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INTERNATIONAL JOURNAL OF CURRENT RESEARCH

International Journal of Current Research
Vol. 5, Issue, 05, pp.1079-1087, May, 2013

ISSN: 0975-833X

RESEARCH ARTICLE

MODIFIED NIGERIA CBR PROCEDURE FOR DESIGN OF CEMENT STABILIZED LATERITIC BASE LOW VOLUME ASPHALT PAVEMENT IN NIGERIA

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ARTICLE INFO

Article History:
Received 28th January, 2013
Received in revised form
16th February, 2013
Accepted 20th March, 2013
Published online 12th May, 2013

Key words:

CBR,
Design,
Cement-stabilized Lateritic base,
Low volume,
Asphalt Pavement.

ABSTRACT

Excessive fatigue and rutting strains due to traffic loading contribute significantly to the failure of asphalt pavement. In the design of asphalt pavement, it is necessary to investigate these critical strains and design against them. In Nigeria, the only developed design method for asphalt pavement is the California Bearing Ratio (CBR) method. Most of the roads designed using the CBR method failed soon after construction by fatigue cracking and rutting deformation. This study was conducted to develop a modified Nigeria CBR procedure for low volume asphalt pavement adopting the layered elastic analysis procedure which involves selection of materials and layer thickness for specific traffic conditions such that fatigue cracking and rutting deformations are minimized. Analysis were performed for hypothetical asphalt pavement sections using the layered elastic analysis program EVERSTRESS. Regression equations were developed for predicting pavement thickness in cement-stabilized base, low-volume asphalt pavement. The result was validated by comparing calculated maximum fatigue and rutting strains developed using the modified procedure and measured strain data from the Kansa Accelerated Testing Laboratory (K-ATL). The calculated and measured fatigue and rutting strain were calibrated and compared using linear regression analysis. The calibration of calculated and measured fatigue and rutting strains resulted in R^2 of 0.999 and 0.994 respectively for subgrade modulus of 31MPa, 0.997 and 0.997 respectively for subgrade modulus of 41MPa, 0.996 and 0.999 respectively for subgrade modulus of 62MPa, 0.992 and 0.995 respectively for subgrade modulus of 72MPa, 0.999 and 0.998 respectively for subgrade modulus of 93MPa, and 0.999 and 0.999 respectively for subgrade modulus of 103MPa. The results indicate that the coefficients of determination were very good.

INTRODUCTION

The almost universal parameter used to characterize soils for pavement design purpose is the California Bearing Ratio (CBR). This empirical index test was abandoned in California about 50 years ago but, following its adoption by the US. Corps of Engineers in World War II, it was gradually accepted World-wide as the appropriate test (Brown, 1997). Given that the test is at best, an indirect measurement of undrained shear strength and the pavement design requires knowledge of soil resilience and its tendency to develop plastic strains under repeated loading, the tenacity exhibited by generation of highway engineers in regard to the CBR is somewhat surprising. Jim Porter, a Soil Engineer for the State of California, introduced the “Soil Bearing Test” in 1929 commented nine years later, that the bearing values are not direct measure of the supporting value of materials (Porter, 1938). In recognition that the CBR design curves give a total thickness of pavement to prevent shear deformation in the soil, Turnbull (1950) noted that the CBR is an index of shearing strength. The shear strength of soil is not of direct interest to the road engineer, the soil should operate at stress levels within the elastic range (Brown, 1997). The pavement engineer is therefore more concerned with the elastic modulus of soil and the behaviour under repeated loading. The CBR method of pavement design is an empirical design method and 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 percent. 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 Subbase, 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. Some of the common CBR design methods include the Asphalt Institute (Asphalt Institute, 1981) method, the National Crushes Stone Association (NCSA) design method (NCSA, 1972), the Nigerian (CBR) design procedure (Highway Manuel, 1973) etc. Road failures in Nigeria have been traced to common causes which can broadly be attributed to any or combination of geological, geotechnical, design, construction, and maintenance problems (Ajayi, 1987). Several studies have been carried out to trace the cause of early road failures, studies were carried out by researchers on the geological (Ajayi, 1987), geotechnical, (Oyediran, 2001), Construction (Eze-Uzomaka, 1981) and maintenance (Busari, 1990) factors while the “design factor” has not been given adequate attention. In Nigeria, the only developed design method for asphalt pavement is the California Bearing Ratio (CBR) method. This method uses the California Bearing Ratio and traffic volume as the sole design inputs. The CBR method relates the material’s CBR value to the required thickness of pavement layer to provide protection against subgrade shear failure. The method was originally developed by the U.S Corps of Engineers

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and modified by the British Transportation Research Laboratory (TRL, 1970), it was adopted by Nigeria as contained in the Federal Highway Manual (Highway Manual-Part 1, 1973). Most of the roads designed using the CBR method failed soon after construction by fatigue cracking and rutting deformation. In their researches (Emesiobi, 2004, Ekwulo *et al.*, 2009), a comparative analysis of flexible pavements designed using three different CBR procedures were carried out, result indicated that the pavements designed by the CBR-based methods are prone to either fatigue cracking or rutting deformation or both. The CBR method was abandoned in California 50 years ago (Brown, 1997) for the more reliable Layered Elastic Analysis or Finite Element Methods. It is regrettable that this old method is still being used by most designers in Nigeria and has resulted in unsatisfactory designs, leading to frequent early pavement failures. Pavement structural design for low volume roads considers two types of pavements; asphalt pavement with asphalt concrete surface and base course, and jointed plain concrete pavements (NCHRP, 2004). The National Cooperative Highway Research Program (NCHRP, 2004) defines low volume roads as roads that can withstand up to 750,000 Equivalent Single Axle Loads (ESAL) as practical maximum within a design period of 20 years. There is currently no pavement design method in Nigeria that is based on analytical approach in which properties and thickness of the pavement layers are selected such that strains developed due to traffic loading do not exceed the capability of any of the materials in the pavement. The purpose of this study therefore is to develop a procedure that will modify the Nigeria CBR method such that the base and subgrade materials are characterized in terms of elastic or resilient modulus using correlation with CBR, and properties and thickness of the pavement layers are selected such that strains developed due to traffic loading do not exceed the capability of any of the materials in the pavement.

METHODOLOGY

The method adopted in this study is to use the layered elastic analysis and design approach to modify the existing Nigerian CBR procedure for design of asphalt pavement.

To achieve this, the study was carried out in the following order:

1. Characterize pavement materials in terms of elastic/resilient modulus and poison's ratio.
2. Obtain expected traffic data needed for a design period of 20 years.
3. Determine the minimum pavement thickness required to withstand expected traffic for low volume roads such that strains developed due to the expected traffic loading do not exceed the capability of any of the materials in the pavement.
4. Using the minimum pavement section in (3) above, compute tensile strain below asphalt layer and compressive strains on top subgrade layer adopting layered elastic analysis approach using the layered elastic analysis software EVERSRESS (Sivaneswaran *et al*, 2001)
5. Using CBR, expected traffic and pavement thickness data, develop relationship between CBR and pavement thickness for particular traffic repetition.

Traffic estimation was in the form of Equivalent Single Axle Load (ESAL) as against the traffic volume approach as is the case with the Nigeria CBR method. The elastic properties (resilient modulus for subgrade, elastic modulus for base, and Poisson's ratio) of the pavement material are used as inputs for design and analysis. The elastic modulus of base material and resilient modulus of subgrade are obtained through correlation with CBR. The layered elastic analysis software EVERSTRESS (Sivaneswaran *et al*, 2001) was employed in all the analysis.

Pavement Material Characterization

Material characterization involves laboratory test on surface, base and subgrade materials to determine the elastic modulus of the asphalt concrete, elastic modulus of the cement-stabilized lateritic material and resilient modulus of the natural subgrade.

Asphalt Concrete Elastic Modulus

The asphalt concrete was prepared according to the Marshall method (Asphalt Institute, 1997). The test specimens were compacted with 35, 50, 75, 100, 125 and 150 blows using a rammer falling freely at 450mm and having a weight of 6.5kg. The elastic modulus of the asphalt concrete was determined using the Witczak model at a loading frequency of 4Hz (Christensen, *et al* 2003) in equation 1.0.

$$\log E = -1.249937 + 0.029232P_{200} - 0.001767(P_{200})^2 - 0.002841P_4 - 0.058097V_a - 0.802208\frac{V_{beff}}{(V_{beff} + V_a)}$$
$$+\frac{\left[3.871977 - 0.0021P_4 + 0.003958P_{38} - 0.000017(P_{38})^2 + 0.00547P_{34}\right]}{1e^{(-0.7919691 - 0.393532\log\eta)}} \qquad (1.0)$$

Where

E = Elastic Modulus (Psi)
η = Bituminous viscosity, in 10^6 Poise (at any temperature, degree of aging)
V_a = Percent air voids content, by volume
V_{beff} = Percent effective bitumen content, by volume
P_{34} = Percent retained on 3/4 in. sieve, by total aggregate weight(cumulative)
P_{38} = Percent retained on 3/8 in. sieve, by total aggregate weight(cumulative)
P_4 = Percent retained on No. 4 sieve, by total aggregate weight(cumulative)
P_{200} = Percent retained on No. 200 sieve, by total aggregate weight(cumulative)

The design asphalt concrete elastic modulus of 3450MPa was determined by developing a regression equation relating the compaction levels and percents air voids on one hand and the percents air voids and elastic modulus on the other hand using equation 1.0.

Base Elastic Modulus Determination

The base material used in the study is cement-treated laterite of elastic modulus of 329MPa. The elastic modulus was determined by correlation with CBR (Ola, 1980) as presented in equation 2.0.

$$E(psi) = 250(CBR)^{1.2} \qquad (2.0)$$

$E(psi)=250(CBR)^{1.2}$(2.0) To obtain a cement treated laterite of 79,5% CBR, trial CBR test were carried out at varying cement contents. From equation 2.0, elastic modulus of 329MPa corresponds with 79.5% CBR approximately 80% CBR.

Subgrade Resilient Modulus Determination

The subgrade resilient modulus was determined in accordance the AASHTO Guide (AASHTO, 1993) using correlation with CBR as shown equation 3.0 (HeuKelom and Klomp, 1962). In order to reflect actual field conditions, samples were collected over one year period and the average CBR determined.

$$M_r(psi) = 1500\,CBR \qquad (3.0)$$

Where,

Mr = Resilient modulus (psi)
CBR = California Bearing Ratio

Poison's Ratio

In mechanistic-empirical design, the Poisson's ratios of pavement materials are in most cases assumed rather than determined (NCHRP, 2004). In this study, the Poisson's ratios of the materials were selected from typical values used by various pavement agencies as presented in Literature (NCHRP, 2004; WSDOT, 2005).

Pavement Material Properties

Asphalt concrete elastic modulus E = 3450MPa
Cement-stabilized base elastic modulus E = 329MPa (CBR = 79.5%)
Subgrade Resilient Modulus Mr = 10 - 103MPa (1- 10% soaked CBR)
Poison's Ration: Asphalt Concrete – 0.35,
Stabilized Base – 0.40, Subgrade – 0.45

Traffic and Wheel load Evaluation

The study considered maximum traffic repetition of 750,000 for low volume roads in terms of Equivalent Single Axle Load (ESAL) repetitions for a design period of 20years (NCHRP, 2004). Traffic estimation is in accordance with the procedure contained in the Nigerian Highway Manual part 1(Nanda, 1981). For the purpose of this study, three traffic categories were considered for design; Light, medium and heavy traffic as presented in Table 1.

Loading Condition and Configuration

The study considered a three layer pavement model. The static load (P) was applied on the pavement surface (the geometry of the load usually specified as a circle of a given radius) using the EVERSTRESS program (Sivaneswaran *et al.*, 2001). The loading condition on pavement was obtained by determining the critical load configuration. From analysis, the critical loading condition was determined to be the single, axle, single wheel since it recorded the highest maximum stresses, strains and deflections. The pavement analysis was carried out using EVERSTRESS program (Sivaneswaran *et al.*, 2001) developed by the Washington State Department of Transportation (WSDOT). The wheel load and pavement material parameters are as presented in Table 2.

determine their various damage factors in terms of fatigue and rutting. Non-linear regression equation relationship between the trial base thickness and damage factor was used to establish the minimum base thickness required to withstand the expected traffic repetition, this was obtained at damage factor of D = 1 with the rutting criterion being the controlling criterion. The same procedure was adopted for other subgrade moduli and traffic categories.

Layered Elastic Analysis of Pavement

Layered elastic analysis of the determined pavement sections were carried out to compute maximum fatigue and rutting strains for each expected traffic, subgrade moduli and traffic category using the EVERSTRESS (Sivaneswaran *et al.*, 2001) program. The program was used to apply a static load on a circular plate placed on a single axle single wheel configuration. A tire load of 40kN and pressure of 690kpa (AASHTO, 1993) was adopted in the analysis. The result of the layered elastic analysis is presented in Table 4 for 3% subgrade CBR (31MPa subgrade modulus) and light traffic situation.

Development of Design Regression Equations

The pavement fatigue and rutting strains for the various traffic categories presented in Tables 4 were used to develop nonlinear regression equations relating expected traffic and pavement thickness; pavement thickness and maximum fatigue (tensile) strain; and pavement thickness and maximum rutting (compressive) strain. The regression equations were developed based on the nonlinear general equations 4.0 and 5.0 using the SPSS program (SPSS 14, 2005). The relationship between expected traffic and pavement thickness were best fitted using equation 4.0 while that of pavement thickness and horizontal tensile (fatigue) strain; pavement thickness and vertical compressive (rutting) strains were fitted using equation 5.0.

Table 1. Traffic Categories (NCHRP, 2004)

Traffic Category	Expected 20 yr Design ESAL	Description of Expected Traffic	A.C. Surface Thickness (mm)	Stabilized Base Thickness (mm)
Light	$1 \times 10^4 – 5 \times 10^4$	50,000 ESAL max – typical of local streets or low volume country roads with very few trucks, approx. 4-5 per day, first year.	50	≥ 50
Medium	$5 \times 10^4 – 2.5 \times 10^5$	250,000 ESAL max– typical of collectors with fewer trucks and buses, approx. 23 per day, first year	75	≥ 75
Heavy	$2.5 \times 10^5 – 7.5 \times 10^5$	750,000 ESAL max. – typical of collectors with significant trucks and buses, approx. 70 per day first year.	100	≥ 100

Table 2. Pavement Load and Material parameters

Wheel Load (kN)	Tire Pressure (kPa)	Pavement Layer Thickness (mm)		Pavement Material Moduli (MPa)			Poison's Ratio		
		A.C. Surface T_1	Base layer T_2	A.C Surface E_1	Base E_2	Subgrade E_3	A.C Surface	Base	Subgrade
40	690	50	≥ 50	3450	329	10-103	0.35	0.40	0.45
40	690	75	≥ 75	3450	329	10-103	0.35	0.40	0.45
40	690	100	≥100	3450	329	10-103	0.35	0.40	0.45

Layered Elastic Analysis and Determination of Minimum Pavement Thickness

The minimum thicknesses of cement-stabilized base layer were determined using the EVERSTRESS program (Sivaneswaran *et al.*, 2001) based on pavement response adopting the Asphalt Institute response model (Asphalt Institute, 1982). The required minimum base thickness for particular expected traffic was determined as that base thickness that resulted in a maximum compressive strain and allowable repetitions to failure (N_r) such that the damage factor D is equal to 1. As presented in Table 3 for 31MPa subgrade resilient modulus and light traffic category, three (3) trial pavement analysis were carried out for each traffic repetition and base thickness to

$$y_1 = ax^b \quad (4.0)$$

$$y_2 = a\ln(x) + b \quad (5.0)$$

Presented in Tables 5a, 5b and 5c are the developed thickness design regression equations relating expected traffic and pavement thickness; pavement thickness and maximum fatigue(tensile) strain; and pavement thickness and maximum rutting (compressive) strain for 1-10% soaked CBR (10 - 103MPa subgrade resilient modulus) for light, medium and heavy traffic categories respectively.

RESULTS

The minimum pavement thickness required to withstand the various expected traffic for the various subgrade CBR as determined using the

Table 3. Layered Elastic Analysis to Determine Minimum Pavement thickness for Light traffic

A.C Mod. E1 (MPa)	Base Mod. E2 (MPa)	Sub Mod. E3 (MPa)	Layer Thickness			Expected Repetitions Ni	Fatigue Criterion				Rutting Criterion			
			A.C Surface T1 (mm)	Stabilized Base T2 (mm)	Total T (mm)		Horizontal Tensile Strain	Allowable Tensile Strain	No. of Repetition to Failure	D.F	Vertical Compressive Strain	Allowable Compressive Strain	No. of Repetition to Failure	D.F
3450	329	31	50	250	300	1.00E+04	2.90E-04	9.55E-04	4.75E+05	0.02	1.35E-03	1.35E-03	9.53E+03	1.05
3450	329	31	50	270	320	1.00E+04	2.85E-04	9.55E-04	5.01E+05	0.02	1.23E-03	1.35E-03	1.48E+04	0.67
3450	329	31	50	290	340	1.00E+04	2.82E-04	9.55E-04	5.22E+05	0.02	1.11E-03	1.35E-03	2.27E+04	0.44
3450	329	31	50	250	300	2.00E+04	2.90E-04	7.74E-04	4.75E+05	0.04	1.35E-03	1.16E-03	9.53E+03	2.09
3450	329	31	50	270	320	2.00E+04	2.85E-04	7.74E-04	5.01E+05	0.04	1.23E-03	1.16E-03	1.48E+04	1.35
3450	329	31	50	290	340	2.00E+04	2.82E-04	7.74E-04	5.22E+05	0.04	1.11E-03	1.16E-03	2.27E+04	0.88
3450	329	31	50	270	320	3.00E+04	2.85E-04	6.85E-04	5.01E+05	0.06	1.23E-03	1.06E-03	1.48E+04	2.02
3450	329	31	50	290	340	3.00E+04	2.82E-04	6.85E-04	5.22E+05	0.06	1.11E-03	1.06E-03	2.27E+04	1.32
3450	329	31	50	310	360	3.00E+04	2.79E-04	6.85E-04	5.38E+05	0.06	1.02E-03	1.06E-03	3.42E+04	0.88
3450	329	31	50	290	340	4.00E+04	2.82E-04	6.28E-04	5.22E+05	0.08	1.11E-03	9.93E-04	2.27E+04	1.76
3450	329	31	50	310	360	4.00E+04	2.79E-04	6.28E-04	5.38E+05	0.07	1.02E-03	9.93E-04	3.42E+04	1.17
3450	329	31	50	330	380	4.00E+04	2.77E-04	6.28E-04	5.50E+05	0.07	9.31E-04	9.93E-04	5.07E+04	0.79
3450	329	31	50	290	340	5.00E+04	2.82E-04	5.87E-04	5.22E+05	0.10	1.11E-03	9.45E-04	2.27E+04	2.20
3450	329	31	50	310	360	5.00E+04	2.79E-04	5.87E-04	5.38E+05	0.09	1.02E-03	9.45E-04	3.42E+04	1.46
3450	329	31	50	330	380	5.00E+04	2.77E-04	5.87E-04	5.50E+05	0.09	9.31E-04	9.45E-04	5.07E+04	0.99

Table 4. Layered Elastic Analysis of LEADFlex Pavement for 31MPa Subgrade Modulus and Light Traffic Category

A.C Mod. E1 (MPa)	Base Mod. E2 (MPa)	Sub Mod. E3 (MPa)	Layer Thickness			Expected Repetitions N_i	Fatigue Criterion				Rutting Criterion			
			A.C Surface T1 (mm)	Stabilized Base T2 (mm)	Total T (mm)		Horizontal Tensile Strain	Allowable Tensile Strain	No. of Repetition to Failure	D.F	Vertical Compressive Strain	Allowable Compressive Strain	No. of Repetition to Failure	D.F
3450	329	31	50	252	302	1.00E+04	289.4E-6	955.5E-6	4.78E+05	0.02	1.339E-03	1.35E-03	1.00E+04	1.00
3450	329	31	50	284	334	2.00E+04	282.5E-6	774.5E-6	5.17E+05	0.04	1.148E-03	1.16E-03	200E+04	1.00
3450	329	31	50	303.6	353.6	3.00E+04	279.8E-6	684.9E-6	5.34E+05	0.06	1.047E-03	1.06E-03	3.00E+04	1.00
3450	329	31	50	318.1	368.1	4.00E+04	278.2E-6	627.8E-6	5.44E+05	0.07	9.808E-04	9.93E-04	4.00E+04	1.00
3450	329	31	50	328.1	378.1	5.00E+04	277.4E-6	586.7E-6	5.49E+05	0.09	9.387E-04	9.45E-04	5.00E+04	1.00

Table 5a. Expected Traffic-Pavement Thickness Regression Equations for various Traffic Categories

A.C Modulus (MPa) E1 (MPa)	Base Modulus (MPa) E2 (MPa)	Subgrade		Expected Traffic – Pavement Thickness Relationship		
		CBR (%)	Modulus (MPa) E3 (MPa)	Light Traffic	Medium Traffic	Heavy Traffic
3450	329	1	10	$T = 110.68(N_i)^{0.129}$ $R^2 = 1$	$T = 104.62(N_i)^{0.131}$ $R^2 = 1$	$T = 98.72(N_i)0^{.133}$ $R^2 = 1$
3450	329	2	21	$T = 92.91(Ni)^{0.136}$ $R^2 = 1$	$T = 86.87(N_i)^{0.138}$ $R^2 = 1$	$T = 80.77(N_i)^{0.140}$ $R^2 = 1$
3450	329	3	31	$T = 83.29(Ni)^{0.140}$ $R^2 = 0.999$	$T = 76.76(N_i)^{0.142}$ $R^2 = 1$	$T = 69.64(N_i)^{0.146}$ $R^2 = 1$
3450	329	4	41	$T = 74.342(Ni)^{0.146}$ $R^2 = 1$	$T = 67.95(N_i)^{0.148}$ $R^2 = 1$	$T = 61.11(N_i)^{0.151}$ $R^2 = 1$
3450	329	5	52	$T = 66.65(Ni)^{0.151}$ $R^2 = 1$	$T = 60.32(N_i)^{0.153}$ $R^2 = 1$	$T = 54.23(N_i)^{0.156}$ $R^2 = 1$
3450	329	6	62	$T = 60.35(Ni)^{0.156}$ $R^2 = 1$	$T = 54.78(N_i)^{0.157}$ $R^2 = 1$	$T = 48.24(N_i)^{0.161}$ $R^2 = 0.999$
3450	329	7	72	$T = 54.88(Ni)^{0.161}$ $R^2 = 0.999$	$T = 49.48(N_i)^{0.162}$ $R^2 = 0.999$	$T = 43.92(N_i)^{0.165}$ $R^2 = 1$
3450	329	8	82	$T = 50.12(Ni)^{0.166}$ $R^2 = 0.999$	$T = 44.62(N_i)^{0.168}$ $R^2 = 0.999$	$T = 39.58(N_i)^{0.170}$ $R^2 = 1$
3450	329	9	93	$T = 44.99(Ni)^{0.172}$ $R^2 = 0.999$	$T = 40.22(N_i)^{0.173}$ $R^2 = 0.999$	$T = 35.26(N_i)^{0.175}$ $R^2 = 1$
3450	329	10	103	$T = 40.66(Ni)^{0.178}$ $R^2 = 0.999$	$T = 36.38(N_i)^{0.178}$ $R^2 = 0.999$	$T = 31.57(N_i)^{0.181}$ $R^2 = 1$

Table 5b. Pavement Thickness – Fatigue Strain Regression Equations for various Traffic Categories

A.C Modulus(MPa) E1(MPa)	Base Modulus (MPa) E2 (MPa)	Subgrade		Pavement Thickness – Fatigue Strain Relationship		
		CBR (%)	Modulus (MPa) E3 (MPa)	Light Traffic	Medium Traffic	Heavy Traffic
3450	329	1	10	$\varepsilon_t = -26.85\ln(T) + 424.29$ $R^2 = 0.975$	$\varepsilon_t = -42.55\ln(T) + 540.39$ $R^2 = 0.983$	$\varepsilon_t = -42.42\ln(T) + 514.40$ $R^2 = 0.994$
3450	329	2	21	$\varepsilon_t = -42.86\ln(T) + 528.09$ $R^2 = 0.974$	$\varepsilon_t = -54.22\ln(T) + 614.60$ $R^2 = 0.987$	$\varepsilon_t = -49.90\ln(T) + 561.97$ $R^2 = 0.996$
3450	329	3	31	$\varepsilon_t = -53.71\ln(T) + 595.49$ $R^2 = 0.980$	$\varepsilon_t = -60.12\ln(T) + 650.75$ $R^2 = 0.989$	$\varepsilon_t = -53.73\ln(T) + 585.07$ $R^2 = 0.994$
3450	329	4	41	$\varepsilon_t = -60.73\ln(T) + 638.39$ $R^2 = 0.982$	$\varepsilon_t = -63.35\ln(T) + 669.84$ $R^2 = 0.990$	$\varepsilon_t = -55.69\ln(T) + 596.13$ $R^2 = 0.995$
3450	329	5	52	$\varepsilon_t = -66.50\ln(T) + 672.79$ $R^2 = 0.985$	$\varepsilon_t = -66.19\ln(T) + 685.88$ $R^2 = 0.989$	$\varepsilon_t = -56.90\ln(T) + 602.12$ $R^2 = 0.997$
3450	329	6	62	$\varepsilon_t = -70.92\ln(T) + 698.39$ $R^2 = 0.987$	$\varepsilon_t = -67.70\ln(T) + 693.70$ $R^2 = 0.991$	$\varepsilon_t = -57.22\ln(T) + 602.67$ $R^2 = 0.996$
3450	329	7	72	$\varepsilon_t = -73.73\ln(T) + 714.29$ $R^2 = 0.988$	$\varepsilon_t = -68.65\ln(T) + 698.09$ $R^2 = 0.992$	$\varepsilon_t = -56.96\ln(T) + 599.74$ $R^2 = 0.996$
3450	329	8	82	$\varepsilon_t = -75.83\ln(T + 725.69$ $R^2 = 0.989$	$\varepsilon_t = -69.17\ln(T) + 699.78$ $R^2 = 0.991$	$\varepsilon_t = -56.79\ln(T) + 597.23$ $R^2 = 0.996$
3450	329	9	93	$\varepsilon_t = -78.01\ln(T) + 737.09$ $R^2 = 0.989$	$\varepsilon_t = -68.96\ln(T) + 696.90$ $R^2 = 0.991$	$\varepsilon_t = -55.96\ln(T) + 590.67$ $R^2 = 0.997$
3450	329	10	103	$\varepsilon_t = -79.17\ln(T) + 742.61$ $R^2 = 0.989$	$\varepsilon_t = -68.79\ln(T) + 694.36$ $R^2 = 0.992$	$\varepsilon_t = -54.68\ln(T) + 581.70$ $R^2 = 0.996$

Table 5c. Pavement Thickness – Rutting Strain Regression Equations for various Traffic Categories

A.C Modulus(MPa) E1 (MPa)	Base Modulus (MPa) E2 (MPa)	Subgrade		Pavement Thickness – Rutting Strain Relationship		
		CBR (%)	Modulus (MPa) E3 (MPa)	Light Traffic	Medium Traffic	Heavy Traffic
3450	329	1	10	$\varepsilon_c = -1930.98\ln(T) + 12715.12$ $R^2 = 0.998$	$\varepsilon_c = -1339.96\ln(T) + 9059.89$ $R^2 = 0.998$	$\varepsilon_c = -971.06\ln(T) + 6712.19$ $R^2 = 0.999$
3450	329	2	21	$\varepsilon_c = -1846.77\ln(T) + 12014.21$ $R^2 = 0.998$	$\varepsilon_c = -1274.29\ln(T) + 8517.94$ $R^2 = 0.998$	$\varepsilon_c = -920.61\ln(T) + 6292.88$ $R^2 = 0.999$
3450	329	3	31	$\varepsilon_c = -1786.67\ln(T) + 11536.74$ $R^2 = 0.999$	$\varepsilon_c = -1226.63\ln(T) + 8142.97$ $R^2 = 0.998$	$\varepsilon_c = -885.48\ln(T) + 6011.51$ $R^2 = 0.999$
3450	329	4	41	$\varepsilon_c = -1723.29\ln(T) + 11066.66$ $R^2 = 0.998$	$\varepsilon_c = -1186.13\ln(T) + 7830.42$ $R^2 = 0.999$	$\varepsilon_c = -855.38\ln(T) + 5775.60$ $R^2 = 0.999$
3450	329	5	52	$\varepsilon_c = -1661.24\ln(T) + 10614.46$ $R^2 = 0.999$	$\varepsilon_c = -1145.03\ln(T) + 7520.87$ $R^2 = 0.999$	$\varepsilon_c = -826.00\ln(T) + 5549.02$ $R^2 = 0.999$
3450	329	6	62	$\varepsilon_c = -1610.94\ln(T) + 10250.97$ $R^2 = 0.999$	$\varepsilon_c = -1110.62\ln(T) + 7265.71$ $R^2 = 0.999$	$\varepsilon_c = -800.57\ln(T) + 5357.36$ $R^2 = 0.999$
3450	329	7	72	$\varepsilon_c = -1556.52\ln(T) + 9873.81$ $R^2 = 0.999$	$\varepsilon_c = -1077.81\ln(T) + 7026.26$ $R^2 = 0.999$	$\varepsilon_c = -778.86\ln(T) + 5192.70$ $R^2 = 1$
3450	329	8	82	$\varepsilon_c = -1509.57\ln(T) + 9545.52$ $R^2 = 0.999$	$\varepsilon_c = -1045.53\ln(T) + 6795.21$ $R^2 = 0.999$	$\varepsilon_c = -757.22\ln(T) + 5032.18$ $R^2 = 1$
3450	329	9	93	$\varepsilon_c = -1454.94\ln(T) + 9174.98$ $R^2 = 0.999$	$\varepsilon_c = -1011.61\ln(T) + 6555.18$ $R^2 = 0.999$	$\varepsilon_c = -734.37\ln(T) + 4864.99$ $R^2 = 1$
3450	329	10	103	$\varepsilon_c = -1406.04\ln(T) + 8848.93$ $R^2 = 1$	$\varepsilon_c = -980.73\ln(T) + 6340.81$ $R^2 = 0.999$	$y = -714.77\ln(T) + 4722.76$ $R^2 = 1$

Table 6. Expected Traffic, Subgrade CBR and Pavement Thickness data for Light Traffic

Pavement Thickness (mm)	Subgrade CBR (%)/ Pavement Thickness (mm)									
	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
1.00E+04	363.14	325.13	302.41	285.25	267.79	253.91	241.78	231.21	219.34	209.49
2.00E+04	397.10	357.27	333.22	315.63	297.34	282.90	270.32	259.41	247.11	237.00
3.00E+04	418.43	377.53	352.69	334.87	316.12	301.38	288.56	277.47	264.96	254.74
4.00E+04	434.25	392.59	367.18	349.24	330.15	315.21	302.24	291.04	278.40	268.12
5.00E+04	446.93	404.69	378.83	360.80	341.46	326.37	313.29	302.02	289.29	278.99

Table 7. Expected Traffic, Subgrade CBR and Pavement Thickness data for Medium Traffic

Pavement Thickness (mm)	Subgrade CBR (%)/ Pavement Thickness (mm)									
	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
5.00E+04	431.70	386.66	356.77	337.01	315.79	299.47	285.54	274.76	261.44	249.62
1.00E+05	472.73	425.47	393.67	373.41	351.12	333.90	319.47	308.69	294.74	282.40
1.50E+05	498.52	449.96	417.00	396.51	373.60	355.85	341.16	330.46	316.16	303.53
2.00E+05	517.67	468.18	434.39	413.75	390.41	372.29	357.43	346.82	332.29	319.48
2.50E+05	533.02	482.82	448.38	427.65	403.97	385.57	370.59	360.07	345.37	332.43

Table 8. Expected Traffic Repetitions, CBR and Pavement Thickness data for Heavy Traffic

Pavement Thickness (mm)	Subgrade CBR (%)/ Pavement Thickness (mm)									
	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
2.50E+05	515.62	460.22	427.52	399.21	376.98	356.84	341.45	327.44	310.40	299.43
3.50E+05	539.22	482.41	449.05	420.02	397.30	376.71	360.94	346.71	329.23	318.24
4.50E+05	557.55	499.69	465.83	436.26	413.18	392.26	376.22	361.84	344.03	333.05
5.50E+05	572.63	513.93	479.68	449.68	426.32	405.14	388.89	374.40	356.32	345.37
6.50E+05	585.49	526.09	491.52	461.17	437.58	416.18	399.75	385.19	366.90	355.97
7.50E+05	596.74	536.73	501.90	471.24	447.45	425.88	409.31	394.67	376.20	365.31

the developed thickness design equations in Table 5a are presented in Tables 6, 7 and 8 for light, medium and heavy traffic categories respectively.

DISCUSSION OF RESULTS

Subgrade CBR and Pavement Thickness Relationship

The relationship between subgrade CBR and pavement thickness is shown in Figures 1, 2 and 3 for light, medium and heavy traffic respectively.

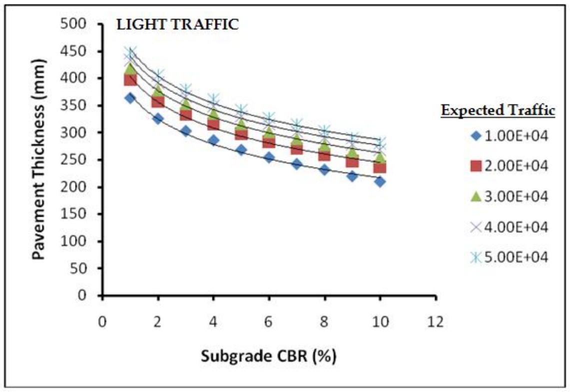

Figure 1. Pavement Thickness Design Chart for Light Traffic

Figure 1 presents the relationship between subgrade CBR and pavement thickness for light traffic category. The result shows that for expected traffic of 1.00E+04 ESAL, as the subgrade CBR increased from 1% to 10%, the pavement thickness decreased from 363.14mm to 209.49mm. Similarly, for expected traffic of 5.00E+04 ESAL, the pavement thickness decreased from 446.93mm to 278.99mm as the subgrade CBR increases from 1% to 10%. The result indicates an average percentage decrease of about 39.50% in pavement thickness as the subgrade CBR increased from 1% to 10%. The same trend was observed for all ranges of traffic. The relationship between subgrade CBR and pavement thickness for medium traffic is shown in Figure 2.

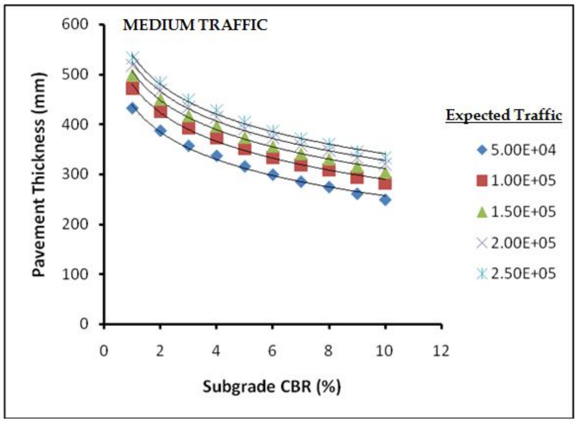

Figure 2. Pavement Thickness Design Chart for Medium Traffic

Result shows that for expected traffic of 1.00E+04 ESAL, as the subgrade CBR increased from 1% to 10%, the pavement thickness decreased from 431.70mm to 249.62mm. Also, for expected traffic of 5.00E+04 ESAL, as the subgrade CBR increases from 1% to 10%, the pavement thickness decreased from 533.02mm to 332.43mm. The result indicates that for the medium traffic category, an increase in subgrade CBR from 1% to 10% resulted in an average percentage decrease of about 39.63% in pavement thickness. The same trend was observed for all ranges of expected traffic. For heavy traffic category, Figure 3 shows that for an expected traffic of 1.00E+04 ESAL, the pavement thickness decreased from 515.62mm to 299.43mm as the subgrade CBR increased from 1% to 10%. Similarly, for expected traffic of 5.00E+04, the pavement thickness decreased from 596.74mm to 365.31mm as the subgrade CBR increases from 1% to 10% resulting in an average percentage decrease of about 40.14% in pavement thickness. The same trend was observed for all ranges of traffic.

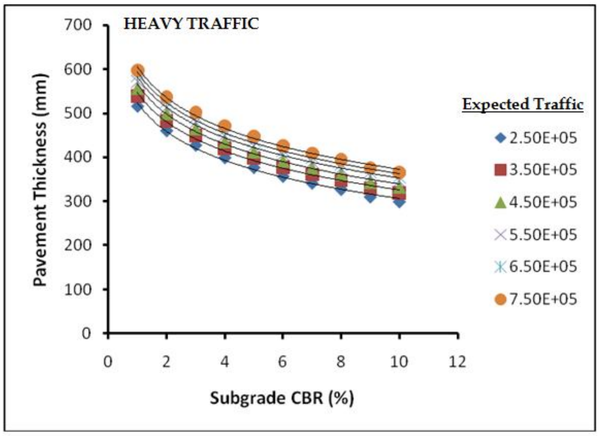

Figure 3. Pavement Thickness Design Chart for Heavy Traffic

Generally, the result shows that increase in subgrade CBR from 1% to 10% resulted in a percentage decrease of about 39.50%, 39.69% and 40.14% in pavement thickness for light, medium and heavy traffic respectively, indicating that for particular traffic repetition, pavement thickness decreases as subgrade CBR increases. This implies that pavement thickness is dependent on subgrade CBR. This trend is in line with previous studies (Nanda, 1981; Siddique *et al*, 2005; NCHRP, 2007).

Validation of Result

The modified Nigerian CBR procedure was validated by comparing the maximum (calculated) fatigue and rutting strains resulting from the modified CBR procedure as presented in Tables 5b and 5c and measured pavement response data from three(3) stations at the South (SM-2A) and North (SM-2A) lanes of the K-ATL (Melhem *et al*, 2000). Six (6) pavement test section were loaded using a falling weight deflectometer load of 40kN. The pavement material consist of natural subgrade with moduli 4.500psi (31MPa), 6000 psi (41MPa), 9,000psi (62MPa), 10,500 psi (72MPa), 13,500psi (93MPa) and 15,000psi (103MPa), aggregate base modulus of 47,717psi (329MPa) and asphalt concrete modulus of 500,377psi (3450MPa).

The resulting tensile and compressive strains from the modified CBR procedure and measured horizontal tensile strains and vertical compressive strain were calibrated and compared using linear regression for subgrade moduli of 31Mpa, 41Mpa, 62MPa, 72Mpa, 93MPa and 103MPa. The coefficients of determination of calculated and measured tensile and compressive strain R^2 were found to be very good with R^2 of 0.999 and 0.994 respectively for subgrade modulus of 31MPa, 0.997 and 0.997 respectively for subgrade modulus of 41MPa, 0.996 and 0.999 respectively for subgrade modulus of 62MPa, 0.992 and 0.995 respectively for subgrade modulus of 72MPa, 0.999 and 0.998 respectively for subgrade modulus of 93MPa, and 0.999 and 0.999 respectively for subgrade modulus of 103MPa.

Comparison between the Existing Nigeria CBR Procedure and the Modified Procedure

The major comparison between the existing Nigeria CBR procedure and the modified procedure are as presented in Table 9.

Table 9. Comparison between Nigeria CBR Procedure and the Modified Procedure

Variables	Nigeria CBR Design Procedure	Modified Nigeria CBR Design Procure
Traffic Estimation	Uses traffic volume in the form of number of commercial vehicles/day exceeding 29.89kN (3 tons).	Traffic estimation is in the form of Equivalent Single axle Load (ESAL) in accordance with AASHTO standard
Analysis Procedure	No analysis procedure involved. Pavement thickness determined based on traffic volume and CBR. No attempt is made to check its adequacy.	Analysis involves selection of materials and layer thickness for specific traffic such that fatigue and rutting strains are within allowable minimum.
Design Pavement Thickness	Not adequate to withstand expected traffic hence does not limit fatigue cracking and rutting deformation.	Adequate to withstand expected traffic hence fatigue cracking and rutting deformation are minimized.

Conclusions

From the result of the study, the following findings and conclusions can be drawn:

1. The Nigerian CBR method could be modified using layered analysis and design procedure
2. For particular expected traffic, cement-stabilized base low volume asphalt pavement thickness decreases as subgrade CBR increases.
3. The study showed that the design procedure is capable of adequately predicting minimum pavement thickness required to withstand expected traffic repetition such that developed fatigue and rutting strains are within allowable limits.
4. The modified procedure and the developed thickness design charts should be adopted for design as a replacement for the existing Nigeria CBR procedure for low volume roads.

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