Analysis of Heavy Load Pavement for Cost Effective Design of Nigerian Port Using British Port Authority Design Charts

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Analysis of Heavy Load Pavement for Cost Effective Design of Nigerian Port Using British Port Authority Design Charts

Yusuf, I. T.[1]; Bilewu, S. O.[2] and Kolo, S.S.[3]
[1]Department of Civil Engineering, University of Ilorin, Ilorin, Nigeria
[2]Department of Water Resources and Environmental Engineering, University of Ilorin, Ilorin, Nigeria
3Department of Civil Engineering, Federal University of Technology, Minna, Nigeria
E-mail: ityusuf4@gmail.com

Abstract
The intensity of traffic/container loads in operation of ports necessitates the provision of zero/low maintenance heavy load pavements. This paper, therefore, presents a construction/maintenance life cycle cost-based pavement that reflects port operational techniques for Nigerian coastal shelf. Data on cargo handling/container traffic statistics were obtained from the Nigerian Ports Authority and Federal Office of Statistics in Lagos. The length of the Nigerian west-east territorial coast, types of handling equipment, available materials and construction technology prevailing at the ports were also extracted from other relevant sources. The British Ports Federation and the Nigeria Highway Design Manuals were used for the design purposes. Design by Charts were employed with the aid of Microsoft Excel software, while the construction cost analysis was carried out for each pavement type at varying California Bearing Ratio (CBR) values of 1, 3, 5, 10 and 30% for the possible subgrade soils. Results indicated that the rigid and reinforced concrete pavements, with low CBR values, are better in technical terms, the reinforced concrete pavement being the best choice economically for all subgrade CBR values and subbase thicknesses.

Keywords: California Bearing Ratio, Cargo handling operation, Design chart, Heavy load pavement, Port.

Introduction

Ports are important and intermodal transfer/operational facility for a marine transportation system. Over 96% or 3.6billion tons of international cargo moved through the ports of the world in 1978 (De-Heer, 1994), which do come in various physical forms of liquid bulk, dry bulk, parcel or pseudo bulk, or containerized break bulk. Of all the componenting elements of a port, the pavement is about the most extensive in fixed land area and physical presentation. Its provision demands much heavily in investment. The terminal surface (or port pavement) constitute the base of all operations as it makes up for about 5 to 25% of the total budget (De-Heer, 1994). The marine economy is such a risky enterprise that cannot tolerate lost or idle time for frequent maintenance activities and hence the most strategic handling of the desirable pavement is for the initial construction cost to be usually very high with very low or zero maintenance cost.

Also a cost-effective pavement practice for a growing marine industry with selection of the pavement types from the list of asphalt, rigid concrete, reinforced concrete and concrete blocks shall be appropriate. The choice of the construction technology and maintenance practice of heavy load pavements is more appropriate for Nigerian ports, prevailing marine traffic and environment. Apart from traffic, the other major inputs in pavement design, construction, maintenance and operation are the physical strength and elastic properties of all the components (Yoder and Witczak 1975; Yusuf, 2005).

This paper investigated the sensitivity of the performance of heavy load pavement within the Nigerian ports, using the British Ports Association (BPA) Charts (Knapton, 2007), for changing materials, construction and maintenance options for a 25 years period, with a view to selecting the most cost effective combinations. The BPA procedure, being an International standard for port design operation, was adopted for the Nigerian case. Moreso, this study intends to look into developing a design/analytic procedure for heavy load pavement in Nigeria to fit the prevailing conditions. The objectives, therefore, are (a) development of unit cost data for construction, maintenance and replacement practices for various pavements in Nigeria, (b) carrying out cost-effective analysis for a 25-year design life, (c) selection of the most economical and cost effective heavy load pavement appropriate for Nigerian ports and hence (d) recommend a draft of design/analytical procedure for heavy load pavement in Nigerian marines.

Materials and Methods

Study Area

The Nigerian west-east territorial costal shelf stretches from Badagry (Bight of Benin) to Calabar (Bight of Bonny) with a total length of 771.38km. Table 1 presents the breakdown of the length of the various segments of the shelf, while Fig. 1 shows the shelf. The coordinates of Bight of Benin is N6^0 01' 52.9''; E4^0 50' 35.1'' and that of Bight of Bonny is N4^0 43' 37.8''; E8^0 31' 35.5'' (Nigeria Direct, 2007). Port facility plans and development is highly dominated by non-Nigerians (foreigners) unlike the highways. There are seventeen (17) ports along the Nigerian west-east territorial coastal shelf where marine activities are in operation. The four major flagship of the port operation are Lagos Port Complex (Apapa and Tin Can Island), Portharcourt Port Complex, Bonny and the Forcados Ports where the volume of the cargoes handling are up to 15% to 56%.

Deskwork

The basic method adopted for this study is in two stages: (i) capture of statistical data on the operation of marine traffic in Nigerian ports system as well as costal material properties using secondary sources and (ii) application for the design of various surface terminal pavements in relation to each container handling system, loadings and pavement materials using Microsoft Excel software and in accordance with British Ports Association analytical procedure.

Data Presentation

The statistics acquired from the Nigerian Ports Authority, Apapa and Federal Office of Statistics, Lagos reflected the desirable factors of traffic type, quantity, growth and handling technology. The yearly totals of cargoes handled at Nigerian Ports are summarized in Table 2. Figs. 2 and 3 present the ten-year (2004-2014) trend for cargo handling at the ports on the west-east territorial coastal shelf on annual basis.

Table 1: Distances Along Nigerian Territorial Coastal Shelf

LOCATION	LEG LENGTH (Km)	DISTANCE (Km)
INTLBR	0	-
LAGOS	78.13	78.13
BHTFB	64.86	142.99
BHGTF1	47.46	190.45
001	57.79	248.24
GLFGNE	35.71	283.95
GLFGN1	52.81	336.76
GLFGN	50.67	387.43
GLFGN3	44.87	432.30
GLFGN4	29.18	461.48
GLFGN5	24.48	485.96
GLFGN6	26.67	512.63
BHGTF2	33.33	545.96
BHGTF3	38.19	584.15
BHGTF4	51.19	635.34
BHGTF5	35.21	670.55
002	50.49	721.04
BHGTF6	18.93	739.97
INTLB1	31.14	771.38

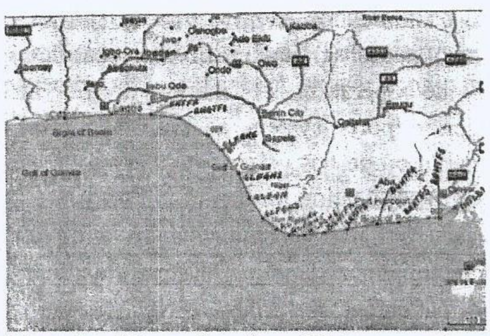

Fig. 1: Map showing Distances along Nigerian Territorial Coastal Shelf (Source: Nigeria Direct, 2007)

Table 2: Yearly Totals of Cargoes Handled at Nigerian Ports

Year	Total Cargo Loaded '000' Tonnes	Total Cargo Unloaded '000' Tonnes
2004	63,036	6,517
2005	75,429	6,749
2006	77,994	6,042
2007	78,594	8,064
2008	68,954	10,999
2009	84,232	10,942
2010	86,305	7,968
2011	89,212	9,262
2012	85,350	8,982
2013	1,912	9,234
2014	100,373	12,892

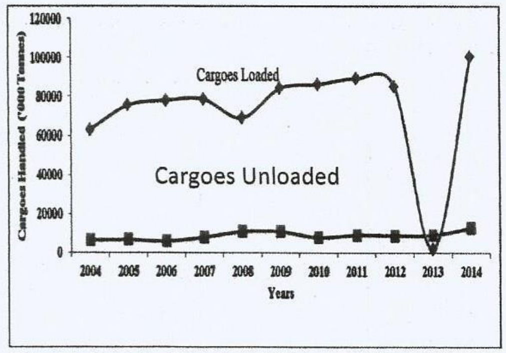

Fig. 2: Yearly Totals of Cargoes Handled at Nigerian West-East Coastal Ports

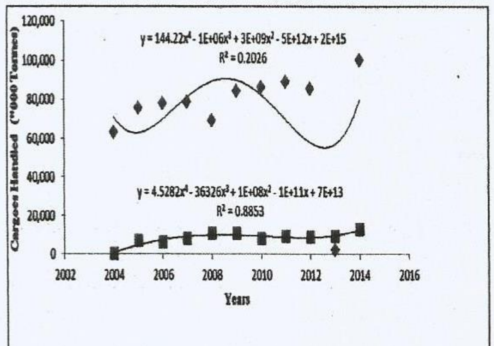

Fig. 3: Trend (Best Fit) of Yearly Totals of Cargoes Handled at Nigerian West-East Coastal Ports

Material Characteristics

In order to ensure the coverage of entire length of the Nigerian costal native soils, the profiles and properties of soils within the Lagos and Port Harcourt port complexes were used as representatives. These are shown in Table 3. Elastic constants (that is, elastic modulus and Poisson's ratio) have to be assigned to the components of the pavement, that is, the subgrade, the subbase, the base and the surface. This is because the design criteria and analysis are based upon elastic theory. The strength of the subgrade is, commonly, referred to in terms of its California Bearing Ratio (CBR) and there is a relationship developed between elastic modulus, Poisson's ratio and CBR.

Table 3: Characteristics of Soil Materials at Lagos and Port Harcourt Ports

Properties	Characteristic Values at		Range (%)
	Lagos	Port Harcourt	
Natural Moisture Content (%)	51	39.1	39.1 – 51.0
Liquid Limit (%)	42	48	42 – 48
Plastic Limit (%)	19	25.5	19.0 – 25.5
Plasticity Index (%)	23	22.5	22.5 – 23.0
Dry Density (kN/m^3)	14.4	13.0	13.0 – 14.4
Specific Gravity	2.52	2.60	1.52 – 2.60
Clay Content (%)	36	33.5	33.5 – 36.0

Source: Ojo (2010).

As advised (Overseas Road Note 31, 2003), it is false economy to minimize the extent of preliminary investigations to determine the variability in material properties. Variability in material properties is, generally, much greater than desired in design processes and must, therefore, be taken into account explicitly during pavement design. The materials characteristics for the pavement which constitutes subgrade, subbase, base and surfacing were determined and obtained as follows:

Subgrade

The subgrade strength is characterised by its California Bearing Ratio (CBR). British Ports Federation design charts are produced for CBR values of 1%, 3%, 5%, 10% and 30% which represent the likelihood of CBR values for very poor to very good subgrade which can prevail in tropical/subtropical regions. According to Knapton (2007, 2009), the subgrade is assumed to be semi-infinite and its elastic modulus is equal to ten times its CBR value (Yusuf and Jimoh, 2009). That is

$E_g = 10 \times CBR^{-1}$ (N/mm^2) (Yusuf and Jimoh, 2009) (1)

CBR of deep organic clay stratum in Nigerian coasts is 5-10% (Yusuf and Jimoh, 2009).

Poisson's ratio, ν, is calculated from

$$\nu = 0.82 - 0.1\log E_g \quad \text{(Beaty, 1996)} \quad (2)$$

where, E_g = elastic modulus of the subgrade (N/mm^2)

Subbase

The elastic modulus of the subbase is calculated from the thickness of the subbase and the elastic modulus of the subgrade (Shell Pavement Design Manual, 1978) from the expression,

$$E_s = 0.2H_s^{0.45} \times E_g \ (N/mm^2) \quad (3)$$

where, E_s = elastic modulus of the subbase (N/mm^2), H_s = thickness of the subbase (mm) and E_g = elastic modulus of the subgrade (N/mm^2).

The Poisson's ratio for the subbase is calculated using equation (2) taking CBR value as 30% and the compressive strength as $12N/mm^2$ (Nigerian Highway Design Manual, 2013).

Base

The CBR, the elastic modulus and the compressive strength for the base course is taken as 80%, $1000N/mm^2$ and $12N/mm^2$ respectively. Relevant clauses of the Nigerian Specification for Construction Technology require compaction on lifts of not more than 150mm to 200mm. Hence, the probable sizes of the subbase and base courses could be either 150mm or 200mm or any of their multiples.

Surfacing

The CBR for the surfacing is at all times greater than 80%, while its elastic modulus and the compressive strength taken as 2000N/mm^2 and 12N/mm^2, respectively. Relevant clauses of the Nigerian Specification for Construction Technology require compacted thickness of between 40mm and 200mm depending on level of traffic. Hence, the probable sizes of the surface course could be 50mm or any of its multiples.

Data Analysis and Design

The BPA manual (Knapton, 2009) gave a realistic method of assessing the damaging effect of container handling equipment which reflects those parameters particular to container terminal pavements as (a) very heavy wheel loads up to 25tons, (b) wide area of operation, (c) severe dynamics, (d) wide range of equipment types and sizes. For each wheel on one side of the plant, the damaging effect is calculated from equation proposed by Tsinker (2004):

$$D = \left(\frac{W}{12{,}000}\right)^{3.75} * \left(\frac{P}{0.8}\right)^{1.25} \qquad (4)$$

where, D = pavement damage; W = wheel load (kg); P = tyre pressure (N/mm^2) which gives pavement damage, D, in the units of Port Area Wheel Load (PAWL).

Based on the deductions from the information in Tables 1-3, the design life of the pavement at Apapa port is 4, 131, 818 passes and the number of repetitions of a straddle carrier over a period of 25years is 3,888,000. This value can be halved and for a critical handling facility like the Apapa port, a value of 2,000,000 repetitions and a life of 25years are adopted for the design (Knapton, 2009). The use of BPF Charts was considered for the pavement design (the Appendix for the Charts). The design approach for heavy load pavement is to compute strains resulting from a defined loading regime and to determine the permissible strains which the pavement construction materials can withstand. A pavement is deemed to be correctly designed when actual and permissible strains are similar. The allowable strain is given by:

$$\varepsilon_v = \frac{21600}{N^{0.28}} \text{ in microstrain} \qquad (5)$$

where, N = number of repetitions of applied load = 2 x 10^6; => E_v = 372microstrain.

The allowable base horizontal tensile strain is given by:

$$\varepsilon_h = \frac{F_c x 993500}{6x E_b^{1.022} x N^{0.052}} \text{ in microstrain} \qquad (6)$$

where, for:

Asphalt Pavement

F_c = characteristic compressive strength of base material in microstrain = 12N/mm^2 (Knapton, 2009)

Since F_c > 7N/mm^2 ; E_b = 16800 x $F_c^{0.25}$ = 31268N/mm^2 => E_h = 24 microstrain

Concrete Block Pavement

F_c = characteristic compressive strength of base material in microstrain = 6N/mm^2 (Knapton, 2009)

Since F_c < 7N/mm^2; E_b = 4000 x $F_c^{0.25}$ = 24000N/mm^2 => E_h = 16 microstrain

Rigid Concrete Pavement

F_c = characteristic compressive strength of base material in microstrain = 18N/mm^2 (BPA manual)

Since $F_c > 7N/mm^2$; $E_b = 16800 \times F_c^{0.25} = 34604N/mm^2 \Rightarrow E_h = 32$ microstrain.

Reinforced Concrete Pavement

F_c = characteristic compressive strength of base material in microstrain = $24N/mm^2$ BPA manual (Knapton, 2009)

Since $F_c > 7N/mm^2$; $E_b = 16800 \times F_c^{0.25} = 37185N/mm^2 \Rightarrow E_h = 40$ microstrain.

Results

Design by use of Charts

Asphalt Pavement with Granular Base

For an asphalt surfaced flexible pavement required to withstand 2.000,000 repetitions

Effective repetitions of LCI-C plant on a subgrade of 10% CBR.

Effective depth of pavement = 2664.0mm.

Assumed thickness of subbase = 300mm.

From BPA charts, 2 x 10^6 repetitions correspond with a permissible compressive vertical microstrain of 375, 375 microstrain corresponds with granular base thickness of 500mm. The results for other CBR values for asphalt pavement as well as design output for Asphalt Concrete Block, Rigid and Reinforced Concrete pavements are shown in Tables 4-7. Samples of the BPA Charts B, C, 10 and 15 used for asphalt pavement with granular base are presented in the Appendix.

Table 4: Design Output for Asphalt Pavement with Granular Base

Subgrade CBR (%)	300mm Subbase Thickness		600mm Subbase Thickness	
	Chart No.	Base Thickness (mm)	Chart No.	Base Thickness (mm)
1	6	No practical solution	11	No practical solution
3	7	No practical solution	12	Not required
5	8	No practical solution	13	Not required
10	9	500	14	Not required
30	10	Not required	15	Not required

Table 5: Design Output for Concrete Block Pavement

Subgrade CBR (%)	300mm Subbase Thickness		600mm Subbase Thickness	
	Chart No.	Base Thickness (mm)	Chart No.	Base Thickness (mm)
1	21	No practical solution	26	No practical solution
3	22	No practical solution	27	No practical solution
5	23	No practical solution	28	No practical solution
10	24	No practical solution	29	270
30	25	No practical solution	30	Not required

Table 6: Design Output for Reinforced Concrete Pavement

Subgrade CBR (%)	300mm Subbase Thickness		600mm Subbase Thickness	
	Chart No.	Base Thickness (mm)	Chart No.	Base Thickness (mm)
1	36	325	41	290
3	37	300	42	280
5	38	275	43	270
10	39	250	44	240
30	40	100	45	0

Table 7: Design Output for Reinforced Concrete Pavement

#	300mm Subbase Thickness		600mm Subbase Thickness	
	Chart No.	Base Thickness (mm)	Chart No.	Base Thickness (mm)
1	36	245	41	205
3	37	205	42	200
5	38	200	43	190
10	39	175	44	110
30	40	0	45	0

Table 8: Prices of Base Course Materials as at August, 2015

Material	Price
Granular Materials	₦5,000.00/m³
Crushed Granite	₦3,500.00/ton
Cement	₦1,800.00/50kg bag
Sharp Sand	₦1,845.00/m³
12mmIron rod	₦2,200.00/length

Cost Data Collection and Analysis

Field (market) survey conducted to obtain prices of materials (Ilorin, Nigeria (2015)) required for construction, maintenance and rehabilitation of heavy load pavements are shown in Table 8. The costs of producing concrete mixes of 1:4:8 and 1:1:2 were calculated as ₦13,600.00/m^3 and ₦31,045.00/m^3 respectively from Table 8. Table 9 shows the cost of materials required for the surfacing (pavement) of one square metre (1m^2) spot on each pavement type at CBR values of 1%, 3%, 5%, 10% and 30%.

Table 9: Cost Analysis

Pavement	Quantity (m^3) for subbase thickness of		Cost / m^3 (₦)	Amount (₦) for subbase thickness of	
	300mm	600mm		300mm	600mm
CBR = 1%					
Asphalt (Granular Base) Concrete Blocks Rigid Concrete Reinforced Concrete	- - 0.325 0.245	- - 0.290 0.205	13,600.00 4,500.00 31,045.00 34,000.00	- - 10,089.63 8,330.00	9,003.05 6,970.00
CBR = 3%					
Asphalt (Granular Base) Concrete Blocks Rigid Concrete Reinforced Concrete	- - 0.300 0.205	- - 0.280 0.200	13,600.00 4,500.00 31,045.00 34,000.00	- - 9,313.50 6,970.00	- - 8,694.00 6,800.00
CBR = 5%					
Asphalt (Granular Base) Concrete Blocks Rigid Concrete Reinforced Concrete	- - 0.275 0.200	- - 0.270 0.190	13,600.00 4,500.00 31,045.00 34,000.00	- - 8,537.38 6,800.00	- - 8,382.15 6,460.00
CBR = 10%					
Asphalt (Granular Base) Concrete Blocks Rigid Concrete Reinforced Concrete	0.500 - 0.250 0.175	- 0.270 0.240 0.110	13,600.00 4,500.00 31,045.00 34,000.00	6,800.00 - 7,761.25 5,950.00	- 1,215.00 7,450.80 3,740.00
CBR = 30%					
Asphalt (Granular Base) Concrete Blocks Rigid Concrete Reinforced Concrete	- - 0.100 0	- - 0 0	13,600.00 4,500.00 31,045.00 34,000.00	- - 3.10450 0	- - 0 0

The results obtained for the design method and pavements using different CBR values are discussed to reveal the changes in material specification, construction technology and corresponding maintenance requirements due to the sensitivity of the performance of heavy load pavement. BPA Charts were employed in the design of the component layers for the four pavements under consideration. The design results show that asphalt pavement on granular base with subgrade CBR values of 1%, 3% and 5% and subbase thickness of 300mm and also with CBR value of 1% and subbase thickness of 600mm did not produce any thickness of base course. This is because asphalt surfacing on such soils and thicknesses are not practical solutions. Asphalt pavement placed on soils of 30% CBR and 300mm thick subbase and on soils of 3%, 5%, 10% and 30% and 600mm thick subbase will not require the provision of a base course as shown in Table 4.

The results also show that it will not be practically wise to construct a concrete block pavement on all the five subgrade CBR values and 300mm thick subbase as well as soils with CBR values of 1%, 3% and 5% and 600mm thick. However, Table 5 shows that a soil of 30% CBR and subbase thickness of 600mm will not require a base course to carry a concrete block pavement. In the case of rigid concrete pavement, with subbase thicknesses of 300mm and 600mm and for all CBR values, its construction is practically possible with resulting base thicknesses reducing with increase in subgrade CBR values as presented in Table 6. Table 7 shows that reinforced concrete pavement is an improvement over the rigid concrete pavement as the resulting base thicknesses in the former are less than those of the latter for all CBR values and subbase thicknesses.

Tables 10 and 11 also show clearly that, for all pavements, the base course thicknesses decrease with increase in the subgrade CBR values, thickness of subbase course notwithstanding. This implies that a better subgrade will require a less pavement thickness. It is also evident that concrete block and reinforced concrete will produce pavements of least thicknesses.

The traditional approach adopted for the design in this paper involves selecting a container handling equipment (in this case a straddle carrier) according to operational requirements, then design a pavement system to withstand the damage afflicted by the selected equipment. The choice will be a compromise between the technicality and economy of the design method. The most important thing is to be aware of the available choices of the relevant factors and adopt them appropriately.

Table 10: Design Results by Analysis Technique

Pavement Type	Base Thickness(m) for 300 mm subbase	Base Thickness(m) for 600 mm subbase
CBR = 1%		
Asphalt (Granular Base)	-	-
Concrete Blocks	-	-
Rigid Concrete	0.325	0.290
Reinforced Concrete	0.245	0.205
CBR = 3%		
Asphalt (Granular Base)	-	-
Concrete Blocks	-	-
Rigid Concrete	0.300	0.280
Reinforced Concrete	0.205	0.200
CBR = 5%		
Asphalt (Granular Base)	-	-
Concrete Blocks	-	-
Rigid Concrete	0.275	0.270
Reinforced Concrete	0.200	0.190
CBR = 10%		
Asphalt (Granular Base)	0.500	-
Concrete Blocks	-	0.270
Rigid Concrete	0.250	0.240
Reinforced Concrete	0.175	0.110
CBR = 30%		
Asphalt (Granular Base)	-	-
Concrete Blocks	-	-
Rigid Concrete	0.100	0
Reinforced Concrete	0	0

Table 11: CBR Values versus Base and Subbase Thicknesses

CBR (%)	Base Thickness(m) for 300 mm subbase	Base Thickness(m) for 600 mm subbase
Asphalt Pavement with Granular Base		
1	-	-
3	-	-
5	-	-
10	0.500	-
30	-	-
Concrete Block Pavement with Lean Concrete Base		
1	-	-
3	-	-
5	-	-
10	-	270
30	-	-
Rigid Concrete Pavement		
1	0.325	0.290
3	0.300	0.280
5	0.275	0.270
10	0.250	0.240
30	0.100	0
Reinforced Concrete Pavement		
1	0.245	0.205
3	0.205	
5	0.200	
10	0.175	
30	0	

Conclusions

The following conclusions can be made from this study:- The results indicate that rigid concrete and reinforced concrete pavements are better practically than other types of pavements. However, the reinforced concrete pavement stands as the best choice economically. This is because for all the subgrade CBR values and subbase thicknesses its construction cost is least. For instance, the cost of constructing the base course of reinforced concrete pavement on a soil of 10% CBR and 300mm thick subbase is ₦5,950.00/m^2 of pavement as compared to costs of asphalt, and rigid concrete pavements which are ₦6,800.00/m^2 and ₦7,761.25/m^2 respectively. In addition reinforced concrete pavement on a subgrade CBR of over 30% and for 300mm and 600mm subbase thicknesses will not require the provision of a base course. This implies that a better subgrade will require less pavement thickness.

Cost analysis shows that all pavement types are cheaper to build on subgrades with CBR values of 30% and for all the CBR values, reinforced concrete pavement is the best choice economically having met all safety conditions. The ideal pavement for marine traffic does not require maintenance or repair and it must be cheap. In real life, a sound compromise has to be found both in the technical and economic fields. An unsuitable pavement will have a negative impact on terminal operations. Hence, selection of suitable and economically feasible pavement is of utmost importance.

Recommendations

The economically and cost effective, fortified pavement for marine operation at the coastal areas is the reinforced concrete pavement with the least construction costs for all subgrade CBR values and subbase thicknesses. It is advisable that reinforced concrete pavement be adopted for Nigeria Port Pavements because of the justifiable cost effectiveness.

Aknowledgements

This paper cannot be put together without the tremendous background information made available by various research workers, authors of excellent books and articles, which have been referred to and listed in the references. I thank them.

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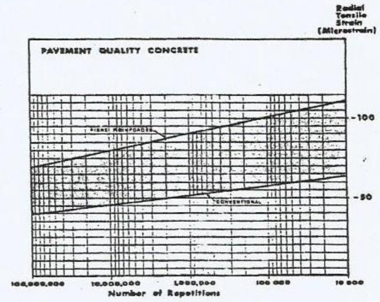
APPENDIX

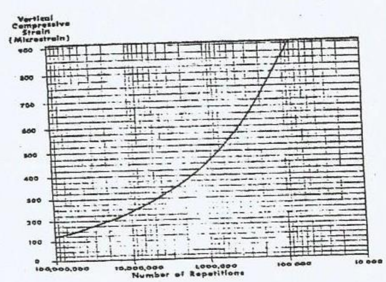
CHART B



PERMISSIBLE TENSILE STRAIN
for
RIGID CONCRETE SLABS

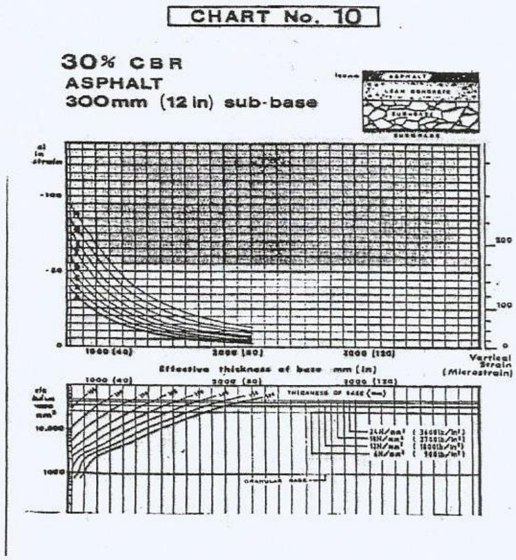
Source: Knapton, 2009

CHART C

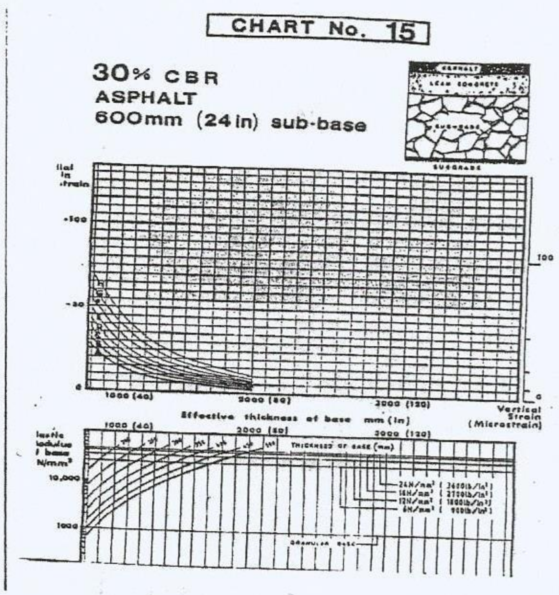


PERMISSIBLE COMPRESSIVE STRAIN
for
GRANULAR BASES

Source: Knapton, 2009



Source: Knapton, 2009



Source: Knapton, 2009