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Samir Hasan Raza
Department of High Way and Bridge Engineering, College of Engineering, Duhok Polytechnic University,Duhok,KurdistanRegion,Iraq,
samir.hasan@dpu.edu.krd

Nazeer Muhammed Ali Abdulah
Department of High Way and Bridge Engineering, College of Engineering, Duhok Polytechnic University,Duhok,KurdistanRegion,Iraq

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RESEARCH ARTICLE

Effects Variability Number of Load Repetitions on the Optimum Thickness of Asphalt Layer with Respect to Fatigue and Rutting Behaviour on the Sand Bed Soil Area

Samir Hasan Arif[1]*, Nazeer Muhammed Ali Abdulah

[1] *Department of High Way and Bridge Engineering, College of Engineering, Duhok Polytechnic University, Duhok, Kurdistan Region, Iraq*

[2] *Department of High Way and Bridge Engineering, College of Engineering, Duhok Polytechnic University, Duhok, Kurdistan Region, Iraq*

***Corresponding author:**
Samir Hasan Arif,
Department High way and Bridge Engineering,
College of Engineering,
Duhok Polytechnic University, Duhok,
Kurdistan Region, Iraq.

E-mail:
samir.hasan@dpu.edu.krd

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ABSTRACT

This study uses a mechanistic design approach to investigate how the elastic modulus of pavement materials and the variability of the number of load repetitions affect the behavior of flexible pavement structural on the sand bed soil with regard to fatigue and rutting damages. The structure is assessed for a system of flexible pavement with six layers. The main sticking point in this paper is the impact of variation in an asphalt layer's thickness and resilient moduli on fatigue and rutting failures. By using the KENLAYER program to analyze strains in the upper and lower of each layer, the methodology is based on the damage analysis idea and is conducted for both fatigue and rutting distress in the flexible pavement. Data gathering is dependent on the sources utilized to create the statistical distributions of layer thicknesses and elastic moduli, which include AASHTO 1993 and Asphalt Institute. According to the findings the pavement analysis on the sand bed soil that elasticity modulus, and thickness of the foundation are the main factors that regulate the balance between fatigue and rutting lives, respectively. The study also found that while raising the elasticity modulus of the surface only slightly prolongs pavement life, increasing the thickness of the surface layer greatly lengthens pavement life. The researched pavement elements are the elasticity modulus and thickness of the pavement layers. Sensitivity analysis were carried out to determine the crucial input variables that have the greatest impact on the ideal thickness of the asphalt layer.

Keywords: Layer thickness, pavement stiffness, Rutting Deformation, and Fatigue Distress.

1-INTRODUCTION

Rutting and fatigue are the most frequently observed in the field for the assessment of pavement surface conditions and are recognized as the most significant distresses surveyed due to their high severity and density levels, and as a result, their large effects on the pavement condition. Flexible pavements ought to be built to offer an impervious, long-lasting surface when in use. Reduced rutting and Fatigue cracking in flexible pavement layers is also crucial. A pavement should typically have a suitably balanced design between the rutting and fatigue modes of distress in order to efficiently employ each pavement material in an economic design. Lack of attention paid to

determining the pavement components that result in a balanced section that delivers equal pavement lives with respect to rutting and fatigue may be to blame for the increased rutting or decreased fatigue life of flexible pavements (Salem, 2008).The mechanistic-empirical design method is based on the mechanics of materials, which combines an input-such as a wheel load and to an output such as stress, strain and Displacement. Laboratory testing and field performance data are utilized to forecast distress using the response values. It is vital to monitor performance because theory by itself has not been shown to be sufficient to design pavements realistically (Younos et al., 2020). As a failure criterion to lessen permanent deformation, vertical compressive strain on the top of the subgrade layer was recommended (Carpenter, 2006). To reduce fatigue cracking, it is advised to decrease horizontal tensile strain at the Lower edge of the asphalt layer (Kim and Siddiki, 2006). The United States was where the usage of the aforementioned concepts for pavement design was first introduced. Mechanistic approaches have the potential to forecast different types of distress, increase design reliability, and make it possible to extrapolate from the sparse field and laboratory data (Priest, 2005).

2-METHODS AND MATERIALS

2-1 Study Objective

The primary goal of this study is to examine how the characteristics of pavement layers such as thickness and elasticity modulus affect pavement longevity in terms of fatigue and rutting failures. In order to identify the essential elements of the pavement that provide balanced sections with equal design lifespan between fatigue and rutting, research interaction employing various asphalt layer thicknesses were undertaken in an effort to determine the ideal asphalt layer thickness. Poisson's ratio (μ) and elastic modulus (E) are properties of pavement materials. Also the study's main objective is to determine how to construct flexible pavements in the best possible way, taking into account design variables' unpredictability and how well they perform in terms of fatigue and rutting criterions.

2-2 KENLAYER Software Program

The multi layering system for the flexible pavement has two main strains. The first strain is the compressive strain on top of the subgrade layer is referred to as the vertical compressive strain. That is a crucial aspect in the design of pavement. The purpose of a pavement is to lessen vertical compressive stress and strain on the subgrade layer's top so that permanent deformations do not happen to this layer (Neves, 2001). The strength or modulus of the subgrade determines the tolerable vertical stress on that subgrade. The vertical compressive strain has most often been used as a design criterion to prevent rutting since it combines the effects of stress and strength (Hornych et al., 1998). Therefore, the second strain is the horizontal strain at the bottom of the asphalt layer is referred to as its tensile strain. Tensile strain has been utilized as a design criterion to avoid fatigue cracking. For this study, there are two different kinds of primary strains that could be used. One is the total principal strain derived from the six normal and shear stress components. Others, which were used in the KENLAYER program, were even more widely known. It is only based on the horizontal normal and shear stresses and represents the major horizontal strain. It is safer to utilize the overall principle strain because it is somewhat larger than the horizontal principal strain.

This study makes use of the KENLAYER software. An elastic multilayer system beneath a circular loaded area can be solved by the program. The answers are combined at different periods for viscoelastic layers, applied repeatedly for nonlinear layers, and superimposed for numerous wheels. Because each layer behaves differently, either linearly elastic, nonlinearly elastic, or viscoelastic. KENLAYER can be used to model layered systems under single, dual, dual-tandem, or dual-tridem wheels. just to be secure.

2-3 Pavement Analysis

Burmister's layered theory is more suited since flexible pavements are layered systems with better materials on top of pavement and cannot be represented by a homogeneous mass (Huang, 2004), With the development of computers, the solution was initially created for a two-layer system and was then expanded to a three-layer system. Any number of layers in a multilayer system can be used to apply the theory (van Niekerk, 2002) . By conceptualizing a flexible pavement as a homogeneous half-space, its behavior under a circular wheel load can be identified (Alemgena, 2002). A six-layered flexible pavement system is used to assess this model.

According to the guidelines provided by AASHTO a nd the Asphalt Institute, the values of the Poisson's r atio are (0.35) for the asphalt, base course, and subb ase layers and (0.45) for the subgrade layer (Neves, 2001). For subbase and subgrade layers, respectively, the minimum CBR required is 20% and 4%. Road profile for analysis is made up of an asphalt layer with thicknesses ranging from (50, 100, 150, 200, 225, 250, and 275 mm) and three different asphalt mixture elasticity modulus kinds (4800, 5800, and 6700 MPa as shown in Fig (1). Two layers make up the base layers; each layer is 150 mm thick, and its elasticity modulus ranges from (240 to 475 MPa). The elasticity modulus of subbase layers' ranges from 91 to 125 MPa and each layer has a thickness of 340 mm. It is recalled by means of Odemark's theory (Galjaard & Het Gebruik van DIANA, 1993). A two-layered

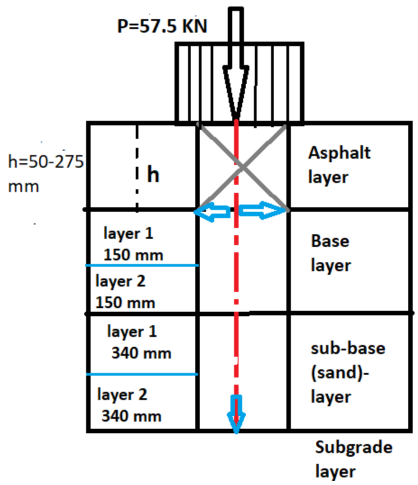


Figure (1) Road profile analysed for heavy and light traffic

system is transferred into a homogenous half-space. it is supported by a subgrade layer whose elasticity modulus is (40 MPa), The California bearing ratio's value (CBR) can be used to estimate the subgrade's Young's modulus (Jobs, 1995).

Different cross sections are produced for analysis by varying these components in combination. Traffic is measured in repetitions of single axle loads (80 KN or 115 KN) applied to the pavement with two sets of dual tires. The measured contact pressure is (0.7 MPa). Two circular plates with a (114 mm) contact radius and (320 mm) center-to-center distance represent the dual tire, respectively. Using KENLAYER software program, it is possible to compute the tensile strain (εt) at the lower of the asphalt layer and the compressive strain (εc) at the upper of the subgrade layer in order to explore the damaging effects of axle load repetitions and tire pressure on various pavement sections. Then, utilizing two strains known as horizontal tensile strain and vertical compressive strain, the damage analysis is carried out to determine the lifespan of the pavement (rutting). Boussinesq's theory can be used for estimation of the traffic stresses in a road embankment due to the circular wheel loads (Heukelom & Klomp, 1962). The use of this theory implies anisotropic, linear elastic and homogenous behaviour of the road materials. The vertical and horizontal stresses are computed when the vertical uniform contact pressure distribution (0.7 MPa). The resilient modulus of granular materials can be determined via a simple relationship between resilient modulus and the first stress invariant that can be computed (Vos et al., 1992). the stiffness modulus values for the base and subbase layers for three different types of asphalt mixtures with various elasticity modulus (Boussinesq, 1885).

The simplified procedure for estimation of stiffness modulus through steps (1 to 4) can be fused with only a marginal loss of accuracy (less than 10%) as mentioned in the section before. wheel load is (F = 57.5 KN), contact pressure for the wheel is 0.7 MPa.

1- Asphalt Mixture Properties)

Asphalt Mixture Properties can be seen in this research for three different conditions, aggregate percent is equal 83%, bitumen is equal 11% and air voids is equal 6%, second aggregate percent is change to 90%, bitumen is decreased to 6% and air voids also is decreased to 4% third and final aggregate is more increased to 93%, bitumen is decreased to 5% and air voids word 2%. Void full with bitumen (VFB) for three different types of asphalt mixture and is equal (64.7%), (60%) and (71.4%). Distribution factor per lane width is equal (2.5), and healing factor is equal (4.5). Penetration for bitumen at 0.1mm, (Pen 25°C (T2) is 50 mm, and (Pen 35°C (T1) is 152 mm. (Pfeiffer, J.P., and Van Doormaal, P.J., 1936). Substituting the values in equation (1), yield to: -

$$A = \frac{Log_{pen\ at\ T1} - Log_{pen\ at\ T2}}{T1 - T2} \quad (1)$$

A = 0.04828 and B = A/0.12 = 0.4023.The tensile strain (ε_f), at the lower of the asphalt layer, must be calculatedusing constant factors (a, k). Equation (2)'s expression for it is the number of axle load repetitions:

$$\varepsilon_f = k \times N_F^{-a} \quad (2)$$

Factor (a) is depended on volume percent of aggregate and B-value , compute according to the Equation (3).

$$a = 0.194 \times B + 0.3 \times \frac{V_{agg}}{100} - 0.09 \quad (3)$$

Also, the Factor (k) can be determined by Equation (4):

$$k = \frac{(75.3E-4)V_{bit}}{V_{bit} + V_a} + \exp\frac{-5 \times V_{agg}}{100} \quad (4)$$

After substituting the values in Equations (3) and (4) then the factor (a); is equal (0.237, or 0.258 or 0.267) and factor (k) is equal to (7.68E-5) or (5.02E-05) or (5.14E-05) for three different types of asphalt mixtures respectively.

2- Determination of the Stiffness of Asphalt Concrete Mixture

Young's modulus of the bitumen depends on the number of factors (loading time, temperature and hardness of bitumen) and can be determined from the Poel diagram (Asphalt Institute, 1982) as shown in Table 1.

Table 1. Stiffness's of Asphalt mixture with three different stiffness's types of bitumen

$S_{bitumen}$ (MPa)	70	52	46
$S_{asphalt\ mixture}$ (MPa)	6700	5800	4800

3- Determination of Thickness Effect (TE)

The thickness effect can be determined from the following equation:

$$TE = \left(\frac{H_{estimated}}{H}\right)^{x} \quad (5)$$

Where: -
TE = Thickness Effect
$H_{estimated}$ = (estimated the minimum thickness of asphalt layer 40mm)
H = Different thicknesses of asphalt layer (50, 100, 150, 200, 225, 250 and 275 mm).
x = Empirical factor that can be determined either:

$$x = 1 - \frac{n}{2} \quad \text{(When n is equal } \frac{1}{a}\text{)} \quad (5a)$$

From previous equations (1 through 5) for the three different types of asphalt mixture and substituting values of a and n, in equation (5a), factor (x) will equal to (-1.11) or (-0.938) or (-0.875) respectively.

$$x = \log \frac{1}{S_{mix}} - \text{Log}(t) \quad (5b)$$

For the three different Asphalt concrete mixture stiffness, (S_{mix} = 4800, 5800 and 6700 MPa) and loading time, t = 0.02 sec, from equation (5b) the x-value will equal to (-1.98) or (-2.065) or (-2.127) respectively.

4- Determine number axle Load of Repetitions

The equation below (Barksdal, 1978) can be used to calculate the initial quantity of axle load repetitions:

$$N_i = (no)_i(G)(D)(L)(275)(Y) \quad (6)$$

Where: -
Ni = Total number of repetitions
G = The growth factor,
D = The directional distribution factor, which is usually assumed to be0.5 unless the traffic in two directions are different
L = The lane distribution factor which varies with the volume of traffic and the number of lanes
Y = The design period in years (is equal 275 work days from 365 per year and for 20 years and annual growth factor percent is 1.5%).

$$EALF_{115} = \left(\frac{Li}{Lst}\right)^4 \text{ and } EALF_{80} = \left(\frac{Li}{Lst}\right)^3 \quad (7)$$

The results of the calculation are shown in Table 2.

Table 2 Displays the calculation's findings.

Li	$EALF = \left(\frac{Li}{115}\right)^4$	$EALF = \left(\frac{Li}{80}\right)^3$	Lane Distribution Factor%	$ESAL_{115(Ni)}$	$ESAL_{80(Ni)}$
140	2.2	5.36	0.2	27980	68169
120	1.19	3.38	1.8	136210	386882
100	0.57	1.95	13	471203	1612010
80	0.23	1.00	25	365643	1589753
60	0.07	0.42	30	133539	801236
40	0.015	0.13	30	28616	248002
Total				**1,163,191**	**4,706,052**

At the end, the total number of axle loads is:
$Ni = (0.6 \times \sum ESAL_{stand\ 115\ KN}) = 0.6 \times 1{,}163{,}191 = 697{,}915$
$Ni = (0.6 \times \sum ESAL_{stand\ 80\ KN}) = 0.6 \times 4{,}706{,}052 = 2{,}823{,}631$
$N_i \leq N_{allowable}$

5- Damage Analysis

For both fatigue damage and permanent deformation (rutting), there are two categories of damages that can be conducted and analyzed:

5-1 Criterion for Fatigue analysis

The effect of wheel loads per layer must be assessed beneath each wheel load and in the space between the wheels because these areas experience the most tensile strain. According to the following connection (Dorman & Metcalf, 1965):, there is a correlation between the number of axle load repetitions and the tensile strain ($\mathcal{E}_f$) at the lower of the asphalt layer. Francken relationship is showing in the following equation:

a. Francken relationship is showing in the following equation:

$$\boldsymbol{\mathcal{E}}_f = k \times N_f^{-a} \quad (8)$$

Where:
N_F = Total number of axle load repetitions.
ε_f = Tensile strain at the lower of the asphalt layer.
k, a = Martials constants
Equation (9) shows a linear relationship for three distinct Smix of asphalt layer between the number of axle load repetitions and tensile strain.

$$\text{Log}(NF) = -\frac{1}{a}\log k - \frac{1}{a}\log \mathcal{E} f \quad (9)$$

We can express the mentioned equation (19) for three different conditions as the follows: -

$$\log(NF) = -17.36 - 4.219 \log \quad (9a)$$
$$\log(NF) = -16.66 - 3.87 \log \varepsilon_f \quad (9b)$$
$$\log(NF) = -16.06 - 3.75 \log \varepsilon_f \quad (9c)$$

b. The tensile strain, (ε_f) can be determined by using the KENLAYER software for different thickness of asphalt layer (50, 100, 150, 200, 225, 250 and 275 mm). The input data (thickness and stiffness) for different layers of flexible pavement can be determined the strain in the upper and lower layer of asphalt by using the above Equations (9a, 9b and 9c), then the number of loads repetitions (NF) can be computed (Burmister, 1945).

5-2 Protection against fatigue failure

Resistance to fatigue cracking can be used to estimate the ideal asphalt layer thickness. The permitted number of load repetitions for two equivalent standard axle loads (ESAL) (80 and 115 KN) can be calculated using Equation (10), The fatigue tensile strain word is stated as the allowable number of load repetitions for these two Equivalent standard axle load (ESAL) for three different estimations of the stiffness's of the asphalt mixture (4800 MPa, 5800 MPa and 6700 MPa). It was stated that the permissible number of load repetitions must exceed the number of axle load repetitions (Ni) and that this is equivalent to 697,915 for (ESAL; 115 KN) and (2,823,631) for (ESAL; 80 KN).

$$N_{allowable} = D_F \times [0.8N_F \times H_f + 0.2N_F \times TE] \quad (10)$$

Where;
$N_{allowable}$ = Allowable number of axle load repetitions
NF1, NF2and NF3 = The numbers of axle load repetitions for three different types of asphalt mixtures.
TE1, TE2 = Thickness Effect
Hf =Healing factor
Df=Distribution factor and is equal (2.5)

5-3 Resistance against Rutting Cracking

After checking the fatigue criteria and choosing the optimum thickness of asphalt layer is (200 mm) when are using the first type of asphalt mixture; with regard to the equivalent standard axle load of 115 KN, the asphalt layer has a stiffness of (4800 MPa), aggregate volume of 83%, binder volume of 11%, and air void volume of 6%. Choose the optimum thickness of asphalt layer is (225 or 275 mm) with respect to the Equivalent standard axle load 80 KN. The relationship is represented between permanent deformation, elastic deformation for each layer and the permitted number of axle load repetitions as shown in Equation (20). So, if the asphalt layer is 225 mm thick, the permitted number of load repetitions (Nallowable) is 1,513,009 in relation to the Equivalent Standard Axle Load (ESAL) of 115 KN, and the allowable number of load repetitions (Nallowable) is (2,962,057) in relation to the Equivalent Standard Axle Load (80 KN). Materials constant factors (a, b) correspond to the sub-base layer (0.10, 0.52), the base layer (2.5, 0.18), and the asphalt layer (2, 0.25), respectively. The permanent deformation (Burmister, 1943) can be determined from the equation (11):

$$U_p = \Delta U_{el} \times a \times N_{allowable}^{b} \quad (11)$$

Where: -
U_P = Permanent deformation (mm)
ΔU_{el}= Different between upper elastic deformation and lower deformation for each layer.
a, b; Material constants and different for each layer.
$N_{\mathbf{allowable}}$ = The allowable number of axle load repetitions.

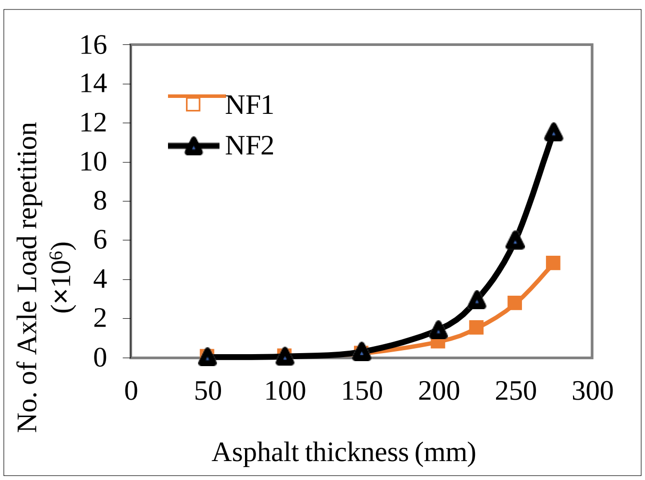
The permanent deformation for three different asphalt mixture stiffness types (4800, 5800, and 6700 MPa) with three different volume ratio percentage of aggregate, bitumen and air voids. Also, two different types of corresponding Equivalent standard axle loads, ESAL (115 or 80 KN) been used, and they are must be less than (20 mm) as shown in Figures (from 2 to 5). Allowable axles load repetitions with difference materials ratio percentages and asphalt mixture stiffness's for 20-year Service.

3-RESULT AND DISCUSION

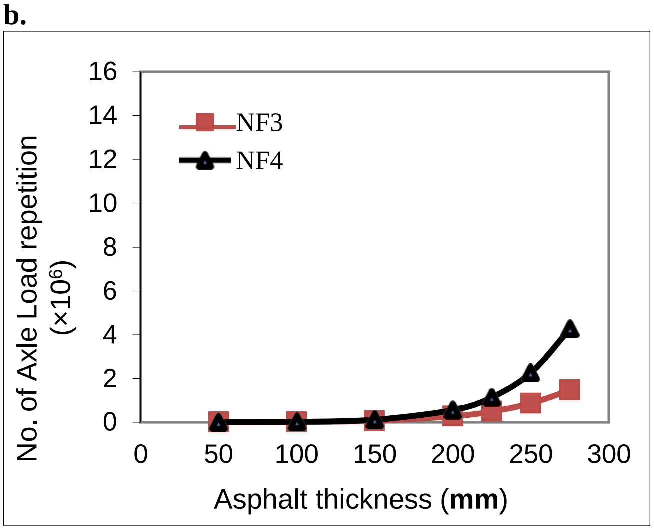
The impact of asphalt layer thickness on flexible pavement in terms of fatigue behavior. As can be observed, the maximum number of load repetitions was used in both instances, (NF1; when Vagg = 83%, Vbit =11% and air voids = 6%) and (NF2; when Smix is 4800 MPa) are increased when the thickness of asphalt layer was increased. Also, the (NF2) are increased more than (NF1) as shown in Fig (2a). Fig(2b) illustrates it for both conditions that (NF3; when Vagg = 90%, Vbit = 6% and air voids = 4%,) and (NF4; when Smix is 5800 MPa) also are increased with increasing thickness of asphalt layer, but less than of the first condition. Finally, that (NF5); when (Vagg = 93%, Vbit = 5% and air voids = 2%) and (NF6; when Smix = 6700 MPa) also are increasing as thickness of asphalt layer was increased, and more than second condition and less than first condition as shown in Fig (2c). Further about the fatigue and rutting behaviors, the effect of base layer and subbase thicknesses layers isn't taken into account throughout pavement design period life. Total number of repetitions for 20 years' Service (Ni) with respect to the Equivalent standard axle load (115 KN) or (80 KN) are equal (697,915 or 2,823,631) respectively. Fig (3) shown effects the allowable number of axles loads on the permanent deformation for different thicknesses of asphalt layer

It can be noticed that both (NF1 and NF2) are increased with increasing the permanent deformation, and also for three different stiffness types of asphalt mixture as shown in Figs (4 and 5). Also, it can be noticed that (NF2) are more sensitive to increasing the permanent deformation than permanent deformation from (NF1). In Fig (4), both (NF3 and NF4) mildly increased as the stiffness of asphalt mixture was increased for the different thicknesses of asphalt layer. It can be noticed that (NF4) is more sensitive to increase the permanent deformation than (NF3). Also, it can be noticed that (NF6) is more sensitive to increase the permanent deformation than (NF5) as shown in Fig (5). It is clear from looking at all of the Figs together that the Permanent deformation produces large values at lower asphalt layer thicknesses and small values at higher asphalt layer thicknesses. This is due to the fact that increasing asphalt layer thickness, aggregate and elastic modulus contents, as well as a reduction in air voids and binder content, resulted in a substantial increase allowable numbers of axle loads repetitions (NF1, NF3, and NF5), as well as a decrease in permanent deformation.

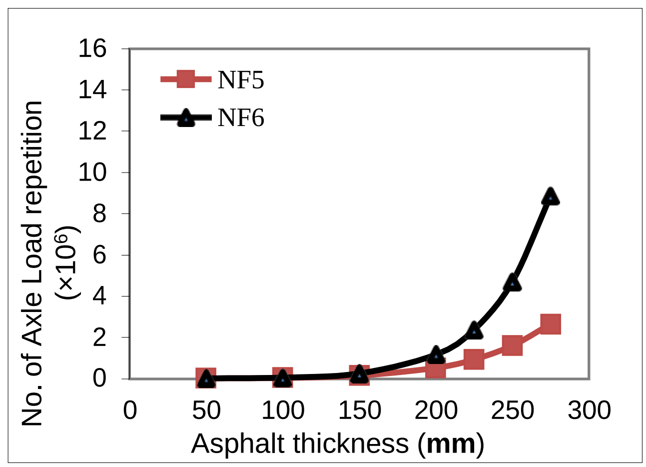
a.



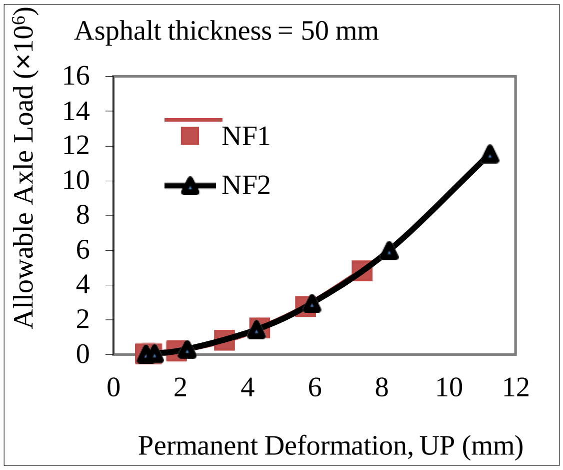
b.

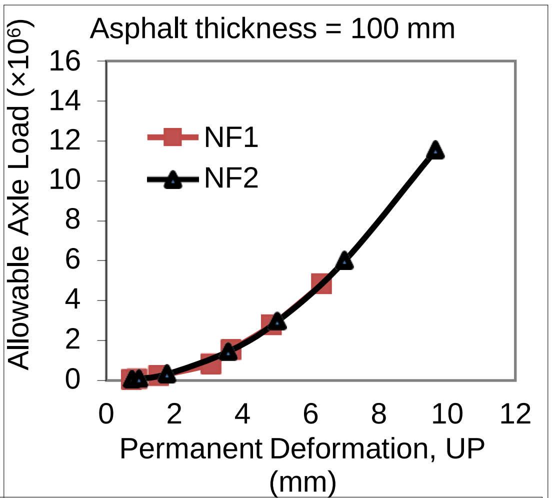


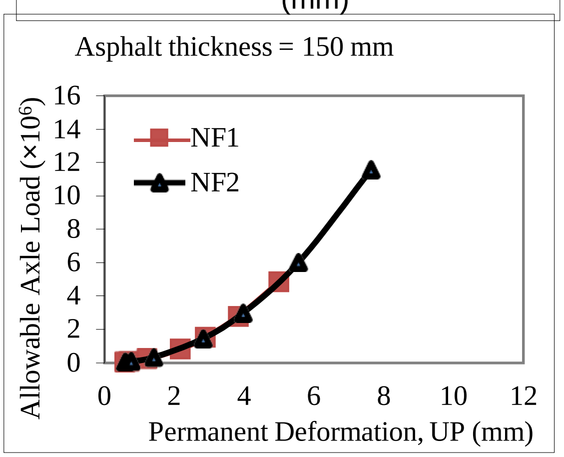
c.

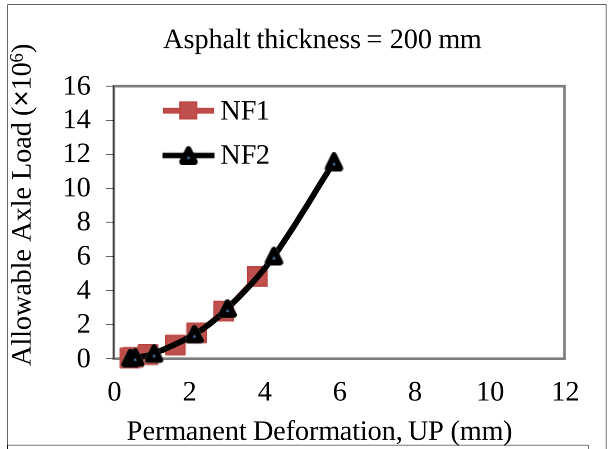


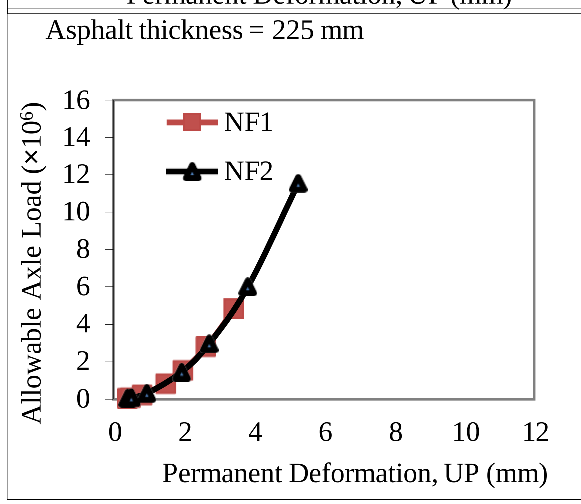
Figures (2a, 2.b and 2c) Effect stiffness of asphalt layer, volume of aggregate and bitumen, and air Voids by different thickness of asphalt layer on the fatigue damage.

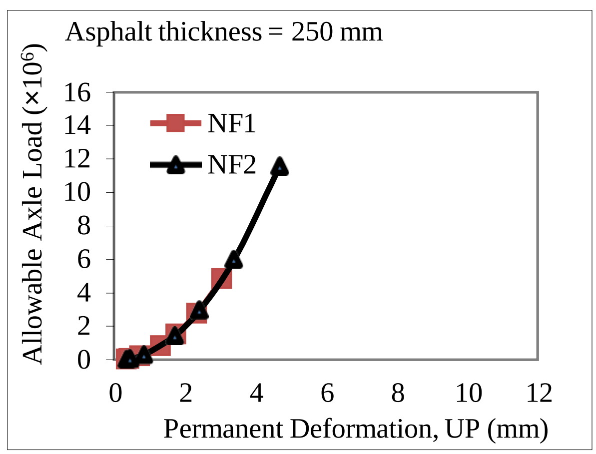

Asphalt thickness = 50 mm
Allowable Axle Load (×10⁶)
NF1
NF2
Permanent Deformation, UP (mm)

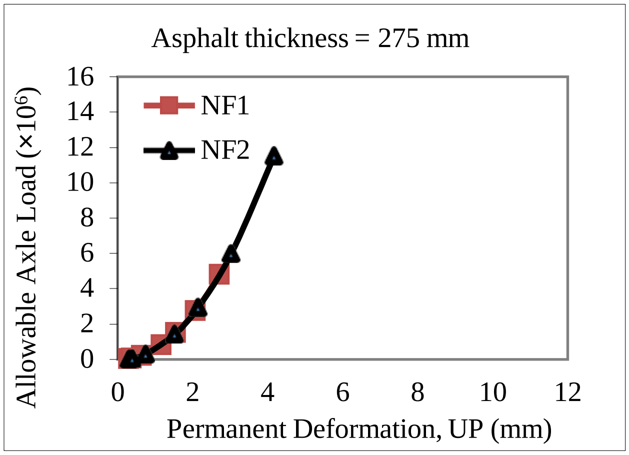

Asphalt thickness = 100 mm
Allowable Axle Load (×10⁶)
NF1
NF2
Permanent Deformation, UP (mm)


Asphalt thickness = 150 mm
Allowable Axle Load (×10⁶)
NF1
NF2
Permanent Deformation, UP (mm)

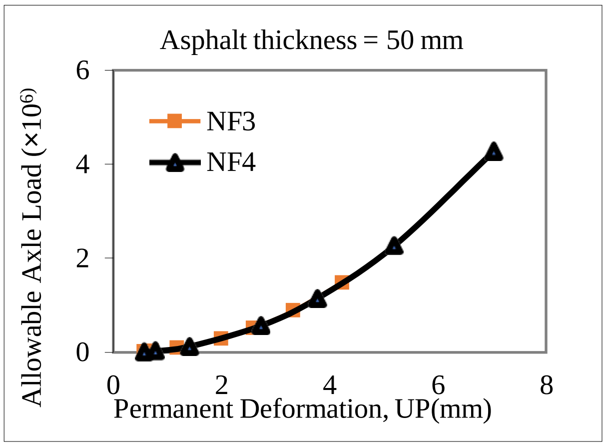

Asphalt thickness = 200 mm
Allowable Axle Load (×10⁶)
NF1
NF2
Permanent Deformation, UP (mm)

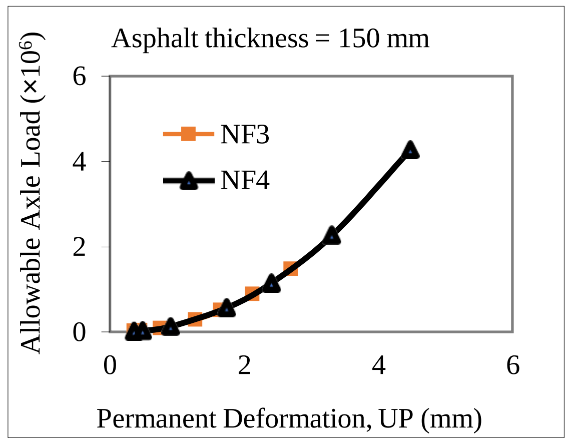

Asphalt thickness = 225 mm
Allowable Axle Load (×10⁶)
NF1
NF2
Permanent Deformation, UP (mm)

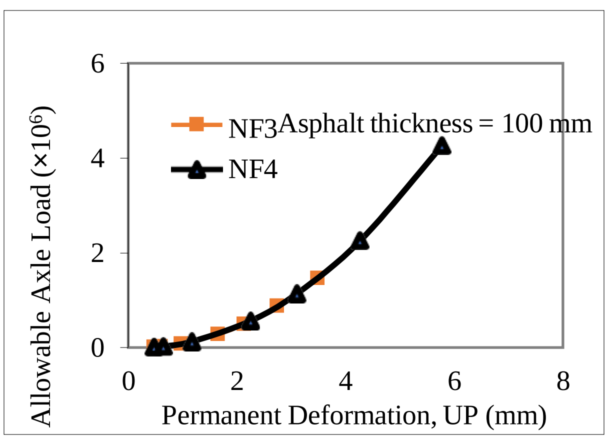

Asphalt thickness = 250 mm
Allowable Axle Load (×10⁶)
NF1
NF2
Permanent Deformation, UP (mm)

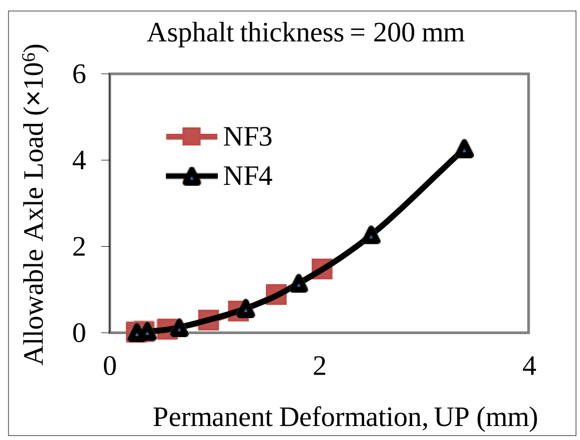


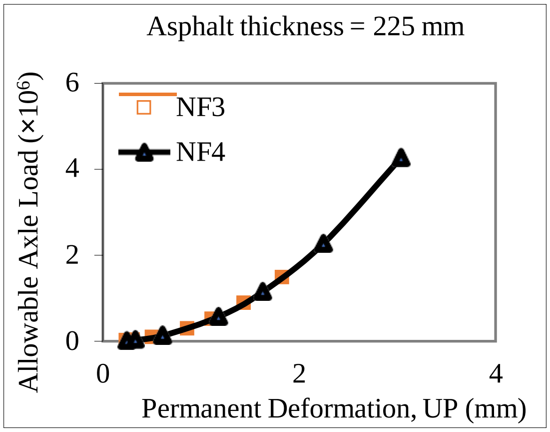
Figures 3. **Effect stiffness of asphalt layer, volume of aggregate and bitumen, and air Voids by different thickness of asphalt layer on the rutting damage (S_{mix} = 4800 MPa, V_{agg} = 83%, V_{bit} = 11%, and air voids = 6%) for The corresponding to the Equivalent standard axle load (ESAL; 115 or 80 KN).**

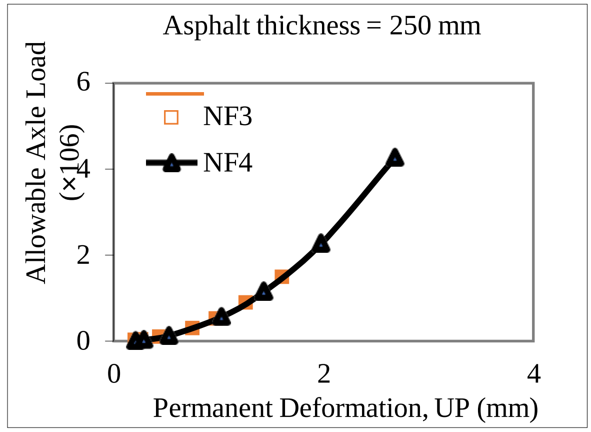


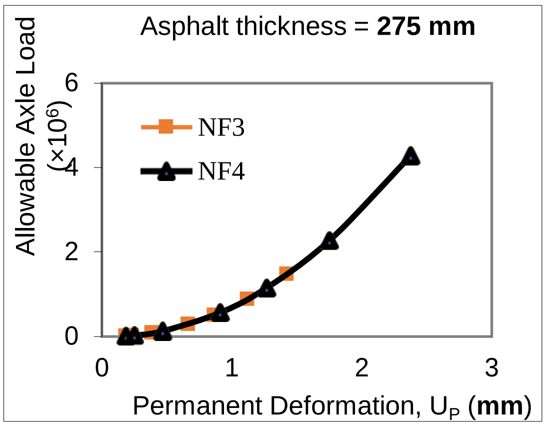




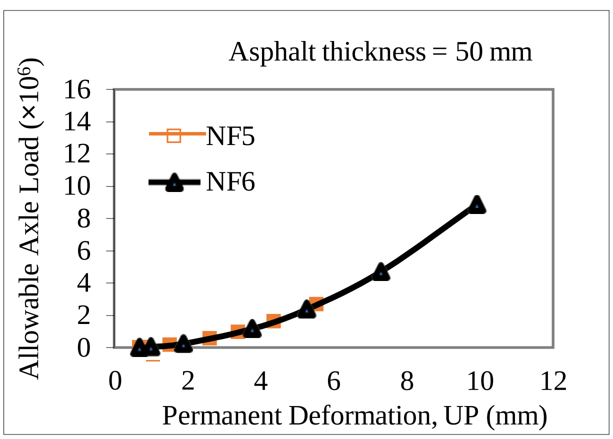


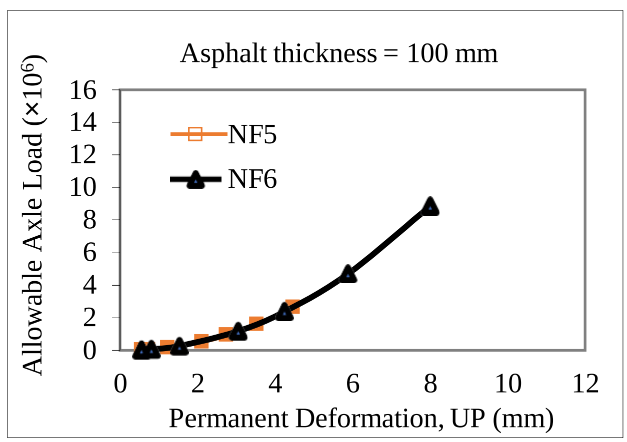


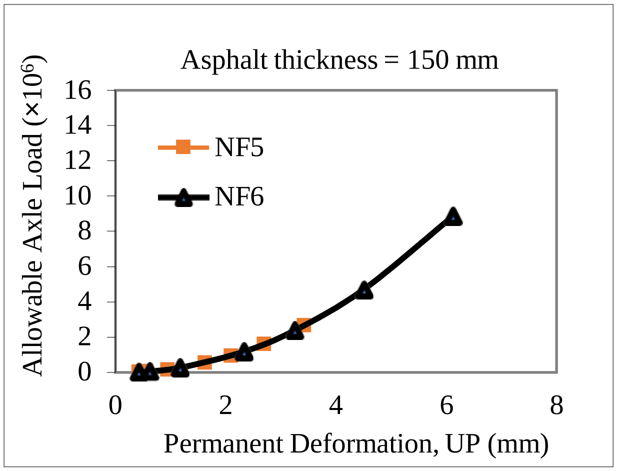


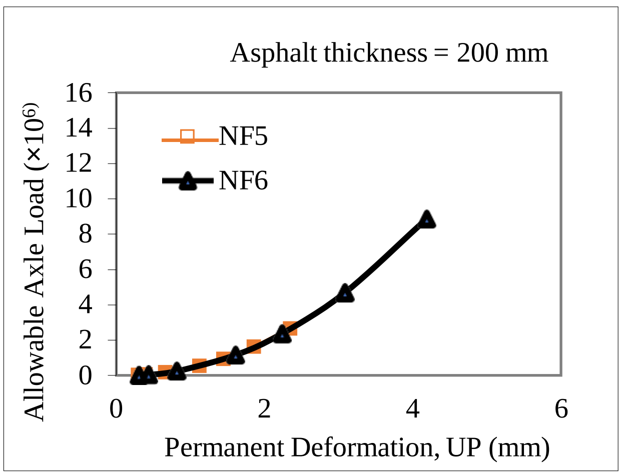


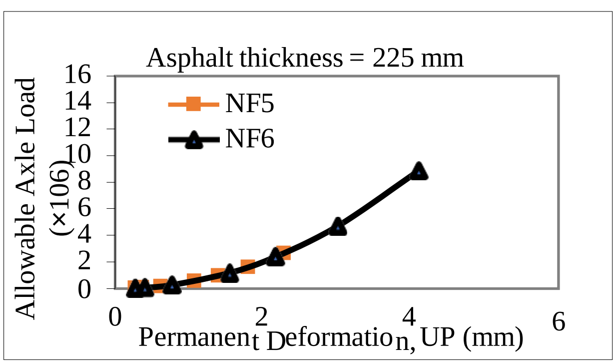
Figures 4. Effect stiffness of asphalt layer, volume of aggregate and bitumen, and air Voids by different thickness of asphalt layer on the rutting damage (Smix = 5800 MPa, Vagg = 90%, Vbit = 6%, and air voids = 4%) for the corresponding to the Equivalent standard axle load (ESAL; 115 or 80 KN).

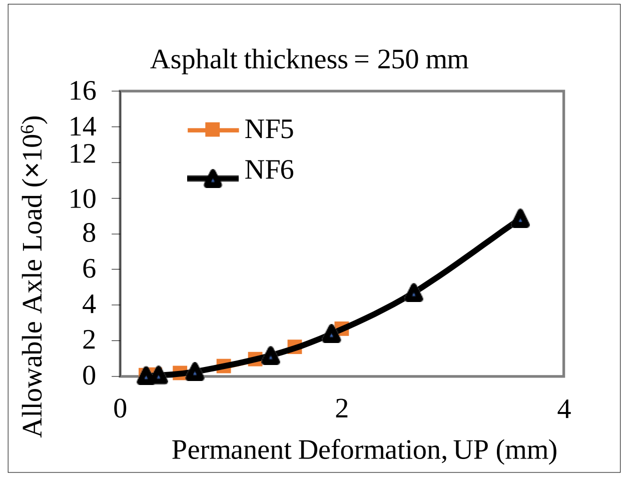


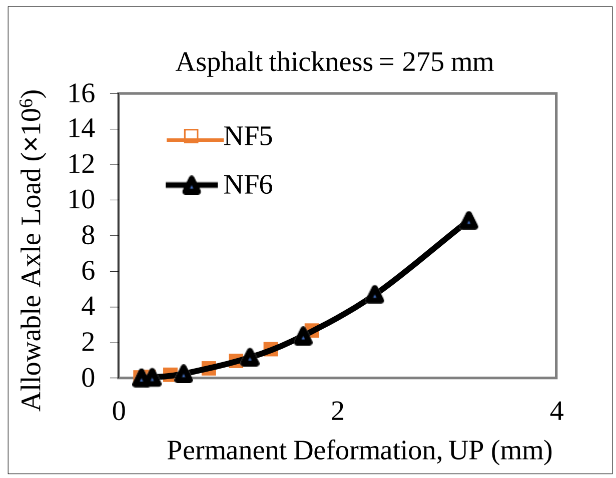












Figures 5. Effect stiffness of asphalt layer, volume of aggregate and bitumen, and air Voids by different thickness of asphalt layer on the rutting damage (S_{mix} = 6700 MPa, V_{agg} = 93%, V_{bit} = 5%, and air voids =2%) for the corresponding to the Equivalent standard axle load (ESAL; 115 or 80 KN).

4- CONCULSION

The following conclusions are reached based on this study's methodology and examination of its findings:

1. Allowable numbers of repetitions (NF1; when Vagg = 83%, Vbit = 11% and air voids = 6%) and (NF2; when Smix is 4800 MPa) are increased when the asphalt layer's thickness is raised.
2. When volume of aggregate in asphalt concrete mixture is increasing from (83% to 90% or 95%), volume of binder in asphalt mixture is decreasing from (11%to 6% or 5%) and, also the air voids in asphalt mixture is decreasing from (6% to 4% or 2%), lead to that (NF5) is increased more than NF3, but there are steeds less than NF1 with increase the thicknesses of asphalt layer.

3. With the increasing stiffness's of mixtures (Smix; from 4800 to 5800 or 6700 MPa), that is led to raising (NF6) more than, (NF4), and that is steeds less than (NF2) with the increasing thickness of the asphalt layer.
4. The Permanent deformation gives high values at lower thickness of asphalt layer and small values at higher thickness of asphalt layer.
5. Allowable numbers of repetitions (NF2, NF4, and NF6) are more sensitive to increase the permanent deformation than (NF1, NF3 or NF6) as shown in Figs (3, 4, and 5).
6. For a 20-year service, the allowable numbers of load repetitions (NF1 to NF6) has been more than the numbers of the Equivalent axle loads repetitions (Ni) at 115 KN or 80 KN, respectively.

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