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Development of Mechanistic-Empirical Pavement Design for Tropical Climate Using Cement-Treated Base Layer

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Abstract: - A mechanistic-empirical pavement design method is developed characterising cement-treated base layers for pavement design in Nigeria or other similar tropical and subtropical countries. Asphalt Concrete surface, Subbase and Aggregate base were characterised based on back calculation data from Claros et al (1986) while cement-treated base layer was based on modulus tests that had been conducted by past researchers. Failure criteria for the Asphalt Concrete fatigue failure and the subgrade rutting failure were based on those by Claros and Ijeh (1987) for Nigerian pavements. Cracking criterion used for the cement-treated layer was that developed by Otee *et al*. (1982). The comparison between the Soil-Cement and Aggregate base showed that at a low Equivalent Single Axle Load (ESAL) (0.5 million repetitions was considered), the use of Aggregate base was better than Soil-Cement base. That for Aggregate base and Cement-Treated Gravel Base showed that the Cement-Treated Gravel Base was better than the Aggregate base at high ESAL (2.5 million repetitions was considered)

I. INTRODUCTION

Many pavement design methods have been developed for different countries to suit different climatic conditions. Most of the design methods used today in the tropical countries were adapted from those developed for the European temperate climate (Gichaga and Parker, 1988). These design methods were developed based on the performance of existed or existing roads. An example of such is the American Association of State Highway and Transportation Officials AASHTO method of pavement design and Road Test. Because the Road Tests cannot be conducted for all variations of pavement design parameters, it therefore means that adaptation of such designs is extrapolations and thus poses serious risks.

The mechanistic-empirical pavement design involves the use of mechanics laws to explain the behaviour of pavements. This is done by computing for stresses and strains and comparing them with the allowable computed from the failure of the material been used. The mechanistic-empirical method makes use of mathematical models unlike the purely empirical methods which makes use of physical models like the Road Test.

Some works have been done by different researchers in developing the mechanistic-empirical method for tropical climate. Most have been based on unbound base layer. The aims of this paper are therefore:

- ✓ To develop the mechanistic-empirical design method for tropical climate when a cement-treated base layer is used; and
- ✓ To promote the use of cement-treated base layer in the tropical countries.

The scope of work involves the characterisation and analysis of two materials - Soil-Cement (SC) and Cement-Treated Gravel Base (CTGB). The analyses of these materials were then compared to that for the Aggregate base.

II. MECHANISTIC-EMPIRICAL APPROACH TO PAVEMENT DESIGN

Various mathematical models are in use for the mechanistic approach. Most are based on the elastic theory and inelastic properties of the pavement materials. The most common of these is the Layered Elastic Model.

2.1 Layered Elastic Model

Layered Elastic Model assumes that each pavement structural layer is homogeneous, isotropic and linearly elastic and upon this theory all stresses and strains are evaluated. These assumptions mean that each layer is the same everywhere and the pavement will rebound to its original form once the load is removed.

Because the mathematical models supporting the layered elastic approach is simple some basic assumptions are required, these are:

- ✓ Pavement layers extend infinitely in the horizontal direction;
- ✓ The bottom layer (usually the subgrade) extends infinitely downwards; and
- ✓ Materials are not stressed beyond their elastic ranges.

Due to the amount of computations involved in the mechanistic approach, several computer programs have been written to perform the stress analysis.

To adequately characterise a pavement structure and its response to loading in a layered elastic approach, the following inputs are desired for the computer programs

1) Material properties of each layer (modulus of elasticity and Poisson's ratio);
2) Pavement layer thicknesses; and
3) Loading conditions (magnitude, geometry **-** radius and contact pressure of load).

The outputs of layered elastic model are stresses, strains and deflections.

2.2 Failure Criteria

This is the empirical aspect of the mechanistic-empirical method. The relationship between physical (outputs) and pavement failure is described by empirically derived equations that compute the number of loading cycles to failure; this is called the failure criterion. Many equations have been derived for several climatic conditions based on road performances. An example is that developed by Claros *et al.* (1986) for the Nigerian environment.

2.3 Advantages of the Mechanistic-Empirical Approach

The basic advantages of the M-E approach over a purely empirical one (according to Washington State Department of Transport (WSDOT), 1998) are

1) It can be used for both existing pavement rehabilitation and new pavement construction;
2) It accommodates changing load types;
3) It can better characterise materials allowing for.
   - ✓ Better utilization of available materials;
   - ✓ Accommodation of new materials; and
   - ✓ An improved definition of existing layer properties.
4) It uses material properties that relate better to actual pavement performance;
5) It provides more reliable performance predictions;
6) It better defines the role of construction; and
7) It accommodates environmental and aging effects on materials.

III. METHODOLOGY

The method used in this study is first the characterization of the materials used. The materials used are Asphalt Concrete (AC), Cement-Treated Gravel Base (CTGB), Soil-Cement (SC) base, Aggregate Base (AB) and soil subbase. Each base material was used for the analysis and comparison was made for all the materials. The CTGB was compared to the AB first and then SC base was also compared to the AB. This was done because the most prominently used material in Nigeria is the Aggregate Base (crushed stone). The analysis of the CTGB was based on Equivalent Single Axle Load ESAL of 2.5 million while that of the SC was based on 0.5 million Equivalent Single Axle Load (ESAL). The flow chart used for the analyses is shown in Figure 1.

3.1 Material Characterisation

This deals with the properties of the materials used. Several past work on each material were considered for this study.

3.1.1 Asphalt concrete

The modulus of the Asphalt Concrete is highly dependent on the air temperature which makes its measurement difficult. The most recent effort has been to measure it through back calculation.

Back calculation performed by Claros *et al.* (1986) for the Nigerian environment showed values between 2000MPa and 6000MPa. Another consideration is the empirical equation given by AASHTO (1993) as:

$\text{Log}(E_{AC}) = 6.451235 - 0.000164671T^{1.92544}$ --------------- (1)
where T is the temperature (degree centtigrade), and
E_{AC} is the Modulus of the Asphalt Concrete

This has been used by Adeniyi (2005) for Nigerian environment. Values ranging from 2000 to 3000MPa were derived by using average temperatures of some selected towns for all the climatic regions of Nigeria. These climatic regions are also those prevailing in other tropical countries. This means values such as 6000MPa are only achievable during the cold months of the tropical climate. From this, therefore the values of 2000MPa, 4000MPa and 6000MPa were used as the modulus of the AC surface.

3.1.2 Soil-cement base

Ola (1983) reported that 3% of cement was adequate in lateritic soils because they had CBR of about 120 which exceeded the requirement of 80% CBR. Jimoh's (1987) work on the resilient modulus of soil-cement gave values in the range of 500MPa to 2000MPa. The values used were therefore 500MPa, 1000MPa and 2000MPa.

3.1.3 Aggregate base

Back calculation values from Claros *et al.* (1986) were considered for aggregate base. Values presented were 413MPa to 689MPa.The moduli used for the base were therefore 413MPa and 689MPa.

3.1.4 Cement-treated gravel base

Ola (1983) found that 3% of cement in lateritic gravels was adequate as base course material because they had California Bearing Ratio (CBR) of about 90% which exceeded the minimum requirement of 80% (FMW, 1973). Also Fossberg (1970) Suggested a gravel treated with 5.5%. He gave modulus of 7000MPa – 21000MPa for the CTGB; which was considered as heavily bound CTGB, while 3% gave a modulus of 2000MPa and 3500MPa and been used before by the Australian Stabilisation Guidelines (2001). Values 2000MPa, 3500MPa and 5000MPa were used for the lightly bound CTGB, while 2000MPa represents a value that continues from values quoted for SC in subsection 3.1.2, 5000MPa represents values near to the heavily bound CTGB.

3.1.5 Subbase

Back calculation values by Claros *et al.* (1986) were used. The values presented were 138MPa to 483MPa and the same values were therefore adopted.

3.1.6 Subgrade

Subgrade value of 100MPa was used corresponding to 10% CBR according to the equation by Heukelom and Klomp (1962), see Equation (2).
$\text{Mr (MPa)} = 10\text{CBR}$ ------------------- (2)

3.1.7 Input parameters

A summary of the input parameters for the mechanistic analysis is shown in Table 1. Also, shown is the type of materials with the modulus used as well as the Poisson ratios.

3.2 Pavement Layer Thickness

The analysis started with 150mm for both the base and subbase and 50mm for the AC surface. The method applied was to first increase the subbase until it became important to increase the base; the base too was increased until it became important to increase the AC surface.

Table 1: Summary of Input Parameters used in Mechanistic Analysis

MATERIAL	MODULUS	POISSON'S RATIO
Asphalt Concrete	2000, 4000, 6000MPa	0.40
Soil-Cement	300, 1000, 2000MPa	0.20
Lightly Bound CTGB	2000, 3500, 5000MPa	0.25
Heavily Bound CTGB	7000, 10000, 14000MPa	0.30
Aggregate Base	413, 689, 873MPa	0.40
Natural Material (subbase)	138, 310, 483MPa	0.40
Subgrade	100MPa	0.45
Tyre Load	40kN	
Tyre Contact Pressure	560kPa	
Radius	150mm	

3.3 Loading Conditions

Full axle loading on dual wheels as shown in Figure 2 was used. Eighty kilo Newton (80kN) spread on two wheels gave 40kN on each wheel. A contact pressure of 560kPa was used for the analysis.

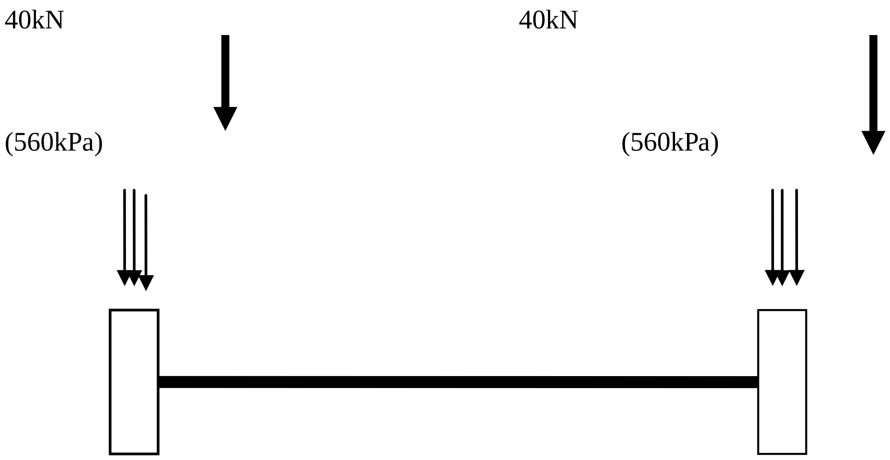

Figure 1: Standard axle load distribution for the analysis

3.4 Layered Elastic Computer Program

Due to the amount of computations involved, a layered elastic computer program was used. The program used is the *EVERSTRESS* developed by Sivaneswarem, Pierce and Mahoney for the Washington State Department of Transportation (WSDOT).

3.5 Failure Criteria

3.5.1 Asphalt concrete fatigue failure criterion

Claros and Ijeh (1987) presented a failure criterion model for the asphalt concrete as

$\text{Log } N_f = 15.947 - 3.291\text{Log } (\text{€}_t/10^{-6}) - 0.854\text{Log } (E/10^3)$ ------------ (3)

Where:

N_f =failure criterion for asphalt concrete.
€_t =Horizontal tensile strain
E =Young Modulus of elasticity

This is computed using the horizontal strain at the bottom of the asphalt concrete

3.5.2 Subgrade rutting failure criterion

Also Claros and Ijeh (1987) presented a model for vertical compressive strain (€v) at the top of the subgrade layer. This is determined by the relationship

$\text{€v} = 1.36\ (10^{-2})\ (N)^{-0.2126}$ -------------- 4

Where terms are as defined previously.

3.5.3 Cemented layer cracking failure criterion

Otee et al (1982) developed a failure criterion model for cement-treated gravels (see Equation (5)).
$€/€_b = 1 – 0.11LogN$ ------------------ 5

Where
$€$ = allowable tensile strain
$€_b$ = Strain at break
N =
The diagrams showing the strain at break to modulus can be found in Otee *et al*. (1982) or Aderinola (1999). Table 2 shows the allowable strains for all the failure criteria, also shown in brackets is the amount of ESAL considered.

Table 2: Allowable strains for all failure criteria

MATERIAL	MODULUS	ALLOWABLE STRAINS
Asphalt Concrete	2000MPa	183 (2.5m ESAL), 300(0.5m ESAL)
	4000MPa	152 (2.5m ESAL), 249 (0.5m ESAL)
	6000MPa	138 (2.5m ESAL), 224 (0.5m ESAL)
Soil-Cement	300MPa	78 (0.5m ESAL)
	1000MPa	58.5 (0.5m ESAL)
	2000MPa	47.4 (0.5m ESAL)
Lightly Bound CTGB	2000MPa	47.4 (2.5m ESAL)
	3500MPa	41.4 (2.5m ESAL)
	5000MPa	40.0 (2.5m ESAL)
Heavily Bound CTGB	7000MPa	38.5 (2.5m ESAL)
	10000MPa	35.5 (2.5m ESAL)
	14000MPa	32.6 (2.5m ESAL)
Subgrade	100MPa	593(2.5m ESAL), 835 (0.5m ESAL)

IV. RESULTS AND DISCUSSION

This section is the analysis of the results obtained for various characterization of the materials used. These materials are Asphalt Concrete (AC), Cement-Treated Gravel Base (CTGB), Soil-Cement (SC) base, Aggregate Base (AB) and soil subbase. Each base material was used for the analysis and comparison was made for all the materials. Table 4.1 to 4.4 show the various characterization of materials with Sub-grade of 100MPa for 0.5m ESAL.

Table 4.1: Mechanistic Analysis of Soil-Cement Base for subgrade of 100MPa for 0.5m ESAL

SUBGRADE				100	MPa	0.45		
MODULUS			Layer Thickness (cm)			STRAINS		
AC	SC	SB	AC	SC	SB	AC Fatigue	SC Cracking	SG Rutting
2000	500	138						
4000	500	138	15	45	30	112	71	99
6000	500	138	15	40	30	95	74	103
2000	500		10	58		161	76	161
4000	500		10	56		141	76	159
6000	500		10	55		123	75	156
2000	1000		10	57		76	55	118
4000	1000		10	55		79	55	116
6000	1000		10	54		75	55	115
2000	2000		10	50		26	45	99
4000	2000		10	47		35	46	100
6000	2000		10	48		38	47	101

Table 4.2: Mechanistic analysis of Aggregate Base for Subgrade 100MPa for 0.5m ESAL

SUBGRADE				100	MPa	Poisson Ratio 0.45	
MODULUS			Layer Thickness (cm)			STRAINS	
AC	AB	SB	AC	AB	SB	AC Fatigue	SG Rutting
2000	413	138	5	15	15	172	717
4000	413	138	5	15	10	155	753
6000	413	138	5	15	10	204	814
2000	413	483	5	15	10	205	774
4000	413	483	5	10	15	176	751
6000	413	483	5	10	15	176	671
2000	689	138	5	10	15	89	824
4000	689	138	5	10	15	145	757
6000	689	138	5	10	15	160	718
2000	689	483	5	10	12	65	785
4000	689	483	5	10	10	111	808
6000	689	483	5	10	10	125	771

Table 4.3: Mechanistic analysis of Cement-Treated Gravel Base for Subgrade 100MPa for 2.5m ESAL

SUBGRADE			100	MPa	Poisson Ratio	0.45
MODULUS		Layer Thickness (cm)		STRAINS		
AC	CTGB	AC	CTGB	AC Fatigue	CTGB Cracking	SG Rutting
2000	2000	10	50	26	45.0	99
4000	2000	10	47	35	46.0	100
6000	2000	10	48	38	46.8	101
2000	3500	10	43	8.2	39.4	89.8
4000	3500	10	40	15.5	40.4	91.5
6000	3500	10	38	19.2	41.3	92.9
2000	5000	15	33	-1.37	38.6	90.3
4000	5000	10	35	5.07	40.0	93.5
6000	5000	10	33	9.3	39.4	91.6

Table 4.4: Mechanistic analysis of Aggregate Base for Subgrade 100MPa for 0.5m ESAL

SUBGRADE				100	MPa	0.45	
MODULUS			Layer Thickness (cm)			STRAINS	
AC	AB	SB	AC	AB	SB	AC Fatigue	SG Rutting
2000	413	138	5	20	20	161	497
4000	413	138	15	20	15	148	257
6000	413	138	15	20	20	120	204
2000	413	483	5	15	20	153	476
4000	413	483	15	15	15	139	270
6000	413	483	15	15	10	117	238
2000	689	138	5	15	20	61	510
4000	689	138	10	20	15	138	313
6000	689	138	10	20	20	125	255
2000	689	483	5	15	15	61	525
4000	689	483	10	15	10	137	419
6000	689	483	10	15	15	120	322

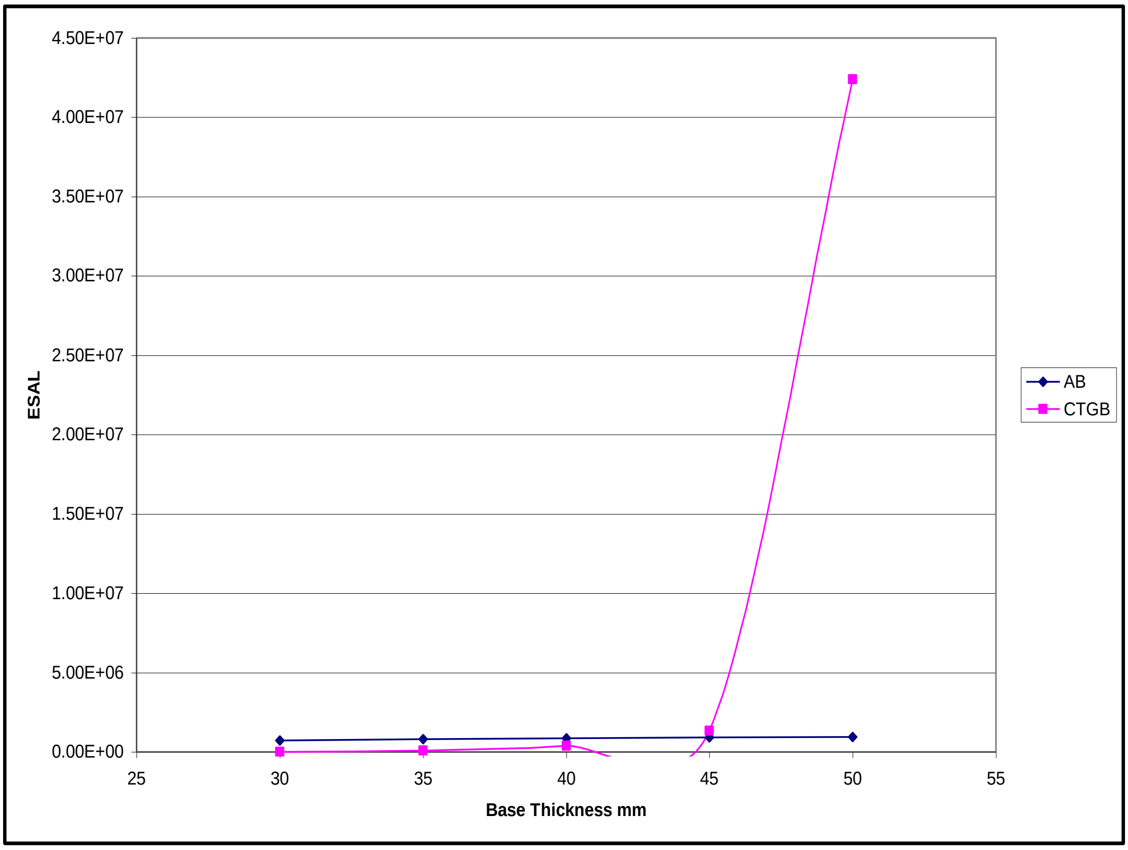

Figure 4.1: Comparison of varying thickness of base for CTAB and AB under 100mm of AC surface

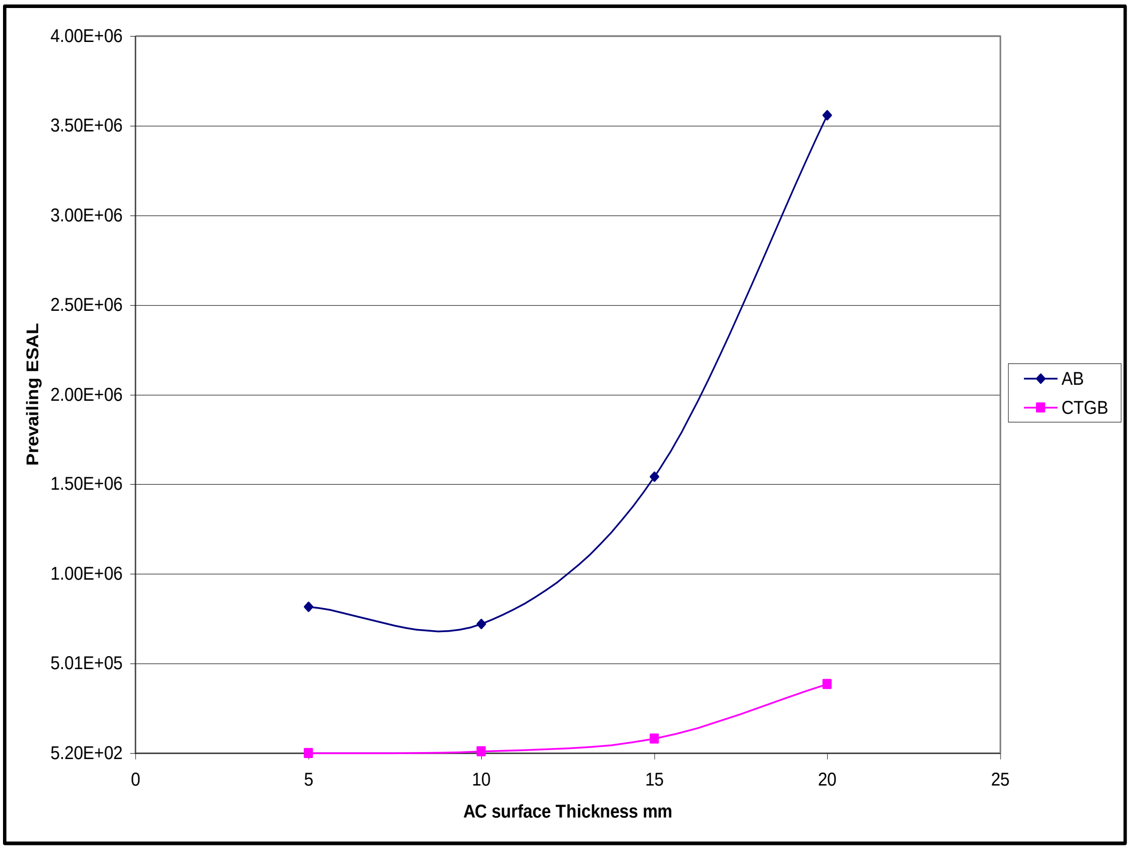

Figure 4.2: Comparison of varying thickness of the AC surface over 300mm of base (CTGB and AB)

Table 4.1 shows mechanistic analysis for the soil-cement (SC) base for an ESAL of 0.5 million with subgrade modulus 100MPa. From this table, the use of subbase with the SC base could not produce results with the 2000MPa AC surface and 500MPa SC base and this was therefore avoided. The use of subbase did not produce results with 100mm of AC surface; the AC surface thickness was therefore increased to 150mm before tangible results were obtained. Another series of analyses were run without the subbase and it was observed that tangible results were obtained with the 100mm of AC surface. This is because the prevailing failure criterion (that of SC base layer) which meant that the presence of subbase has no tangible influence on the pavement. This also did not allow the increase of the SC base thickness. For the analysis of SC base, the subbase was avoided. Increase in the AC surface modulus as well as that of the SC base modulus, brought about a decrease in the thickness of the pavement. 6000MPa of AC surface with 2000MPa of SC base gave the best results of 100mm AC surface with 450mm SC base. The worst result obtained was 100mm AC surface over 580mm SC base from 2000MPa AC surface over 500MPa SC base.

Table 4.2 shows mechanistic analysis of aggregate base, AB (crushed stone) for an ESAL of 0.5 million. The results were consistent with only a difference of 50mm from the base and subbase. Increase in any of the modulus brought about decrease of the pavement thickness. The worst results obtained were from 2000MPa AC, 413MPa AB, 138MPa SB with 50mm AC, 150mmAB, 150mm SB; while the best came from 6000MPa AC, 689MPa, 483MPa with 50mm AC, 100mm and 100mm SB.

Cost analysis of SC base and AB on Table 4.3 shows N5678/m^2 and N3285/m^2 respectively. This shows that the AB is far cheaper than SC base and therefore better for use when a low ESAL is involved (say ESAL 0.5 million).

Table 4.4 shows mechanistic analysis for the CTGB for an ESAL of 2.5 million. From Table 4.3, the use of subbase with CTGB was avoided; this was done because the modulus of the SB was far less than that of CTGB, thereby making its presence irrelevant. The analysis of SC on Table 4.1, also attest to this method. The worse result obtained was with 100mm AC over 430mm CTGB. An unexpected result occurred at 5000MPa CTGB overlaid by 2000MPa of AC which gave horizontal compressive strains instead of tensile strains. This occurred because the AC surface modulus was far lower than the CTGB modulus, thereby making the AC surface behaves as lean under the base. Australian Stabilisation Association in its guidelines provided that when a lean AC surface with low modulus is underlain by cemented layer with high modulus, the analysis is likely to show that the AC surface will not act normally. The best case analysed was with 100mm and 380mm CTGB at 6000MPa AC over 5000MPa CTGB.

Figures 4.1 and 4.2 show that adequate improvement of the pavement cannot be achieved with the increment of the base for the AB but at 400mm, further increase in the CTGB base brings about appreciable increase in the pavement structure. Increase in the AC surface brings about appreciable increase in the properties of the pavement with AB while it does not improve a pavement with CTGB. This implies that the CTGB would provide a better pavement structure since the AC surface is more expensive than other pavement materials.

V. CONCLUSION

A mechanistic-empirical pavement design method for the cement-treated base has been developed for use in Nigeria. Also, proper characterization has been done to compare both the cement-treated materials (soil-cement and Cement Treated Gravel Base) and Aggregate Base (crushed stone). The mechanistic-empirical design has proved that any material could be characterised for pavement design thereby allowing for the flexibility of choice of materials by the designer. The Cement-Treated Gravel Base proves to be a better material than the Aggregate Base for heavily trafficked roads.

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