

Effect of temperature on service life of flexible pavement using finite element analysis

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Abstract. Temperature is one of the most critical elements that influence the rutting and fatigue resistance of flexible pavements. Particularly in extreme hot regions in Saudi Arabia, high temperature would significantly reduce the rutting resistance of flexible pavements leading to reduction of pavement service life. Due to the impacts of global warming, average temperature in Saudi Arabia is expected to further increase by about 4°C by the end of the 21st century. The substantial increase in average temperature will elevate the expected pavement maintenance and rehabilitation cost. This paper analyzes the structural effects of temperature on pavement using layered elastic analysis based on finite element techniques. The research team calculated the potential loss of pavement service life due to the projected temperature increase and climate change. The paper also analyzed potential impact of using carbon waste in asphalt concrete to tackle the derogatory impacts of temperature rise.

Keywords: carbon waste; finite element analysis; multilayered pavement; thermal effect

1. Introduction

An effective transport system is essential for the economic and social development of any country. Roads are one of the most popular elements of transportation system, (Shanbara *et al.* 2020, Dey *et al.* 2023). Flexible pavement is a complex structure including layers of asphalt concrete surface, granular base strata, and granular subgrade. The primary objective of roadway construction is to offer a safe and comfortable medium for vehicle movement. Performance and durability of flexible pavement depends on traffic load, layer thickness, material properties and environmental condition. Pavement design science started through empirical models developed by AASHTO Road Tests (Asphalt Institute 1982, Huang 1993). These models were applicable for particular set of environmental, material and loading conditions and used average conditions in design of layer thicknesses. In the past decade, Mechanistic-Empirical (ME) design gained a substantial momentum because of its ability to model future pavement distresses through transfer functions and provide more reliable design (Qiang *et al.* 2011, Shi *et al.* 2020). In addition, Mechanistic-Empirical (ME) design tool was utilized to determine the significance of subgrade strength on the thickness of pavement structure (El-Hakim *et al.* 2015). ME method is based on mechanistic properties of pavement materials, axle loads and climatic conditions to calculate the pavement response in the form of stresses, strains and deformations. Mechanistic properties of pavement materials are determined using laboratory tests. According to

AASHTO T 342 specification, the mechanistic properties, like dynamic modulus, are determined at limited number of standard temperatures (AASHTO T 342 2022). This represents a shortfall by ignoring the expected future temperature increase due to global warming. Ling *et al.* (2019) studied the critical responses of airfield composite pavements that are composed of hot-mix asphalt (HMA) overlay and Portland cement concrete (PCC) pavement using FEM. Garcia and Thompson (2007) suggested that temperature may have significant nonlinear impacts on pavement characteristics and detrimental effect on pavement service life. The analysis of temperature susceptibility of pavement is a classical research issue that traditionally relied on mechanical examination of stress-strain behavior using elastic layered system (Westergaard, 1926 and Warren and Dieckman, 1963). As well, Raffaniello *et al.* (2022) utilized the ME design tools to compare the pavement distresses and rutting in two different climate zones in North America and at different traffic loads. The research concluded that rutting increases in hot climate especially with the increase of HMA thickness compared to cold climate. Yoder and Witczak (1975) provided constitutive relationships for the magnitudes and locations of various stresses and strains in multilayered pavement system. However, Bazlamit and Reza (2005) concluded that temperature had a significant impact on the frictional characteristics of flexible pavements. Mechanical Empirical (ME) methods expanded the procedure to incorporate actual field conditions in pavement design process to facilitate micro-level design refinement. The ME design method leads to significant enhancements in pavement performance prediction and could be utilized to increase the durability of pavement sections. Deng *et al.* (2020) developed a model to evaluate the shear strength of unsaturated soil under nonlinear

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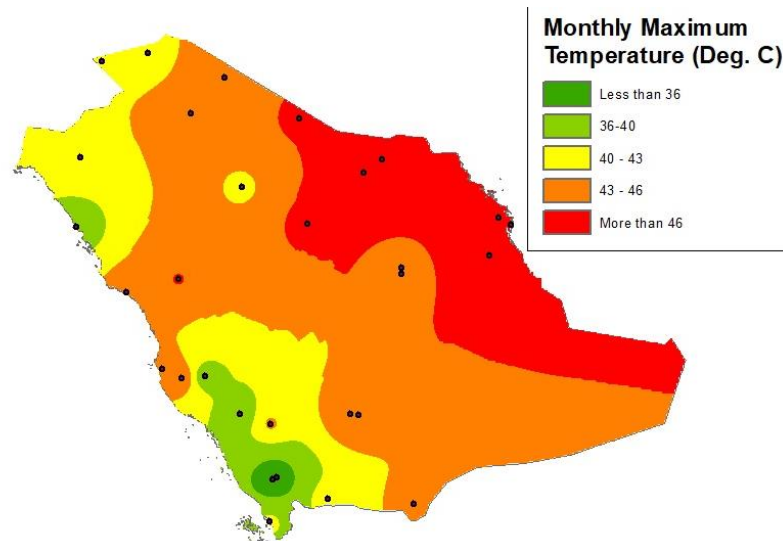


Fig. 1 Monthly Maximum Temperature in Different Regions of Saudi Arabia. Krishna (2014)

strength theory. Ranadive and Tapse (2013) explored the applicability finite element approach to investigate behavioral aspects of flexible pavement. Luo *et al.* (2021) studied the viscoelastic behavior of the asphalt mixture, as well as mechanical reinforcement using geosynthetics in flexible pavements. Chiasson *et al.* (2008) and Deifenderfer *et al.* (2006) analyzed temperature profile and thermal stress in pavement structure. Alnujaie *et al.* (2021a,b) and Bashiri *et al.* (2021) studied the forced vibration of a functionally graded porous beam resting on viscoelastic foundation. Assie *et al.* (2022) studied dynamic response of porous functionally graded layered deep beams with viscoelastic core. Mahmoodzadeh *et al.* (2022) used Gaussian process regression in prediction of duration and construction cost of road tunnels. Vaziri *et al.* (2022) presented 2D numerical study of the mechanical behavior of non-persistent jointed rock masses under uniaxial and biaxial compression tests. Chinnapandi *et al.* (2022) examined the vibro-acoustics response of functionally graded porous beams subjected to thermo-mechanical loads. Zadehmohamad *et al.* (2022) evaluated long-term benefits of geosynthetics in flexible pavements built over weak subgrades by FE and Mechanistic-Empirical analyses. Esen *et al.* (2022) studied the free vibration and buckling stability of FG nanobeams exposed to magnetic and thermal fields. Banerji *et al.* (2023) studied the effect of wheel load and temperature on rutting damage of composite flexible pavement using FEM. Research work can be extended to assess the effects of climate change induced temperature increase on the service life of pavement structure. Wahhab and Balghunain (1994) identified the vulnerability of asphalt pavement in arid Saudi environment. Considering high temperature and its expected rise due to climate change, further investigation is required.

This paper focused on the impact of temperature variation on stress and strain at different pavement layers and associated service life using finite element technique.

The research methodology utilized the constitutive model to account for temperature impact on elastic

properties of constituent materials. It also examined the impact of using carbon waste to improve pavement structural performance to withstand temperature-related distresses. The paper is organized as follows: section 2 presents the geographic pattern of temperature and its trend in Saudi Arabia and the methodology of Finite Element analysis applied in the paper. Section 3 presents the analysis and results of the research work which is followed by discussion of the results in Section 4. The major findings and conclusions of the study are summarized in Section 5.

2. Temperature zones and trends in Saudi Arabia

The current monthly maximum temperature in Saudi Arabia exceeds 40°C in most of the country. Fig. 1 presents the regional variations of monthly maximum air temperature in the Saudi Arabia.

Due to the effects of global warming induced by climate change the mean and maximum temperature in the country are expected to increase. Various models of climate forecast reveal that the temperatures are expected to increase by about 4°C in the central region by the end of 21st century and the extent of increase may vary among regions. As shown in Fig. 2, Central and Northern regions are expected to experience the highest increase in air temperature.

3. Finite element analysis

A two-dimensional finite element model was used to analyze a typical pavement section used in Saudi Arabia on Highway assuming plane strain condition. The pavement cross-section included 100-, 150- and 200-mm surface layers (Asphalt Concrete), 300 mm Base layer (Bituminous Macadam) and 600 mm Subbase layer (compacted sand), and subgrade as presented in Fig. 3. Flexible pavement is modeled as multilayer system subjected to static loading. Although there are several computer programs available for

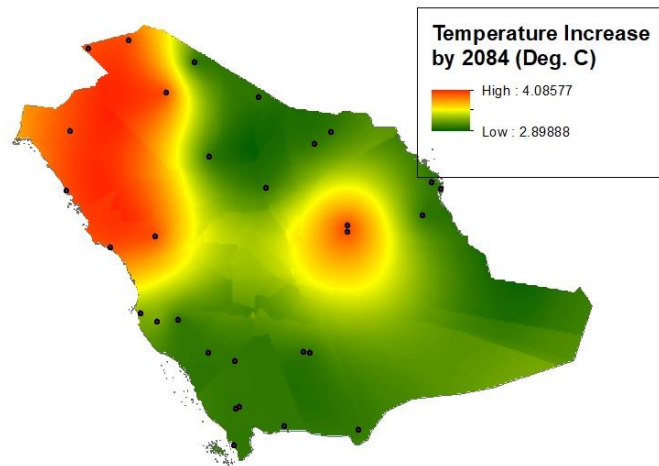


Fig. 2 Forecasted Increase in Air Temperature in Saudi Arabia, Odnoletkova and Patzek (2021)

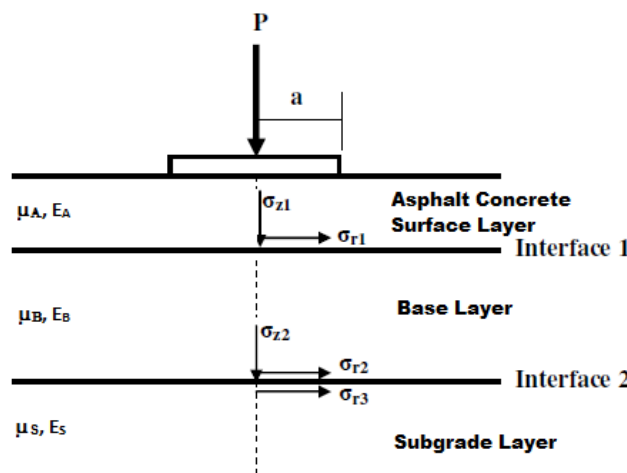


Fig. 3 Multilayered pavement system showing static loading and stresses

Table 1 Material Properties in Standard Laboratory Temperature

Material	Surface (AC)	Base (BL)	Sub-Base (SB)	Subgrade (SG)
Thickness (mm)	100, 150 and-200	300	600	1000
Dry Unit Weight (kN/m ³)	22.5	22	15	14
Elastic Modulus (MPa)*	4000	800	300	50
Poisson's Ratio	0.35	0.40	0.45	0.45

* Base condition

analyzing multi-layer pavement system including ELSYM5 (Alhborn 1972), EverStress (Sivaneswaran *et al.* 2001), DAMA (Huang and Witczack 1981, Witczack 1972) etc., most of them are based on aggregate material properties. Yavuzturk *et al.* (2005) explored the potential application of finite-difference approach to assess temperature fluctuation effects on asphalt pavement. To deal with microscopic parameters, the system modeled in this study used ABAQUS finite element software with varying properties and thickness of different layers (Smith 2009). Using the software, horizontal tensile stress at the bottom of asphalt concrete layer and compressive strain at the top of the subgrade were calculated under different conditions. Allowable load repetitions until fatigue and permanent

deformation failure were calculated using formulas presented in equations 1 to 6 (Heukelom and Klomp 1962, Asphalt Institute 1982). A uniform pressure of 0.575 MPa was applied on a circular contact area having a radius of 150 mm which is equivalent to 40kN single wheel load (Ranadive and Tapase 2016). Shen *et al.* (2022) presented dynamic elastic analysis of flexible pavements under moving Vehicles using a semi-analytical finite element treatment.

3.1 Finite element model parameters

Two-dimensional axisymmetric model is developed to simulate loading condition as shown in Fig. 4 below. 8-node

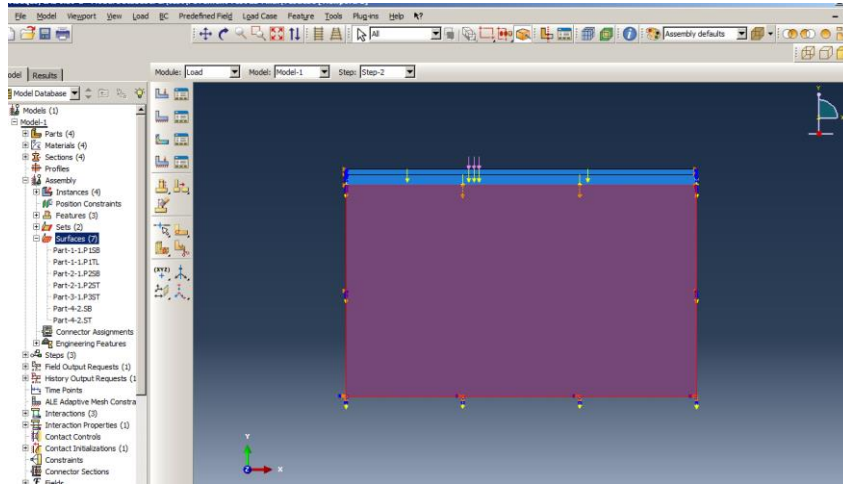


Fig. 4 FEM Model of Pavement Layers and Loads in Abaqus

quadrangular element is considered in meshing. Boundary condition of the finite element model is imposed considering sufficient horizontal and vertical extent in order to minimize boundary effect. Multilayered pavement model set the boundary at 1.25 m away from the edge of the load. Depth of the FE model is set at 1.5 m from the loading surface. Fixed support is considered at the bottom and right edges where no vertical and horizontal movements are allowed. Material properties considered in the model are summarized in Table 1 below. Material properties are determined from laboratory experiments.

3.2 Analysis of pavement life

The life of Pavement is determined by the allowable number of load repetitions due to fatigue and rutting failure of pavement structure. The fatigue failure results in the development of alligator cracks due to excessive tensile strain at the bottom of asphalt layers. Conversely, the rutting failure results in a permanent deformation of the pavement layer due to excessive compressive strain at the top of subgrade layer. Finite element analysis using elastic theory can be applied to compute limiting strains in the asphalt bound layer (fatigue analysis) and permanent deformation (rutting) in the subgrade.

In the case of fatigue failure, Heukelom and Klomp (1962) developed a relationship between the number of load repetitions to failure and horizontal tensile strain in asphalt concrete as follows

$$N_f = 10^{-X} \quad (1)$$

$$X = 5 \log_{10} \epsilon_t + 2.665 \log_{10} \left(\frac{E_A}{14.22} \right) + 0.392 \quad (2)$$

Where N_f is the number of load repetition till failure, ϵ_t is the horizontal tensile strain at the bottom of asphalt layer and E_A is the modulus of elasticity of asphalt concrete.

According to Asphalt Institute (1982) the relationship between number of load repetitions and elastic properties of asphalt concrete for fatigue failure is given as follows

$$N_f = 0.0796 (\epsilon_t)^{-3.291} (E_A)^{-0.854} \quad (3)$$

Rutting failure in pavement structure results from deflection of pavement due to settlement and permanent shear failure. For rutting failure, Heukelom and Klomp (1962) suggested relationship between the number of load repetitions to failure and vertical compressive strain in asphalt concrete as follows

$$N_r = 10^{-X} \quad (4)$$

$$X = \{2.408 + \log_{10}(\epsilon_c)\}/0.1408 \quad (5)$$

Where N_f is the number of load repetition till failure and ϵ_c is the vertical compressive strain at top of subgrade layer.

According to Asphalt Institute (1982) the relationship between number of load repetitions and elastic properties of asphalt concrete for fatigue failure is given as follows

$$N_f = 1.365 X 10^{-9} (\epsilon_c)^{-4.477} \quad (6)$$

In this study we analyzed strain at corresponding layers using finite element model and then estimated number of load repetition using Asphalt Institute method.

3.3 Application of finite element method for pavement life assessment

Finite element method is applied to assess the strains at the desired locations for varying characteristics of pavement materials and layer thicknesses. Material properties and layer thicknesses used in the analysis are summarized in Table 1. To study the effects of varying material properties on rutting and fatigue life, different types of materials are examined with varying elasticity for each layer. Base elasticity of asphalt concrete, granular base and subbase layer varied from 1000 to 3000 MPa, 400 to 1000 MPa, and 50 to 200 MPa respectively. Poisson's ratio was assumed to be 0.35 for all layers. The modulus of subgrade was assumed as 10 MPa. To analyze the effects of varying layer thickness, asphalt concrete (h_1) and base layer (h_2) were examined for three trial thicknesses for each layer.

The loading condition was simulated assuming a uniform pressure of 0.575 MPa caused by single axle load

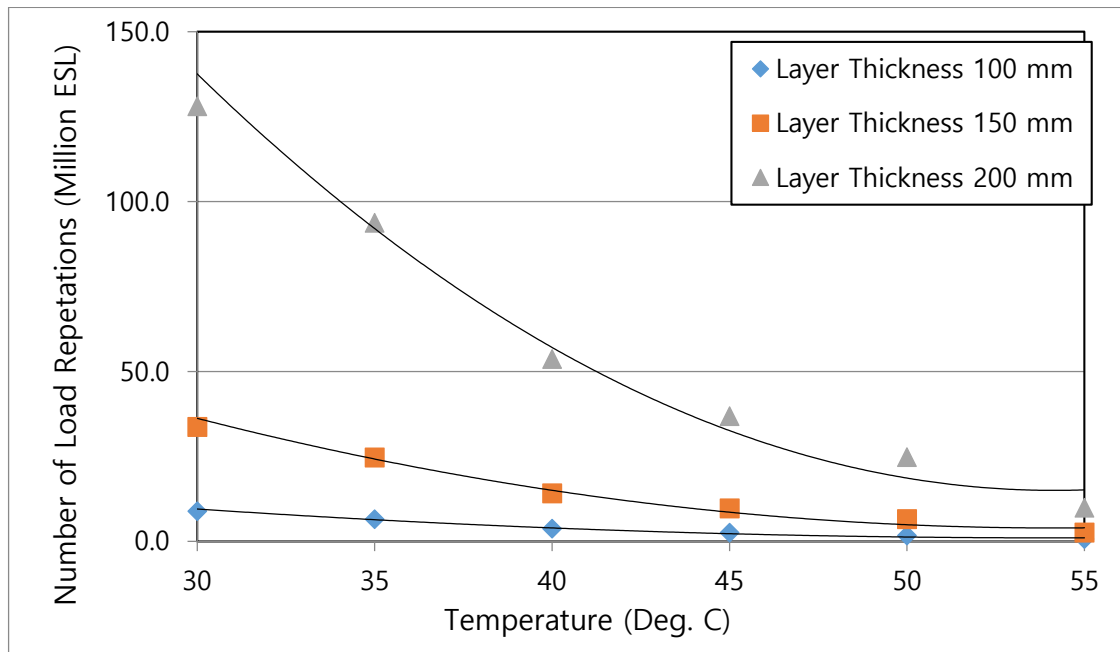


Fig. 5 Effect of Temperature Increase on Number of Load Repetitions (Fatigue)

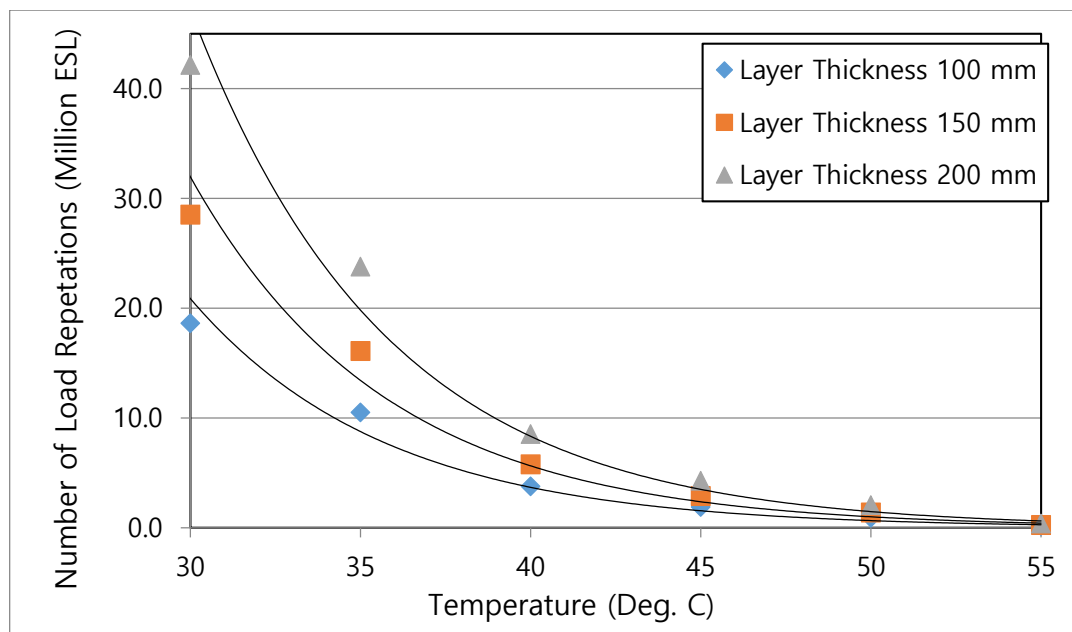


Fig. 6 Effect of Temperature Increase Number of Load Repetitions (Rutting)

of 40.80 kN applied on a circular contact area with radius of 150 mm as shown in Fig. 1 (Sinha *et al.* 2014).

The effect of temperature on pavement service life was analyzed through its impact on layer elastic properties. Thompson *et al.* (1987) observed that asphalt concrete moduli is temperature dependent and proposed the following model to correlate air temperature with asphalt layer temperature at different depths using heat transfer model.

$$T_{AC} = (0.02Z + 55.9) + (2.214 - 0.00121Z)MMAT \quad (7)$$

Where, T_{AC} is asphalt layer temperature ($^{\circ}\text{C}$), Z is layerdepth (mm) and $MMAT$ is mean air temperature ($^{\circ}\text{C}$).

Lee *et al.* (2016) concluded that the impact of temperature on strains and elastic modulus of asphalt layers is nonlinear. The authors found that strain decrease exponentially with the increase of asphalt concrete stiffness. Garcia and Thompson (2007) also observed significant impact of temperature on asphalt moduli. Lukanen *et al.* (2000) and Marshall *et al.* (2001) suggested the use of adjustment factors in the design process to deal with the effects of temperature on flexible pavement structure. Nazarian and Alvarado (2006) analyzed the effects of temperature gradient on modulus of asphalt concrete layers. Asadi *et al.* (2013) observed that flexural modulus is affected by both temperature and strain levels. The authors

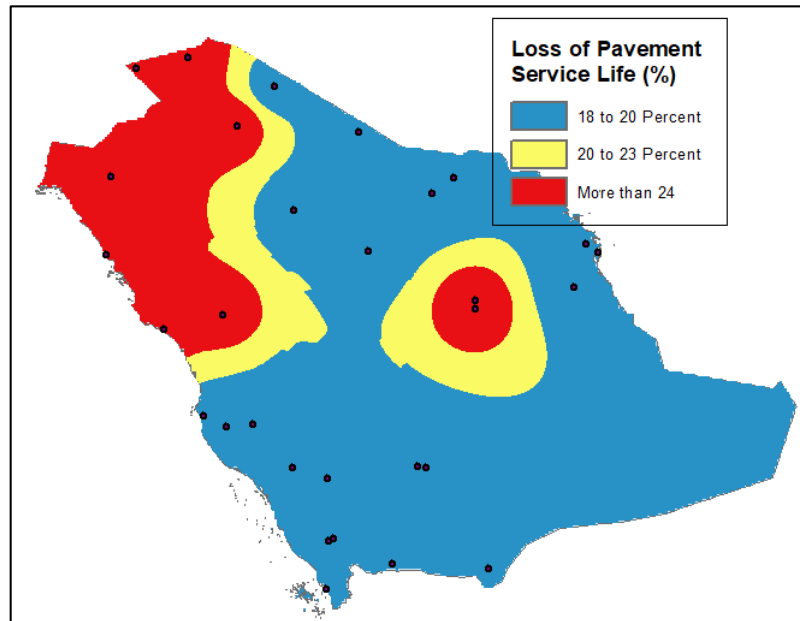


Fig. 7 Expected Reduction in Pavement Service Life Due to Climate Change Induced Temperature Increase (in Percent)

Table 3 Variation of Resilient Modulus with Carbon Waste and Temperature

Temperature, Deg. C	Increase in Resilient Modulus, MPa		Expected Increase in Pavement Service Life	
	Carbon Waste (1%)	Carbon Waste (2%)	Carbon Waste (1%)	Carbon Waste (2%)
30	1249	1549	12.7	16.2
40	1073	1342	11.3	14.5
50	809	1195	9.7	11.9
60	678	912	6.2	9.2

revealed that temperature significantly affects the initial flexural modulus at all strain levels and the modulus is inversely proportional to temperature.

All these studies clearly demonstrate that asphalt concrete elasticity critically relies on temperature. In this study the effects of temperature on critical stress and strain of pavement layers is considered through modified elasticity of asphalt concrete. A constitutive model is developed for this purpose correlating nonlinear relationship between mean air temperature and elasticity of asphalt layers. FEM model of pavement layer is executed with different air temperatures and layer thicknesses in accordance with temperature patterns and expected future variability in Saudi Arabia.

4. Analysis of results

Firstly, a preliminary analysis was conducted to verify the accuracy and performance of FEM model. Initially all the layers were assigned the same elastic properties and the results obtained from FEM model were compared to the deformations calculated using Boussinesq equation (Burmister 1945, Huang 2008). Results obtained from the FEM and the Boussinesq equations were congruent. In the second stage of verification, a multilayered system, with the base values of material properties for all the layers, was

analyzed using Everstress package through a conventional framework without considering temperature effect and the results were compared to the corresponding model in ABAQUS. In this case also the results agreed satisfactorily.

The FEM is then applied to analyze fatigue and rutting life of multilayered pavement structure for which a sample deformed shape is presented in Fig. 7. As shown in Figs. 8 and 9, both fatigue and rutting life of flexible pavement declined significantly due to increase in temperature. The effect is highly prominent at higher thickness of asphalt later. For asphalt layer thickness of 200 mm, fatigue and rutting life decreased by 25% and 50% for increase in temperature from 30°C to 55°C respectively.

In the following stage of the research, the FEM model was applied to analyze expected reduction of pavement service life in different regions of Saudi Arabia due to the impact of temperature increase induced by climate change. Based on FE analysis, the reduction of fatigue and rutting service life is presented in Figs. 5 and 6 respectively. As mentioned earlier in Fig. 2, by 2080 temperature is expected to increase by about 4°C in the Central and Northern regions of the country and for the other regions it is expected to rise by about 3°C. Combining baseline temperature pattern in different parts of Saudi Arabia with the expected temperature increase in corresponding regions, expected reduction in fatigue service life is estimated and summarized in Fig. 7.

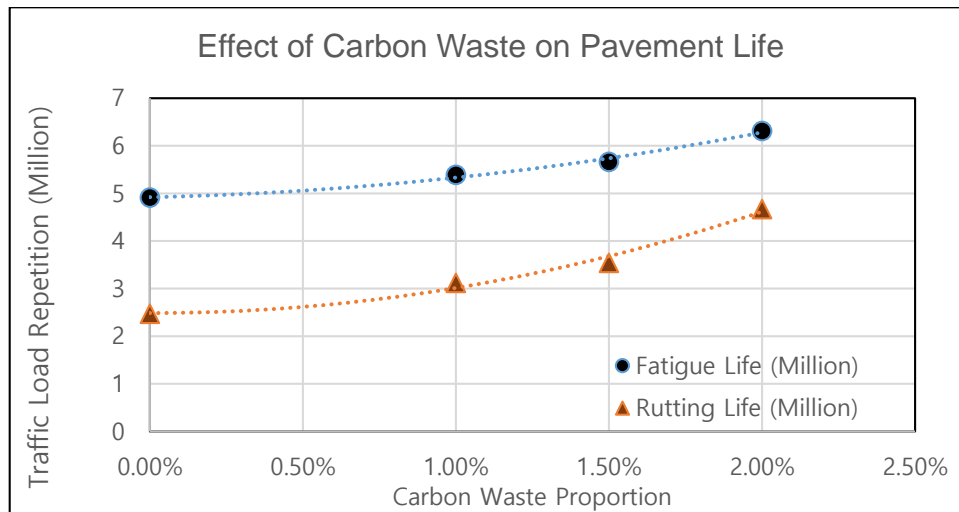


Fig. 8 Effect of Carbon Waste on Pavement Service Life

5. Conclusions

The current study analyzes the effect of temperature on pavement fatigue and rutting. A finite element model was developed for this purpose using Abaqus. The developed model concluded that.

- fatigue and rutting life of asphalt pavement decline with increase of pavement temperature. The reduction in pavement life is more prominent in thick pavement layers.
- For 200 mm asphalt concrete surface layer, if the temperature increased from 30°C to 50°C, allowable fatigue and rutting load repetitions reduce by 20% and 40% respectively.
- The rate of change in service life declines with the increase of temperature. The author recommended the utilization of carbon waste to alleviate the detrimental effects of increasing temperature on flexible pavement.
- The service life of Carbon waste modified asphalt mixture increased by about 30% in both fatigue and rutting through adding 2% carbon waste in asphalt mixes. Results outline that temperature is a major concern in pavement service life and performance.
- The impact of future increase in temperature (global warming) should be considered in current design practices. Moreover, appropriate type of mixture modification could reduce temperature susceptibility of asphalt mixtures.
- Carbon waste possesses a potential material that could be utilized to reduce the impact of global warming on service life of asphalt mixtures. The research work will be extended in future to incorporate dynamic loading scenarios and temperature variation effects.

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References

- Ahlborn G (1972), *ELSYM5 Computer Program for Determining Stresses and Strains in Five Layer System*. University of California, Berkeley.
- Alnujaie, A., Akbas, S.D., Eltaher, M.A. and Assie, A. (2021), "Forced vibration of a functionally graded porous beam resting on viscoelastic foundation", *Geomech. Eng.*, **24**(1), 91-103. <https://doi.org/10.12989/gae.2021.24.1.091>.
- Alnujaie, A., Akbas, S.D., Eltaher, M.A. and Assie, A.E. (2021), "Damped forced vibration analysis of layered functionally graded thick beams with porosity", *Smart Struct. Syst.*, **27**(4), 679-689. <https://doi.org/10.12989/sss.2021.27.4.679>.
- Asadi, H., Leek, C. and Nikraz, H. (2013), "Effect of temperature on fatigue life of asphalt mixture", *Proceedings of the AAPA International Flexible Pavements Conference*, Brisbane, Queensland, Australia
- Asphalt Institute (1982), "Research and development of asphalt institute's thickness design manual", 9th Ed., *Research Report*, **82**(2), The Asphalt Institute.
- Assie, A., Akbas, S.D., Kabeel, A.M., Abdelrahman, A.A. and Eltaher, M.A. (2022), "Dynamic analysis of porous functionally graded layered deep beams with viscoelastic core", *Steel Compos. Struct.*, **43**(1), 79-90. <https://doi.org/10.12989/scs.2022.43.1.079>.
- Banerji, A.K., Topdar, P. and Datta, A.K. (2023), "Study on the effect of wheel load and temperature on rutting damage of composite flexible pavement using finite element method", *Proceedings of the International Conference on Advances in Structural Mechanics and Applications*.
- Bashiri, A.H., Akbas, S.D., Abdelrahman, A.A., Assie, A., Eltaher, M.A. and Mohamed, E.F. (2021), "Vibration of multilayered functionally graded deep beams under thermal load", *Geomech. Eng.*, **24**(6), 545-557. <https://doi.org/10.12989/gae.2021.24.6.545>.
- Bazlamit, S.M. and Reza, F. (2005), "Changes in asphalt pavement friction components and adjustment of skid number for temperature", *J. Transp. Eng.*, **131**, 470-476.
- Burmister, D.M. (1945), "The general theory of stresses and displacement in layered systems", *J. Appl. Phys.*, **16**(2), 89-94.

- <https://doi.org/10.1063/1.1707558>.
- Chiasson, A.D., Yavuzturk, C. and Ksaibati, K. (2008), "Linearized approach for predicting thermal stresses in asphalt pavements due to environmental conditions", *J. Mater. Civil Eng. ASCE.*, **20**, 118-127.
- Chinnapandi, L.B.M., Pitchaimani, J. and Eltaher, M.A. (2022), "Vibro-acoustics of functionally graded porous beams subjected to thermo-mechanical loads", *Steel Compos. Struct.*, **44**(6), 815-829. <https://doi.org/10.12989/scs.2022.44.6.815>.
- Deifenderfer, B.K., Al-Qadi, I.L. and Deifenderfer, S.D. (2006), "Model to predict pavement temperature profile: Development and validation", *J. Transportat. Eng. ASCE.*, **132**, 162-167.
- Deng, D., Wen, S., Lu, K. and Li, L. (2020), "Calculation model for the shear strength of unsaturated soil under nonlinear strength theory", *Geomech. Eng.*, **21**(3), 247-258. <https://doi.org/10.12989/gae.2020.21.3.247>.
- Dey, N., Debnath, B. and Sarkar, P.P. (2023), *Finite element analysis of flexible pavement with non-linear material behaviour*. In Recent Trends in Civil Engineering, 789-795. Springer, Singapore.
- Dong, S., Yuan, X.X. and Hao, P. (2020), "An advanced local calibration method for mechanistic-empirical pavement design", *Comput. Aided Civil Infrastruct. Eng.*, **35**(11), 1276-1290. <https://doi.org/10.1111/mice.12574>.
- El-Hakim, M., Jadoun, F.M., Lee, S. and Ningyuan, L. (2014), "Sensitivity analysis of field-to-laboratory subgrade conversion factors with AASHTOWare pavement ME design", *Transport. Res. Record*, **2456**(1), 115-123. <https://doi.org/10.3141/2456-12>.
- Esen, I., Abdelrhmaan, A.A. and Eltaher, M.A. (2022), "Free vibration and buckling stability of FG nanobeams exposed to magnetic and thermal fields", *Eng. with Comput.*, **38**, 3463-3482. <https://doi.org/10.1007/s00366-021-01389-5>.
- Garcia, G. and Thompson, M. (2007), "Hma Dynamic Modulus – Temperature Relations", *Project Report FHWA-ICT-07-006*, Illinois Department of Transportation.
- Hamid, A., Baaj, H. and El-Hakim, M. (2019), "Enhancing asphalt cement properties using geopolymers based on fly ash and glass powder", *Proceedings of the 7th CSCE International Specialty Conference on Engineering Mechanics and Materials*, Laval, QC, Canada.
- Hamid, A., Baaj, H. and El-Hakim, M. (2023), "Temperature and aging effects on the rheological properties and performance of geopolymer-modified asphalt binder and mixtures", *Materials*, **16**(3), 1012. <https://doi.org/10.3390/ma16031012>.
- Hamid, A., Baaj, H., Eng, P. and El-Hakim, M. (2022), "Effect of high temperature on the behaviour of geopolymer modified asphalt binders", *Proceedings of the Transportation Association of Canada 2022 Conference and Exhibition- Changing Ways for our Changing Climate//Association des transports du Canada 2022 Congrès et Exposition-Approches Adaptées pour un Climat changeant*.
- Heukelom, W. and Klomp, A.J.G. (1962), "Dynamic testing as a means of controlling pavements during and after construction", *Proceedings of the Int. Conference on the Structural Design of Asphalt Pavement*, Ann Arbor, Michigan, U.S.A.
- Huang, D. and Witczack, M.W. (1981), "Program DAMA (Chevron), User's Manual", *Dept. of Civil Eng.*, University of Maryland.
- Huang, H.Y. (2008), "Pavement analysis and design", *second.*, Pearson Education Inc, and Dorling Kindersley Publishing Inc.
- Krishna, L.V. (2014), "Long term temperature trends in four different climatic zones of Saudi Arabia", *Int. J. Appl.*, **4**(5).
- Lee, L., Charles, R. and Simson, N. (2016), "Stress-strain behavior of Asphalt concrete in compression", *Procedia Struct. Integrity*, **2**, 2913-2920.
- Li, Q., Xiao, D.X., Wang, K.C.P. Hall, K.D. and Qiu, Y. (2011), "Mechanistic-empirical pavement design guide (MEPDG): a bird's-eye view", *J. Modern Transport.*, **19**, 114-133. <https://doi.org/10.1007/BF03325749>.
- Ling, J., Wei, F., Zhao, H., Tian, Y. and Han, B. (2019), "Analysis of airfield composite pavement responses using full-scale accelerated pavement testing and finite element method", *Constr. Build. Mater.*, **212**, 596-606. <https://doi.org/10.1016/j.conbuildmat.2019.03.336>.
- Lukanen, E., Stad, R.S. and Briggs, R. (2000), "Temperature prediction and adjustment factors of asphalt pavement", *Office of Infrastructure Research and Development Federal Highway Administration. McLean, Virginia*, 5-10.
- Luo, J., Huang, H., Qamhia, I.I., Tutumluer, E. and Tingle, J.S. (2021), "C-FLEX advanced finite element analysis program for flexible pavement analysis and design", *Transport. Res. Record*, **2675**(9), 1238-1249. <https://doi.org/10.1177/03611981211006724>.
- Mahmoodzadeh, A., Mohammadi, M., Abdulhamid, S.N., Ibrahim, H.H., Ali, H.F.H., Nejati, H.R. and Rashidi, S. (2022), "Prediction of duration and construction cost of road tunnels using Gaussian process regression", *Geomech. Eng.*, **28**(1), 65-75. <https://doi.org/10.12989/gae.2021.28.1.065>.
- Marshall, C., Meier, R.W. and Welsh, M. (2001), "Seasonal temperature effects on flexible pavements in Tennessee", *Transportation Research Board*, 80th Annu. Meeting, Jan., Washington DC.
- Nazarian, S. and Alvarado, G. (2006), "Impact of temperature gradient on modulus of asphaltic concrete layers", *J. Mater. Civil Eng. ASCE*, **18**, 492-499.
- Odoletkova, N. and Patzek, T.W. (2021), "Data-driven analysis of climate change in Saudi Arabia: Trends in temperature extremes and human comfort indicators", *J. Appl. Meteorol. Clim.*, **60**(8), 1055-1070. <https://doi.org/10.1175/JAMC-D-20-0273.1>.
- Qabur, A., Baaj, H. and El-Hakim, M. (2022), "Incorporation of the multi-layer plastic packaging in the asphalt binders: Physical, thermal, rheological, and storage properties evaluation", *Polymers*, **14**(24), 5396. <https://doi.org/10.3390/polym14245396>.
- Raffaniello, A., Bauer, M., Safiuddin, M. and El-Hakim, M. (2022), "Traffic and climate impacts on rutting and thermal cracking in flexible and composite pavements", *Infrastructures*, **7**(8), 100. <https://doi.org/10.3390/infrastructures7080100>.
- Ranadive, M.S. and Tapase, A.B. (2013), "Investigation of behavioral aspects of flexible pavement under various conditions by finite element method", *Constitutive modeling of geomaterials*, Springer-Verlag, Berlin, **2013**, 765-770. http://dx.doi.org/10.1007/978-3-642-32814-5_100.
- Ranadive, M.S. and Tapase, A.B. (2016), "Parameter sensitive analysis of flexible pavement", *Int. J. Pavement Res. Technol.*, **9**(6), 466-472. <https://doi.org/10.1016/j.ijprt.2016.12.001>.
- Shanbara, H.K., Shubbar, A., Ruddock, F. and Atherton, W. (2020), "Characterizing the rutting behaviour of reinforced cold mix asphalt with natural and synthetic fibres using finite element analysis", *Adv. Struct. Eng. Rehab.*, 221-227. https://doi.org/10.1007/978-981-13-7615-3_20
- Shen, K., Zhang, H., Tong, J., Wang, H. and Chen, X. (2022), "Dynamic elastic analysis of flexible pavements under moving vehicles: a semi-analytical finite element treatment", *Road Mater. Pavement Des.*, **23**(6), 1440-1450. <https://doi.org/10.1080/14680629.2021.1883467>.
- Sinha, A.K., Chandra, S. and Kumar, P. (2014), "Finite element analysis of flexible pavement with different subbase materials", *Indian Highways, New Delhi*, **42**(2), 53-63.
- Sivaswaran, Y.N., Picce, L.M. and Mahoney, J.P. (2001), Everstress (Version 5.0), "Layered Elastic Analysis Program", *Washington State, Department of Transportation*.
- Smith, M. (2009), *ABAQUS/Standard User's Manual*, Providence,

RI: Simulia.

- Thompson, M.R., Dempsey, B.J., Hill, H. and Vogel, J (1987), "Characterizing temperature effects for pavement analysis and design", *Transport. Res. Record*, **1121**.
- Vaziri, M.R., Tavakoli, H. and Bahaaddini, M. (2022), "2D numerical study of the mechanical behaviour of non-persistent jointed rock masses under uniaxial and biaxial compression tests", *Geomech. Eng.*, **28**(2), 117-133. <https://doi.org/10.12989/gae.2022.28.2.117>.
- Wahhab, H.I.A.A. and Balghunain, F.A. (1994), "Asphalt pavement temperature related to arid Saudi environment", *J. Mater. Civil Eng. ASCE*, **6**(1), 12-15. [https://doi.org/10.1061/\(ASCE\)0899-1561\(1994\)6:1\(1\)](https://doi.org/10.1061/(ASCE)0899-1561(1994)6:1(1)).
- Warren, H. and Dieckman, W.L. (1963), "Numerical computational stresses and strains in multi-layer asphalt pavement system", *Internal Report, Chevron Res. Corporation*, Richmond, CA.
- Westergaard, H.M. (1926), "Stresses in concrete pavement computed by theoretical analysis", *Public Roads*, **7**(2), 25-35.
- Witczak, M.W. (1972), "Design of full-depth asphalt airfield pavements", *Proceedings of the 3rd International Conference on the Structural Design of Asphalt Pavements*.
- Yavuzturk, C., Ksaibati, K. and Chiasson, A.D. (2005), "Assessment of temperature fluctuations in asphalt pavements due to thermal environmental conditions using a two-dimensional transient finite-difference approach", *J. Mat. Civil. Eng.*, **17**, 465-475. [https://doi.org/10.1061/\(ASCE\)0899-1561\(2005\)17:4\(465\)](https://doi.org/10.1061/(ASCE)0899-1561(2005)17:4(465)).
- Yoder, E.J. and Witczak, M.W. (1975), *Principles of Pavement Design*, 2nd Ed., John Wiley and Sons, Inc. New York.
- Zadehmohamad, M., Luo, N., Abu-Farsakh, M. and Voyiadjis, G. (2022), "Evaluating long-term benefits of geosynthetics in flexible pavements built over weak subgrades by finite element and Mechanistic-Empirical analyses", *Geotext. Geomembranes*, **50**(3), 455-469. <https://doi.org/10.1016/j.geotextmem.2022.01.004>.