

A MULTILAYERED THICKNESS DESIGN
METHOD FOR HIGHWAYS IN EGYPT

طريقة لتصميم سمك الرصف للطرق المرصفة

بأسلوب الطبقات المتتالية

By

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الخلاصة - تعتبر الحاجة ملحة في مصر لوجود طريقة لتصميم سمك طبقات الرصف مبنية على أسس علمية وبأسلوب يعكس الظروف البيئية والجوية المحيطة بالطرق المرصفة . والغرض من هذا البحث هو استخدام طريقة تحليل الطبقات المتتالية لعمل طريقة تصميم تعكس ظروفنا والمواد المتاحة لنا في مصر . وقد تم ذلك أولاً بتحديد خواص طبقات الرصف من طبقات سطحية ورابطة وأساس من الحجر الجيري وأساس مساعد من التربة الرملية ومدى تغيير خواص الطبقات السطحية والطبقة الحاملة خلال شهور السنة . ثانياً باستخدام برنامج على الحاسب الآلي مشابه للبرنامج المستخدم في إيجاد طريقة معهد الأشغال الجديدة والتي تمت عام ١٩٨١ بعد تعديله طبقاً للتطوير الذي حدث في إيجاد معامل المرونة للطبقات الأسفلتية وحتى يسمح باستخدام طبقة أساس مساعد بالإضافة لطبقة الأساس . وقد روعى أن يكون تقسيم انهيار الطريقة على أساس معامل الخدمة الذي كان نتيجة الأبحاث الخاصة باختبار الـ A . ش . ت . و . وقد تم التوصل في النهاية لعدد ستة علاقات بيانية لتحديد سمك طبقات الأساس والأساس المساعد بمعلومية السمك المطلوب للطبقة السطحية (١٠ سم ، ١٥ سم ، ٢٠ سم) وذلك بمعرفة قيمة معامل انضغاط كاليفورنيا للطبقة الحاملة وكثافة المرور .

ABSTRACT- A flexible pavement is classified by a pavement structure having a relatively thin asphalt wearing course with layers of granular base and subbase being used to protect the subgrade from being overstressed. In the past, the design of such pavements was based primarily upon empiricism or experience, with theory playing a secondary role in the procedure. However; design and construction of flexible highway pavements has changed significantly during the past three decades.

Since the performance of the AASHTO Road Test, many important concepts have been brought forth. Among these were the demonstration of the major influence of traffic loads and repetitions upon design thickness. Also, the quantitative definition of pavement failure based on user-oriented rather than only structural failure was a major contribution by that test. That concept led to development of the serviceability-performance method. Based on the observed performance of the AASHTO Road Test many thickness design methods have been developed.

The purpose of this study was to incorporate mechanistic and empirical information in developing a reliable design procedure for highway pavements in Egypt. An engineering technique employing the multilayered elastic concept that has been used in all worldwide recently developed thickness design methods was adopted. Environmental and climatic conditions as applicable to the Egyptian highways were introduced. Design charts were developed in an easy way to use by engineers. Comparison between our method and other methods used by some Egyptian agencies are presented. It can be concluded that this pavement design method is reliable, rational and reflecting our own environmental conditions.

INTRODUCTION

The objective of any pavement design procedure is to provide a structure which will be suitable in a specific environment and be able to sustain the anticipated traffic loading. It is generally conceded that pavements deteriorate or lose serviceability with and from traffic load repetitions. Since the publication of the results from the AASHTO Road Test in 1962 (1), most design methods which incorporated the results from this project defined performance as the serviceability history of a pavement. Serviceability, as measured by the present serviceability index (PSI), is defined as the present riding quality of a pavement. This is considered as a functional performance definition and is related to the users response or comfort provided to the travelling public. It has been known that the riding quality of a pavement is controlled by the longitudinal profile of the pavement. Till the mid-seventies no clear relationship between serviceability and physical distress was released. Information from the AASHTO Road Test suggested that there might be some correlation between average rut depth and serviceability while there was very little about between cracking and serviceability.

During the late 70's the Asphalt Institute has succeeded in incorporating both mechanistic and empirical information in their latest pavement design procedure. The use of mechanistic procedures along with field experience has made it possible to evaluate more accurately the seasonal influence of temperature on the properties of asphalt concrete, and the loss of strength of unstabilized materials from month to month during the year. Their use of such procedures, also, provided the capability of extrapolating beyond the limits of field experience which have been considered as one of the major limitations of the AASHTO Road Test.

In addition to that, another major improvement in the Asphalt Institute method was the inclusion of not only functional performance characteristics, but also structural performance characteristics. The later refers to fatigue cracking and surface rutting associated with traffic. This technique is believed to facilitate the prevention of excessive physical distress and the retention of adequate riding quality for the design life of the pavement.

In this study, the latest approach employed in the development of the 1981 Asphalt Institute thickness design manual (MS-1, Ninth Edition) has been adopted (2). The program computer DAMA was modified to allow for the improvements gained during recent years in the determination of the elastic moduli of asphalt concrete. Assumed environmental and climatic conditions as applicable to the Egyptian case was introduced. Final design charts relating the traffic density as measured by the number of load repetitions of the 80 KN standard axle to the subgrade strength as determined by the California Bearing Ratio (CBR) and pavement thickness is presented.

BASIC ASSUMPTIONS

In our method of design the pavement structure is considered as a multilayered elastic system. The material in each layer is characterized by a modulus of elasticity and a poisson's ratio. Traffic is represented in terms of repetitions of an 80 KN single axle applied to the pavement on two sets of dual tires. The dual tire is depicted by two circular plates with a radius of 115.0 mm spaced 345 mm apart which correspond to an 80 KN axle load and a 483.0 KPa contact pressure.

These assumptions allowed for the design of flexible pavements composed of as much as five layers. These layers are: an asphalt surface course, an asphalt binder or base course, a crushed stone untreated base course, a sandy gravel subbase, and the bearing soil. The subgrade, lowest layer, is assumed infinite in the vertical lay downward and horizontal directions. The other layers, of finite thickness, are assumed infinite in extent in the horizontal direction. Full friction is also assumed at the interface between each of the layers. Figure (1) illustrates the composition of system.

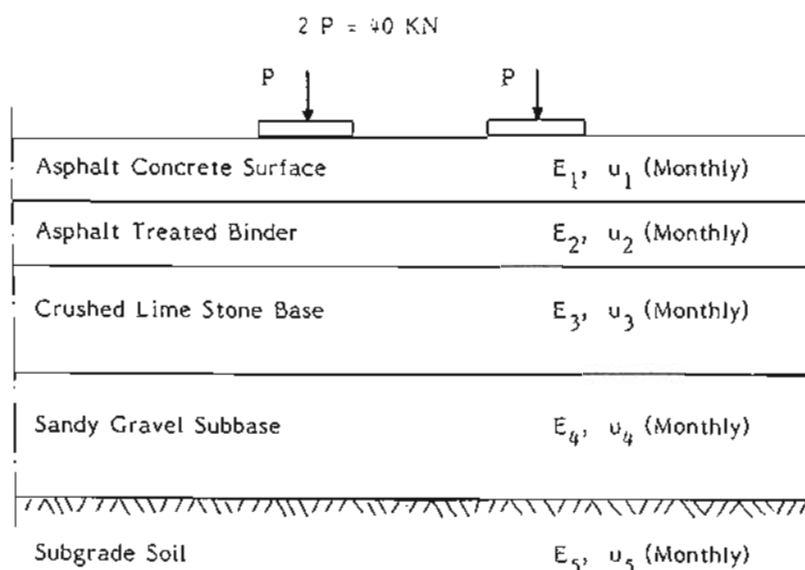


Figure (1) General Pavement System

DESIGN CRITERIA

Two strains are conceived to be critical for design of multilayered pavement system; they are, the horizontal tensile strain on the underside of asphalt treated layer and the vertical compressive strain at surface of subgrade (2). Many other researchers have expressed their feeling that only the response of subgrade deformation is more sensitive to the contribution of any selected layer (surface or base) to the performance of the total system. They have formed their thoughts on the basis of the AASHTO Road Test serviceability model in which the value of that index has shown low sensitivity to surface cracking. However, considering the cracking of asphalt bound layer as a design criterion, in addition to subgrade strain or deformation is believed to be a better approach. Although this assumption might be on the conservative side, it is no longer conservative in a pavement design method for highways in Egypt. Our country is flat surface water draining is a well known problem and routine maintenance through regular patching and crack filling is not always guaranteed. When an asphaltic layer is cracked by fatigue, the riding quality or serviceability may not be significantly reduced; however water intrusion of moisture through cracks will reduce the stiffness properties of downward layers during a short period of time. Based on our understanding of that matter the two strains mentioned previously, were simultaneously considered in the design criteria.

Compressive Strain

The allowable subgrade strain criteria utilized in this design to limit surface rutting was adopted after the Asphalt Institute (2). That rutting criterion was obtained from analysis of pavements designed by the California procedure. It is more conservative than other criteria and developed from data obtained from a state that has overall environmental and climatic conditions imitating that in Egypt. The general form of

The compressive subgrade strain criterion is as follows:

$$\log(N_f) = -8.865 - 4.477 \log(\epsilon_v) \quad (1)$$

where: N_f = No. of 80 KN equivalent single axle loads

ϵ_v = vertical compressive strain at subgrade surface, mm/mm

In our method of design rutting should not exceed 13 mm for design traffic (N_f), so long as asphalt bound layers are well designed and other pavement layers are well compacted.

Tensile Strain

Based on lab to field correlation of 17 sections in loops 4 and 6 on the AASHTO Road Test during a two years period; from 1958 to 1960, Finn, et al. have come up with a fatigue cracking model which is still used in many design methods (3). That model was further modified by others (4) to allow for fatigue prediction of a wider range of asphalt mixes. The final model computes fatigue life of a pavement as a function of the elastic tensile strain of asphalt layer (ϵ_t) as well as its modulus of elasticity, percent voids and percent asphalt content. The form of fatigue equation employed in our method of design is:

$$\log(N_f) = -3.291 \log(\epsilon_t) - .854 \log(E) - 6.285 + 4.84(V_b/V_b + V_v) \quad (2)$$

where: N_f = No. of equivalent single axle loads

ϵ_t = tensile strain in asphalt layer, mm/mm

E = elastic modulus of asphalt bound layer, MPa

V_b, V_v = volume of asphalt and volume of air voids, percent

For high quality asphalt concrete; i.e., surface or binder courses, the effect of V_b and V_v on the results of the original model developed by Finn et al. is almost neglected. That model provides an indication of approximately 20 percent or greater fatigue cracking area based on total pavement area or 45 percent fatigue cracking based on wheel path area (2, 3).

MATERIAL CHARACTERISTICS

In the analysis of a multilayered system, material of each layer is characterized by a modulus of elasticity and a Poisson's ratio. The latter was assumed to be 0.35 for all layers except for subgrade where a value of 0.45 was assumed. These values of Poisson's ratio were kept constant through all the stages of our pavement design method development.

Asphalt Treated Layers

In developing the design charts, two asphalt treated layers were considered; a surface and a binder course. The gradation limits of the two crushed lime stone aggregates for both surface and binder courses and the range of asphalt content for both layers are presented in Table 1. The asphalt cement commonly used in the production of asphalt concrete in Egypt is a 60/70 penetration type. Laboratory determined physical properties of mixes made for surface and binder courses are given in Table 2, they are needed in determining their elastic characteristics.

The elasticity modulus for asphalt treated layers were determined on monthly basis during the year using the latest model developed by Witczak (5). The computer program was modified to allow for using that model. In general, this modulus predictive equation relates the elasticity modulus as the independent variable to the major properties of an asphalt concrete, the loading frequency and pavement temperature.

Table 1 Gradation of Surface and Binder Courses

Sieve	Surface Course	Binder Course
25 mm	100 ¹	
19 mm	88-100	100
13 mm	55-86	86-100
10 mm	45-72	70-90
No. 4	31-50	45-70
No. 10	19-35	30-52
No. 20	12-26	22-40
No. 40	7-20	16-30
No. 80	4-12	9-19
No. 200	0-6	3-7
Asphalt Content	4-6.5	4.5-7.5

Table 2 Some Basic Properties of Asphalt Surface and Binder Courses

Property	Surface	Binder
Effective Asphalt content (Peff.) % ¹	10.5	8.5
Percent Air Voids (Pair) ¹	3.6	4.8
Percent Asphalt Absorbed (Pabs.) ²	1.5	1.5
Asphalt Viscosity (η), Poises	3.1	3.1
Load Frequency (f), Hertz	10.0	10.0
Temperature (T)	Changes monthly	

Notes:

- 1- By mix volume
- 2- By mix weight

A loading frequency [f] of 10 Hertz which represents a load duration of 0.10 second was assumed in this analysis. This is close to the same duration as was obtained by Benkleman beam method and widely accepted by most investigators (2, 6). The mean monthly air temperatures adopted in evaluating the elastic moduli of asphaltic layers are given in Table 3. Since asphalt concrete is susceptible to temperature (T), computation of their elastic properties every month during the year is important in developing design charts for Egyptian roads.

Table 3 Monthly Air Temperature in °C

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
16	17	21	25	27	35	39	40	35	27	20	15

Untreated Granular Materials

In the construction of highways in Egypt it is widely accepted to use untreated crushed aggregates; lime stone or dolomite have a nominal size of 60.0 mm, as a base course material. Sometimes a premixed Macadam is used as a base course; however, it has experienced low performance and fatigue life (7). Sandy gravel is in most cases employed in subbase courses.

Generally, the stiffness features of untreated aggregates are stress dependent. Their behavior is nonlinear in nature even when the stress is well below the yield point of the material. Here, the elastic modulus; known as the resilient modulus, increases with an increase in the isotropic stresses. This stress dependency is described in terms of the bulk stress $\Theta = \sigma_x + \sigma_y + \sigma_z$, by the equation:

$$M_r = k_1 \Theta^{k_2} \quad (3)$$

where: k_1, k_2 are experimentally determined constants. Typical values of these constants are in the range of 0.32 to 0.73 for k_1 and from 2900 to 12000 for k_2 [when stresses are in psi] (2). In our analysis k_1 was assumed to be 0.50 for both base and subbase layers whilst k_2 was assumed 8000 for a crushed lime stone base and 3000 for sandy gravel subbase.

Subgrade Soil

It is the soil prepared and compacted to support a structure or a pavement system. As mentioned previously, in a multilayered system analysis the subgrade, as well as other layers, are evaluated by their elastic properties. Therefore, the resilient modulus of subgrade soil was required as an input during the computer analysis process. However, since the resilient modulus (M_r) of soils is not a popularly used in Egypt a relation between M_r and CBR has been considered when developing the design charts.

A well known approximate relationship between M_r and CBR has been developed by others (8). Knowing the design CBR value, the M_r value of subgrade was approximated from the following equation:

$$\begin{aligned} M_r (\text{MPa}) &= 10.35 \text{ CBR} & \text{or} \\ M_r (\text{psi}) &= 1500 \text{ CBR} \end{aligned} \quad (4)$$

To consider the environmental consequences on subgrade during the year, moisture change was considered from month to month. For design purposes the influence of water is considered by predicting the properties of materials at water contents which are assumed of those which may develop at some time subsequent to construction. Estimates of expected in-situ moisture conditions together with an indication of how these conditions might develop are needed.

In our design method the strength of subgrade soil was assumed at its design value during the first two months of the year. This value was reduced 10 percent during the following seven months and 20 percent for the last three months. It was believed that these conditions are simulating the condition of ground water changes due to planting seasons, specially in the delta region. However more research considering soil moisture suction may provide more accurate information about subgrade soil.

TRAFFIC CONSIDERATION

For a specific pavement-loading system, each vehicle has a certain number of repetitions to failure, N_i . The unit damage or damage per pass of each vehicle is:

$$d_i = \frac{1}{N_i} \quad (5)$$

To simplify the traffic input requirements for the load-associated distress models; equations (1), (2), it is now widely accepted to convert mixed traffic to equivalent 80 KN single axle loads using for example the AASHTO load equivalency factors... The traffic effect considered in this analysis as well as in presenting the design charts was represented by the number of 80 KN load repetitions. The pavement is considered failed when the total damage (D) produced as a result of either subgrade compressive strain (ϵ_v) or asphalt treated layers tensile strain (ϵ_t) has reached unity. The total pavement life (EAL) is defined as the number of standard single axles that the pavement can sustain until total damage $D = 1.0$.

To help the designer overcoming the situation of lack of loadometer information, traffic was characterized to five groups adopted from the National crushed stone Association method of design (9). These categories are shown on the design charts as occupying a range of total number of load repetitions. These ranges were based on a 20 years design period. Details of the traffic categories are given in Table 4, where five traffic indices are defined from I 1 to I 5.

RESULTS AND DISCUSSION

In developing the charts three thicknesses of asphalt surface courses are considered. They are, 10 cm, 15 cm and 20 cm, each surface thickness level is presented in a separate chart. In any of the above surfaces at least one half of it is a binder course. The first three charts are relating the subgrade CBR and the total number of single 80 KN axles to failure to the thickness of crushed lime stone base course, no sandy gravel subbase is used. Charts are illustrated in Figure (2), where the number written on each curve presents the thickness of base. The following three charts shown in Figure (3), crushed lime stone base as well as sandy gravel subbase are considered. The number on curves denotes the subbase thickness whilst the base course thickness is grouped and distinguished from one level to another.

To compare thickness design using our method to other popular pavement design methods a very simple example is given below.

Example :

For a total EAL of 500,000 and a subgrade CBR of 5 a flexible pavement comprising an asphalt concrete surface, a crushed lime stone base and a sandy gravel subbase (AASHTO R is assumed 4.0) is designed

Solution of the above example using our method and three other methods; CBR method, AASHTO (original method) and the Asphalt Institute (A.I.) latest method, is summarized in Table 5. Also to facilitate using the AASHTO and the CBR methods the CBR value for subbase and base course are assumed 15 and 40 respectively.

Table 4. Traffic Categories, After NCSA

Daily ¹ EAL	Index	Description
5	11	Light Traffic, only passenger cars, pick up trucks and similars.
6-20	12	Light-Medium Traffic, max. 1000 VPD, including max. 5% of <u>loaded two axle trucks</u> and similar.
21-75	13	Medium Traffic, max. 3000 VPD, including max. 9% of <u>Loaded Two axle trucks</u> and 1% <u>loaded three or more axle vehicles</u> and similars.
76-250	14	Medium-Heavy Traffic, max. 6000 VPD, including max 14% of <u>Loaded two axle trucks</u> and 1% <u>Loaded three or more axle vehicles</u> and similars
251-900	15	Heavy Traffic, max 6000 VPD, include 15% of <u>loaded Two axle trucks</u> and 10% <u>loaded three or more axle vehicles</u> and similars

Notes:

1. Daily EAL: Equivalent 80 KN single axles in design lane, average daily use over a 20 years life.
2. VPD = vehicles per day, all types, using design lane.

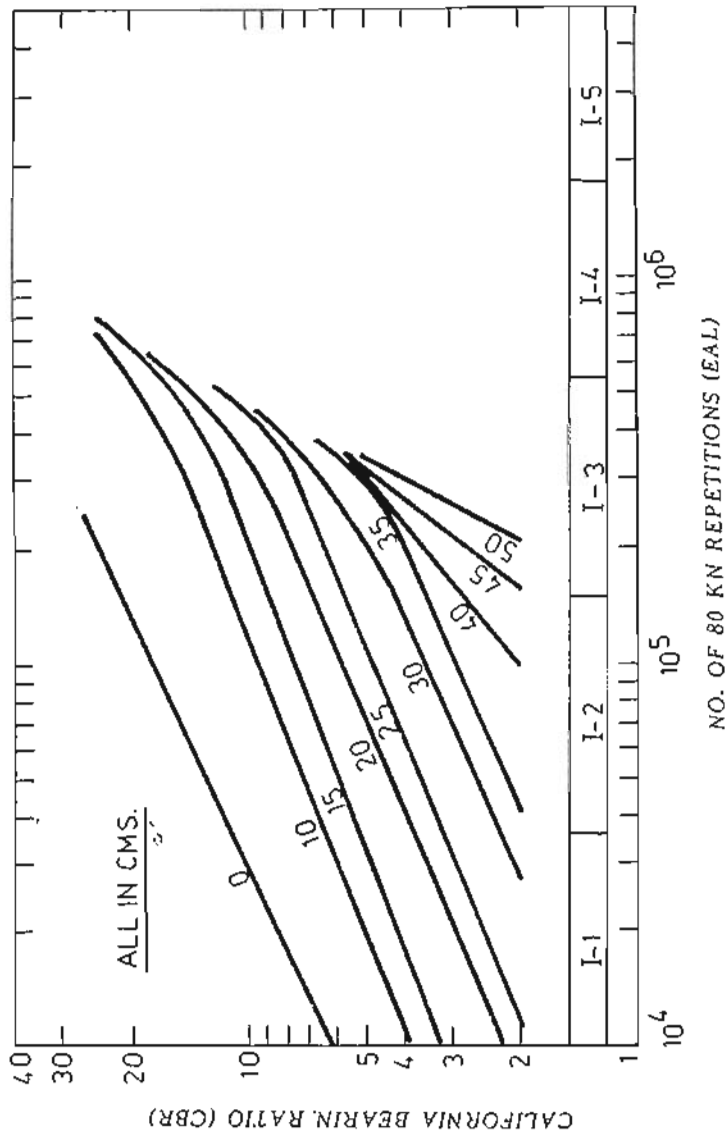


Figure (2) a - Base Thickness, Case of no Subbase (surface course = 10 cm)

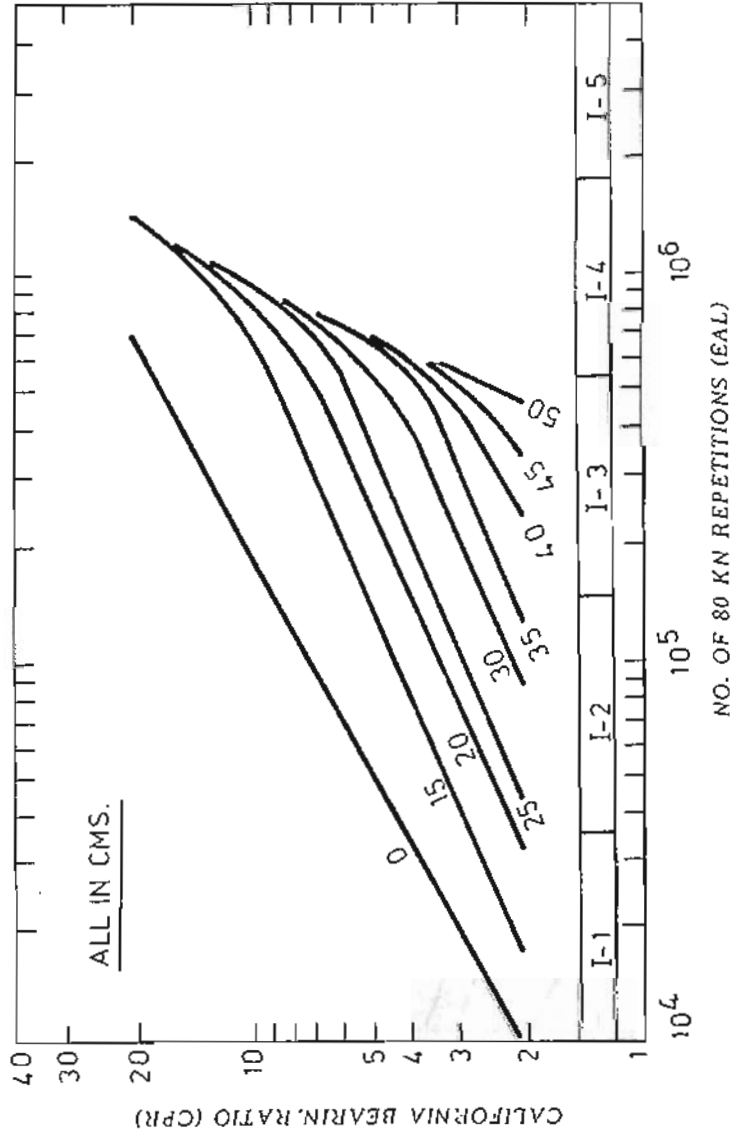


Figure (2) b- Base Thickness, Case of no Subbase (surface course = 15 cm)

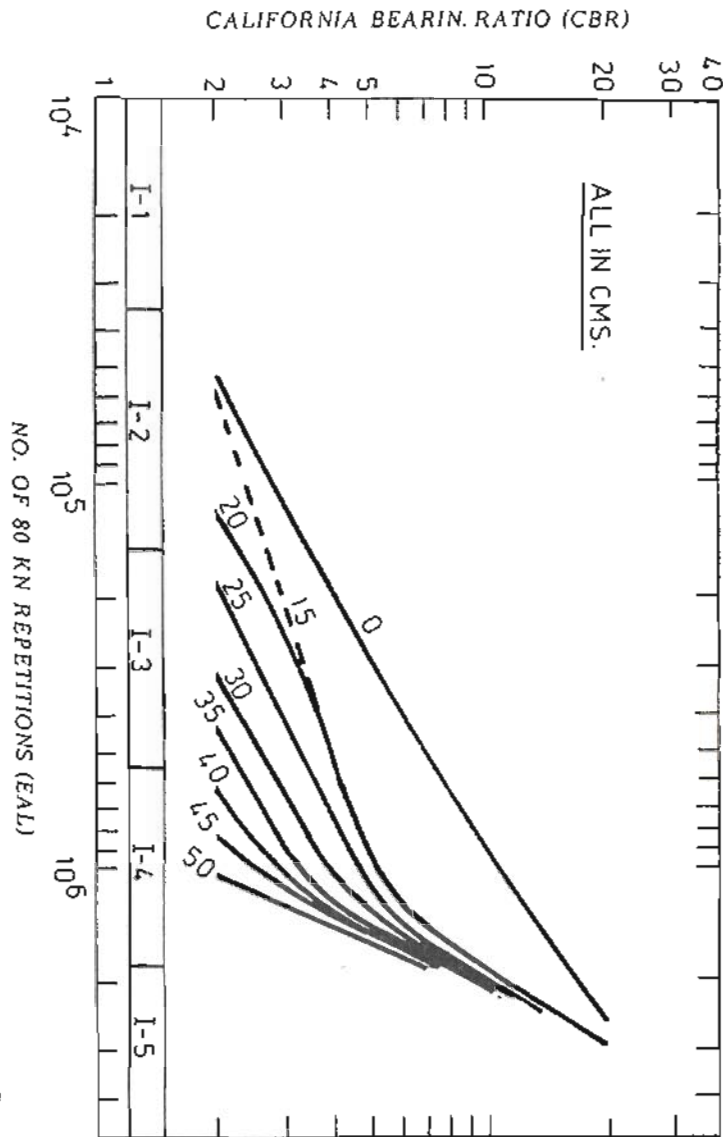


Figure (2) c - Base Thickness, Case of no Subbase (surface course = 20 cm)

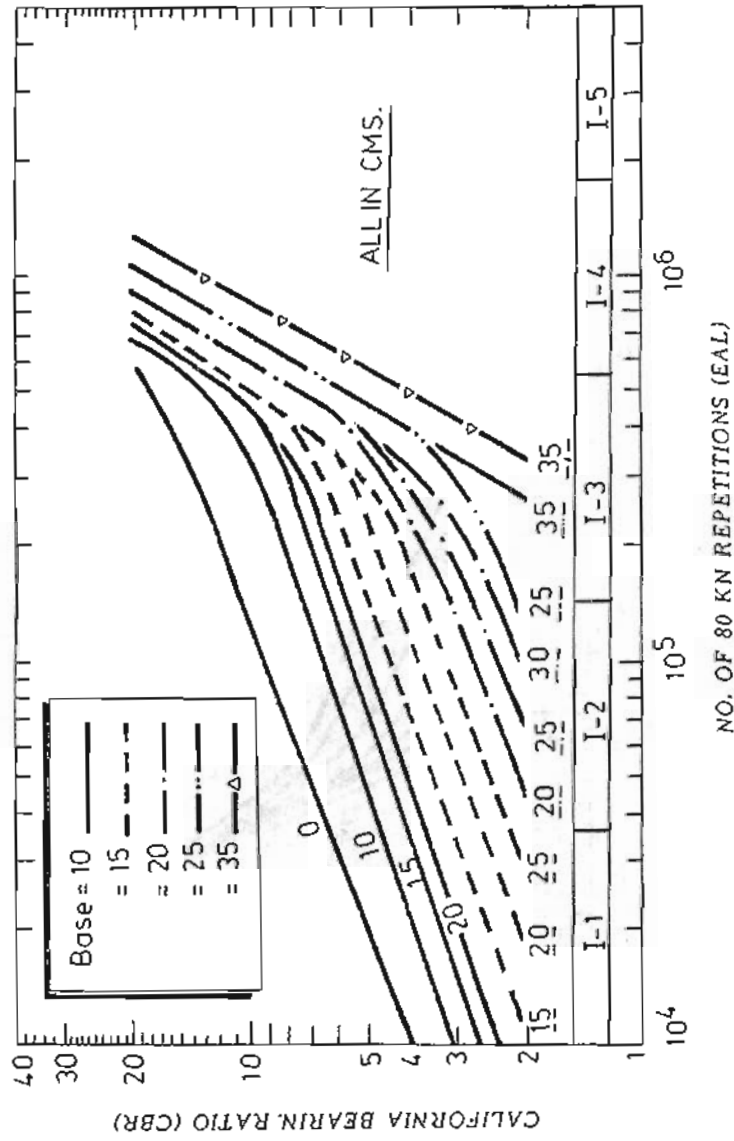


Figure (3) a- Subbase Thickness for a Given Base (surface course = 10 cm)

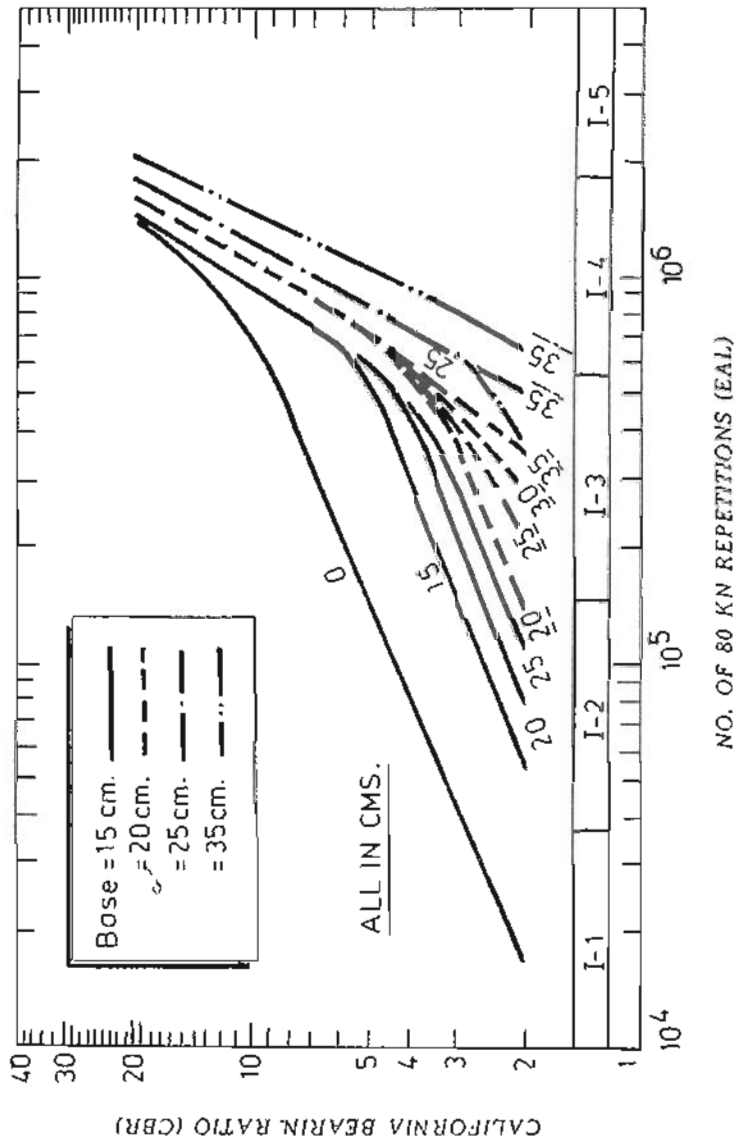


Figure (3) b- Subbase Thickness for a Given Base (surface course = 15 cm)

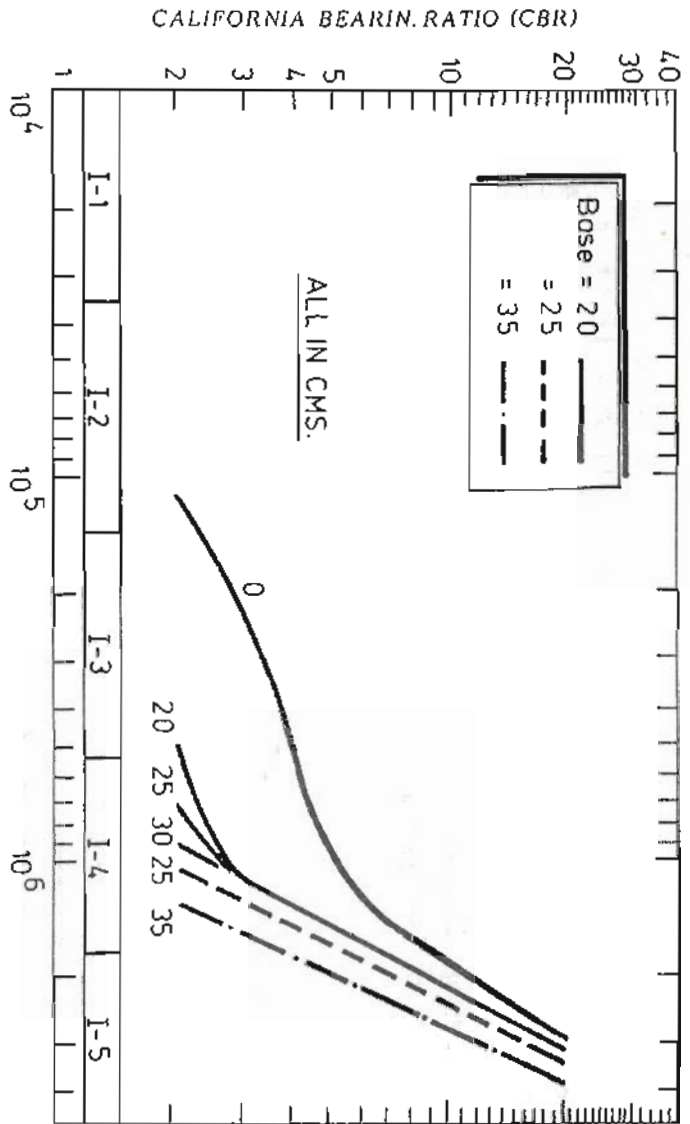


Figure (3) c- Subbase Thickness for a Given Base (surface course = 20 cm)

Table 5 Comparison Between Four Design Methods

Design Method	Thickness of layer in cm		
	Surface	base	subbase ¹
AASHTO ²	15.0	15.0	20.0
Asphalt Inst.	15.0	20.0	—
CBR	10.0	10.0	25
New Alt. (1)	15.0	15.0	15.0
New Alt. (2)	15	28.0	—
New Alt. (3)	10.0	27.0	27.0

1 Only base course in the Asphalt Institute method

2 Based on an SN = 3.95 and R = 4

As can be observed in Table 5, the CBR method gives the lowest pavement thickness. The thickness of base course required by our method when no subbase is used is 28 cm versus 20 cm for the Asphalt Institute. This is expected since their method is averaged to design pavements all over the United States where freeze is present in one state and very high temperature is experienced in another. In the AASHTO method of design a minimum surface course thickness of 15 cm is required. For a surface thickness of 15 cm and using our method we get the same base course thickness as the AASHTO whilst a lower subbase thickness; 15 cm vs. 20 cm. This might be due to our assumption of a regional factor of 4.0; which is considered somewhat high, when designing by the AASHTO.

Back to the CBR method results, it is clear that it underestimates the pavement thickness when compared to all other methods. Although we get almost very close values for subbase thickness; 25 from CBR and 27 from our method, only 10 cm base course is required by CBR method versus 27 cm in ours. Again, one can say that no indication of the effect of environmental changes during the year are known to be considered in the CBR method. Hence our values are more realistic than theirs since the proposed new method is considering the Egyptian climatic and environmental effects based on a rational elastic analysis.

CONCLUSIONS

Based on our study it can be concluded that the use of elastic multilayer analysis opens the field for engineers in any country to develop their own layers design method. This approach enable the designer to consider the effects of the environmental conditions in his area as well as the properties of the available materials in pavement thickness design. The charts developed for pavement design have reflected the author own assumptions of environment and material properties. The lack of field performance informations about highways in Egypt is responsible for our assumptions.

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