International Scholars Journals

Advanced Journal of Environmental Science and Technology ISSN 7675-1686 Vol. 5 (3), pp. 001-010, March, 2014. Available online at www.internationalscholarsjournals.org © International Scholars Journals

Full Length Research Paper

Fatigue and rutting strain analysis of flexible pavements designed using CBR methods

Emmanuel O. Ekwulo[1*] and Dennis B. Eme[2]

[1]Civil Engineering Department, Rivers State University of Science and Technology P.M.B. 5080 Port Harcourt, Rivers State, Nigeria.

[2]Civil and Environmental Engineering Department, University of Port Harcourt. Port Harcourt, Rivers State, Nigeria.

Accepted 25 November, 2013

The layered elastic analysis of pavements designed using three known CBR methods; the Asphalt Institute, the National Crushed Stone Association and the Nigerian CBR methods were carried out to evaluate their fatigue strain and rutting deformation characteristics. The elastic properties of the materials were determined. Structural thickness requirement of the pavements were carried out using their respective design charts for a traffic volume of 3000 vehicles/day and expected load repetition of 3.2 x 10^6. Stresses, strains and deflections due to 80 kN single axle load having a tyre pressure of 690.78 kPa were computed by analyzing the effect due to 20 kN single axle load spaced 30.5 mm centre to centre. Strain evaluation was carried out at the underside of the asphalt bound layer and at the top of the subgrade 15.25 mm (midway) between the 20 kN axle loads. The Heukelom and Klomp Model, and the Asphalt Institute Model were used to evaluate pavement response. Results showed that the horizontal tensile strains on the underside of the asphalt bound layer were 355.50, 355.34 and 371.91 μЄ for Asphalt Institute CBR, NCSA CBR and the Nigerian CBR methods respectively. Similarly, the vertical compressive strains at the top of the subgrade were found to be -924.033, -906.7 and -774.24 μЄ for Asphalt Institute CBR, NCSA CBR and the Nigerian CBR methods respectively. The resulting fatigue and rutting strains were compared with the permissible values using the Heukelom and Klomp Model, and it was found that the computed vertical compressive strains were more than permissible values. In terms of fatigue, the damage factors were found to be less than 1.0 while in terms of rutting, the damage factors were greater than 1.0 for both models. It was concluded that flexible pavements designed using the three known CBR methods are prone to failure due rutting deformation and recommended the use of mechanistic procedures in the design of flexible pavements in developing tropical countries. The study was carried out with the layered elastic analysis software EVERSTRESS.

Key words: Layered elastic analysis, fatigue, rutting, strains, design, flexible pavement, CBR.

INTRODUCTION

Studies in pavement engineering have shown that the design procedure for highway pavement is either empirical or mechanistic. An empirical approach is one which is based on the results of experiments or experience. This means that the relationship between design inputs and pavement failure were arrived at through experience, experimentation or a combination of both. The mechanistic approach involves the determination of material parameters for the analysis, at conditions as close as possible to what they are in the road structure. The mechanistic approach is based on the elastic or visco-elastic representation of the pavement structure. In mechanistic design, adequate control of pavement layer thickness as well as material quality are ensured based on theoretical stress, strain or deflection analysis. The analysis also enables the pavement designer to predict with some amount of certainty the life of the pavement.

Pavement failures in most developing tropical countries have been traced to any or combination of geological, geotechnical, design, construction, and maintenance problems (Ajayi, 1987). While several researches have

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*Corresponding author. E-mail: eoekwulo1@yahoo.com. Tel: +234-8033421341 been carried out in these countries to investigate the contribution of each of these factors, the design factor has in most cases been overlooked. It is generally known that failure of asphalt pavement is due to fatigue cracking and rutting deformation, caused by excessive horizontal tensile strain at the bottom of the asphalt layer and vertical compressive strain on top of the subgrade. In the design of asphalt pavement, it is necessary to investigate these critical stresses and strains and design against them. While there have been moves towards the use of the mechanistic approach in pavement design in many developed countries, the use of the empirical California Bearing Ratio (CBR) procedure is still gaining ground in some developing tropical countries even when the original owners of the procedures have long began the application of the mechanistic approach to pavement design.

The purpose of this paper is to use the mechanistic procedure (layered elastic analysis) to investigate failure due to fatigue cracking and rutting deformation in flexible pavements designed by CBR procedures. The use of the layered elastic analysis concept is necessary in that it is based on the elastic theory (Yang, 1973) and can be used to investigate excessive horizontal tensile strain at the bottom of the asphalt layer(fatigue cracking) and excessive vertical compressive strain on top of the subgrade (Rutting deformation) in asphalt pavement in order to design against them. This is not the case with the CBR procedure, the CBR procedure determines thickness of asphalt pavement but does investigate fatigue and rutting strains that cause failure in asphalt pavement.

Elastic layered system

The response of pavement systems to wheel loading has been of interest since 1926 when Wetergaard used elastic layered theory to predict the response of rigid pavements (Westergaard, 1926). It is generally accepted that pavements are best modeled as a layered system, consisting of layers of various materials (concrete, asphalt, granular base, sub-base etc.) resting on the natural subgrade. The behaviour of such a system can be analyzed using the classical theory of elasticity (Burmister, 1945). The Layered Elastic Analysis (LEA) is a mechanistic procedure capable of determining pavement responses (stress and strain) in asphalt pavement. The major assumptions in the use of layered elastic analysis are that;

i) The pavement structure is regarded as a linear elastic multilayered system in which the stress-strain solution of the material are characterized by the Young's modulus of Elasticity E and poison's ratio μ.

ii) Each layer has a finite thickness h except the lower layer, and all are infinite in the horizontal direction.

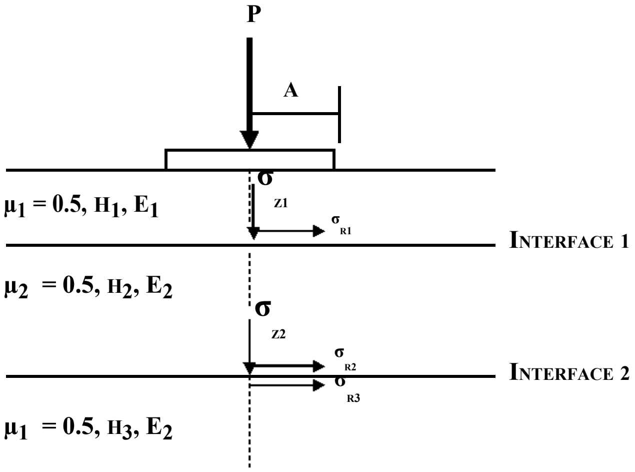

Figure 1. Three –layer pavement system showing location of stresses

iii) The surface loading P can be represented vertically by a uniformly distributed vertical stress over a circular area.

Layered elastic analysis

In multilayered pavement system (Yoder and Witczak, 1975), the locations of the various stresses in a three-layered pavement system are as shown in Figure 1. The horizontal tensile strain at the bottom of the asphalt concrete layer and vertical compressive strain at the top of the subgrade are given by equations 1.0 and 2.0 respectively;

$$\epsilon_{r1} = \frac{\sigma_{r1}}{E_1} - \propto_1 \frac{\sigma_{r1}}{E_1} - \propto_1 \frac{\sigma_{z1}}{E_1} \qquad (1.0)$$

$$\epsilon_{z1} = \frac{1}{E_3}\left(\sigma_{z2} - \sigma_{r3}\right) \qquad (2.0)$$

Where;

σ_{z1} = vertical stress at interface 1 (bottom of asphalt concrete layer)

σ_{z2} = vertical stress at interface 2

σ_{r1} = horizontal stress at the bottom of layer 1

σ_{r2} = horizontal stress at the bottom of layer

2 σ_{r3} = horizontal stress at the top of layer 3

E_1 *and* E_3 are Modulus of elasticity of layer 1 and 3 receptively.

$\propto$ = Poisson's ratio of the layer

A number of computer programs based on layered elastic theory (Burmister, 1945) have been developed for layered elastic analysis. The program CHEV (Warren and Dieckman, 1963) developed by the Chevron Research Company can be applied to linear materials, however, Huang and Witczak (1981) modified the program to account for material non-linearity and named it DAMA. The DAMA computer program can be used to analyze a multi-layered elastic pavement structure under single or dual-wheel load, the number of layers cannot exceed five. In DAMA, the subgrade and the asphalt layers are considered to be linearly elastic and the untreated subbase to be non-linear, instead of using iterative method to determine the modulus of granular layer, the effect of stress dependency is included by effective elastic modulus computed according to equation 3.0.

$$E_2 = 10.447 h_1^{-0.471} h_2^{-0.041} E_1^{-0.139} E_3^{-0.287} K_1^{0.868} \qquad (3.0)$$

Where; E_1, E_2, E_3 are the modulus of asphalt layer, granular base and subgrade respectively; h_1, h_2 are the thicknesses of the asphalt layer and granular base. K_1 and K_2 are parameters for K-θ model with $k_2 = 0.5$

ELSYM5 developed at the University of California is a five layer linear elastic program for the determination of stresses and strains in pavements (Ahlborn, 1972). The KENLAYER computer program developed at the University of Kentucky in 1985 incorporates the solution for an elastic multiple-layered system under a circular load. KENLAYER can be applied to layered system under single, dual, dual-tandem wheel loads with each layer material properties being linearly elastic, non-linearly elastic or visco-elastic.

The Everstress (Sivaneswaran et al., 2001) layered elastic analysis program from the Washington State Department of Transportation was developed from WESLEA layered elastic analysis program. The pavement system model is multilayered elastic using multiple wheel loads (up to 20). The program can analyze hot mix asphalt (HMA) pavement structure containing up to five layers and can consider the stress sensitive characteristics of unbound pavement materials. The consideration of the stress sensitive characteristics of unbound materials can be achieved through adjusting the layer moduli in an iterative manner by use of stress-modulus relationships in equations 4.0 and 5.0;

$E_b = K_1 \theta K_2$ for granular soils (4.0)

$E_b = K_3 \sigma_d K_4$ for fine grained soils (5.0)

Where;

E_b = Resilient modulus of granualar soils (ksi or MPa)
E_s = Resilient modulus of fine grained soils (ksi or MPa)
Θ = Bulk stress (ksi or MPa)
σ_d = (Deviator stress (ksi or Mpa) and
K_1, K_2, K_3, K_4 = Regression constants

K_1, and K_2, are dependent on moisture content, which can change with the seasons. K_3, and K_4 are related to the soil types, either coarse grained or fine-grained soil. K_2 is positive and K_4 is negative and remain relatively constant with the season.

Failure criteria in mechanistic analysis

The use of mechanistic approach requires models for relating the output from elastic layered analysis (that is stress, strain, or deflections) to pavement behaviour(e.g. performance, cracking, rutting, roughness etc). As elastic theory can be used to compute only the effect of traffic loads, most of the principles in mechanistic design of highway pavements are based on limiting strains in the asphalt bound layer (fatigue analysis) and permanent deformation (rutting) in the subgrade.

Fatigue cracking is a phenomenon which occurs in pavements due to repeated applications of traffic loads. The fatigue criterion in mechanistic design approach is based on limiting the horizontal tensile strain on the underside of the asphalt bound layer due to repetitive loads on the pavement surface, if this strain is excessive, cracking (fatigue) of the layer will result. Various researchers have shown that the relationship between load repetitions to failure N_f and strain for asphalt concrete material is dependent on the horizontal tensile strain at the bottom of the asphalt bound layer and the elastic modulus of the asphalt concrete.

Heukelom and Klomp (1962) suggested relationship between the number of load repetitions to failure and strain in asphalt concrete as follows:

$$N_f = 10^{-X} \qquad (6.0)$$

Where;
N_f = Number of load applications to failure
$X = 5\log \varepsilon_t + 2.665\log_{10}(E/14.22) + 0.392$

ε_t = Horizontal tensile strain at the bottom of asphalt bound layer
E = Elastic Modulus of asphalt concrete

The allowable horizontal tensile strain at the bottom of asphalt concrete layer according to Heukelom and Klomp, (1962) is given by:

$$\epsilon_{AC} = 10^{-A} \qquad (7.0)$$

Where;
ϵ_{AC} = Allowable Strain at the bottom of the asphalt layer
$A = (\log_{10}N_i + 2.665\log_{10}(E/14.22) + 0.392)/5$

N_i = Number of actual repetitions
E = Elastic Modulus of Asphalt Concrete

The asphalt institute (Asphalt Institute, 1982) suggested that the relationship between fatigue failure of asphalt concrete and tensile strain is represented by the number of load repetitions as follows:

$$N_f = 0.0796(\varepsilon_t)^{-3.291}(E)^{-0.854} \qquad (8.0)$$

Where;
N_f = Number of load applications to failure
ε_t = Horizontal tensile strain at the bottom of asphalt bound layer
E = Elastic Modulus of asphalt concrete

Permanent deformation or rutting is a manifestation of both densification and permanent shear deformation. As a mode of distress in highway pavements, pavement design should be geared towards eliminating or reducing rutting in the pavement for a certain period. Rutting criterion is based on limiting the vertical compressive subgrade strain, if the maximum vertical compressive strain at the surface of the subgrade is less than a critical value, then rutting will not occur for a specific number of traffic loadings. The magnitude of rutting has been correlated with the amount of traffic and the vertical compressive strain level at the surface of the subgrade. For permanent deformation, Heukelom and Klomp (1962) expressed the relationship between the number of repetitions to failure and the vertical compressive strain level at the surface of the subgrade as follows:

$$N_f = 10^{-X} \qquad (9.0)$$

Where;
N_f = Number of load applications to failure
X = $(2.408 + \log \varepsilon_c)/0.1408$
ε_c = Vertical compressive strain at the surface of the subgrade

The allowable vertical compressive strain at the top of the subgrade (Heukelom and Klomp, 1962) is given by:

$$\epsilon_{SUBG} = 10^{-A} \qquad (10.0)$$

Where;
ϵ_{SUBG} = Allowable vertical compressive strain at the top of subgrade
A = $0.1408\log_{10}N_i + 2.408$

The relationship between rutting failure and compressive strain at the top of the subgrade is represented by the number of load applications as suggested by asphalt institute (Asphalt Institute, 1982) in the following form:

$$N_f = 1.365 \, x \, 10^{-9}(\varepsilon_c)^{-4.477} \qquad (11.0)$$

Where;
N_f = Number of load applications to failure
ε_c = Vertical Compressive strain at the bottom of asphalt bound layer

In mechanistic design, failure criterion (transfer function) is used to define the point at which failure occurs in a pavement by determining the incremental damage. The incremental damage is simply the number of a particular axle load expected during a given design period divided by the number of repetitions to failure. The incremental damage is summed for all axle loads to obtain the expected damage factor over the life of the pavement. The damage factor is given by:

$$D = \sum \underline{N_i} \qquad (12.0)$$

Where;
D = Damage factor
N_i = Actual number of load repetitions
N_r = Number of load repetitions to failure

If D is less than a value of one, then the pavement can be expected to exceed its design life, if D is greater than one, the pavement is expected to fail prematurely. If this value is much less than one, the pavement is probably designed too conservatively.

CBR DESIGN METHODS

The CBR method of pavement design was first used by the California Division of Highways as a result of extensive investigations made on pavement failures during the years 1928 and 1929 (Corps of Engineers, 1958). To predict the behaviour of pavement materials, the CBR was developed in 1929. Tests were performed on typical crushed stone representative of base course materials and the average of these tests designated as a CBR of 100%. Samples of soil from different road conditions were tested and two design curves were produced corresponding to average and light traffic conditions. From these curves the required thickness of Sub-base, base and surfacing were determined. The investigation showed that soils or pavement material having the same CBR required the same thickness of overlying materials in order to prevent traffic deformation. So, once the CBR for the subgrade and those of other layers are known, the thickness of overlying materials to provide a satisfactory pavement can be determined. The US corps of Engineers adopted the CBR method for airfield at the beginning of the Second World War Since then; several modifications of the original design curves have been made (Oguara, 2005). The relationship between pavement thickness and CBR is as stated in equation 13.0 (Yoder and Witczak, 1975).

$$t = \sqrt{W\left(\frac{1}{8.1CBR} - \frac{1}{p\pi}\right)} \qquad (13.0)$$

This and other relationships have been used to derive other charts for flexible pavements.

The Asphalt Institute CBR Method

Although the Asphalt institute has developed a new thickness design procedure base on the mechanistic approach (Asphalt institute, 1981), the original asphalt institute thickness design procedure is based on the concept of full depth asphalt that is, using asphalt mixtures for all courses above the subgrade or improved subgrade. Traffic analysis is in terms of 80 kN equivalent single axle load in the form of a Design Traffic Number, DTN. The DTN is the average daily number of equivalent 80 kN single-axle estimated for the design period. The CBR, Resistance value or Bearing value from plate loading test is used in subgrade strength evaluation. The Thickness of the Asphalt pavement structure layer is determined using Asphalt Institute design chart and is dependent on the CBR, and DTN. The recommended minimum total asphalt pavement (T_A) is given as shown in Table 1.

The national crushed stone association CBR method

The National Crushes Stone Association (NCSA) empirical design method (NCSA, 1972) is based on the US Corps of Engineers pavement design. Traffic analysis is based on the average number of 80 kN single-axle loads per lane per day over a pavement life expectancy of 20 years. The method incorporates a factor of traffic in the design called Design Index (DI). In the absence of traffic survey data, general grouping of vehicles can be obtained from spot checks of traffic and placed in one of the three groups as follows:

Group 1: Passenger cars, panel and pickup trucks
Group 2: Two-axle trucks loaded or larger vehicles empty or carrying light loads
Group 3: All vehicles with more than three loaded axles

Subgrade strength evaluation is made in terms of CBR and compaction requirement is provided to minimize permanent deformation due to densification under traffic. In the NCSA design procedure, the thickness of the pavement as determined using the NCSA chart is dependent on the CBR and flexible pavement design index.

Table 1. The recommended minimum total asphalt pavement (T_A).

Traffic	DTN	Minimum T_A(mm)
Light	Less than10	100
Medium	10 - 100	125
Heavy	100 – 1000	150
	More than 1000	175

The Nigerian CBR method

The Nigerian (CBR) design method is an empirical procedure which uses the California Bearing Ratio and traffic volume as the sole design inputs. The method uses a set of design curves for determining structural thickness requirement. The curves were first developed by the US Corps of Engineers and modified by the British Transportation and Road Research Laboratory (TRRL, 1970), it was adopted by Nigeria as contained in the Federal Highway Manual (Highway Manuel, 1973). The Nigerian (CBR) design method is a CBR-Traffic volume method, the thickness of the pavement structure is dependent on the anticipated traffic, the strength of the foundation material (CBR), the quality of pavement material used and the construction procedure. This method considers traffic in the form of number of commercial vehicles/day exceeding 29.89 kN (3 tons). Subgrade strength evaluation is made in terms of CBR. The selection of pavement structure is made from design curves. The thickness of the pavement layers is dependent on the expected traffic loading. Recommended minimum asphalt pavement surface thickness is considered in terms of light, medium and heavy traffic as follows:

Light traffic - 50 mm
Medium - - 75 mm
Heavy - 100 mm

METHODOLOGY

The traffic data used for thickness design using the three CBR procedures is as shown below:

Facility: 6-lane highway
No. of vehicles per day: 3,0000veh/day
Traffic growth rate: 6%
Design period: 20 years

Table 2. Pavement material properties and thickness.

Layer No.	Material	CBR (%)	Resilient modulus, E (Mpa)	Poison's Ratio	Thickness of pavement layer (mm)		
					Asphalt institute CBR	NCSA CBR	Nigerian CBR
1	Surface (Asphalt Concrete)	-	5,000	0.35	100	100	100
2	Base (granular material)	80	824	0.40	182	200	210
3	Subbase(stabilized)	30	309	0.45	-	-	120
4	Subgrade	8	82.4	0.45	-	-	-

Table 3. Result of layered elastic analysis using everstress.

CBR procedure	Layer No.	Depth: Z Position (cm)	Horizontal tensile strain at the bottom of the asphalt Layer $(X\ 10^{-6})$		Vertical compressive strain at the top of subgrade $(X10)^{-6}$
			E_{xx}	E_{yy}	E_{zz}
	1	9.999	355.5	112.01	-
Asphalt institute CBR	4	28.201	-	-	924.03
	1	9.999	355.34	111.83	-
NCSA CBR	4	30.001	-	-	906.74
	1	9.999	371.91	124.31	-
Nigerian CBR	4	43.001	-	-	774.24

ESAL: 3.2×10^6
Expected Traffic, N_{i} ; = 3.2×10^6

Material Characterization was carried out in the laboratory to determine the CBR and resilient modulus of the pavement materials as shown in Table 2. Pavement thicknesses were determined using the three CBR procedures and analysis carried using the pavement material properties. The Everstress (Sivaneswaran et al., 2001) layered elastic analysis software was employed in the the simulation of stresses, fatigue and rutting strains in the designed pavements. Stresses, strains and deflection due to 80 kN single axle load having a tyre pressure of 690.78 kPa was computed by analyzing the effect due to 20 kN single axle load spaced 30.5 mm centre to centre. Evaluation of fatigue and rutting strains were carried out on the underside of the asphalt bound layer and on top of the subgrade at 15.25 mm (X=0, Y = 15.25) between the 20 kN axle loads. The Heukelom and Klomp (1962) model, and the Asphalt Institute (1982) model were adopted in the analysis of the pavement response.

RESULT AND DISCUSSION

The result of structural thickness design carried out for the three CBR methods are presented in Table 2, while the result of the layered elastic analysis by Everstress are presented in Table 3. The pavement response using Heukelom and Klop (1962) and Asphalt Institute (1982) models are presented in Tables 4 and 5 respectively.

Results show that the computed maximum horizontal tensile strain at underside of the asphalt concrete layer for the Asphalt Institute, NCSA and Nigerian CBR methods are 355.50, 355.34 and 371.91 µЄ respectively. Using the Heukelom and Klomp model, the permissible tensile strain as presented in Table 4 for the expected traffic is 1820 µЄ, and the number of load repetitions to failure are 1.2×10^{10}, 1.0×10^{10} and 9.3×10^{9} resulting in damage factors of 2.7×10^{-4}, 3.2×10^{-4} and 3.4×10^{-4} for the Asphalt Institute, NCSA and Nigerian CBR methods respectively. With respect to the Asphalt Institute model, the number of load repetitions to failure for the computed strains are 1.20×10^{7}, 1.24×10^{7} and 1.06×10^{7} resulting in damage factors of 0.27, 0.26 and 0.30 for the Asphalt Institute, NCSA and Nigerian CBR methods respectively. This implies that fatigue failure due to fatigue cracking will not occur in the pavements since the computed strains are less than the permissible value and the damage factors are less than 1.

Similarly, the computed vertical compressive strain on top of the subgrade are -924.03, -906.74 and -774.24 µЄ for the Asphalt Institute, NCSA and Nigerian CBR methods respectively. Using the Heukelom and Klomp model, the permissible compressive strain as presented in Table 4 for the expected traffic is 478 µЄ, and the number of load repetitions to failure are 2.8×10^{4}, 3.2×10^{4} and 1.0×10^{5} resulting in damage factors of 114, 100 and 32 for the Asphalt Institute, NCSA and Nigerian CBR procedures respectively. With respect to the Asphalt Institute model, the number of load repetitions to failure for the computed strains as presented in Table 5 are 5.3×10^{4}, 5.7×10^{4} and1.2×10^{5} resulting in damage factors of 61, 56 and 28 for the Asphalt Institute, NCSA and Nigerian CBR methods respectively. This result

Table 4. Fatigue and rutting failure analysis based on Heukelom and Klomp response model (1962).

Procedure	Fatigue Criterion				Rutting Criterion			
	Actual Strainε_t (10^{-6})	Allowable Strain ϵ_t (10^{-6})	No. of Repetitions to Failure N_f	Damage Factor $D = N_i/N_f$	Actual Strain ε_c (10^{-6})	Allowable Strain ϵ_c (10^{-6})	No. of Repetitions to Failure N_r	Damage factor $D = N_i/N_r$
Asphalt institute CBR	355.5	1820	1.2×10^{10}	2.7×10^{-4}	924.03	478	2.8×10^{4}	114
NCSA CBR	355.34	1820	1.0×10^{10}	3.2×10^{-4}	906.74	478	3.2×10^{4}	100
Nigerian CBR	371.91	1820	9.3×10^{9}	3.4×10^{-4}	774.24	478	1.0×10^{5}	32

Table 5. Fatigue and Rutting Failure Analysis Based on Asphalt Institute Response Model (1982)

Procedure	Fatigue Criterion			Rutting Criterion		
	Actual Strainε_t (10^{-6})	No. of Repetitions to Failure N_f	Damage Factor $D = N_i/N_f$	Actual Strainε_c (10^{-6})	No. of Repetitions to Failure N_r	Damage Factor $D = N_i/N_r$
ASPHALT INSTITUTE CBR	355.50	1.20×10^{7}	0.27	924.03	5.3×10^{4}	61
NCSA CBR	355.34	1.24×10^{7}	0.26	906.74	5.7×10^{4}	56
NIGERIAN CBR	371.91	1.06×10^{7}	0.30	774.24	1.2×10^{5}	28

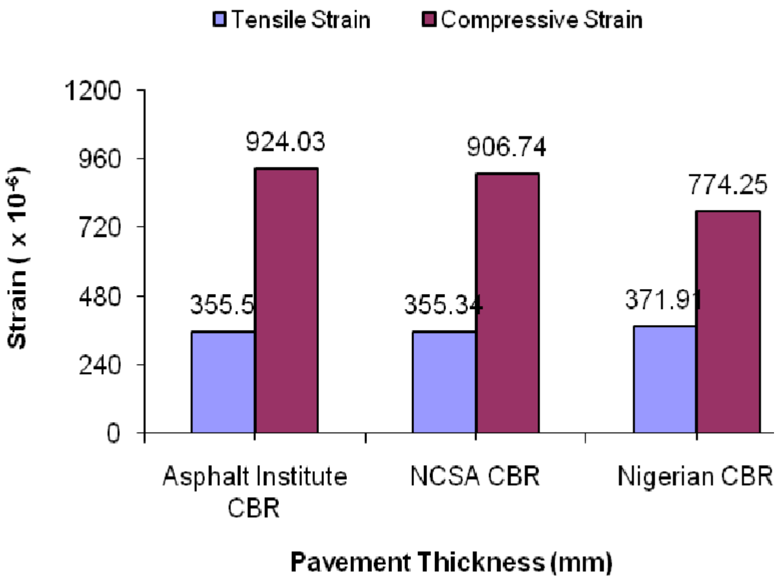

Figure 2. Tensile and compressive strain, and design methods

indicates that rutting failure will occur in the pavement as a result of rutting deformation since the computed strains are greater than the permissible value and the damage factors are greater than 1.

Result of the three CBR procedures shows that in terms of strains, the Nigerian CBR procedure recorded the highest tensile strain of 371.91 µЄ while the NCSA recorded the least tensile strain of 355.50 µЄ at the bottom of the asphalt concrete layer. Similarly, the Asphalt Institute procedure recorded the highest compressive strain of 924.03 µЄ while the Nigerian CBR procedure recorded the least compressive strain on top of the subgrade as shown in Figure 2.

In terms of pavement response using the Heukelom and Klomp model, as shown in Figure 3a, the Asphalt Institute procedure recorded the best result in terms of

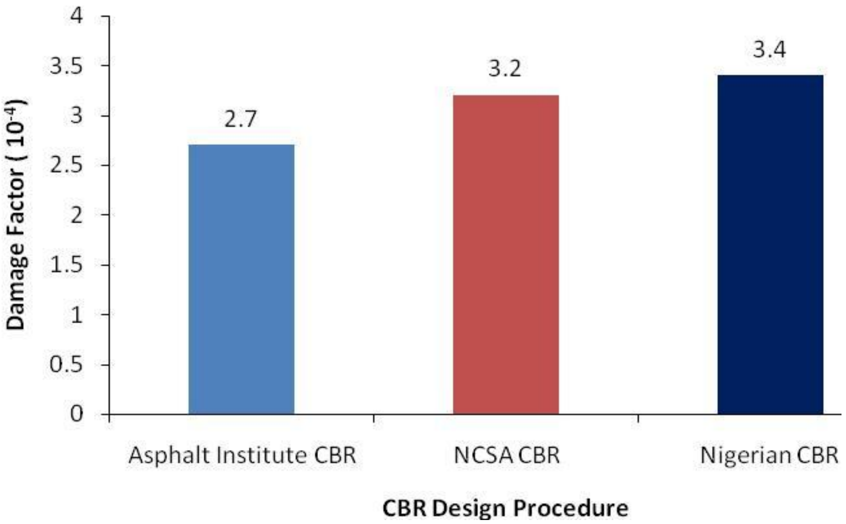

Figure 3a. CBR methods and fatigue damage factors – Heukelom and Klomp model (1962).

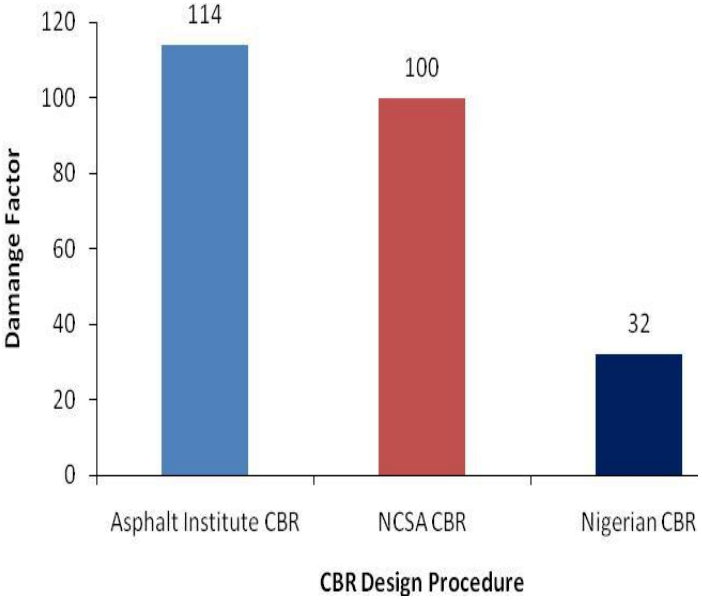

Figure 3b. CBR methods and rutting damage factors – Heukelom and Klomp model (1962).

fatigue resistance with a damage factor of 2.7 x 10^{-4} while the Nigerian CBR procedure recorded the least fatigue resistance with a damage factor of 3.4 x 10^{-4}. Similarly, the Nigerian CBR procedure recorded the best result in terms of rutting deformation with a damage factor of 32 while the Asphalt Institute procedure recorded the least result with a damage factor of 114 as shown in Figure 3b.

Results from the Asphalt Institute model shows that, the NCSA recorded the best result in terms of fatigue resistance with a damage factor of 0.26 and the Nigerian CBR procedure recorded the least with a damage factor of 0.3 as shown in Figure 4a. In terms of rutting deformation as shown in Figure 4b, the Nigerian CBR procedure recorded the best result with a damage factor of 28 while the Asphalt Institute procedure recorded the least with a damage factor of 61.

In general, the result of the pavement response indicates that the pavements will not fail due to fatigue cracking, however, the pavements will fail in terms of rutting and the Asphalt Institute Pavement will be most

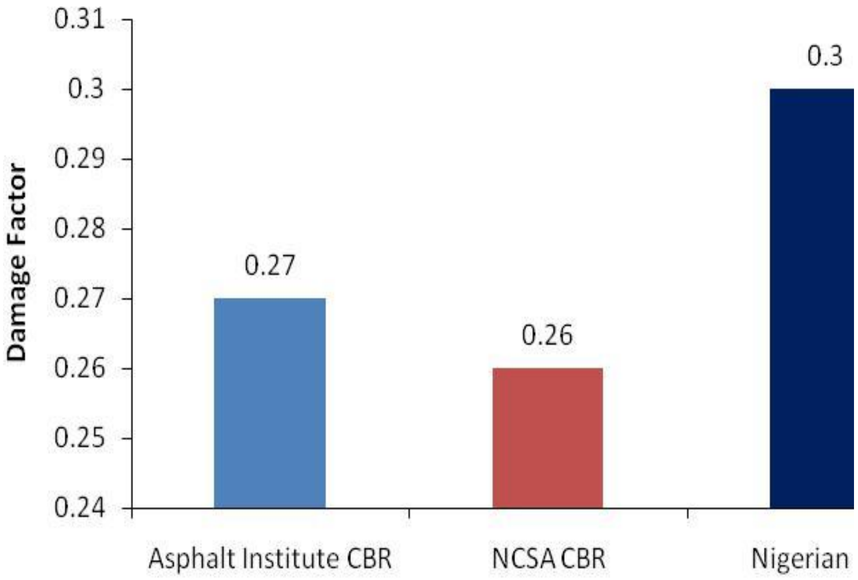

Figure 4a. CBR methods and fatigue damage factors – Asphalt Institute model (1982).

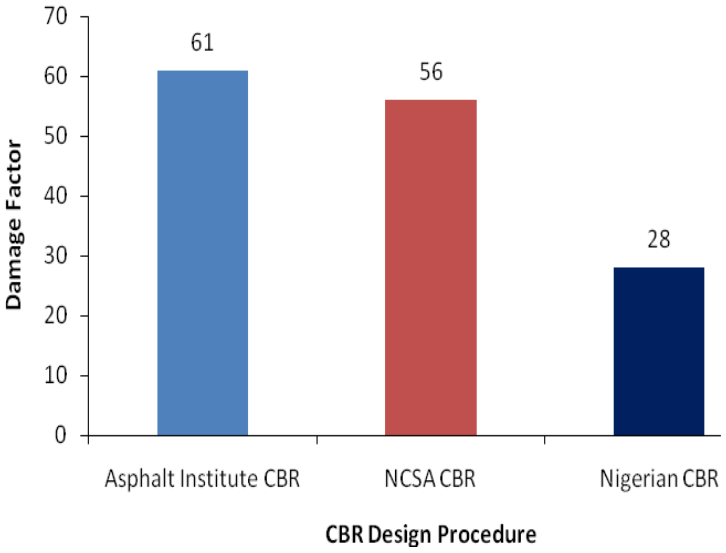

Figure 4b. CBR methods and rutting damage factors – Asphalt institute model (1982).

susceptible to rutting deformation and the Nigerian CBR – designed pavement the least. The implies that pavements designed using the three CBR-based procedures will not serve their intended traffic as a result of failure due to rutting deformation.

Conclusions and Recommendations

This study presents a layered elastic analysis of flexible pavements designed by the Asphalt Institute CBR method, the National Crushed Stone Association CBR method and the Nigerian CBR method. From the results obtained, the following conclusions are hereby made:

i) The rutting strains of flexible pavements designed using the three known CBR methods are greater than permissible values.

ii) Flexible pavements designed using the three known CBR methods are prone to early failure due to rutting deformation.

iii) The "design factor" is one of the causes of road failures in some developing tropical countries.

iv) The use of CBR procedure in the design of flexible pavement should be discontinued.

iv) There is need for the use of mechanistic approach in the design of flexible pavements in developing tropical countries.

v) Field measurement of fatigue and rutting strains should be carried out to determine error margins and validate the accuracy of the Everstress software.

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