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Development of a Simplified Structural Design Procedure for Flexible Pavements in Sudan

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Abstract: The inconsistencies and variations in design of pavements arising from using different methods has become a critical issue in Sudan. This paper is aimed to develop a structural design procedure for flexible pavements in order to simplify the design process by using a software program and provide a uniform structural design result. The literature of the conventional design methods commonly experienced in Sudan was intensively reviewed. In fact, these design methods were not designed to cater for the current needs and conditions of Sudan. Thus, an attempt was made to establish a simplified design procedure to accommodate the ever increasing traffic loads, available pavement materials and significant change in climate conditions in Sudan. Based on previous experiences, a design chart for a particular set of traffic loading and CBR values of subgrade soils and granular materials was developed. A software program using Visual Basic language of the Microsoft was created to facilitate the design process. To verify the validity of the developed design chart, three existing roads in Khartoum were redesigned by the new design chart and compared with their previous designs. The results proved that the new design is more realistic, reliable, and accurate design than the previous design. Therefore, adopting the developed design procedure in Sudan might help in enhancing the performance and sustainability of roads. Finally, recommendations are provided for further improvement in design of pavements in view of future developments.

Keywords: Design Procedure, Conventional Methods, Flexible Pavement, Software Program

1. Introduction

Asphalt concrete pavement is the most common type of pavements used in Sudan and wide-world. Various design methods and codes of practice are currently experienced in many countries for structural design of flexible pavements. Among these methods, Transport Research Laboratory (TRL) [1], California Bearing Ratio (CBR) [2] and AASHTO [3] methods are the most famous pavement design methods used in Sudan for their simplicity and economical. However, these methods are currently undergoing improvement by many researchers.

Recently, the inconsistencies and variations in the result of structural thickness design of pavements arising from individual differences in sight and judgment in the use of design charts and tables have become a matter of concern for pavement designers. Hence, the need to develop a more precise and accurate design tool that will enable pavement designers produce uniform structural thickness design results. There is no existing computer program for the structural design of flexible pavement in Sudan.

The purpose of this paper is to establish a new design procedure for flexible pavements that can cater for Sudan needs and conditions. A software program of Visual Basic language is created to facilitate the design process and provide a uniform structural design result.

2. Literature Review

2.1. Flexible Pavement Principles

Road pavements are broadly divided into three categories; flexible pavements, rigid pavements and composite pavements. In this paper, study is limited to flexible pavements only. The flexible pavement consists of a relatively thin wearing surface layer of asphalt concrete material built over a base course and subbase course, and they rest upon compacted subgrade. The main function of the surface layer is to provide a running surface capable of carrying wheel loads without undue discomfort to drivers. It also protects the underlying layers from adverse weather conditions and provides the necessary skid resistance for ensuring road safety characteristics when braking becomes necessary. The base layer is the main load carrying structural component in a flexible pavement. It is designed to resist and distribute stresses induced by vehicles to the underlying layers. While the role of the subbase layer is to help in distributing induced stresses into the subgrade as well as protecting the base from adverse soil conditions that may prevail in the natural soil. The subgrade is the natural or improved ground on which the pavement structure is constructed. Structural design of road pavement depends on the strength and behavior of the subgrade soils.

2.2. Pavement Design

Pavement design is the process aimed at achieving a pavement structure which is economical and comfortable to the drivers and which minimizes development of pavement distress features such as rutting, cracking, potholes, raveling, and depressions during the design life of the pavement. The design should take account of traffic loads, pavement materials and environmental factors and must also aim at desirable balance between construction, road users and maintenance costs [4].

Pavement design consisted basically of determining thicknesses of layered materials that would provide strength and protection to subgrade soils. Unlike other civil engineering structures, the structural design of a pavement is a complex task due to uncertainty, variability and approximations of most factors associated with the design process. Traffic loading is a heterogeneous mix of vehicles, axle types, and axle loads with distributions that vary with time throughout the day, from season to season, and over the pavement design life. Thus, traffic forecasting is very difficult to estimate correctly [5]. Pavement materials respond to traffic loading influenced by stress magnitude, temperature, moisture, time, loading rate, and other factors. Pavements exhibit significant variation in condition over its design life and therefore, performance predictions and its relation to input variables add further complications [5].

2.2.1. Design Factors

Pavement design is a complex process, since it involves many variable factors. Usually the design factors for flexible pavements are broadly divided into three categories that are traffic loading, pavement materials properties, and environmental conditions [6].

I Traffic loading

Traffic loading is the most important design factor, as a pavement structure is designed to carry traffic. The key factors of traffic loading include contact pressure, wheel load, axle configuration, moving loads, and load repetitions [7]. The influence of traffic on pavement not only depends on the magnitude of the wheel load, but also on the frequency of the load applications [8]. As there is a wide range of vehicles over the highway having different axle types and axle loads, which has to be converted to the Standard Load (8.2 tons) to avoid facing problems in design. Therefore the Equivalent Single Axle Load (ESAL) causes a unit damage per pass. The load equivalency factor (LEF) or Relative damage factor (RDF) can be calculated as

$$LEF(orRDF) = \left[\frac{AxleLoad}{StandardLoad}\right]^n \quad (1)$$

in which n is the damage power equals to 4 (or 4.5 in some design methods).

II Material characterization

Effective characterization of pavement materials is a key requirement for a successful and effective pavement design. The characterization of different materials forming the pavement layers changes with variation in density and moisture condition which in turn affected the structural response of the pavement structure subjected to traffic loading [6].

The materials characterized by index properties, mechanical properties like elastic modulus of bituminous materials and the CBR and resilient modulus of unbound materials (granular materials or natural soils). The materials properties over the entire design period are influence by environmental conditions and the variation in applied stress state and pavement depth [8].

III Environmental factors

Environmental factors that affect pavement include temperature and precipitation. Temperature affects the resilient modulus of asphalt layer. Dynamic modulus of asphaltic concrete varies with temperature. The properties of asphalt materials are greatly affected by temperature change such as penetration, ductility, viscosity, softening point, flash and fired points [9]. Higher temperatures cause asphalt bleeding on road surface which adversely affects surface skid resistance. The precipitation from rain affects the quantity of surface water infiltrating into the subgrade and the depth of ground water table. Change in water content of expansive subgrades causes differential heave and pavement roughness [7]. Most detrimental effect of percolated water through the asphalt surface and road edges occurs during the rainy season period when the subgrade soil in a saturation condition.

2.2.2. Design Methods

Pavement design methods are grouped as empirical and mechanistic-empirical methods. An empirical design method is one that is based solely on the results of experiments or experience [5]. There are many examples of empirical methods such as California Bearing Ratio (CBR), Transport Research Laboratory (TRL), AASHTO methods, etc. In an empirical pavement design approach, the relationship between design inputs (e.g., traffic loads, materials, and environment) and pavement (performance) failure were arrived through empirical correlations between required pavement thickness and soil classification or simple strength tests of subgrade materials using the data of past experience, experiments or a combination of both [5].

Mechanistic-empirical (M-E) methods represent one step forward from empirical methods. The induced state of stress and strain in a pavement structure due to traffic loading and environmental conditions is predicted using theory of mechanics. Empirical models link these structural responses to distress predictions. Shell method [10] and the Asphalt Institute method [9] incorporated strain-based criteria in their mechanistic-empirical procedures.

2.3. Conventional Design Methods

2.3.1. California Bearing Ratio (CBR) Method

California bearing ratio method was developed by the California division of highway during 1928-29. In this method the strength of the soil is represented by the CBR value and the traffic load as heavy commercial vehicles (load ≥ 1.5 tons) per day of the design period. On the basis of this method, the US corps of Engineers [2] showed that the pavement thickness also depends upon the wheel load, tyre pressure, and CBR value.

The design of the pavement layers to be laid over subgrade soil starts with the estimation of subgrade strength and the volume of traffic measured in wheel load, Average Daily Traffic (ADT) or Equivalent Single Axial Load (ESAL). For the design of pavement, CBR value is invariably considered as one of the important parameter. With the CBR value of the soil known, the appropriate thickness of construction required above the soil for different traffic conditions is determined using the design charts (see Figure 1).

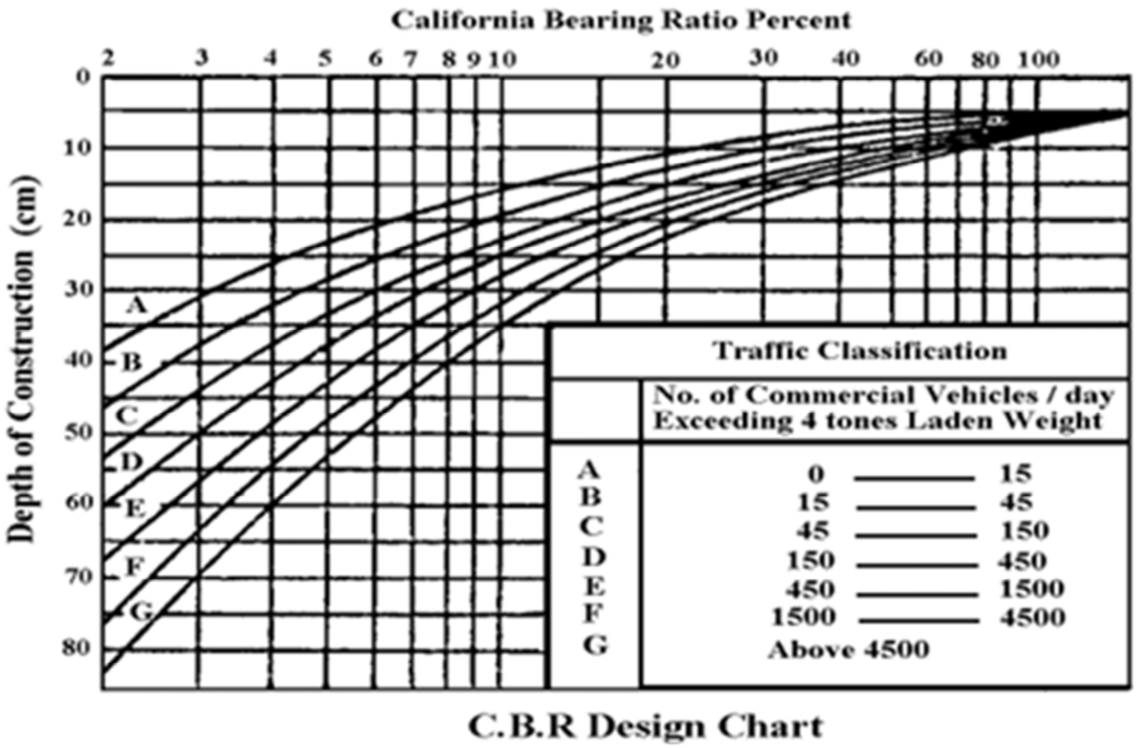

Figure 1. *CBR design curves (source [2]).*

To find out the pavement thickness the following formulas are also used

$$T = \sqrt{P} \times \left[\frac{1.75}{CBR} - \frac{1}{p \times \pi}\right]^{\frac{1}{2}} \quad (2)$$

$$T = \left[\frac{1.75 \times p}{CBR} - \frac{A}{\pi}\right]^{\frac{1}{2}} \quad (3)$$

Where,
T = Pavement thickness, (cm)
P = Wheel Load, (kg)
CBR = California bearing ratio, (%)
p = Tire pressure, (kg/cm^2)
A = Area of contact, (cm^2)

2.3.2. Transport Research Laboratory (TRL) Method

The Transport Research Laboratory (TRL) Overseas Road Note 31 (ORN31) [1] is the most popular design procedure for bitumen surfaced roads in tropical and sub-tropical countries. TRL recommends a design life of twenty years for flexible pavements. For design purposes, it is important that the traffic loading and the subgrade strength are properly estimated. If the characteristics of the subgrade change significantly over sections of the route, different subgrade strength values for design should be calculated for each nominally uniform section.

The structural catalogue of the ORN 31 [1] requires that the subgrade strength for design is assigned to one of six strength classes reflecting the sensitivity of thickness design to subgrade strength. The subgrade strength classes are defined in Table 1 in addition to the road traffic classes which are obtained after an estimate of the cumulative equivalent standard axle loading of the road. For subgrades with CBR less than 2%, soil stabilization is required. The design subgrade strength class together with the traffic class obtained is then used with the catalogue of structures to determine the pavement layer thicknesses [1].

The design process is carried out in three steps; (i) estimating the amount of traffic and the cumulative number of standard axle load,(ii) measure the strength of subgrade soil by CBR test, and (iii) based on the traffic class and the subgrade strength class, select the design cell of pavement layers thickness.

Table 1. *Traffic classes and Subgrade strength classes [1].*

Traffic classes (10^6 esa)		Subgrade strength classes (CBR %)	
T1	< 0.3	S1	2
T2	0.3 – 0.7	S2	3, 4
T3	0.7 – 1.5	S3	5 – 7
T4	1.5 – 3.0	S4	8 – 14
T5	3.0 – 6.0	S5	15 – 29
T6	6.0 – 10	S6	30+
T7	10 – 17		
T8	17 – 30		

2.3.3. AASHTO Method

The design method developed by American Association of State Highway and Transportation officials (AASHTO) is an empirical method based on the tests results conducted in Ottawa and Illinois. The first AASHTO Pavement Design Guide was introduced in 1972 [11]. Changes to the design methods were made over the years in 1986 [12] and again in 1993 [3].

The original design equation was empirically developed for the specific subgrade type, pavement materials and environmental conditions at the location of the AASHO Road Test. The basic equation of AASHTO flexible pavement design given in 1993 design guide for flexible pavements:

$$\log(W_{18}) = Z_R \cdot S_0 + 9.36\log(SN+1) - 0.20 + \frac{\log(\Delta PSI)/(4.2-1.5)}{0.4+1094/(SN+1)^{5.19}} + 2.32\log(M_R) - 8.07 \quad (4)$$

in which:

W_{18} = Accumulated 18 kip equivalent single axle load for the design period

Z_R = Reliability factor

S_0 = Standard deviation

SN = Structural number

ΔPSI = Initial PSI – terminal PSI

M_R = Subgrade resilient modulus (psi)

The structural number is the parameter that represents the pavement structural strength can be determined from a graph presented by AASHTO called the Nomo graph (Figure 2).

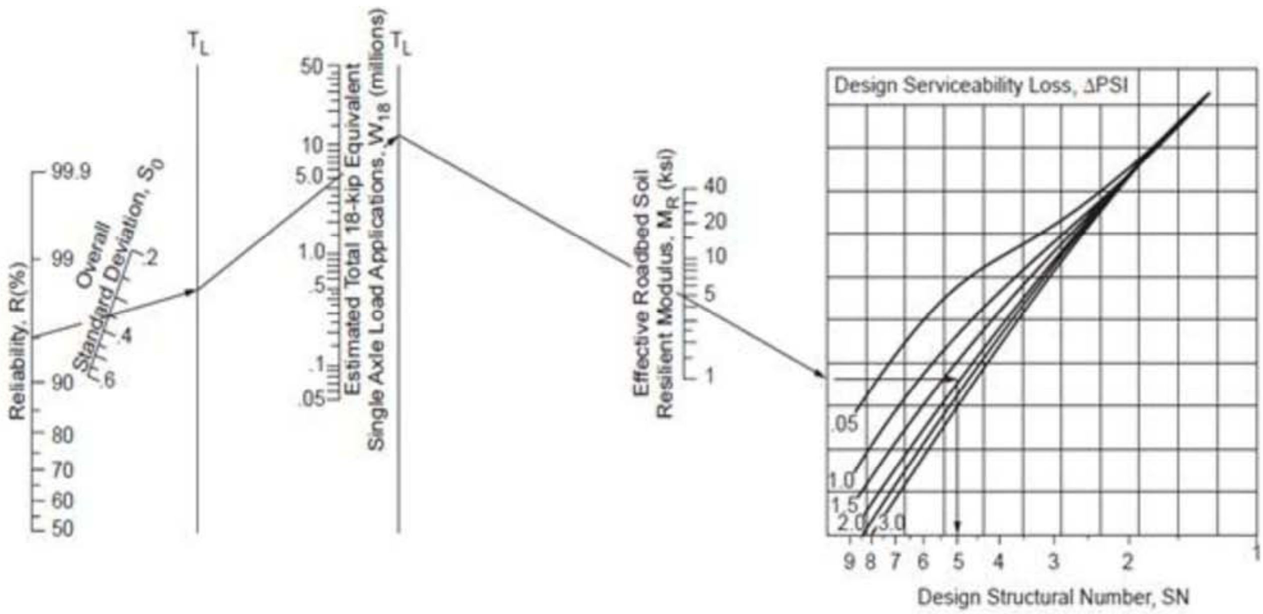

Figure 2. *AASHTO Nomo graph for Flexible Pavement Design.*

The structural number (SN) is a function of layer thickness, layer coefficient, and drainage coefficients, is given by:

$$SN = a_1 D_1 + a_2 m_2 D_2 + a_3 m_3 D_3 \quad (5)$$

in which:

a_1, a_2, a_3: Structural layer coefficients for surface, base and sub-base respectively

D_1, D_2, D_3: Thickness for surface, base, and sub-base.

m_2, m_3: Drainage coefficients for base and sub-base.

Given all the inputs, Eq. (4) is solved for the structural number (SN) and then the layer thicknesses can be computed. The solution is not unique and different combination of thicknesses can be found. Additional design constraints, such as costs and constructability, must also be considered to determine the optimal final design. The 1993 Guide recommends the top-to-bottom procedure in which each of the upper layers is designed to provide adequate protection to the underlying layers. Figure 3 illustrates the procedure for a 3-layer flexible pavement. The steps in this case are as follows:

- Calculate SN_1 required to protect the base, using elastic modulus of asphalt concrete (E) as M_R in Eq. (6), and compute the thickness of layer 1 as:

$$D_1 \geq \frac{SN_1}{a_1} \quad (6)$$

- Calculate SN_2 required to protect the subgrade, using Eq. (7), with the subgrade effective resilient modulus as MR. The thickness of the base is computed as:

$$D_2 \geq \frac{SN_2 - a_1 D_1}{a_2} \quad (7)$$

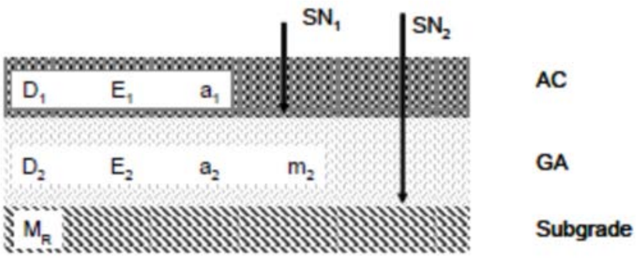

Figure 3. *General procedures for computing thickness.*

3. Development of New Design Procedure

As conventional empirical design approaches rely entirely on past observations of field performance and they could not be used for traffic loading and environment conditions well beyond their observational domain. Hence, such approaches are considered to possess only limited capabilities. The AASHTO method, for example, was adjusted several times over the years to incorporate extensive modifications based on theory and experience that allowed the design equation to be used under conditions other than those of the AASHO Road Test. To overcome limitations and empiricism in pavement design as previously discussed, attempts were made to propose a new procedure for flexible pavement design to accommodate Sudan traffic loadings and local materials. Guidelines for the proposed new design procedure are briefly outlined below:

3.1. Design Criteria

3.1.1. Subgrade Strength

The type of subgrade soil is largely determined by the location of the road. However, where the soils within the possible corridor for the road vary significantly in strength from place to place, it is desirable to locate the pavement on the stronger soils if this does not conflict with other constraints.

The strength of the road subgrade for flexible pavements is commonly assessed in terms of the California Bearing Ratio (CBR). Thus, the new approach adopted the CBR to obtain the subgrade strength and to be measured after soaking the soil for 4 days. If the subgrade CBR value is less than 5%, it needs to be stabilized chemically.

3.1.2. Traffic Loading

A simple approach is used to quantify the characteristics of traffic loads carried by a flexible pavement structure as it allows mixed traffic to be analyzed directly and thus, enhances pavement design process. The approach estimates the effects of actual traffic on pavement response and distress. Vehicle class distributions, daily traffic volume, and axle load distributions are essential for design. The vehicles are classified into five main classes; cars, mini-buses, buses, trucks and trailers. Traffic count is considered to determine initial traffic volumes.

In order to determine the cumulative axle load damage that a pavement will sustain during its design life, it is necessary to express the total number of vehicles that will use the road over this period in terms of the cumulative number of equivalent standard axles (ESA). The damaging power of axles is related to a “Standard” axle of 8.16 tones using empirical equivalency factors with the damage exponent (n = 4.5).The Load Equivalent Factor (LEF) for the different classes of traffic are estimated based on maximum gross vehicle weight and permissible maximum axle loads as shown in Table 2.

Table 2. *Average equivalency factors for different vehicle types.*

Vehicle Class	Axle Load (Tone)	LEF
Car	4.0	0.04
Mini-Bus	6.0	0.3
Bus	9.5	2.0
Small Truck	9.0	1.5
Medium Truck	12.0	5.5
Large Truck	13.5	10.0
2-axled Trailer	13.5	10.0
3 or 4-axled Trailer	14.5	12.0

In order to determine the total traffic over the design life of the road, the following steps are to be followed.

i Determine the traffic flow ($AADT_P$) from traffic count.

ii Estimate the future traffic ($AADT_F$) for certain design life (n) and annual traffic increment (r) using eq. (8)

$$AADT_F = AADT_P \left(\frac{(1+r)^n - 1}{r}\right) \quad (8)$$

iii The Load Equivalent Factor (L.E.F) for different types of vehicles is given in Table 3.

iv The total cumulative (∑ ESAL) is determined using eq. (9)

$$\sum ESAL = LEF \times AADT_F \times 365 \quad (9)$$

v Select the traffic load class from Table 3

Table 3. *Equivalent load factor for different classes of vehicles.*

Traffic Class	ESAL (10^6)
T1	≤ 1
T2	1 – 10
T3	10 – 30
T4	> 30

3.1.3. Unbound Pavement Materials

Variability in material properties is generally much affect pavement design. It is the task of the designer to estimate likely variations in layer thicknesses and material strengths so that realistic target values can be set in the specifications to ensure satisfactory road performance is possible.

The new approach has considered for pavement design a four layer structure consisting of surface layer of asphalt concrete, granular base course of crushed stones or natural gravels, granular subbase course of natural gravels, embankment of clayey (or silty) gravel (or Sand) and compacted subgrade.

The specifications required for the unbound pavement materials and asphalt concrete are shown below in Table 4.

Table 4. *The recommended properties of Pavement Unbound Materials.*

Pavement Layer	Materials Used	Symbol	Properties
Surface	Hot Mix Asphalt Concrte	HMA	Marshall specification for asphalt concrete
	Crushed rock	GB1	Well graded, CBR = 100%, PI=0
Base	Crushed stone or gravel	GB2	CBR ≥ 80%, LL ≤ 25%,PI≤6%
	Natural gravel	GB3	
Subbase	Sandy Gravel soil	GS	CBR ≥ 30%, LL ≤ 30%, PI ≤ 12%
Embankment	Clayey (or Silty) Gravel (or Sand)	GC or SC	CBR ≥ 15%,LL <50%, PI<15%

3.2. Developing Design Curves

The following steps were adopted in the development of the design curves:

1) To generate the design curve data for curves A, B, C, and D, interpolations were carried out at intervals of 1% CBR on the CBR-Pavement thickness chart. The interpolations produced the "thickness above layer" and the corresponding CBR for curves A to D.
2) The data generated in step 1 was modeled using the Microsoft Office Excel Program (Exponential Option) with “CBR” as X-axis and “Thickness above layer” as the Y-axis to obtain the curve equations. The curve equations for curves A to D are as presented in Eq. (8) to (11).

$$Y = 744\, e^{-0.03X} \text{Curve A (T1} \leq 1 \text{ million)} \quad (10)$$

$$Y = 834\, e^{-0.03X} \text{Curve B (1} \leq \text{T2} \leq 10 \text{ million)} \quad (11)$$

$$Y = 915\, e^{-0.03X} \text{Curve C (10} \leq \text{T3} < 30 \text{ million)} \quad (12)$$

$$Y = 1008\, e^{-0.03X} \text{Curve D (T4} \leq 30 \text{ million)} \quad (13)$$

Where,
X = CBR (%); Y = D = Thickness above layer(mm)
Thickness Description:
D_1 = Total thickness
D_2 = Thickness of base and surface
D_3 = Thickness of surface = $D_{surface}$
$D_2 - D_3$ = Thickness of base = D_{base}
$D_1 - D_2$ = Thickness of sub-base = $D_{subbase}$

It is generally impractical and uneconomical to use layers of material that are less than some minimum thickness. Furthermore, traffic considerations may dictate the use of a certain minimum thickness for stability. Table 5 shows the minimum thickness of asphalt surface and aggregate base.

Table 5. *Minimum thickness of pavement surface, base and subbase.*

Traffic Class	ESAL (millions)	Asphalt(mm)	Base (mm)	Subbase(mm)
T1	≤ 1	50	150	150
T2	1 – 10	75	175	200
T3	10 – 30	100	200	250
T4	> 30	100	250	300

3.3. Design Process

The main steps involved in designing a new road pavement are shown in Figure 4:

1) Estimating the traffic in terms of the cumulative number of equivalent standard axles that will use the road over the selected design life. Then from Table 3 the traffic class can be identified.
2) Assessing the strength of the subgrade soil over which the road is to be built. Thus, the subgrade CBR can be determined from laboratory testing.
3) Based on traffic class and subgrade strength, the total pavement thickness (D_1) can be determined from Figure 5.
4) Selecting pavement materials and using their minimum strength (CBR) to determine the pavement thickness above the subbase and base (D_2 and D_3 respectively).
5) Using the data obtained in steps 3 and 4 to select a suitable the most economical combination of pavement materials and layer thicknesses that will provide satisfactory service over the design life of the pavement.

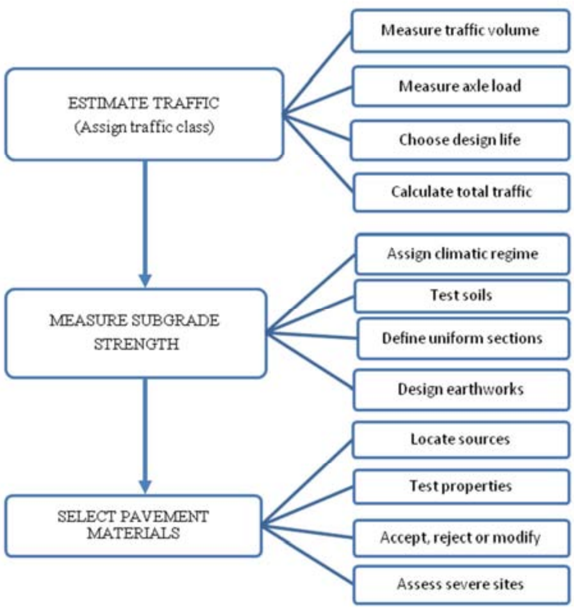

Figure 4. *Pavement Design Process.*

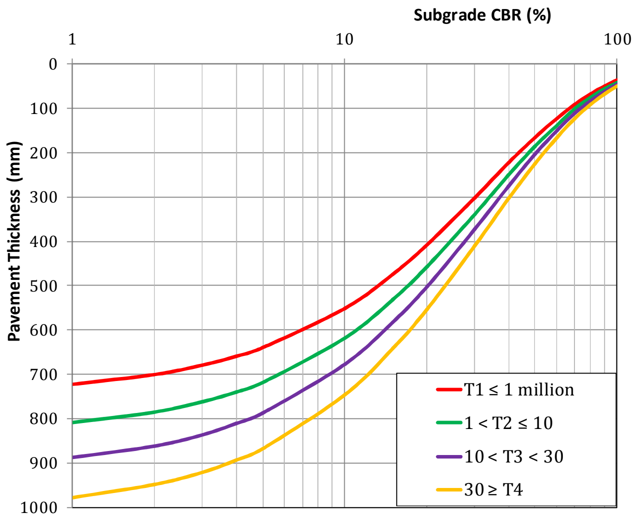

Figure 5. *The developed Flexible Pavement design chart.*

3.4. Software Program

The development of software for the pavement design is very important as it makes the design process very easy and accurate and saves a lot of precious time. Hence the design process can be done in very short time and accurately avoiding the computational and calculation errors of the conventional manual design method.

A computer program using visual basic program language was developed to facilitate the flexible pavement design of roads in Sudan. Visual basic is a simple, easy and widely used program. The developed program is named Sudan Pavement Design Method "SPDM". A brief description of the program is outlined below.

3.4.1. Input Data

The data required for the design process are to be entered in the program in the following steps.

Step 1: The basic information about the road like name, classification (urban or rural), length, width, number and width of lanes as shown below in Figure 6.

Step 2: Traffic data obtained from traffic survey conducted on the road counting the number of five vehicle classes. Design life in years and annual traffic increment rate are required (Figure 7).

Step 3: The subgrade soil strength measured by CBR or resilient modulus and materials used for pavement construction; surface, base and subbase layers (Figure 8).

3.4.2. Output Results

When all the necessary design input parameters have been made as previously described. The program can run successfully in less than 30 seconds. The program outcomes show the thicknesses and materials of the flexible pavement structure of four layers: Surface, base, subbase and embankment (see Figure 9).

Figure 6. *Road basic information.*

Figure 7. *Traffic loading data.*

Figure 8. *Subgrade strength and pavement materials input data.*

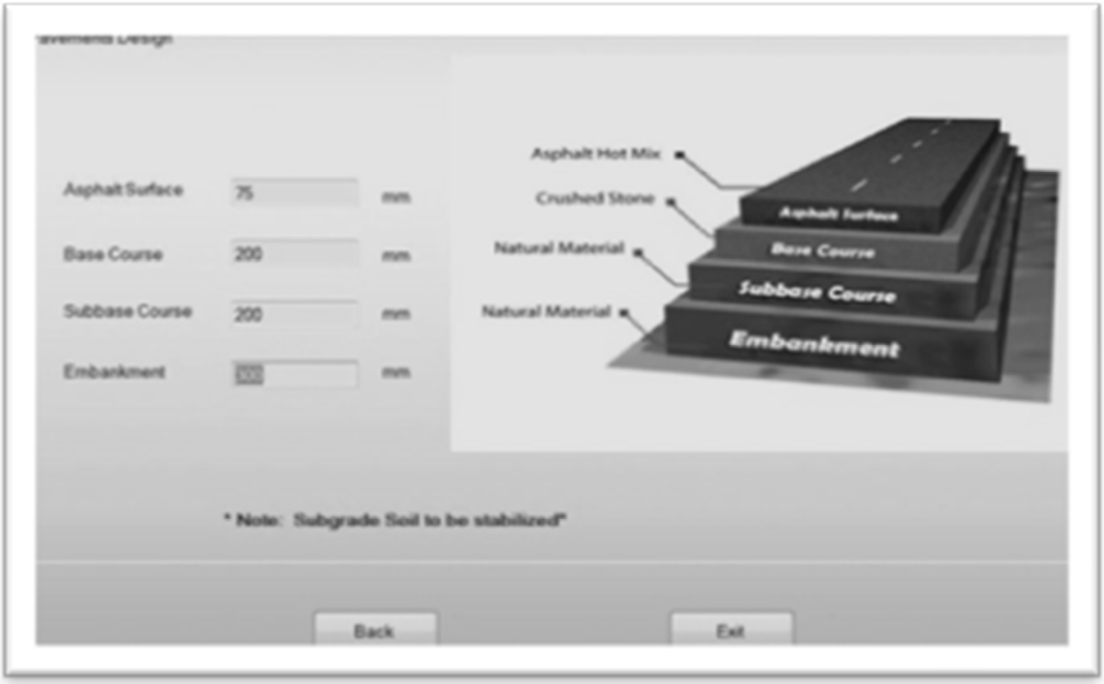

Figure 9. *The program outcomes.*

4. Case Study

The objective of this study is to develop a structural design procedure for flexible pavements in Sudan. The investigation based on the commonly used design approaches and the needs and conditions of Sudan to develop a simplified procedure for pavement design. To verify the validity of the developed design approach, redesign of pavement was carried out on existing roads in Khartoum. Three roads were selected as case study; Elsiteen Road, Eljama Road and Mohamed Najeeb Road.

4.1. Data Collection

A detailed records review was conducted with the great help of the engineers of Highway Cooperation, Ministry of Infrastructure in Khartoum State to obtain some information and reports about the design and preliminary studies of the selected roads. The documents contain information data about the project design, traffic studies, construction materials properties and specifications, and other relevant information such as soil or geological records, and weather data. Some of the documented design data of the three roads were collected as shown in Table 6.

Table 6. *Data collected for the three roads.*

Item		Elsiteen Road	Eljama Road	Mohamed Najeeb Road
Road	Length (km)	7.5	2.5	6
	Width (m)	25	12	22
Thickness of Pavement Layers (mm)	Surface	100	50	50
	Base	250	175	175
	Subbase	550	200	250
	Embankment	0	300	0
Traffic Count (at peak hour)	Cars		1480	2916
	Mini-bus		435	1050
	Buses	NA*	15	25
	Trucks		40	71
	Trailers		0	1
Design ESAL (in millions)		18.6	2.1	3.5
Subgrade CBR (%)		3.0	3.1	8.0
Design Method Used		AASHTO	TRL	TRL
Existing Condition		Good	Bad	Moderate

Note: NA* means data is not available

4.2. Results and Discussion

The results of structural thickness design using the suggested new design chart (ND) and the original design (OD) of the pavements of the three studied roads are presented in Tables 7 to 9. These tables show the comparison between the pavement thicknesses determined from the new design chart and the measured thicknesses using the original design. The results revealed the following comments:

- The design thicknesses vary according to traffic loading and strength of subgrade soil. For Elsiteen road of relatively high traffic load and low subgrade strength, the total thickness of pavement is quite high, 900 mm. While the other two roads have relatively low traffic load with varying subgrade strength, Eljama road has lower subgrade strength than Mohamed Najeeb road, hence its pavement structure is thicker, 825 mm compared to 700 mm.
- The pavements thicknesses obtained from the design curves for the roads were found equal or higher than the actual values. The existing conditions of the three roads as shown in Table 6.It is cleared that the two designs of Elsiteen are similar while the other two roads their origin designs are less than the new designs. This result assures that the developed design is absolutely accurate and precise than the original designs.
- The actual asphalt and base layers in Eljama and Mohamed Najeeb roads are less than that determined by the new design chart. The thicknesses are not sufficient to withstand the traffic loading and therefore the road suffered from severe distresses. This may be the reason of their failure.

Table 7. *Pavement design for Elsiteen Road.*

Layer	CBR(%)	Thickness above layer (mm)		Thickness of layer (mm)		Adjusted/Actual Thickness (mm)	
		ND	OD	ND	OD	ND	OD
Subgrade	3	835	900				
Embankment	15	570	--	265	--	300	--
Subbase	30	380	350	190	550	200	550
Base	80	80	100	300	250	300	250
Surface				80	100	100	100
Total Thickness (mm)				835	900	900	900

Table 8. *Pavement design for Eljama Road*

Layer	CBR(%)	Thickness above layer (mm)		Thickness of layer (mm)		Adjusted/Actual Thickness (mm)	
		ND	OD	ND	OD	ND	OD
Subgrade	**3**	**775**	**725**				
Embankment	15	500	425	275	300	300	300
Subbase	30	320	225	180	200	200	200
Base	80	70	50	250	175	250	175
Surface				70	50	75	50
Total Thickness (mm)				775	725	825	725

Table 9. *Pavement design for Mohamed Najeeb Road.*

Layer	CBR(%)	Thickness above layer (mm)		Thickness of layer (mm)		Adjusted/Actual Thickness (mm)	
		ND	OD	ND	OD	ND	OD
Subgrade	8	660	475				
Embankment	15	500	--	160	--	175	--
Subbase	30	320	225	180	250	200	250
Base	80	70	50	250	175	250	175
Surface				70	50	75	50
Total Thickness (mm)				660	475	700	475

5. Conclusion and Recommendations

The objective of this study is established a new structural design procedure for flexible pavements to cater for Sudan conditions and needs. From the results of the study, the following conclusions and recommendations are hereby made:

- A structural design procedure and a software program using Visual Basic language were developed for flexible pavements in Sudan. The software program named "Sudan Pavement Design Method" (SPDM) was created to facilitate the developed design procedure.
- To validate the developed design procedure with the software, three existing roads in Khartoum were redesign by the new procedure. A comparison between the results obtained using the "SPDM" and the original design of the roads, clearly assure the validity of the developed procedure for Sudan.
- The pavement design for the highways in Sudan ask for thicker asphalt concrete layer and pavement structure to withstand the rapid increasing in traffic loading and climatic changes in future.
- It is recommended to establish manuals or codes of practice for the design of roads in Sudan contain this structural design procedure for flexible pavements.
- The developed structural design procedure and the software program are limited to the flexible pavements so it can further be extended for the rigid pavement design.

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