Analysis of Non-Linear Dynamic Behaviours in Asphalt Concrete Pavements Under Temperature Variations

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Summary: This paper presents a method to evaluate the nonlinear behaviour of asphalt concrete pavements under temperature variations. Temperature variations could significantly reduce the service life of pavement structures. Although, most pavement analysis models assume linear behaviour of pavement layers, it is important to consider the nonlinear behavior of pavements. Nonlinear responses of asphalt concrete pavemnets increase the critical stresses applied on pavements, which reduces its strength. To determine the nonlinear responses of asphalt pavements when subjected to changes in temperatures, KENLAYER which is a pavement analysis and design software was used to analyze the pavement responses under temperature variations. The results of the modeling performed in KENLAYER showed that temperature variations could significantly reduce the service life of asphalt concrete pavements by increasing tensile and compressive strains.

Introduction

The objective of this paper is to investigate the non-linear responses of flexible pavements under temperature variations. 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 can have both linear and non-linear behaviours. The linear behaviour of asphalt occurs at low stress levels, while at high stress asphalt exhibits non-linear behaviour (Delgadillo et al. 2012). Most of the existing models for pavement analysis assume linear behaviour of layers in asphalt concrete pavements to reduce the complexity of computations. However, previous studies showed that flexible pavements exhibit nonlinear behaviours (Hadi and Bodhinayake, 2003). Thus, it is essential to study the nonlinear responses of flexible pavements to predict its performance. Several factors can impact the performance of hot mix asphalt concrete pavements such as, the applied traffic load, soil, environmental and climate 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, speed of wind as well as solar radiation. Temperature data is important to determine the amount of stress and strain acting on a pavement surface. As, the deflection of pavements is highly influenced by its temperature (Wang and Roseler, 2014). Temperature is also a main contributor to multiple types of pavement distresses, resulting in a significant impact on the service life of pavement (MATIĆ et al. 2013). There are two main types of critical strains that affect Asphalt Concrete pavements which are, tangential and compressive strains. Tangential strain occurs at the bottom of asphalt layer, while compressive strain occurs at the surface of subgrade layer. Tangential strain is responsible for fatigue cracking at the surface of asphalt concrete pavements, while compressive strain impacts rutting distress of the pavement.

Background

To study the influence of temperature variations 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 cross-section consists of an overlay layer constructed using rubberized modified asphalt mixtures (RMA), followed by 10 inches of asphalt concrete base layer, 10 inches of aggregate subbase layer, and a subgrade layer, as illustrated in figure 1. This section was used to analyse the performance of asphalt concrete pavements under different temperatures.

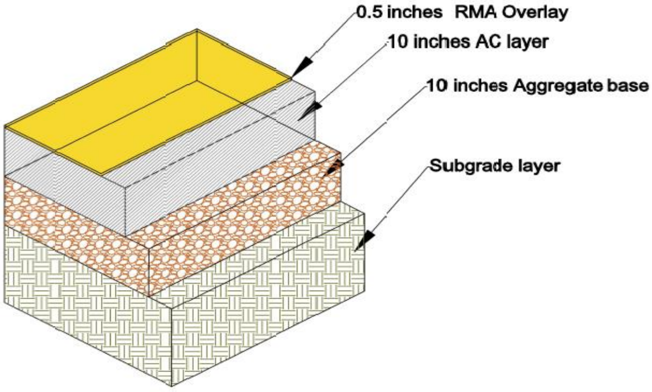

Figure 1. The pavement structure

Methodology

Prediction of Pavement Temperature

The temperature of the pavement was predicted using a model provided by the Canadian Strategic Highway Research Program (C-SHRP) for low temperature performance (Ho and Romero, 2009) as shown in equation 1:

$$T_{pavement} = T_{air} \text{ x } 0.859 + (0.002\text{-}0.0007 \text{ x } T_{air}) D + 0.17 \qquad (1)$$

Where:
$T_{pavement}$: pavement temperature at calcualted depth (ºC)
T_{air}: low air temperature (ºC)
D: depth (mm)

The pavement performance was evaluated at 8 different air temperatures: -10, -5, 0, 5, 10, 15, 20 and 25 ºC. To conduct the analysis the temperature at the overlay layer and the AC base layer were obtained. The pavement response was evaluated at half the depth of the overlay layer at 6.35 mm from the pavement surface where the tensile strain occurs. While the compressive strain occurs and at the bottom of the asphalt layer located at a depth of 266.7 mm. The calculated pavement temperatures obtained from the C-SHRP model were used in a software called KENLAYER to analyze the influence of temperature variations on asphalt concrete pavements.

Bending Beam Rheometer Testing

Bending Beam Rheometer (BBR) tests were performed to obtain the stiffness and creep compliances of the asphalt mixture to evaluate the performance of the pavement under different temperatures. The BBR 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 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 temperature increased, as shown in figure 2.

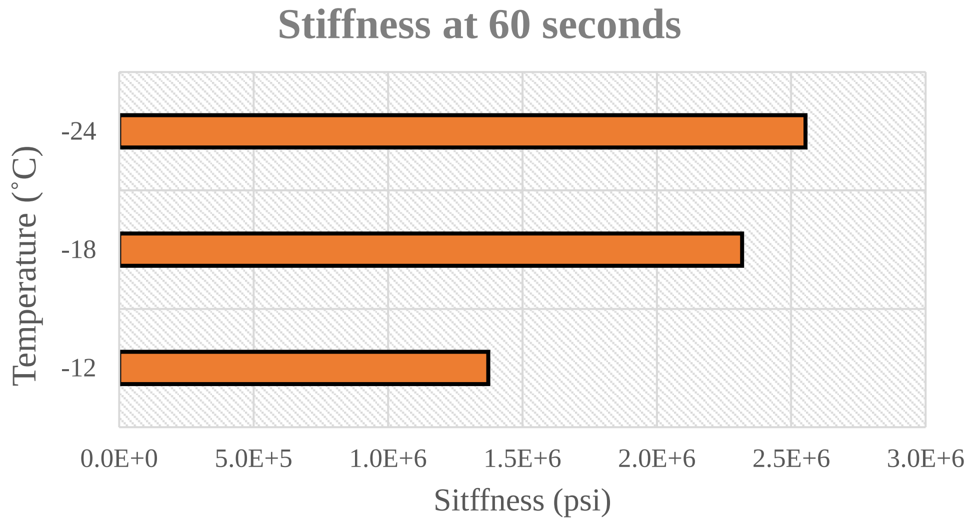

Figure 2: Stiffness of asphalt mixture at different temperatures using BBR tests

Modelling the Non-linear Behaviour 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 behaviours. KENLAYER is a pavement design and analysis software that applies to flexible pavements. The solutions of the software can be applied to linear, nonlinear and viscoelastic layered systems. The model can be used to compute the critical strains at the bottom of asphalt layer and top of subgrade layer. The computer program can create damage analysis for any asphalt concrete pavement structure that has a maximum of 5 layers. The nonlinear damage analysis is done by considering any asphalt layer to be linear elastic, and considering untreated granular base layers to be nonlinear elastic. Granular materials have nonlinear resilient behaviour 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 4 steps. First, the characteristics of the structure of the pavement were entered along with the nonlinear model characteristics. Then granular layers were divided into number of sub-layers, where the stress was chosen to be at the middle depth of the layer. Then, 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 analysed.

Table 2. 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

Results and Discussion

The Effect of Temperature Variations on Tangential Strain

To determine the influence of temperature variations on the tangential strain at the bottom of the asphalt layer, tangential strain was plotted against different temperature values, as illustrated in figure 3. The results of KENLAYER showed that tangential strain increases as the temperature increase. For example, the tangential strain at temperature of 15 °C was higher than the strain at -10 °C by 15%. While, after the temperature reached 10 °C , the strain remained constant. The tangential strain at the bottom of the asphalt layer is important because it is responsible for fatigue cracking of the asphalt layer. Fatigue cracking is one of the primary distreses that occur at a pavement surface that could potentially lead to the failure of the structure. Fatigue cracking leads to a significant reduction in the pavement service life, by allowing water to infiltrate through the cracks, resulting in large patholes along the pavement surface. The relationship between temperature variation can be expressed using a polynomial function as exhibited in figure 3.

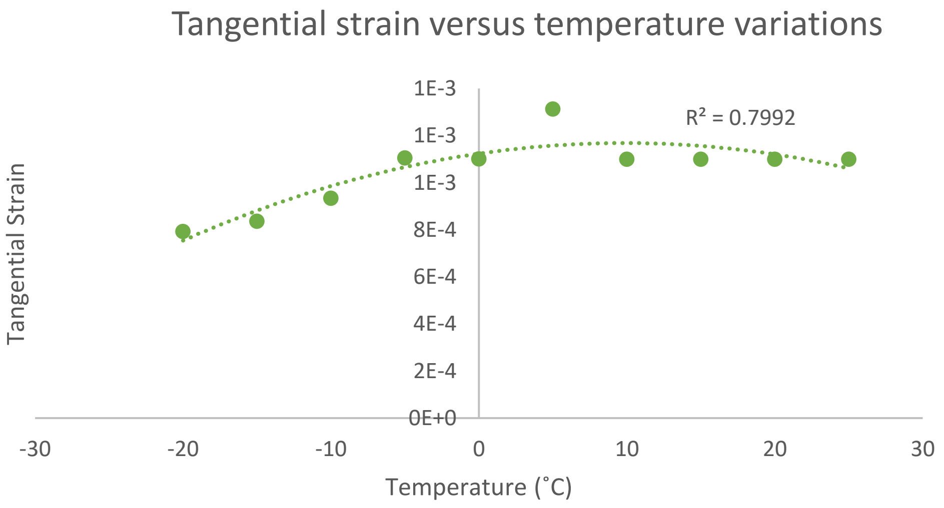

Figure 3: Effect of temperature on tangential strain

Statistical Analysis: Influence of temperature variations on Tangential Strain

To evaluate the relationship between tangential strain and temperature variations, statistical analysis was conducted using R statistical software, utilizing the one-way anova approach and the results are summarized in table 3.

Table 3. Statistical Analysis for temperature variations and tangential strain

	df	Sum f squares	Mean Squares	F-value	p-value
Tensile Strain	1	960.99	960.99	6.9795	0.02963
Residuals	8	1101.51	137.69		

As illustrated in table 3, the p-value calculated for the relationship between temperature variations and tensile strain is very small, less than 5%. As a result, the null hypothesis stating that there is no relationship between different temperatures and tensile strain at the bottom of the asphalt layer could be rejected. Thus, it can be concluded that there is a significant relationship between temperature and tangential strain.

The Effect of Temperature Variations on Compressive Strain

The relationship between compressive strain and temperature variations is illustrated in figure 4. As shown in figure 4, the compressive strain increased with the increase in temperature. Compressive strain significantly increased between -20 ºC and -5 ºC. The compressive strain at -20ºC was less than the strain at -5 ºC by 9%. After the temperture reached -5 ºC, there was almost no change in compressive strain with the increase in temperature. The compressive strain at the top of the subgrade layer affects rutting distress along the pavement surface. Rutting is a main type of pavement distress that occurs due to plastic deformation of the asphalt concrete layer (Huber et al. 1987). As shown in figure 4, the relationship between compressive stress and temperature variations can be represented using a polynomial function.

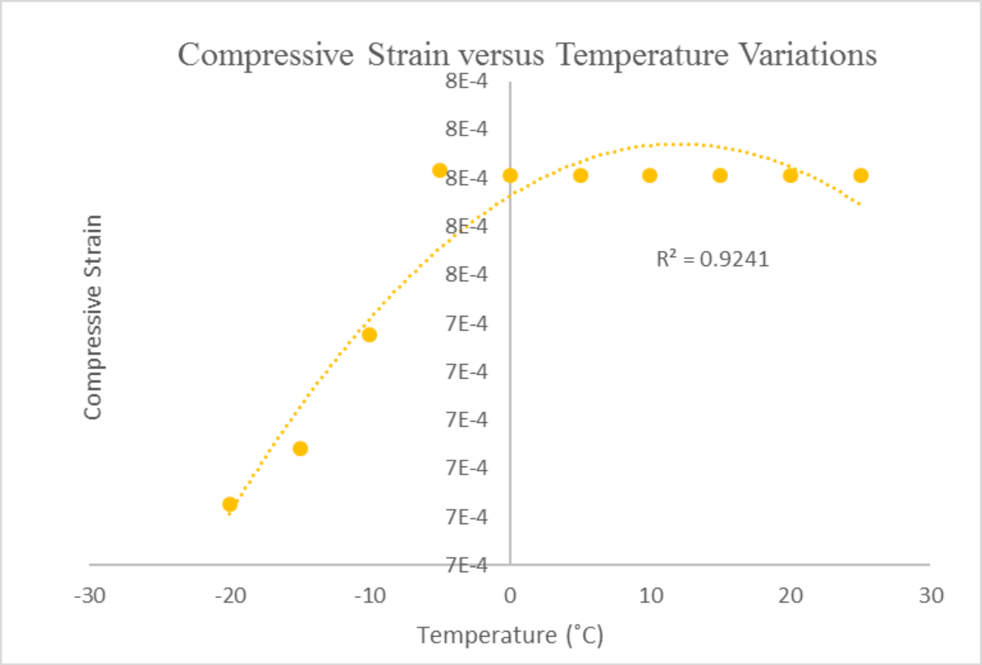

Figure 4: Effect of temperature on compressive strain

Statistical Analysis: Influence of Temperature Variations on Compressive Strain

The significance of the relationship between compressive strain and temperature variations evaluated using R statistical analysis and the one-way anova approach, the results are summarized in table 4.

Table 4. Statistical Analysis for temperature variations and tangential strain

	df	**Sum f 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 4, the p-value obtained for the relationship between temperature variations and compressive strain is approximately 0.005, which is a very small value. Therefore, the null hypothesis states that there is no relationship between compressive strain and temperature variations is rejected and it can be concluded that there is a substantial relationship between temperature and compressive strain

Influence of Temperature variations on the lifespan of pavement

Fatigue cracking and rutting are two of the main pavement distress types, that occur at flexible pavements. Fatigue and rutting lead to the early deterioration of Asphalt Concrete Pavements. Thus, resulting in additional maintenance and repair costs. Fatigue cracking depends on the tangential strain at the bottom of the overlay layer, while rutting depends on the compressive strain. To study the effect of temperature variations on fatigue cracking and rutting, fatigue and rutting models were used to determine the influence of temperature variations on the lifespan of pavements. The models used to calculate fatigue and rutting lives are shown in equations 2 and 3, respectively.

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

Where:

N_f is 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 are constants obtained from fatigue tests.
E_1 represents the stiffness of the asphalt overlay layer.

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

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 fatigue and rutting lives for the pavement section using the models, N_f and N_d were plotted against different temperature values, as illustrated in figures 5 and 6.

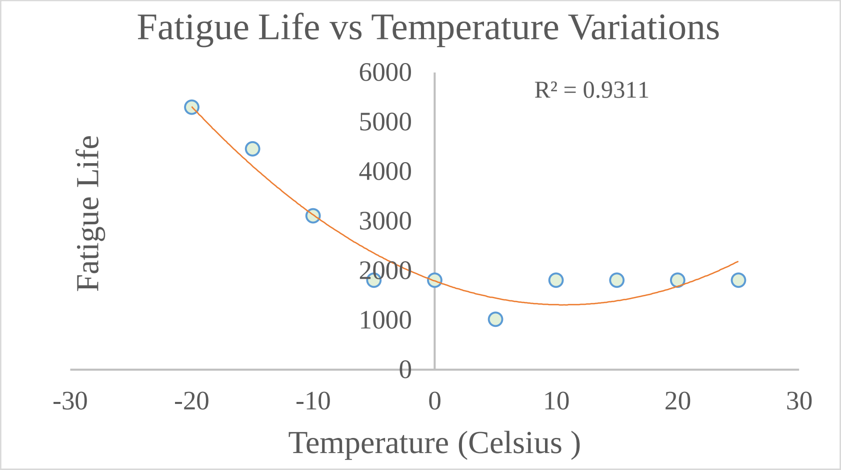

Figure 5: Fatigue Life versus Temperature Variations

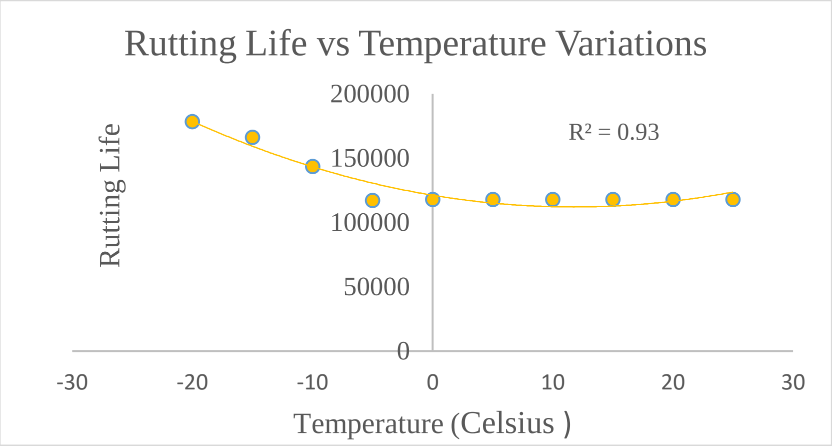

Figure 6: Rutting Life versus Temperature Variations

As shown in figures 5 and 6 above, the increase in temperature leads to a reduction in the fatigue and rutting lives. Most of the reduction occurred at temperature values of less than 0 °C. The correlation between the increase in temperature and the reduction in rutting and fatigue lives can be represented by a polynomial function. Thus, it is important to consider the temperature variations when designing a pavement section to maximize the life span of the pavement structure.

Conclusions

This study evaluated the influence of temperature variations on the performance of asphalt concrete pavements by evaluating the non-linear response of the pavement at different temperatures. The study was done by conducting lab experiments followed by software analysis and statistical analysis. Based on the study, the following can be concluded:

- Stiffness of asphalt mixtures decreases as temperature increases.
- There is a direct correlation between temperatures and compressive and tensile strains. As the temperature increases, compressive and tensile strain increase as well.

- The relationship between temperature and compressive and tensile strain can be expressed by a polynomial function.
- The change in temperature could significantly impact the performance of asphalt concrete pavements by increasing fatigue cracking and rutting which eventually lead to pavement failure.
- It is important to consider the effect of temperature variations when designing a pavement structure to maximize service life of pavements.

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