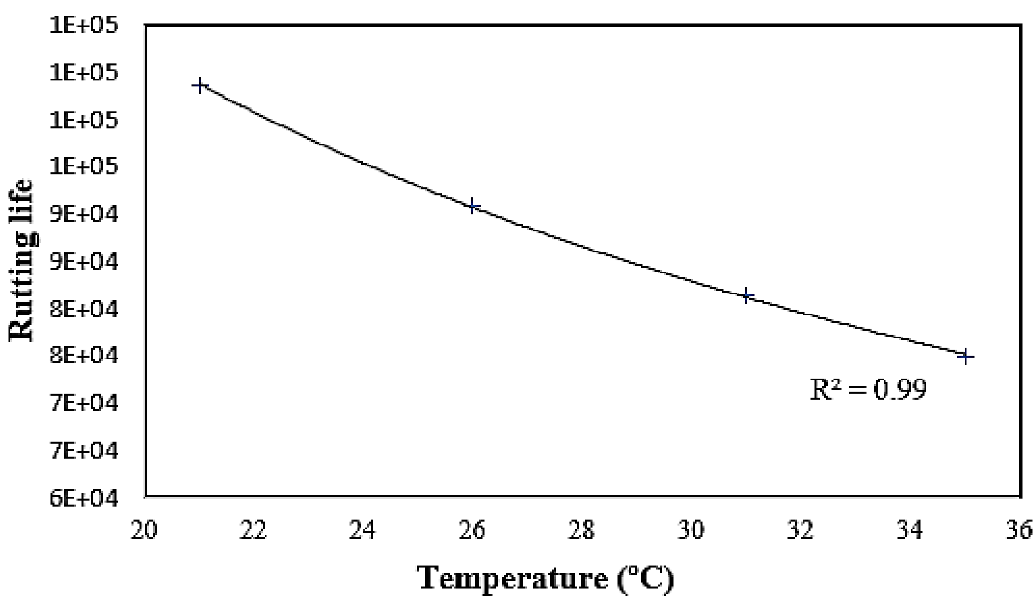

Figure 9. Rutting Life versus Temperature

As shown in Figure 9, the increase in temperature lead to a large reduction in the rutting life of the section. Most of the reduction occurred at temperature values of higher than 24 ºC. The correlation between the increase in temperature and the reduction in rutting can be represented by a power function.

4. Conclusions

This paper presents a method to characterize the influence of the increase in temperature due to global warming on the performance of asphalt concrete pavements by evaluating the nonlinear response of an asphalt pavements at different temperatures. The research work was done by conducting lab experiments followed by software analysis and statistical analysis. Based on the study, the following conclusions are presented:

- The increase in temperature reduces the stiffness of the asphalt mixtures.
- There is a direct correlation between the temperature increase and the compressive strain of the asphalt mixtures.
- The relationship between temperature and compressive strain can be expressed by an exponential function.
- The increase in temperature could significantly influence the performance of asphalt concrete pavements by increasing the rate of permanent deformation which eventually leads to pavement failure.
- It is important to consider the effect of temperature variations when designing a pavement structure to maximize service life of pavements.
- Using recent climate prediction models in designing pavement infrastructures, could potentially improve the life cycles of the pavements in the future.

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CHAPTER 7

EVALUATING THE EFFECT OF SOLAR RADIATIONS ON THE PERFORMANCE OF ASPHALT CONCRETE PAVEMENTS

Parts of the contents of this has been accepted for publication in the Sustainable Civil Infrastructure Series by Springer

Abstract

In recent years, severe weather events have impacted the performance of transportation infrastructures. The increase in temperature and heatwaves, lead to the early deterioration of pavement structures. The purpose of this paper is to study the effect of solar radiations on the behavior of flexible pavements. A project was implemented in Flagstaff, Arizona, to evaluate the impact of solar radiations on asphalt concrete pavements. The analysis was performed using similar road sections with shaded and unshaded areas. A three-dimensional model of the study area was built using MicroStation, to generate solar analysis study using specified time periods. To validate the numerical analysis, field visits were conducted to measure pavement surface temperatures, and evaluate distress types along pavement surfaces for areas with solar exposure and areas without sun exposure. Bending Beam Rheometer (BBR) tests were performed to determine the stiffness of the asphalt mixtures. ANSYS, a finite element analysis software, was used to analyze the critical tensile and compressive strains exerted on the pavement. According to the results, pavement sections exposed to solar radiations, experience a significantly higher level of critical tensile and compressive strains compared to shaded pavement areas. Based on test findings and analysis results, the paper concluded that solar radiations lead to the early deterioration of asphalt pavements by increasing fatigue distress and rutting.

1. Introduction

Urban Heat Islands (UHI) describes areas that are significantly warmer than nearby rural areas. Roads and pavements cover a significant percentage of urban surfaces; as a result, paved roads are considered one of the main contributors to urban heat islands (Yang et al. 2016). Pavement surfaces cause urban heat islands due to their low solar reflectance and high heat storage capacity (Chen et al. 2017). The high thermal capacity of pavements, allow them to absorb huge amount of solar energy, causing high temperatures along the surface (Wan et al. 2012). High temperatures could significantly shorten service life of pavement by increasing the rate of distress. As the temperature rises, asphalt binders are degraded by volatilization and oxidation, resulting in a rapid hardening of the pavement, which leads to the formation of cracks and severe damage to the surface (McPherson and Muchnick, 2005).

Previous research showed that Ultraviolet radiations affect the upper layer of asphalt pavements and progresses the aging of the pavement, by influencing the low temperature ductility and resistance of cracks characteristics of asphalt binders and mixtures. Thus, it is essential to consider not only the effect of thermal stress on asphalt mixtures due to solar radiations but also the UV radiations effect as well. To mitigate the effect of solar radiations on asphalt pavements, researchers used carbon black and layered double hydroxide modifiers. These modifiers reduce the impacts of solar radiations by reflecting and absorbing the UV radiations, resulting in an improvement in the UV ageing resistance characteristics (Hu, 2017).

In recent times, modeling solar radiations is becoming more common, particularly due to the increase in unpredicted weather events. Modeling solar radiations can be performed using different techniques and computer programs, which includes geospatial data methods such as

ArcGIS software, weather generators tools or global solar radiation tools that are based on deterministic or stochastic methods (Donatelli, 2006). In this paper, solar radiations were estimated using MicroStation Software. MicroStation is a modeling, documentation and visualization software that can be used for two dimensional and three-dimensional designs. Solar radiation analysis in MicroStation can be performed over a user-defined period. Moreover, the software is capable of creating animations of solar studies from day to night, taking into account solar intensity and shadowing effects.

Fatigue cracking due to repeated traffic loads and rutting are two major modes of failure in asphalt pavements. Both types of pavement distresses occur mainly due to the applied traffic load and environmental conditions (Gogoi et al. 2013). The exposure of asphalt to solar radiations simulates the atmospheric degradation process of asphalt binders, resulting in the occurrence of fatigue cracking (Lins et al. 2008). Fatigue distress affects the strength and stiffness properties of asphalt mixtures (Jiangmiao and Guilian, 2013). In addition, fatigue loading could lead to a reduction in the pavement service life, by allowing moisture to infiltrate through the cracks, resulting in large potholes (Gao et al. 2012). Rutting or permanent deformation can also influence the service life of asphalt pavements, especially during warm climates (Hossain and Zaman, 2012). High temperatures increase fatigue cracking and rutting along the pavement surface, by influencing the elastic modulus of the top asphalt layer. Previous studies showed that temperature and elastic modulus of asphalt are inversely proportional. As the temperature increases, the elastic modulus of asphalt layer decreases (Behiry, 2012). The reduction in the modulus or strength of asphalt increases the critical strain and shear stress exerted on the pavement, which makes the pavement surface more prone to deformation (Xiaodi et al. 2017).

The objective of this study is to investigate the influence of solar radiations and high temperatures on the performance of flexible pavements. The major concern of the study is to evaluate the effect of solar radiations on the intensity of fatigue cracking and rutting along asphalt concrete pavement surfaces. A three-dimensional model of the study area was created in MicroStation Software to simulate real world conditions in terms of shaded and unshaded areas. Bending Beam Rheometer tests were conducted to determine the creep compliance and stiffness values of the asphalt mixture used in the study. Finite element analysis was performed to determine the critical stresses exerted on the pavement surface at different temperatures. Fatigue and rutting lives were predicted based on the calculated critical stresses and strains.

2. Methodology

2.1 Study Area

In the study, six different road sections were used to evaluate the influence of solar radiations on asphalt concrete pavements. The study area is located at downtown Flagstaff, Arizona. The city of Flagstaff is located at an elevation of approximately 7000 feet, above the sea level. The climate is characterized by very dry, hot summers, and cold, snowy winters. The average temperature in Flagstaff is around 43.8°F. The temperature in the summer gets as high as 80°F. While, winter temperatures usually fall below 20°F. Due to the high elevation of the city, temperature varies significantly during the day and night (Climate Flagstaff, 2017). Thus, making it a suitable place to study the effect of temperature variations and solar radiations on pavement structures. The road sections were chosen to have the same geometric properties, layered pavement systems, and approximately equal average daily traffic. The shading of pavements in the study area is mainly due to the surrounding buildings.

2.2 Solar Radiation Modeling

A knowledge of the intensity of solar radiations received by pavement surfaces is essential to evaluate the influence of solar energy on pavement performance. To predict solar radiations absorbed by pavement, a three-dimensional model of the study area was built, based on the existing geometric features using MicroStation Software, as illustrated in Figures 1 and 2. The advantages of using MicroStation for modeling purposes include its ability to generate solar analysis studies and shadowing effects based on the existing features of the study area. The software also provides animation tools to create images of shadow locations over specified period of time. Moreover, the solar animation in MicroStation includes the color and intensity of solar lightning.

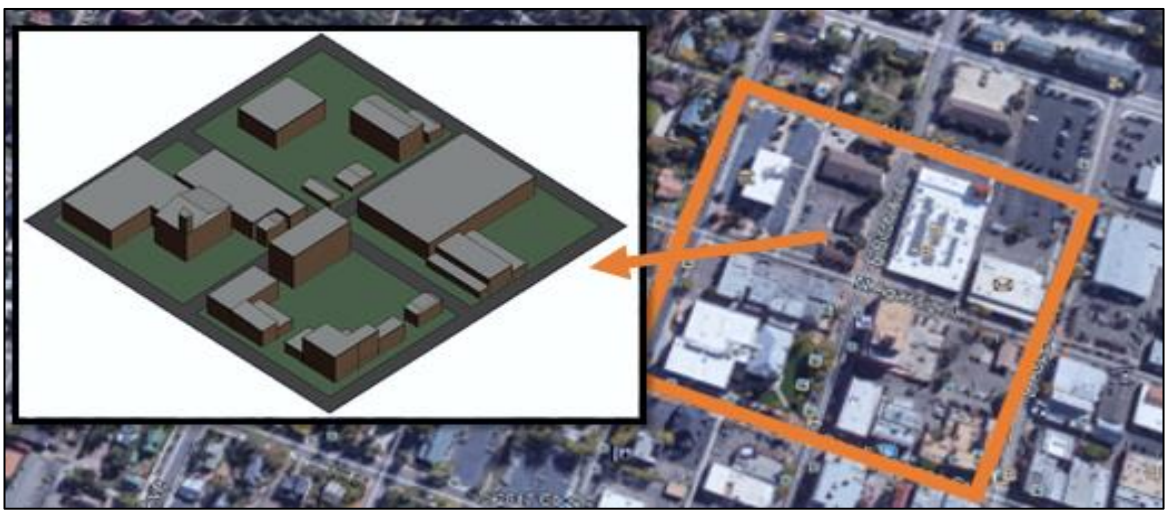


Figure 1. 3D view of the MicroStation Software Model

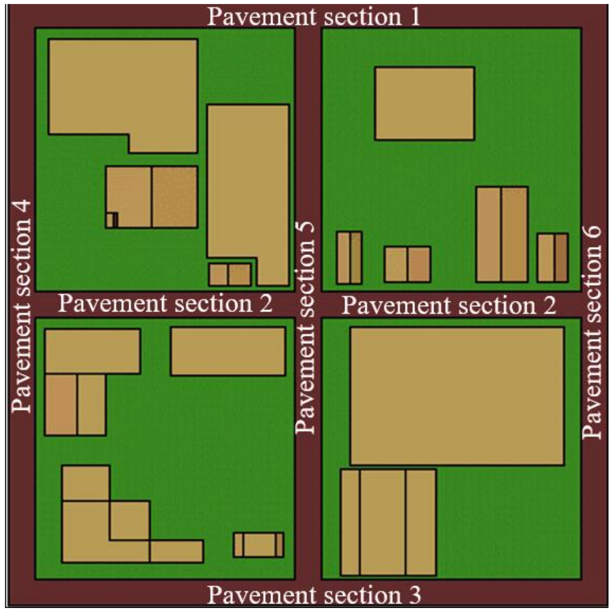


Figure 2. Top view of the MicroStation Software Model

A solar analysis study was generated for the model, using MicroStation. The study was done based on the exposure time of the pavement to solar radiations for a period of 24 hours. A solar intensity of 1000 watts per square meters was used for the analysis. The results of the solar analysis study are presented in Figures 3 and 4. Figure 3 represents the amount of time, for which the model is exposed to solar radiations in a 1-day period. The difference in the amount of solar radiations received by pavement is due to the shadows produced by the surrounding buildings. Pavement sections covered by the shadow of buildings, received less solar radiations than sections exposed to sunlight. The amount of time in which pavement surfaces were exposed to solar radiations varied between 5 and 13 hours daily. Figure 4 illustrates the amount of solar radiation received by pavement in kilowatt-hours per square meters. Pavement surfaces received solar radiations between 2.9 and 7.4 KWh /m^2.

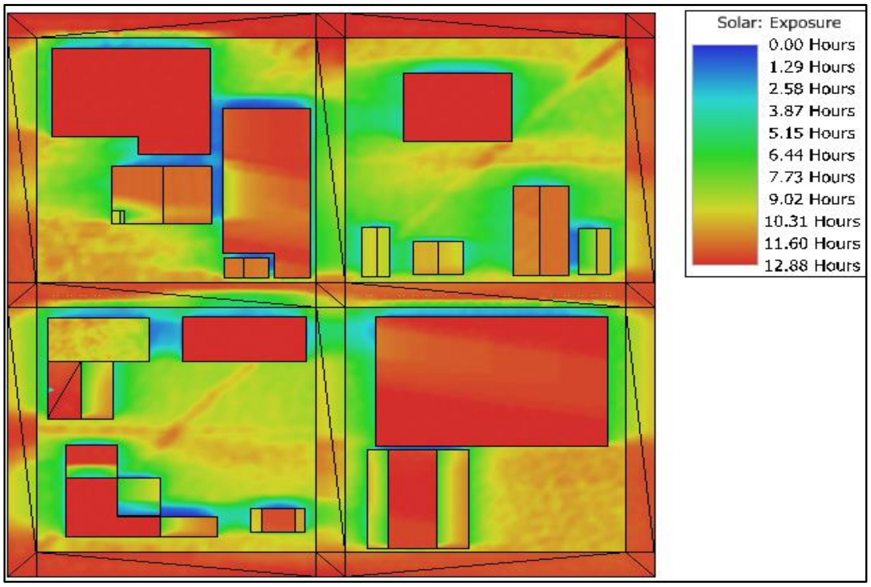


Figure 3. Amount of solar exposure received by pavement surface

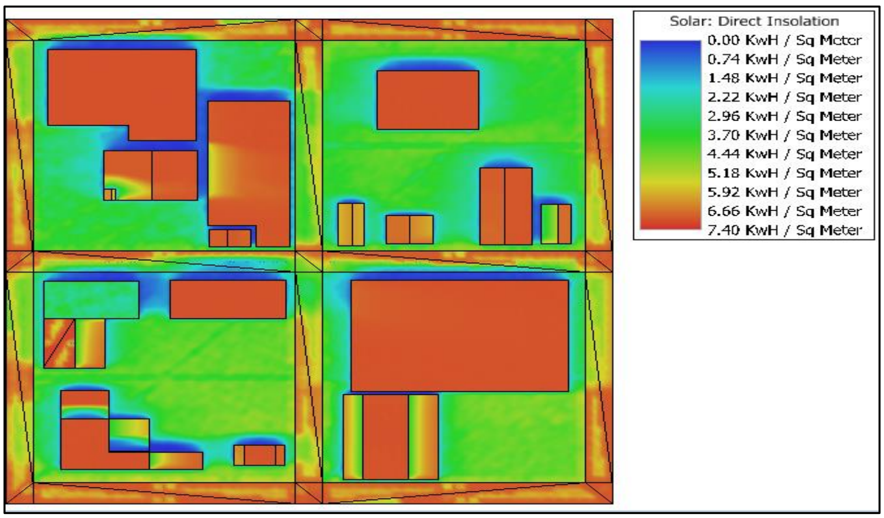


Figure 4. Amount of solar radiation received by pavement surface

2.3 Field Data

Field visits were conducted to validate the software simulation results and to collect temperature data. It was observed that pavement surfaces exposed to sunlight have relatively more distress than shadowed pavement sections. Two main types of pavement distress were found: fatigue and thermal cracking. Pavement surface temperatures were measured using a thermal gun for the same day chosen to simulate solar radiation analysis in MicroStation. The highest pavement surface temperature recorded was 140°F, and it was measured at noon. The average measured temperature of shaded pavement sections is equal to 80°F. While, the average temperature of pavement surfaces exposed to sun is equal to 130°F. The temperatures at the depth of asphalt pavement were determined based on Equation 1 (Ho and Romero, 2009).

$$T_{Pav} \times 0.859 + (0.002 - 0.0007 \times T_{air}) \times D + 0.17 \qquad (1)$$

Where:

T_{pav} = temperature of pavement at calculated depth (°C),

T_{air} = low air temperature (°C), and

D = depth (mm).

2.4 Bending Beam Rheometer Testing

Bending Beam Rheometer (BBR) tests were performed at temperatures of 12˚C, -18˚C, and -24˚C to determine creep compliances and stiffness values of the asphalt mixture used in the pavement test sections. The procedures used in BBR tests are based on the American Association of State Highway and Transportation Officials standard T313 for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (AASHTO, 2009). Modifications were performed to test the creep compliances and stiffness values for the thin asphalt beams (Ho and Romero, 2011 and 2012). A BBR test is performed by applying a constant load on an asphalt beam, and measuring its corresponding deflection as a function of time. The BBR test measures the deflection of the beam at a time increment of 0.5 seconds. The stiffness values of the asphalt mixture at 60 seconds were used to determine the critical strains exerted on pavement layers.

2.5 Prediction of Stiffness Properties of Asphalt Mixtures at Different Temperatures

Stiffness of asphalt concrete mixtures is influenced by pavement surface temperature. Thus, the stiffness of asphalt pavement under shaded and unshaded areas are different. The LTPP Guide to Asphalt Temperature Prediction and Correction was used to estimate the value of elastic modulus at different pavement surface temperatures (Predictions, 2000). The modulus of the asphalt layer was adjusted for different temperatures using the following model:

$$ATAF = 10^{\text{slope}\,(Tr - Tm)} \tag{2}$$

Where:

ATAF: calculation adjustment factor.

Slope: depends on the characteristics of the mix design including binder and aggregate properties. A default value of -0.021 was used to estimate the stiffness.

T_r: reference temperature, in Celsius.

T_m: measured temperature, in Celsius.

The estimated elastic modulus values for the asphalt layer were used along with the pavement structure properties in the finite element model to predict the tensile and compressive strains acting on the pavement layers. Tensile strain (ε_t) occurs at the bottom of the asphalt layer, and compressive strain (ε_c) occurs at the top of subgrade layer. Excessive tensile strain (ε_t) could result in pavement failure by increasing fatigue cracking. While, excessive compressive strain (ε_c) causes permanent deformation of the pavement surface due to rutting (Behiry, 2012).

2.6 Finite Element Analysis

A three-dimensional model was developed using ANSYS, a finite element software. Finite element analysis was performed to predict critical tensile strain at the bottom of the asphalt layer and compressive strain at the top of the subgrade layer, for different temperatures. To model the pavement structure, geometric properties, materials, mesh, and boundary conditions were assigned. The pavement structure consists of three layers: top asphalt concrete layer, gravel base layer, and subgrade layer with thicknesses of 14 cm, 16 cm, and 40 cm, respectively, as illustrated in Figure 5. The structural layer properties of the model are presented in Table 1. The model was meshed using 6176 nodes and 900 elements. Elastic materials were used in the finite element analysis model. The boundary conditions were assigned by using horizontal and vertical constraints at the subgrade soil. The top two layers were modeled by restricting the displacement in all directions, except the vertical component. The responses of the pavement were evaluated by applying a tire pressure of 80 psi at the top layer.

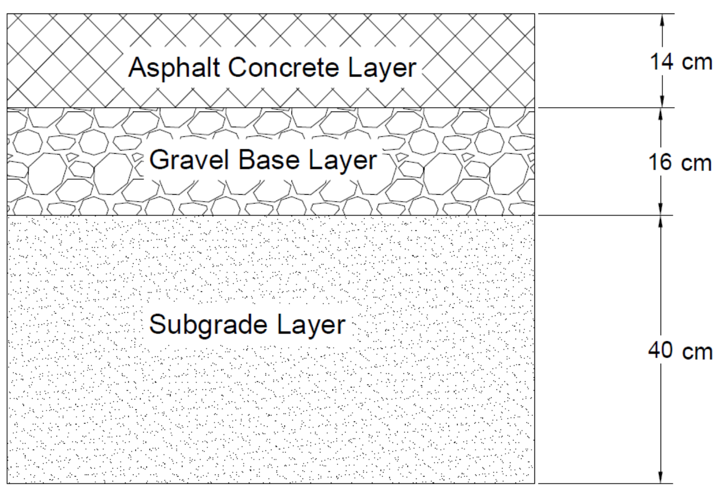


Figure 5. The pavement structure

Table 1. Parameters of the layers of pavement structure

Layer Name	Pavement Thickness (cm)	Young's Modulus/ Stiffness (MPa)	Poisson's Ratio	Bulk Modulus (MPa)	Shear Modulus (MPa)
AC Layer	14	526-2635	0.35	584-2928	195-976
Base layer	16	345	0.25	230	138
Subgrade	40	34.5	0.38	48	12.5

2.7 Pavement Damage Analysis: Fatigue Distress and Rutting

The following models were used to predict the number of load repetitions to prevent fatigue and rutting, based on the estimated elastic modulus values of asphalt and the critical strains acting on pavement.

2.7.1 Fatigue model

Fatigue damage was predicted using the following criteria:

$$N_f = f_1(\varepsilon_t)^{-f2} (E_1)^{-f3} \quad (3)$$

where:

N_f: is the allowable number of load repetitions to prevent fatigue cracking.

f_1, f_2, and f_3: are constants obtained from fatigue tests.

E_1: represents the stiffness of the asphalt overlay layer.

2.7.2 Rutting model

Damage due to rutting can be expressed as follows:

$$N_d = f_4 (\varepsilon_c)^{-f5} \quad (4)$$

where:

N_d: is the allowable number of load repetitions to prevent rutting.

f_4 and f_5 : are constants that are determined from road tests.

The values used for the road tests coefficients: f_1, f_2, f_3, f_4 and f_5 were determined based on the asphalt institute method specifications (Huang, 2004), and are summarized in Table 2.

Table 2. Road test coefficients of fatigue life and rutting life models

Road test coefficient	F_1	F_2	F_3	F_4	F_5
Value	0.0796	3.291	0.854	1.365×10^{-9}	0.0796

3. Results and Discussion

3.1 Influence of Solar radiations on the Stiffness of Asphalt

To determine the influence of solar radiations on the stiffness or the strength of the asphalt mixture, the elastic modulus values were graphed against pavement surface temperatures. The relationship between solar radiations and stiffness of asphalt layer was found to be inversely proportional, as shown in Figure 6. Pavement sections with higher solar exposure had a lower elastic modulus values compared to shaded sections. The elastic modulus of the asphalt layer at a pavement surface temperature of 140°F was lower than the stiffness at 80°F by 80%. The significant reduction in the asphalt stiffness due to the increase in temperature is critical as it increases the critical stresses applied on the pavement, resulting in a reduction in the overall lifespan of the pavement structure.

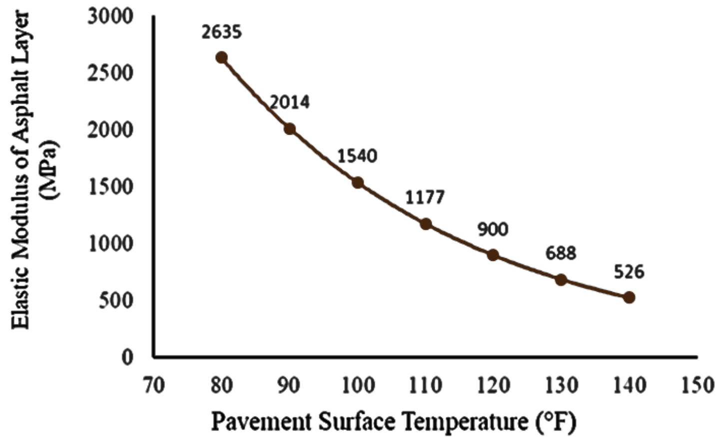


Figure 6. Elastic modulus of asphalt layer versus temperature variations

3.2 Effect of Solar Radiations on Critical Strains

The results of ANSYS analysis of determining the tensile and compressive strains applied on the pavement structure are shown in Figures 7 and 8. Based on the results, the maximum tensile and compressive strains occur at the bottom subgrade layer. To evaluate the influence of solar radiation on the critical strains exerted on asphalt pavement surface, critical strains were plotted against field-measured temperatures, as illustrated in Figures 9 and 10. Tensile and compressive strains significantly increase with the increase in pavement temperature. The high correlation coefficient observed in the graphs indicates that the relationship between critical strain and the increase in temperature is significant and can be expressed using an exponential function. The results also show that the tensile strain at the bottom of the asphalt layer was higher than the compressive strain at the top of the subgrade layer.

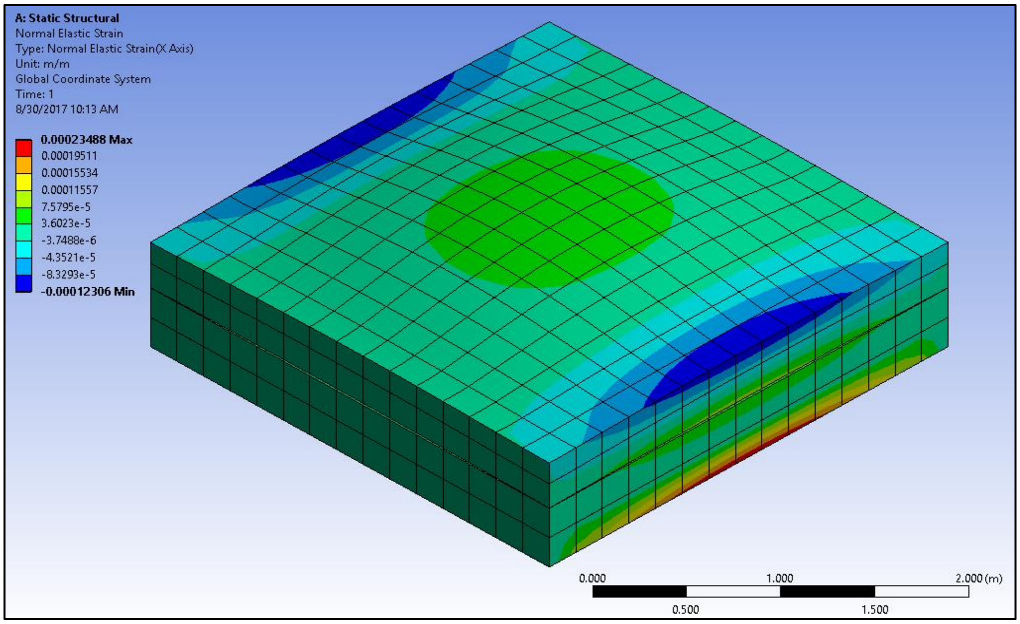


Figure 7. Tensile strain applied on pavement structure

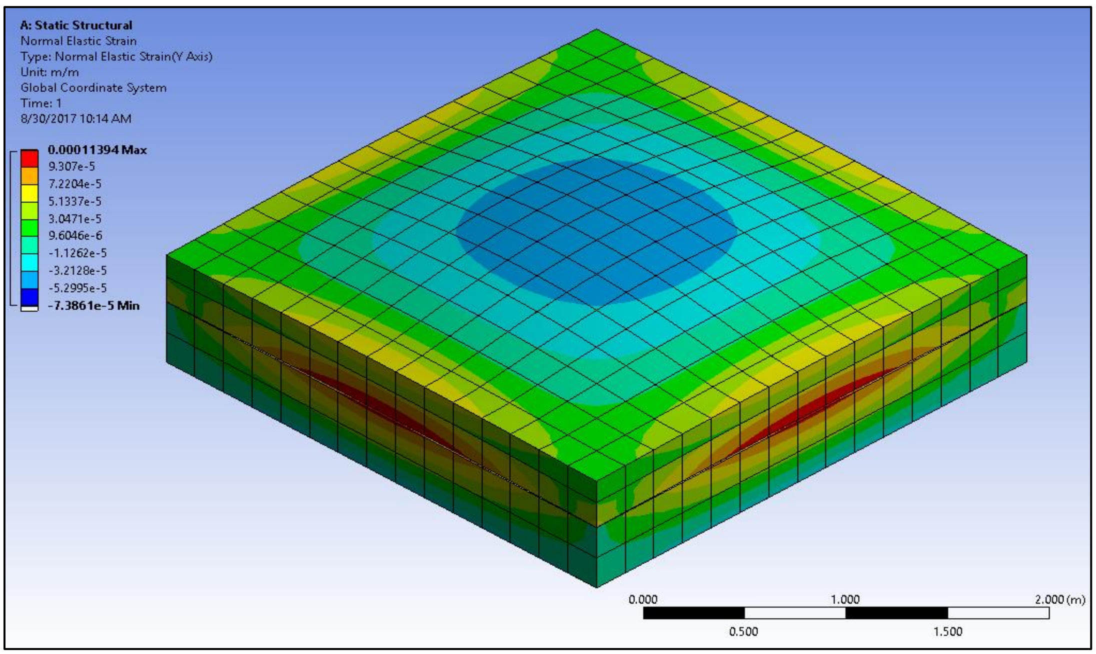
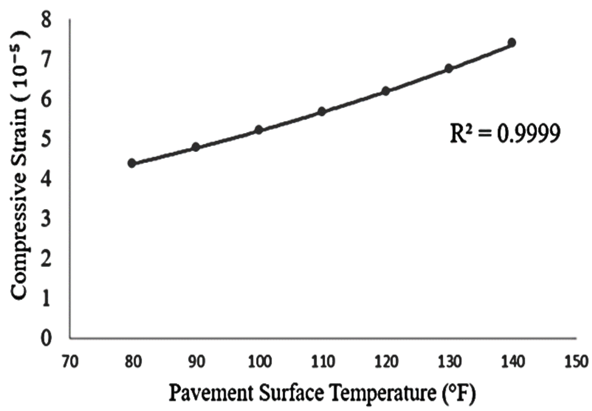


Figure 8. Compressive strain applied on pavement structure



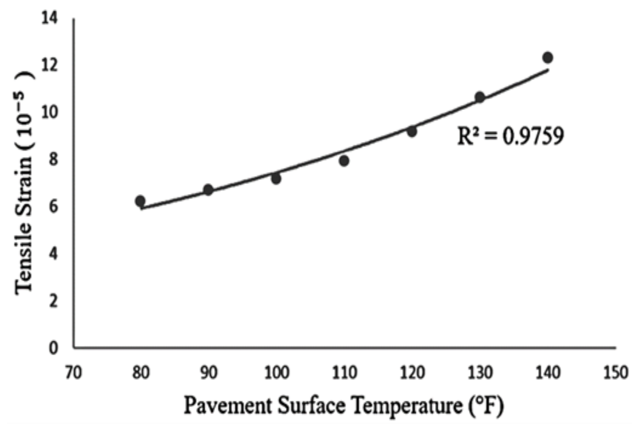


Figure 9. Compressive strain versus temperature **Figure 10. Tensile strain versus temperature**

3.3 Effect of Solar Radiations on Fatigue Distress and Rutting

To evaluate the effect of solar radiations on pavement distress, the number of allowed load repetitions to prevent fatigue cracking and rutting were graphed against different pavement surface temperatures, as shown in Figures 11 and 12. The results show that fatigue life is shorter than rutting life. Thus, it can be concluded that fatigue cracking is the controlling parameter of the pavement structure failure. The relationship between fatigue life and the increase in temperature can be represented by a logarithmic function. While, the correlation between rutting life and temperature can be expressed by an exponential function. Based on the results, solar radiations could lead to a substantial reduction in rutting and fatigue lives. Pavement sections exposed to solar radiations are expected to have more than 50% shorter fatigue and rutting lives, compared to areas with no solar exposure. Moreover, the fatigue life of pavement sections at shaded regions is predicted to be higher than areas with sun exposure by 66%.

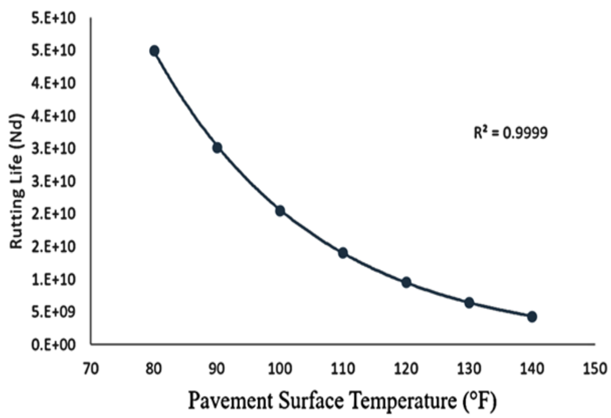


Figure 11. Rutting Life versus temperature

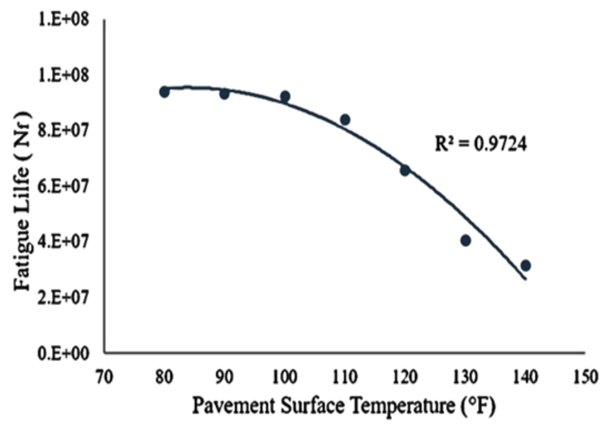


Figure 12. Fatigue Life versus temperature

3.4 Statistical Analysis

3.4.1 The Influence of Solar Radiations on the Stiffness of Asphalt Layers

To determine the statistical significance of the relationship between solar radiations and the elastic modulus of the asphalt layer, a t-test was performed. The results of the t-test showed a t-statistic value of - 4 and t-critical value of 2. Since, the magnitude of t-statistic is higher than t-critical, the null hypothesis can be rejected and it can be concluded that there is a significant relationship between solar radiations and stiffness of asphalt layers. In addition, this conclusion can be validated by observing the p-values. Both the one-tail and two-tails p-values are lower than 0.05, as a result it can be concluded that the effect of solar radiations on the elastic modulus of asphalt layer is significant.

3.4.2 The Relationship between Solar Radiations, Fatigue, and Rutting Lives

A one-way analysis of variances (ANOVA) approach was performed to determine the statistical significance of the relationship between solar radiations and the expected fatigue and rutting lives. The results of the statistical analysis are summarized in Tables 3 and 4. The statistical P-values calculated for the influence of pavement surface temperature on fatigue and rutting lives are 0.00192 and 0.00101, respectively. Based on the P-values obtained from the statistical analysis, it can be concluded that the increase in pavement surface temperature has a significant impact on fatigue and rutting lives.

Table 3. ANOVA analysis of the relationship between temperature and fatigue life

Source of Variation	Degrees of freedom	Sum Squares	Mean square	F-value	P-value
Between Groups	1	3.64×10^{15}	3.64×10^{15}	35.4	0.00192
Within Groups	5	5.15×10^{14}	1.03×10^{14}		

Table 4. ANOVA analysis of the relationship between temperature and rutting life

Source of Variation	Degrees of freedom	Sum Squares	Mean square	F-value	P-value
Between Groups	1	1.16×10^{21}	1.16×10^{21}	46.8	0.00101
Within Groups	5	1.24×10^{20}	2.48×10^{19}		

4. Conclusions

This study evaluated the effect of solar radiations on the performance of asphalt concrete pavements through laboratory tests and finite element analysis methods. Based on the results obtained from the study, the followings can be concluded:

- The elastic modulus of the top asphalt layer significantly decreases as pavement surface temperature increases.
- The relationship between tensile and compressive strains and the increase in pavement surface temperature can be represented by an exponential function.
- The maximum tensile and compressive strains occur at the bottom subgrade layer.
- The relationship between the increase in temperature and fatigue and rutting lives can be expressed using logarithmic and exponential functions, respectively.
- Solar radiations have negative effects on the life cycles of asphalt pavements. Pavement

sections exposed to solar radiations had a dramatically lower fatigue and rutting lives, compared to pavement sections at shaded regions.

- Considering the intensity of solar radiations received by pavement surfaces is essential to maximize the life span of pavement structures.

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CHAPTER 8

SUMMARY AND CONCLUSIONS

In this thesis, the effects of different climate conditions on the performance of asphalt concrete pavements were evaluated using laboratory tests, numerical analysis and software simulations. In chapters 2 and 3, the low temperature properties of SBS polymer modified asphalt binders were evaluated. In chapters 4 and 5, the effect of freeze-thaw cycles on fatigue cracking and rutting of asphalt pavements was investigated. Finally, chapters 6 and 7 discussed the impact of extreme high temperatures and solar radiations on asphalt mixtures. Based on the analysis results obtained from the different study cases considered in this thesis, the following conclusions were drawn:

- The BBR test is a feasible method to determine the low temperature properties of asphalt binders and mixtures.
- The use of SBS polymer modifiers has a positive effect on the low temperature properties of asphalt binders. SBS polymer modified binder showed to have better capabilities in reducing the thermal induced stress compared to unmodified virgin binders.
- Freeze-thaw cycles can significantly reduce the fatigue and rutting lives of asphalt pavements. As the number of freeze-thaw cycles increases, the stiffness of asphalt mixtures substantially decrease.
- Generally, fiber reinforced asphalt (FRA) mixtures have a better performance in resisting fatigue cracking and rutting due to freeze-thaw cycles as compared to rubber modified asphalt (RMA) mixtures.

- The increase in temperature due to climate change has negative impacts on the performance of asphalt mixtures. As the temperature increases, asphalt pavements are more likely to experience permanent deformation or rutting.
- Solar radiations have a significant impact on the service life of asphalt pavements. Pavement sections that are exposed to solar radiations are more likely to experience lower fatigue and rutting lives, compared to pavement sections at shaded regions. For a successful pavement design, it is necessary to consider the intensity of solar radiations in the region.
- The impacts of the different climate conditions considered in this study on the performance of asphalt mixtures, suggests replacing historical climate models by recent climate prediction models to design asphalt pavements, as with the current changes in weather patterns, pavements could potentially be subjected to different stresses, impacting its performance over the design period.