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Influence of Compressive, Tensile and Fatigue Stresses on Asphalt and Concrete Cement Road Pavements in Nigeria - Using Linear Elastic Theory

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Authors' contributions

This work was carried out in collaboration between all authors. Authors JEO, AIA and ASA designed the study. Author JEO performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors JEO and ASA managed the analyses of the study. Author AIA managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The high brittle nature of pavement structures have been carefully examined based on compressive, tensile strain and the harsh effects of fatigue cycle with reference to the base layer thicknesses and elastic strains during and after construction were examined. Subjection of asphalt and concrete-cement pavements to traffic loading and tyre pressure also influences the vertical stress and strain values for the asphalt and concrete materials under the same axial loading conditions. Using various fundamental equations under linear elastic conditions for the analysis of Asphalt and Concrete Cement structure revealed that both materials do respond differently to compressive and tensile stresses under similar mechanical conditions. Effect of compressive stresses and strains on concrete pavement is larger compare to asphalt pavement due to large thickness sub-base layer of its pavement structure. Both pavement layer thicknesses are independent of fatigue cycle under harsh traffic loading. Thus, concrete pavement has shown better fatigue resistance and less tensile strain values than asphalt pavements due to high pavement layer thickness regardless of the load distribution.

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Keywords: Pavements; fatigue cycle; traffic load; axle pressure and horizontal tensile strains.

1. INTRODUCTION

Defect free, access roads are very important, as they contribute a vital role to the economic development, growth of a country and have important social benefits to humans [1]. A road's defects may be defined as the visible evidence of an undesirable condition in the pavement affecting serviceability, structural condition or appearance [2,3]. Most of the roads in developing countries of Africa are in deplorable conditions where Nigeria is not an exception. Several factors account for this, which include road design, poor maintenance, low quality of materials, inadequate funding, corruption, poor workmanship and supervision, heavy traffic, etc. The subject of road design is considered part of highway engineering as structural road design remains the science of designing a road for its environment in order to extend its longevity and reduce maintenance. Thus, the effect of compressive forces due to traffic load on the road especially at the bend area of the road cannot be over emphasized. It has been discovered that the damages of the roads start from the bends of the road. It is noted that the advancement and technical development of truck production technology most likely causes more distress to road pavements [4]. The response of a pavement structure to traffic loading is calculated by computing stresses and strains within its layers. Excessive compressive stresses or forces which are likely to be the result when vehicles turn through a bend cause pavement fatigue cracking and/or surface defects. This may result in both structural and functional failure of the road [5].

True tyre contact pressure is composed of vertical, transverse and longitudinal contact pressures. The largest component of stress is the vertical contact pressure, the next largest is the transverse contact pressure and the smallest is the longitudinal contact pressure. The transverse and longitudinal contact pressures are similar in magnitude with the vertical component being much larger [6]. There are three types of pavement namely, flexible pavement, rigid pavement and composite pavement.

1.1 Flexible Pavement

A pavement structure that maintains intimate contact with, and distributes loads to the subgrade, depends on the aggregate interlock, particle friction, and cohesion for stability. Cementing agents used are generally bituminous materials, as contrasted to Portland cement in the case of rigid pavements structures. This is also known as bituminous pavement consisting of the combination of mineral aggregates with bituminous binders (Bitumen of various grades and tar). Asphalt is usually flexible and are laid with no reinforcement or with a specialized fabric reinforcement that permits limited flow or repositioning of the road bed underground changes. The design of flexible pavement is based on load distributing characteristics of the component layers. The black top pavement including water and gravel bound Macadam fail in this category. Flexible pavements usually have a design life of between 5 to 20 years.

1.2 Rigid Pavement

This is also known as Portland cement concrete pavement consisting of a relatively rich mixture of Portland cement, mineral aggregate (coarse and fine aggregates) and water laid as a single course over the subgrade. Pavements that will provide high bend resistance and distribute loads to the foundation over a comparatively large surface area must have good mechanical properties in terms of rigidity and flexural strength [7]. The rigid pavement characteristics are associated with rigidity or flexural strength or slab action so the load is distributed over a wide area of subgrade soil. Rigid pavement is laid in slab with steel reinforcement [8]. They have a design life of about 40 years and relatively needs little maintenance. They are used on heavily travelled roads and in water logged area which is economically justified [9]. The principal disadvantage associated with this pavement is that it has a relatively high initial cost for construction when compared with flexible pavements [10].

1.3 Composite Pavement

This consists of reinforced Portland cement concrete overlaid with bituminous concrete. It is mostly recommended where subgrades are of doubtful quality in areas that are extensively disturbed by excavations or where there are shallow service trenches. This pavement occurs where a flexible layer has been added on top of the surface of a rigid road or where a concrete layer exists below a bitumen top surface. This form of construction minimizes the risk of uneven settlement in areas formerly occupied by buildings. Sometimes old cement concrete pavement could be overlaid with bituminous surfacing in city streets. Because of its initial high cost of construction, this form of construction is not recommended if the road will not carry over 2.5million standard axles during its design life [11].

The definition of road defect includes any part of a road, highway or construction site that does not meet the regulation for a safe road. According to Ok-kee et al. Nigeria is ranked one of the worst among all the neighbouring countries in terms of the road network. In a country with scarcely any rail way, a risky air service and now no roads, the citizens of Nigeria feel trapped with no better alternative route to use [12].

The wide use of thin asphalt surfacing in Nigeria which are considered economical, required more studies into understanding the traffic load response of these layers. [13] asserted that the lack of maintenance of roads in Nigeria has become a public issue because it has led to a reduction in travel and luxury buses are having difficulty filling their seats.

Excessive stresses may cause pavement fatigue cracking and surface crumbling which may result in both structural and functional failure, consequently causing safety hazards to motorists and vehicles. These devastation and sufferings are reduced by the use of effective balanced pavement designs. With the ever increasing truck tyres loading and inflation pressures, a better understanding of the pavement stress-strain behaviour is an enhancement in the development of more designed models centred on pavement-traffic load response and distress minimization.

Furthermore, Lee, et al. stated that Nigerian roads are death traps. In the developing world which includes Nigeria, road network is the most developed transport mode and the most used means of transportation [14]. The Nigerian government over the years have tried to construct and rehabilitate the roads. Considerable interest as indicated by the government has been investing in road construction and maintenance. The issue has been addressed to the extent to which such interests have been driven to achieve the desired result.

Okiigbo, (2013), also asserted that roads represent the major areas of investment in transportation and are the most dominant travel mode accounting for over 90% of passengers and goods transport in Nigeria. One of the main problems of road work in Nigeria is the lack adequate data on the Nigerian roads [15]. Some studies have been done on the state of Nigerian roads. Sharad, et al. [16] stated that there was a road network study that was commissioned in 1998/99. This study covered all inters-urban roads which had traffic of more than 30 vehicles/day and a total length of around 53,000 km. Urban roads were not included in this study. The outcome of the study is shown in Table 1. The problems of the Nigerian roads are looked into in this paper and their causes analyzed with the proffering of solutions to these problems. The Nigerian president once said on 11th September 2011 that all contractors that could not live up to contract expectation in their project would be sanctioned. If this threat is well carried out it will go a long way in accelerating job completion in Nigeria. The stress-strain distributions and the three-dimensional stress state in relation to the asphalt surfacing layer thickness are also presented. Stresses in two layer pavement systems were extensively studied by [9,17].The analysis was based on a mechanistic design approach, and a linear elastic two-layer pavement system was adopted. All the layers under the asphalt surfacing (top-layer) were theoretically characterized by one composite elastic modulus (E_2). Consequently, the following design criteria have been discussed;

The response to load of Asphalt Concrete (AC) is best captured with a thermo-sensitive anisotropic non-linear viscoelasto-plastic constitutive theory. For pavement design purposes, AC modeling is currently limited to small-strains and taken as a thermo-rheological simple linear isotropic viscoelastic solid. Such parsimonious description, which is inconsistent with observed behavior, is driven by practicality:

(i) it involves a relatively small set of material parameters and hence easy to comprehend;
(ii) It is simple to calibrate and therefore allows substantial reduction in laboratory workload for characterization; and
(iii) It greatly accelerates subsequent pavement modeling computations, mainly due to the legitimacy of applying superposition. When such a limited-complexity model is imposed on calibration test data, systematic errors are included in the inferred material parameters.

Fig. 1. The asphaltic roads being built by Ikpeazu in Aba (4:42pm on 9th October, 2015)

Fig. 2. Cement roads being built by Ikpeazu in Aba (4:42pm on 9th October, 2015)

According to Xuemei, et al. [18], a new or leans based writer, he stated that the African county of Nigeria has a 120,546 mile network of roads the quality of which is very poor Nigeria annual traffic fatality rate was reported as 5000 in 2009. A major contributor to this statistics is the poor conditions of the roads. Potholes are numerous leading drivers to swerve around them sometimes putting themselves and those in other vehicle at risk. Nigeria has among the highest number of road accidents in the world according to people's dailyonline.com. In the developing world which includes Nigeria, road network is the most developed transport mode and the vastest in usage. The Nigerian government over the year has tried to construct and rehabilitate the roads considerable interest has been shown by the government to road investment. The issue has been the extent these interest has been driven to achieve the desirable result.

Researchers used models that existed for low to normal strength concrete to compare experimental data and model the stress strain curve for permeable concrete. This method of comparison as well as the information obtained in the research done by [5] will be used in this investigation by considering the stress-strain relationship of cement concrete to develop relationships of the stress strain behaviour of asphalt concrete. Ciro, (2012) asserted in his research that the corresponding strain at peak stress greatly affects the ascending and descending branches of the stress-strain curves of concrete and results obtained showed a linear relationship between compressive strength and the corresponding strain under uniaxial compression [19]. A similar relationship was explored for Asphalt-Cement pavement using the uniaxial compression test method. Mahdi, et al. [9] also developed a new tri-axial method to study the failure criteria of asphalt mixtures. An increase in confining pressure (giving smaller compressive strength) showed mainly shear failure and a further increase in confining pressure resulted in rheological failure. In comparison to the uniaxial test, the failure from the tri-axial test would allow for more failure modes to be analyzed. The stress-strain relationship of the specimen tested in [4,5] research showed that larger values of horizontal stress having a curve with an initially ascending limb that levels off after failure of the specimen (or after the elastic state is surpassed).

Most of the theoretical models for mechanical behavior of asphalt concrete are based on the theory of linear viscoelasticity. In these models the linear viscoelastic behavior of asphalt concrete is assumed and the viscoelastic material properties in terms of creep compliance, relaxation modulus, and complex modulus were obtained. Mechanical models such as Maxwell, Kelvin and Burgers models were employed. These models were used to describe the time and temperature dependence of the response of asphalt concrete. A low-temperature cracking model was developed for asphalt concrete by using linear viscoelasticity. Yuhong-Wang, et al. [19] also developed a viscoelastic constitutive model, which incorporated damage growth under cyclic loading linear viscoelastic models could be appropriate to model the low- temperature properties of asphalt concrete. But, at higher temperatures, the deformation of asphalt concrete is non-linear and contains both time dependent and time independent plastic components.

Few attempts have been made to model asphalt concrete as an elasto-viscoplastic material. Prominent among these efforts is the strain decomposition approach. This approach involves decomposing the total strain into elastic, viscoelastic, plastic, and visco-plastic components and modeling the components separately. This model is theoretically sound and it is reported to have been successfully applied to model damage development in asphalt concrete under falling weight deflectometer. Ciro, (2012) also reported a model for rutting and cracking of asphalt concrete using the elasto-viscoplastic approach. Generally, elasto-viscoplastic models are highly sophisticated, contain large numbers of material parameters and thus require substantial effort in material testing and computations [2].

In this study, the elasto-viscoplastic model reported by [6,7] based on strain decomposition approach is used to analyze results of tri-axial creep and recovery test on asphalt-cement and concrete-cement specimens based on traffic load data extract from Nigeria Highways as used in [13] and [1] using MS word Excel 2010 version. Also in the following sections, the material used, specimen preparation and testing procedures are described followed by details of the analysis.

2. METHODOLOGY

The theoretical calculations by multilayer or finite element computer programs are relatively cheap and easy but because the basic assumptions of the behaviour of the tyres and the pavements must be simplified, the results may be unreliable and would be verified. Nevertheless, the scope of the results received by other means can be extrapolated with theoretical calculations.

It is worthy to note that the elasto-viscoplastic model based on strain decomposition approach is used to analyze results based on numerical testing procedure as employed in this work as carried out on some major roads in Ibadan metropolis. The peak stress, peak stain, compressive stress and strains, modulus of elasticity at each stages of deformation were all investigated for proper caption of deformation parameters on asphalts and concrete pavements. Data used were extracted from existing articles with proven results on compressive and tensile stress as imposed on each material.

2.1 Calculation of Strain Components

The elastic strain component is obtained from recovery curve and is equal to the instantaneous decrease in the total strain, which occurs at the moment the load is removed. The plastic strain component is then obtained by subtracting the elastic component from the instantaneous increase in the total strain at the beginning of loading.

Accurate prediction of stress–strain relationship of concrete was conducted to accurately predict the overall structural behavior of reinforced concrete members for the prediction of its behavioral characteristics to axial loading. Since existing literature already shows that existing stress–strain models for unconfined and confined concretes are limited in their application domains, defined by the parametric range of the experimental results considered in their development.

2.2 Other Parameters

This paper presents a simplified linear elastic analysis of the stress-strain behaviour of asphalt surfacing layer and concrete pavement under static traffic loading. According to Lubinda, et al. [1], the top of both asphalt and concrete layers could be modelled by investigating the effects of the variation of the following parameters:

(i) The asphalt surfacing layer and concrete pavement layer thickness (h)
(ii) The material elastic modulus (E_1 and E_2) for asphalt and cement
(iii) The traffic loading (the axle load (Q) and tyre contact pressure (p)

These parameters could be subsequently correlated to the pavement service life in terms of the number of load repetitions to initiation of fatigue cracking (relative fatigue life).

The stress-strain distribution and the three-dimensional stress state in relation to the asphalt and cement surfacing layer thickness and concrete layer are also presented. Stresses in two layer pavements were also investigated in [14, 15] as shown in Fig. 3 below.

2.2.1 Pavement cracking due to fatigue

Fatigue can simply occur on a material when subjected to continued loading over a period of time [14]. It can also be defined as the form of failure that occurs in structures subjected to dynamic and fluctuating stresses. It is the progressive cracking of the surfacing or stabilized base layers due to cumulative repeated traffic loading [15]. This occurs as a result of tensile stresses and strains in the bottom zone and propagates upward to the top. On the pavement surface, it finally manifests different forms of cracks along the wheel tracks as shown in Fig. 4(a) and (b) below.

2.2.2 Fatigue life cycle: Compressive N_C and Tensile N_T

It is an established fact that Fatigue cracking in pavement layers is considered a major structural distress as it is predominantly caused by traffic loading. In addition, ingress of rainwater through the cracks can lead to serious structural failure of the underlying layers particularly granular and unbound materials including the subgrade where the cracks are measured in square meters of the surface area. The general fatigue life prediction equations used to relate tensile stresses or strains to the number of load repetitions to fatigue cracking are sourced from [6] are shown below:

The number of cycles to fatigue due to tensile (N_T) and compressive stress (N_c) at the top of the surface due to axial loading as well as back pressure effect due to tensile stress at the bottom of the asphalt and cement pavement were also investigated.

$$N_C = x^y({}^1/_{\varepsilon_C})^y \tag{1}$$

The strain ratio $X = {}^{\varepsilon_c}/_{\varepsilon_{co}}$ and Stress ratio $Y = {}^{f_c}/_{f_{co}}$ are constants. Similarly, rewriting the relation above, the axial strain becomes the peak compressive strain which in turn results into fatigue cracking due to tensile stress given rise to horizontal crack propagation beneath the surface.

$$N_T = x^y({}^1/_{\varepsilon_{co}})^y \tag{2}$$

Where N_C represents the number of cycles to fatigue due to compressive stress, N_T is the number of cycles to fatigue due to tensile strength.

2.2.3 Axle load and tyre pressure

Effect of traffic loading conditions is determined by the isotropic linear elastic nature of the material used in road constructions. As depicted in Fig. 3 above, Q is the tyre load in kN, P or σ is the vertical Tyre pressure kPa while h is the corresponding asphalt and cement surfacing pavement thickness in mm. while E_1 and E_2 are the elastic moduli due to axial compressive strength for both asphalt and concrete layers in MPa. The analytical model used in this work to measure the response traffic and axle loading is given as:

$$\sigma = 10^3 \frac{Q}{A} = f_c = 4 * 10^3 \frac{Q}{\pi D^2} \tag{3}$$

Where: A is the load-surface contact area in mm^2, and D is the tyre-pavement surface contact diameter in mm.

2.3 Pavement Stresses and Strains

Strain (Ɛ) is defined as the relative deformation (tensile or compressive) of a material in response to stress normally expressed as dimensionless. The following definitions relates strains to stresses for asphalt and cement materials depending on deformation parameters under consideration.

2.3.1 Axial strain $\mathcal{E}_c$

The can be defined as the strain developed on the pavement layer as a result of direct impact of the vertical tyre pressure on the road surface over a long period of time.

2.3.2 Axial stressf_c

This can be defined as the applied axle pressure at the top surface of pavement due to traffic loading. It can also be referred to as the vertical compressive stress from the truck axle as imposed by the tyres.

2.3.3 Axial compressive strain $\mathcal{E}_{co}$

This is defined as the compressive strain obtained at axial compressive stress as a result of traffic loading which is enough to cause plastic deformation at pavement bottom due to cumulative shear tensile stress as imposed by the vehicle tyres on roads over a period of time.

2.3.4 Axial compressive stress f_{co}

This can be defined as the maximum allowable compressive stress imposed by the tyres on the road which is sufficient to cause horizontal crack propagation beneath the surface of the road pavement.

$$\mathcal{E}_{co} = \frac{f_{co}^{0..225k_d}}{1000} \qquad (4)$$

$$K_d = (2400/\rho)^{0.45} \qquad (5)$$

$$K_s = (\frac{2D}{H})^{1.3} \qquad (6)$$

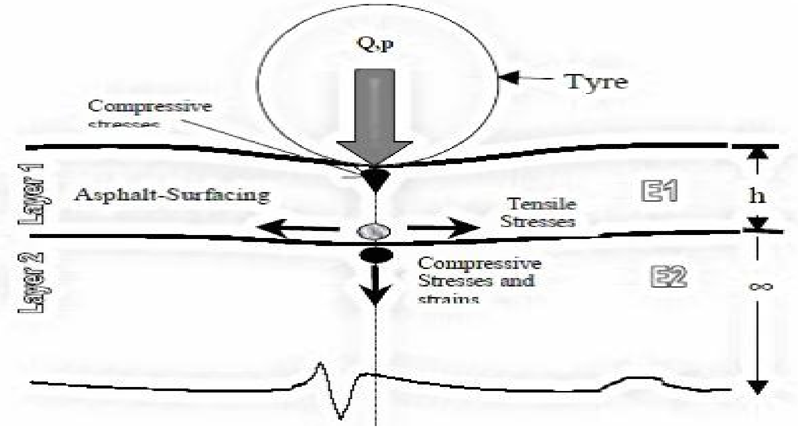
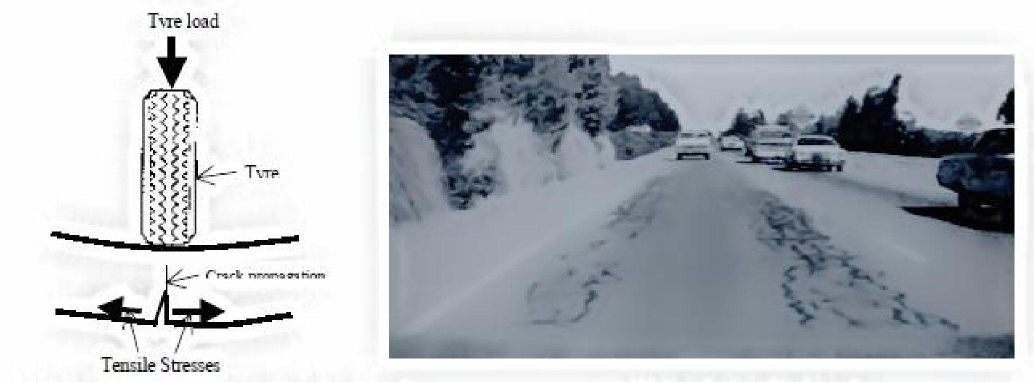


Fig. 3. Simplified two-layer pavement system [1]



(a) Crack development under wheel load

(b) Cracks in wheel tracks

Fig. 4. Cracks due to fatigue stresses on pavement layer [1]

Where f_{co} is in MPa, and ρ is the constant material density in kg/m^3, and D and H are in mm. where K_d and K_s are taken as unity respectively (i.e. K_d=K_s=1). These are the coefficients of specimen's size and specimen aspect ratio for asphalt or concrete materials.

Based on the geometric dimensions of the specimens used in the development of the model expressions, it is recommended in Equations (5) and (6), that the range of aspect ratios (H/D) be limited to constant tyre diameters (D) to 152 mm, and heights (H) to 100-305 mm concrete material and 50-200 mm for asphalt material.

2.4 Peak Stresses and Strains

2.4.1 Elastic moduli E_1 and E_2

Based on the observed difference in asphalt and concrete compressive behavior, cement concretes with a density of 2400 kg/m^3 were categorized as Normal Weight Concrete NMC, whereas asphalt- concretes with a density below the limit (2400 kg/m^3) were categorized as Light Weight Asphalt material [10].

The moduli of elasticity analysis for cement and asphalt layers are calculated using equation 6 below:

$$E_m = 4400\sqrt{f_{co}}\left(\frac{\rho}{2400}\right)^{1.4} \quad (7)$$

Where E_m and ρ are in MPa and kg/m^3 respectively

2.4.2 Peak compressive stress f_{cc}

This can be defined as maximum attainable axle stress as a result of continuous loading of road pavement which is enough to cause horizontal fatigue due to the vertical axle stress.

$$f_{cc} = f_{co} + f_{co}^{0.91}\left({}^{f_c}/_{f_{co}}\right)^{a} \quad (8)$$

Where $a = f_{co}^{-0.06}$

2.4.3 Peak compressive strain Ɛ cc

This can be defined as maximum attainable axle strain as a result of continuous loading of pavement which is enough to cause horizontal fatigue due to the vertical axle stress.

$$\mathcal{E}_{cc} = \mathcal{E}_{co} + 0.045\left({}^{f_c}/_{f_{co}}\right)^{1.15} \quad (9)$$

This work also shows the effect of water which can result into loss of asphalt stiffness due to degradation and stripping. Besides, pavement structural damage, surface rutting poses a serious safety threat to motorists. Water infiltration through pores generally weakens the pavement structure, and therefore, water-loggings on the pavement surface are undesirable.

Therefore, this paper conveniently caters for the effect of compressive stresses and other mechanical properties on existing road pavements through comparative analysis of structural deformed asphalt and concrete cement road pavements where the Tyre Pressure, Axle Load, assigned Layer thicknesses and the asphalt and concrete pavements properties are depicted in Tables 1 and 2 below.

Table 1. The overview of input parameters as used in Microsoft excel 2010 version

Axle load (KN)	Tyre pressure (KPa)	Asphalt layer thickness (mm)	Concrete –layer thickness(mm)
80	500	20	100
90	520	30	134
100	550	50	157
110	600	60	186
120	690	70	205
130	700	75	223
140	750	100	245
150	800	120	265
160	900	150	294
200	1000	200	305

Table 2. Overview of material properties of asphalt-concrete material as inputted in excel 2010 version

Tyre diameter(mm)	Asphalt density(kgm^{-3})	Concrete density(kgm^{-3})
152	2320	2400

3. RESULTS AND DISCUSSION

The results of the calculations using Microsoft Excel 2010 Version is based on the linear-elastic theory as presented below. The Elastic Modulus “E’ values are also calculated to show the worst case scenario. In this analysis as depicted in Fig. 5 to Fig. 14, the number of cycles to fatigue due to compressive and tensile loading respectively for each case of material thickness or height for asphalt and concrete pavements at their respective axle loads and tyre pressures were also investigated.

3.1 Effect Stress-strain Distribution

The stress-strain behavior within the asphalt and concrete surfacing layers for selected thicknesses 20mm-200mm and 100mm-305mm respectively under same traffic loading conditions were investigated as the effect of compressive, tensile and fatigue stresses on the pavement was revealed even as the material properties remains isotropic (i.e. unchanged). In both surfacing, at all instances the axle pressure due reveals a high concentration compressive stresses which progresses vertically downwards from the immediate top zone (Fig. 5(a) and 5(b)). Also, the graph of surface thickness against Peak compressive Stress, Axle Pressure and Tyre pressure for asphalt and concrete pavements are shown in Fig. 5(a) and (5b) below. It is also evident from the figure 5 above that for both materials the peak compressive stress and vehicle axle pressure increases steadily with pavements layer thickness while the tyre pressure remain almost steady regardless of the layer thickness. This may be due to the fact that the weight/load imposed by automobile tyre on asphalt or concrete is quite insignificant compared to the overall weight of the automobile itself. Because tyre weight even for truck are already suspended considering the newton’s second law of motion after inflating the tyre. The Fig. 5 to Fig. 14 below also shows the linearly elastic nature of road pavements for both materials but there is high tendency for the concrete material to last longer due to its higher pavement thickness and high particle compactness and homogeneity. Also, asphalt materials possess lesser particle compactness and homogeneity with less layer thickness during construction, thereby exposing the asphalt layer to severe cracking in little or no time.

As shown in Table 3 below, the axial vertical stress from the axle and the tyre is due to compressive stresses which proceed in similar direction as a result of direct axial loading from the wheels, while the peak compressive axial stress proceeds in similar way. This may likely occur due to continuous traffic loading on the asphalt or concrete material thereby giving rise to horizontal tensile stress as shown in Fig. 5(a) and 5(b) below. The top surface 20mm for asphalt and 100mm for concrete are both subjected to axial loading and tyre pressure, it is evident that the peak compressive stress for both materials were the same (6.7MPa) and they are tensile stresses. As the peak compressive stresses for asphalt surface and concrete layer are also the same irrespective of surface layer thickness. This implies that peak stresses along pavements are almost the same regardless of the depth of the type of material used, as derived in equation 7 above.

The intermediate surfacing at 20mm, 70mm and 150mm for asphalt layer while for concrete layer at 100mm, 205mm and 294mm exhibited the highest peak compressive strains respectively compared to the axial strains at the same layer thickness. The axial strains significantly decrease with layer depth and increases intermediately as surface layer thickness increases for both materials. This is due to the fact that much traffic load is absorbed with intermediate region of the layer depth compared depth. It is also worthy of note the concrete layers has tendency for high load absorbed compared to other road construction materials (e.g. asphalt).

As depicted in Fig. 6 below, the axial (compressive) strain generally increases with layer thickness as the intermediate layer exhibits more sensitivity in terms of strain magnitude. It is known that, from the vertical strain profile above the pavement response to traffic loading for asphalt and concrete materials are largely dependent on factors such as material property in terms of homogeneity and high strength support to sustain the traffic load. Therefore, it appears from the above analysis, that thicker asphalt layer would be required if the material is to perform a similarly traffic load absorption as obtained in concrete pavement for better contribution to the structural integrity of its structural members. Also, thin concrete surfacing layers appears to have essentially less load transfer component ability with high susceptible to fatigue damage which may require high strength support layer for traffic load sustainability compared to asphalt surfacing layer with similar thickness.

3.2 Variation of Composites Surfacing Layer Thicknesses with Elastic Moduli

Considering equation 6 above as used to compute the different elastic moduli at various layer thicknesses. The base of the layer was later revealed that tensile stresses are highly dependent on the composite stiffness for both materials. Stresses for both moduli were of the same magnitude for the respective h-values. The effect of the composite modulus of the underlying layers on the asphalt and concrete response as discussed subsequently Elastic modulus (98MPa) at the intermediate position (at 50mm) for asphalt pavement and concrete pavement (at 100mm) are almost the same. This implies that for concrete structure twice the thickness for asphalt would be required constructing pavement with almost the same material stiffness. Elastic modulus of concrete material is likely to increase with pavement layer thickness which is less achievable for asphalt material because construction of road pavements with concrete requires larger surface layer thickness compared to that of asphalt pavements. Depicted in Fig. 7 below is the thickness range for both materials (i.e. 20-200mm and 100-300mm) the load is absorbed over a greater depth of influence with highest elastic moduli (i.e. 132.7Mpa and 139.1MPa respectively). Such large stiffness may likely have occur as the axle pressure graduate to peak axial stress which in-turn results in tensile stress occurrences at the layer base on continuous application of axial compressive loadings.

Fig. 7 above shows the effect of the composite moduli of the immediate underlying layers on the stress-strain response of the asphalt and concrete layers for the selected thickness 20mm and 100mm respectively, for the same traffic loading of 80kN-4000kPa. As shown in Fig. 7 (a) above, the stresses in the asphalt layer are independent of the stiffness of the underlying layers. The result shown in Fig. 7 above also reflects the overall effect mechanical properties of the asphalt and concrete-cement pavement on their surface layer thicknesses. Variation of the composite modulus E_A and E_C had no effect on the magnitude of both the axle pressure and axial compressive stresses.

For all the surface thicknesses, the axial stress ratio f_c/f_{co} and peak stress ratio f_{cc}/f_{co} proceed steadily as shown in Fig. 8, but varied linearly elasto-plastically with the axial compressive strain Fig. 9 below with respect to both materials been considered. From this, it is apparent that the stress ratio has a little significant effect on the stress-strain response of both asphalt and concrete layers. However, horizontal tensile strains showed an inverse relationship, and increased as the axial compressive strain transcends to the peak compressive strain beneath the layer. In both the surfacing layers, the highest strain values are shown for E_A=132.7MPa and for E_C =139.1MPa. Thus, based on traffic loading pattern, surfacing resting on low strength support layers (base, sub-base, and subgrade) may be potentially susceptible to traffic damage.

This is further evident when comparing the load distribution based on the relative fatigue life of the pavement layer thicknesses at h=20mm for asphalt-cement and 100mm for concrete-cement surface as shown in Fig. 10 and Fig. 11 above at traffic load of 80kN and axle pressure of 500kPa. Also shown in Figs. 10 to 11 below are the graphs of peak compressive stress, axle pressure and axial pressure against axial strain and compressive strains respectively.

In Fig. 10 and Fig. 11 above, both materials shows similar linear elastic mechanistic response to all available loading conditions for both compressive stains and axial stain effect regardless of structures sub-layer thickness. Also observed in Fig. 6 above, thin asphalt surface layers have better tensile stress-strain behavior at low compressive stress ratio than concrete surface layers. Thicker concrete layer shows better mechanical advantage over asphalt layer as load impact are readily absorbed at the top surface of concrete layer of the pavement where lesser load are eventually transmitted to the sub-grade level. But the case is not same for asphalt pavement as traffic loading are readily transmitted to the sub-base and sub-grade layer in little or no distant time.

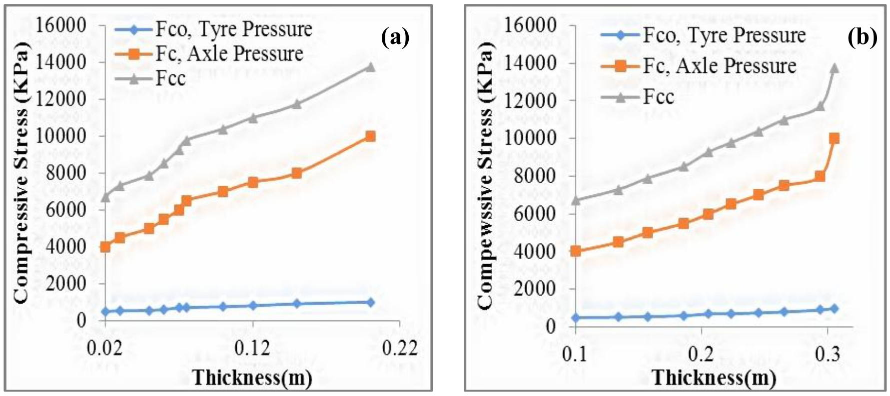


Fig. 5. Graph of layer thickness against peak compressive stress, axle pressure and tyre pressure: (a) Asphalt pavement (b) Concrete pavement

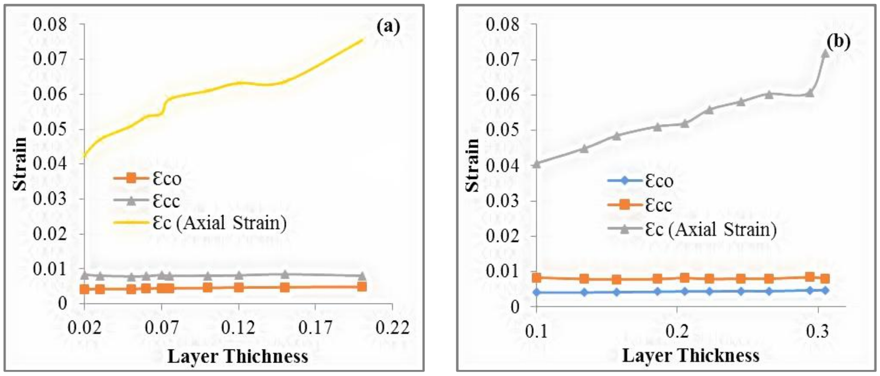


Fig. 6. Graph of layer thickness against peak compressive strain, axial strain and compressive strain: (a) Asphalt pavement (b) Concrete pavement

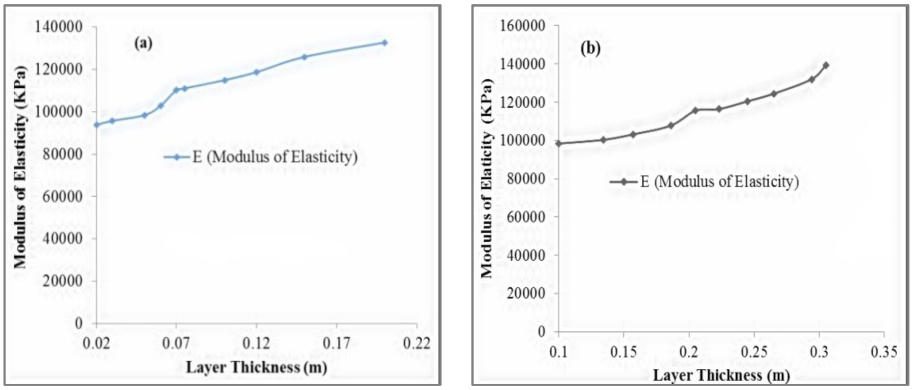


Fig. 7. Graph of layer thickness against elastic modulus: (a) Asphalt pavement (b) Concrete pavement

3.3 Relative Fatigue Life under Compressive and Tensile Strains (Nc and N_T)

Equation 1 and 2 reveals the crack propagation factor as used for calculating the number of load repetitions of the asphalt and concrete layer based on compressive strain (at top surface layer) and tensile strain at the bottom-zone.

3.3.1 Relation between fatigue life (Nc and N_T) and layer thickness (h)

In thick surfacing (h≥100 mm), relative fatigue increases with elastic modulus irrespective of the type of material used. For compressive stress condition, the least number of fatigue load cycles obtained was 1.03×10^{19} (at h=150 mm for asphalt) and 1.25×10^{19} (at h = 100 mm) for concrete. In thin surfacing, (h≤100 mm) relative fatigue life is highest for asphalt but lowest for concrete. This is due to the fact that, the mechanical response of concrete material to repeated traffic load relies more on the material thickness else, failure under repeated load is inevitable. This also agreed with the tensile strain loading conditions at the sub-base of the material as Axle pressure from traffic loads transcends into peak compressive stress within the layer thereby causing shear horizontal strain at the subgrade level for both materials as depicted in Fig.12 and Fig. 13 below.

Fig. 12(a) and Fig. 12(b) have shown that concrete material do have better mechanical response when subjected to repeated fatigue load. Due to high moisture content retention capacity. Uniform load distribution is more attainable on thick concrete materials as shown in Fig. 12(b) above than thin asphalt surfacing as shown in Fig. 12(a) under repeated traffic load which later result into fatigue failure over time. Consequently, this work also revealed in Fig. 13(a) and Fig. 13(b) above, the number of fatigue load cycles under peak strain condition which results into shear tensile strains beneath the surfaces as it propagates regressively as the uniformity of load distribution beneath the surface regressively dies down, but this maybe largely dependent on the load distribution ability and the load absorption capacity of the type of material in use.

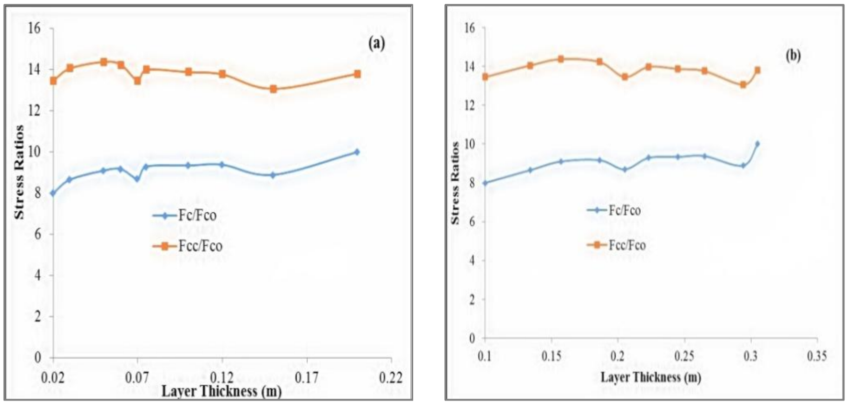


Fig. 8. Graph of layer thickness against axial stress and peak stress ratio (a) Asphalt-cement pavement (b) Concrete cement pavement

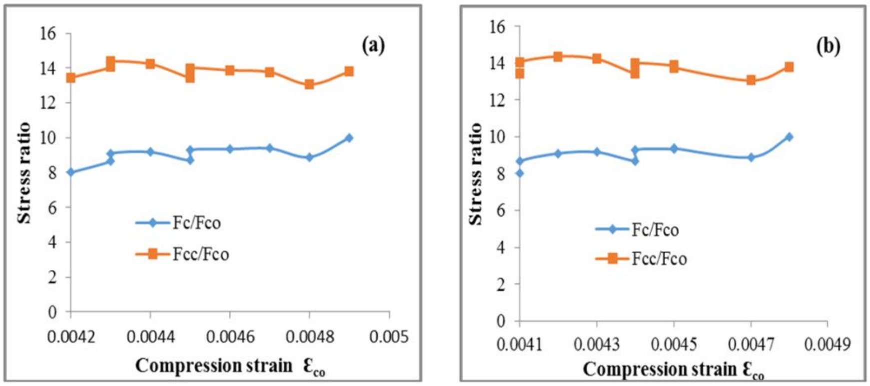


Fig. 9. Graph of Compressive strain against axial stress and peak stress ratios: (a) Asphalt pavement (b) Concrete pavement

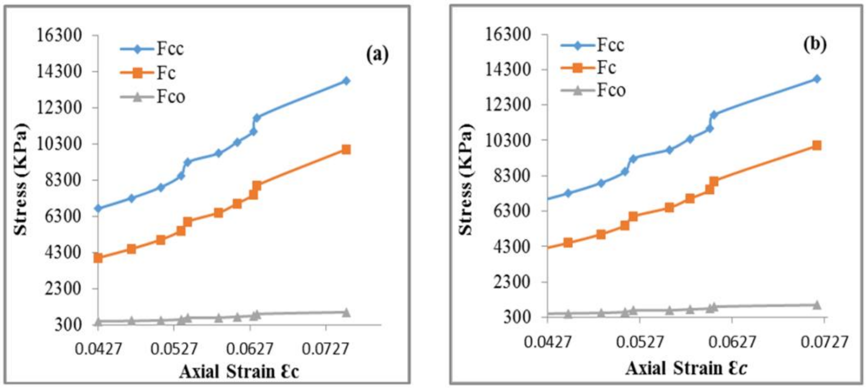


Fig. 10. Graph of axial strain against peak compressive stress, tyre pressure and compressive stresses: (a) Asphalt pavement (b) Concrete pavement

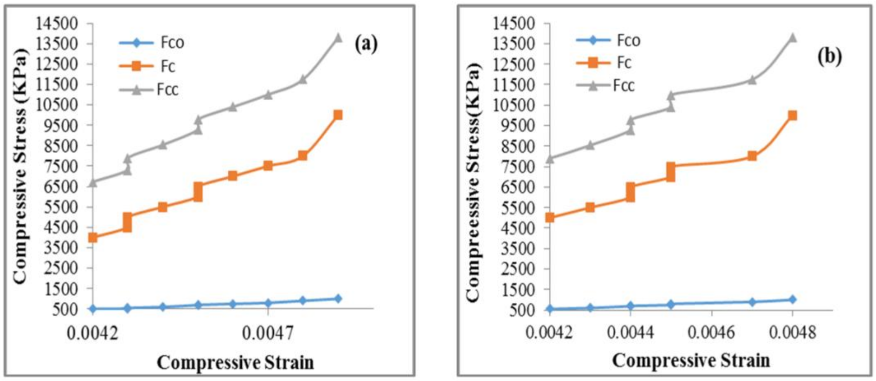


Fig. 11. Graph of compressive strain against compressive stress, tyre pressure and peak compressive stress: (a) Asphalt pavement (b) Concrete pavement

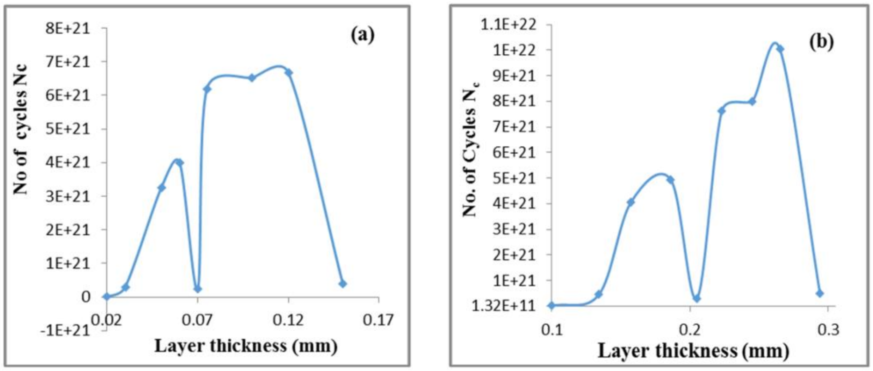


Fig. 12. Graph of layer thickness versus No. of cycle to figure under compression stress at top surface layer: (a) Asphalt pavement (b) Concrete pavement

3.3.2 Fatigue life cycles (N_C and N_T) versus tyre pressure

Effect of variation of axle loading on the relative fatigue life of asphalt and concrete layers respectively are shown below in Fig. 13(a) and 13(b). The least number of fatigue load cycles was obtained under high traffic loading, at 150 KN, 800 KPa for asphalt and 200 KN, 1000 KPa for concrete layer respectively. The

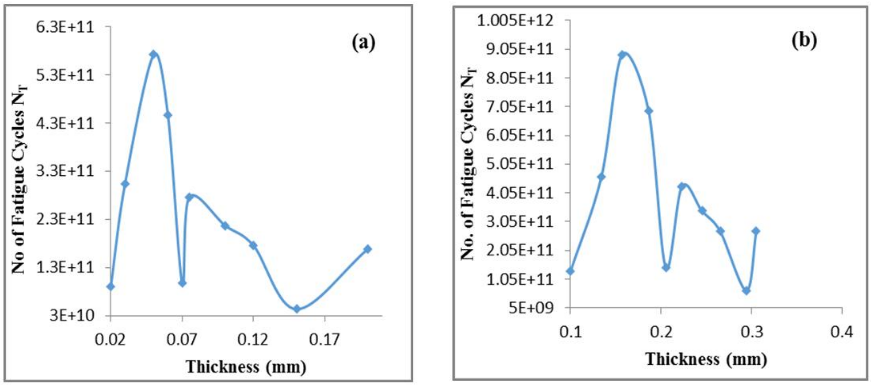


Fig. 13. Graph of layer thickness versus No. of cycle to figure under shear tensile load at Sub-grade level: (a) Asphalt pavement (b) Concrete pavement

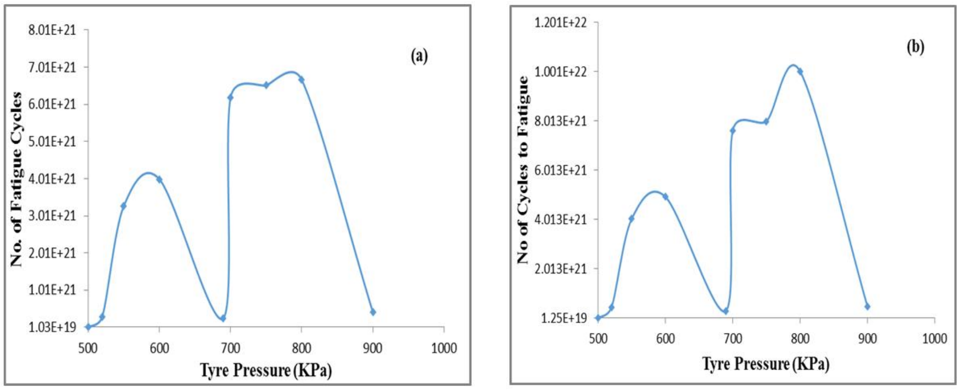


Fig. 14. Graph of layer tyre pressure versus No. of cycle to fatigue under compressive stress at top surface layer for: (a) Asphalt pavement (b) Concrete pavement

highest fatigue is noticed at 200KN for concrete while the same is noticed for asphalt at 150KN which is about 150% overload above 80KN standard axle load. The axle loading appears to have little effect on the relative fatigue life of the 100mm surfacing for concrete pavements but has quite has quite largely affected on asphalt pavement. Thus, whilst in the thicker layers, the relative number of fatigue load cycles to failure decreased with increase in axle loading.

4. CONCLUSION

The use of linear elastic theory to analyse the stress-strain analyses of asphalt and concrete pavements structures have been carefully investigated using vertical compressive stress, tensile strains as the fatigue criteria. It can be concluded that:

- The surface deformation of pavement structures in response to axle loading and tyre pressure have shown that, subjection of asphalt or concrete to the same axle pressure and axial loading shows a tendency for uniform load distribution over a thick surface for concrete while a thin surface of asphalt layer with approximately half layer thickness will exhibit the same ability. Due to the fact that most traffic loadings are transferred to the sub-base layers as the layer depth must be of high quality and strength for the top thin asphalt layer support.
- Vertical Stresses as a result of axial loading of pavement, immensely contributes to the tensile stress (horizontal) which propagate when the pavement structure is overloaded. Axial stress do graduates into peak compressive stress along the layer sub-base sub-grade level for both materials thereby generating a horizontal shear stress under tension.

- Effect of high traffic loading and its possible potential damage on pavement structures regardless of the type of material used in its construction is inevitable, if the actual pavement contact pressure for heavy-duty trucks is not checked for standard specifications (i.e. not more than 700KPa). Also, overloaded trucks should be bound from plying our highways as traffic law and regulations must be enforced on our roads. Proper monitor of the axle loading and tyre pressures must be employed as standard designs must be improvised to cater for the current high traffic challenges.
- Materials made from asphalt or concrete are highly brittle in nature. It is also worthy of note that traffic overload of structures made of such material must be checked. This is due to the fact that fatigue cycle parameters are largely dependent on the mechanistic response of such structure to vertical compressive forces. Moreover, concrete pavements shows a high resistant to fatigue due to its capacity for uniform load distribution over larger sub-base level than the asphalt pavement. This can also occur because of its high particle compactness and homogeneity.
- Larger layer thickness(h>100mm) exhibits lower tensile strain at the sub-grade level for concrete structures while lesser layer thickness may be required for asphalt materials for less tensile strain beneath its layer base.
- The intermediate layer thickness (20<h<200mm for asphalt) and (100<h<305mm) for concrete cement structure have revealed high horizontal tensile strain value with appreciable modulus of elasticity and high sensitivity to fatigue. This is because of the considerable amount of high tensile stress as contributed by the vertical compressive stresses as a result of immense traffic loads. Also, concrete pavement at intermediate positions do possess large fatigue resistance because of its high particle compactness and structural homogeneity strong enough to withstand harsh effect of vertical compressive stress due to traffic loading.
- From the aforementioned analyses, it can be inferred that, thick concrete-cement structures can be more durable than the thin asphalt-cement structures for road pavements constructions due to its ability for uniform load distribution over larger surface, low tensile strain and particle compactness.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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APPENDIX

Table 3. Derived Pavement Stresses and Elastic Modulus for Asphalt-Cement Road Layer

F, axle load (KN)	f_{co}, tyre pressure (KPa)	f_c, Axle pressure (MPa)	f_{cc}, Peak stress, (MPa)	Diameter (m)	Area (m^2)	H, asphalt thickness (mm)	Modulus of elasticity, E_A (MPa)
80	500	4000	6724	0.152	0.02	0.02	93826.42
90	520	4500	7305.04	0.152	0.02	0.03	95684.55
100	550	5000	7898.69	0.152	0.02	0.05	98405.98
110	600	5500	8536.6	0.152	0.02	0.06	102781.69
120	690	6000	9278.53	0.152	0.02	0.07	110221.09
130	700	6500	9784.55	0.152	0.02	0.075	111016.92
140	750	7000	10396.39	0.152	0.02	0.1	114913.42
150	800	7500	11001.08	0.152	0.02	0.12	118682.07
160	900	8000	11745.19	0.152	0.02	0.15	125881.35
200	1000	10000	13784.89	0.152	0.02	0.2	132690.59

Table 4. Derived pavement strains with fatigue life for asphalt-cement road layer

ε_{co}	ε_{cc}	ε_d	Axial strain, ε_c	Fatigue life (Comp.) Nc	Fatigue life (Tension) Nt	Brittleness constant, r	f_c/f_{co}	f_{cc}/f_{co}
0.0042	0.0084	0.14	0.0427	1.033E+19	9.0485E+10	0.0427	8	13.45
0.0043	0.0081	0.12	0.0471	3.017E+20	3.0442E+11	0.0471	8.66	14.05
0.0043	0.0079	0.11	0.0509	3.265E+21	5.71625E+11	0.0509	9.1	14.37
0.0044	0.008	0.11	0.0536	3.997E+21	4.4598E+11	0.0536	9.17	14.23
0.0045	0.0083	0.11	0.0545	2.552E+20	9.7243E+10	0.0545	8.7	13.45
0.0045	0.008	0.1	0.0586	6.189E+21	2.76026E+11	0.0586	9.29	13.98
0.0046	0.0081	0.1	0.061	6.52E+21	2.17231E+11	0.061	9.34	13.87
0.0047	0.0082	0.1	0.0632	6.669E+21	1.75096E+11	0.0632	9.38	13.76
0.0048	0.0085	0.11	0.0636	4.085E+20	4.3245E+10	0.0636	8.89	13.06
0.0049	0.0081	0.09	0.0754	1.253E+23	1.6838E+11	0.0754	10	13.79

Table 5. Derived pavement stresses and elastic modulus for concrete-cement road layer

Axle Load, F (KN)	f_{co}, tyre pressure (KPa)	f_c, Axle pressure (MPa)	f_{cc}, Peak stress, (MPa)	Diameter, D (m)	Area (m^2)	Concrete thickness, h (m)	Modulus of elasticity, E_C (MPa)
80	500	4000	6724	0.152	0.02	0.1	98387
90	520	4500	7305.04	0.152	0.02	0.134	100335.44
100	550	5000	7898.69	0.152	0.02	0.157	103189.15
110	600	5500	8536.6	0.152	0.02	0.186	107777.55
120	690	6000	9278.53	0.152	0.02	0.205	115578.55
130	700	6500	9784.55	0.152	0.02	0.223	116413.06
140	750	7000	10396.39	0.152	0.02	0.245	120498.97
150	800	7500	11001.08	0.152	0.02	0.265	124450.8
160	900	8000	11745.19	0.152	0.02	0.294	132000
200	1000	10000	13784.89	0.152	0.02	0.305	139140.22

Table 6. Derived pavement strains and fatigue life for concrete-cement layer

ε_{co}	ε_{cc}	ε_d	Axial strain, ε_c	Fatigue life (Comp.) N_c	Fatigue life (Tension)N_t	Brittleness constant, r	f_c/f_{co}	f_{cc}/f_{co}
0.0041	0.0083	0.0063	0.0407	1.252E+19	1.32814E+11	0.14	8	13.45
0.0041	0.0079	0.0068	0.0449	4.556E+20	4.60525E+11	0.13	8.66	14.05
0.0042	0.0078	0.0069	0.0485	4.044E+21	8.86752E+11	0.12	9.1	14.37
0.0043	0.0079	0.0067	0.0511	4.934E+21	6.90995E+11	0.12	9.17	14.23
0.0044	0.0082	0.0059	0.052	3.103E+20	1.46281E+11	0.12	8.7	13.45
0.0044	0.0079	0.0063	0.0559	7.625E+21	4.27736E+11	0.11	9.29	13.98
0.0045	0.008	0.0061	0.0581	8.005E+21	3.4226E+11	0.11	9.34	13.87
0.0045	0.008	0.006	0.0603	1.003E+22	2.71973E+11	0.1	9.38	13.76
0.0047	0.0084	0.0053	0.0607	4.926E+20	65478771667	0.11	8.89	13.06

Table 7. Crack Propagation Constants with Respective Material Densities

K_s	K_a	Asphalt_K_d	Concrete_K_d	Asphalt density (Kg/m^3)	Concrete density (Kg/m^3)
1	1	1.02	1.00	2320	2400

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