DESIGN METHODS FOR CLAY AND CONCRETE BLOCK PAVING

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SUMMARY

This paper presents structural design methods for concrete and clay paver pavements subject to highway vehicles, industrial loading and aircraft. It takes three different design procedures and integrates them into a common format. The highway design procedure described is currently being published as a British Standard Design Guide. As with all of the UK paver design guides, it uses the asphalt pavement design procedure and substitutes pavers for bituminous material on an equivalence basis. The pavement thickness selection procedure has been rationalised into a simple flow chart. The industrial pavement design procedure has evolved during the last sixteen years and has been adopted by the British Ports Federation, the American Association of Port Authorities and many other trade bodies. The aircraft pavement design method was first presented at the Third International Conference on Concrete Block Paving in 1988 and has now been approved by the Federal Aviation Administration.

1.0 INTRODUCTION

In each of the design methods, it has been assumed that the pavers and their laying course material contribute to the strength of the pavement and that the materia! behaves in a similar manner to a homogeneous elastic material. The justification for this assumption is explained in the next section. As a result of this it has been possible to modify conventional flexible pavement design procedures by substituting pavers for their structural equivalent thickness of asphalt.

The above assumption is one of several paver design principles which have been found to be correct through research and use. The full range of principles is as follows:

1. Pavers develop "interlock" such that an individual unit cannot move in isolation from its neighbours.

2. As a result of interlock, pavers behave in a similar manner to a flexible pavement material.

3. Pavers can be equivalenced to bituminous material in terms of thickness.

4. Pavers need to be at least 65mm thick to accept traffic. Thickness greater than 80mm is unnecessary.

5. Paver shape has almost no influence on pavement performance.

6. Pavers are sufficiently pervious to saturate underlying materials.

7. The laying course should be as thin as possible, subject to pavement construction tolerances.

8. Laying course material should not lose stability when saturated.

The assumption that paver shape has almost no structural significance is now held by most authorities worldwide. Only in Australia and in countries which have adopted Australian practice, is any credence given to the philosophy that the "wiggly brick" improves pavement performance. It is interesting to note that when pavers were first used for road building in the UK in 1973, all of the pavers were of a proprietary shape. Since then the rectangular paver has established itself as the common road building material. (1) Estimates of its use range between 80% and 90% of total usage, the remainder being largely in decorative areas.

There have been several failures of paver surfaced pavements and a common factor in these failures has been that the pavements have been designed by those whose experience of soil behaviour under dynamic loading is limited. Too many Pavement Engineers have avoided becoming involved in the developing technology of pavers, preferring the comfort of dealing with established materials. This paper can be used as a reference guide by those needing to design most categories of pavements.

2.0 BASIS OF DESIGN

The assumption that pavers can be equivalenced with asphalt dates back to research undertaken at the Cement and Concrete Association in 1974 and published in 1976. Static loading was applied to the surface of various types of concrete pavers and the resulting vertical stress was measured at the underside of the laying course sand. The pavers and sand were laid directly over reinforced concrete. The stresses recorded were compared with those determined mathematically by Jones (2) from which it was concluded that concrete pavers were equivalent to 160mm thickness of asphalt.

Prior to using the equivalence figure, discussions were held with engineers in other countries, all of whom agreed that their experience suggested that this figure was substantially correct. Since then, researchers in many parts of the world have investigated the structural performance of pavers and the following conclusions can be drawn from a review of that work.

1. The original figure of 160mm applied to the asphalt materials referred to by Jones. Developments in flexible roadbuilding materials during the last twenty five years have increased the performance of those materials such that the equivalence figure today is probably on a one to one basis i.e. 80mm thick pavers on 40mm laying course sand equates with 120mm asphalt. As an example of the development of bituminous materials, many UK local authorities now specify designed mixes rather than prescribed ones. This permits the use of stiffer materials, principally to avoid deformation at bus stops.

2. The equivalence technique is suitable for pavements comprising pavers laid directly over a granular base and for heavy duty pavements employing a cement stabilized base. There remains a question mark over the use of the equivalence technique for pavers laid over bituminous roadbases for heavily trafficked highway pavements. Laboratory tests suggest that pavers contribute little to the strength of such pavements. The reasons for this are not fully understood but it may relate to the lack of stiffness in the laying course material.

3. The equivalence technique has been adopted throughout the world. The authors have visited concrete block and clay brick promotional bodies in every continent of the world and have found that the original UK equivalence work forms the basis for many design methods. This is significant as the current UK usage of 12,000,000m^2 per annum is small compared with the estimated worldwide figure of 240,000,000m^2 per annum. The major markets are:

West Germany	75,000,000m^2/ annum
Rest of Europe	55,000,000m^2/ annum
US and Canada	18,000,000m^2/ annum
Central America	40,000,000m^2/ annum
South America	25,000,000m^2/ annum
Australasia	8,000,000m^2/ annum
Africa	25,000,000m^2/ annum
Middle East	30,000,000m^2/ annum

Note : this represents an industry with a turnover of three billion pounds which is growing by between 5% and 40% in each market. Worldwide, it is estimated that between 300,000 and 4000,000 people are involved in block or brick paving.

In view of the above it is considered that the equivalence technique has been thoroughly verified and can be accepted.

3.0 LOADING ASSESSMENT

The three types of pavement considered all require a different approach to loading. Pavements trafficked by highway vehicles or lighter loading require either the cumulative number of standard axles, or alternatively the number of commercial vehicles per day, the design life and the number of standard axles per commercial vehicle. Heavy duty industrial pavements traffic can be categorised according to the Load Glassification Index (LCI) system developed in the British Ports Federation pavement design method (3). In the method, the fourth order damaging rule is applied whereby pavement damage is calculated in Port Area Wheel Load (PAWL) units according to the equation:

$$\text{No. of PAWL's} \qquad \left(\frac{W}{12000}\right)^{3.75} \times \left(\frac{P}{0.8}\right)^{1.25}$$

Where W = wheel load (kg)

P = tyre pressure (N/mm^2)

The following table relates PAWL values to LCI categories and gives an example of the types of vehicle falling into each category.

TABLE 1. Load Classification Index for heavy duty industrial pavements

No. of PAWLS	LCI	Typical example
Less than 2	A	Highway vehicle
2-4	B	FLT carrying empty container
4 - 8	C	Straddle carrier
8- 16	D	FLT carrying 20ft container
16-32	E	FLT carrying 40ft container
32-64	F	Heavy FLT braking
64 - 128	G	Laden earth scraper
128 - 256	H	Rubber tyred gantry crane

FLT = front lift truck

An important factor in assessing the damage inflicted on pavements by industrial handling equipment is the increase in wheel load resulting from mass transfer during operations. The following table indicates the factors by which wheel loads are increased

prior to PAWL assessment. Note the figures in Table 2 are upper bound values and where a manufacturer quotes lower values for a specific vehicle then those lower figures should be used.

TABLE 2 Dynamic factors for various operating conditions

Type of Vehicle	Type of Operation			
	Braking	**Cornering**	**Accelerating**	**Uneven Surface**
Front lift Truck	1.3	1.4	1.1	1.2
Straddle Carrier	1.5	1.6	1.1	1.2
Side Lift Truck	1.2	1.3	1.1	1.2
Tractors and Trailers	1.1	1.3	1.1	1.2

Aircraft pavement design follows the Federal Aviation Administration method whereby loading is characterised by type of undercarriage gear and maximum individual wheel load. For example, a specific design chart is available for dual tandem gear, but within that chart, there is a series of curves for different wheel loads. The charts have been developed by considering the addition of stress caused by multiple wheel systems at critical positions in the pavement. Wide bodied aircraft are dealt with separately.

4.0 SUBGRADE ASSESSMENT

California Bearing Ratio (CBR) is used to assess the strength of the subgrade in all types of pavement. A problem facing engineers in many countries is the assessment of the CBR of clays and silts. BS1377 (4) recommends that the CBR test is not undertaken on these materials. In these situations, Table 3 can be used to determine design CBR. Table 3 is taken from LR1132 (5) and highlights the particularly low CBR's which should be used in poorly drained situations. If measured CBR values are to be used in design, it is recommended that values are measured in a laboratory, using the soaking procedure described in BS1377.

Table 3 illustrates the error which may occur in measuring CBR. The table shows that a material with a Plasticity Index of 10 can have a CBR of between 1.5% and 10%. These two figures represent the two extremes which a pavement designer might normally encounter. A 1.5% CBR subgrade would lead to a 1000mm thick highway pavement whereas a 10% CBR would require 350mm thickness.

TABLE 3 Equilibrium Suction - Index CBR Values

Type of soil	Plasticity Index	High Water Table Construction Condition						Low Water Table Construction Condition					
		Poor		Average		Good		Poor		Average		Good	
		Thin	Thick	Thin	Thick	Thin	Thick	Thin	Thick	Thin	Thick	Thin	Thick
Heavy Clay	70	1.5	2.0	2.0	2.0	2.0	2.0	1.5	2.0	2.0	2.0	2.0	2.5
	60	1.5	2.0	2.0	2.0	2.0	2.5	1.5	2.0	2.0	2.0	2.0	2.5
	50	1.5	2.0	2.0	2.5	2.0	2.5	2.0	2.0	2.0	2.5	2.0	2.5
	40	2.0	2.5	2.5	3.0	2.5	3.0	2.5	2.5	3.0	3.0	3.0	3.5
Silty Clay	30	2.5	3.5	3.0	4.0	3.5	5.0	3.0	3.5	4.0	4.0	4.0	6.0
Sandy Clay	20	2.5	4.0	4.0	5.0	4.5	7.0	3.0	4.0	5.0	6.0	6.0	8.0
	10	1.5	35	3.0	6.0	3.5	7.0	2.5	4.0	4.5	7.0	6.0	10.0
Silt	0	1.0	1.0	1.0	1.0	2.0	2.0	1.0	1.0	2.0	2.0	2.0	2.0

Note : A high water table is 300mm or less below formation

A thick pavement is 2000mm deep, including 650mm capping

A thin pavement is 300mm deep

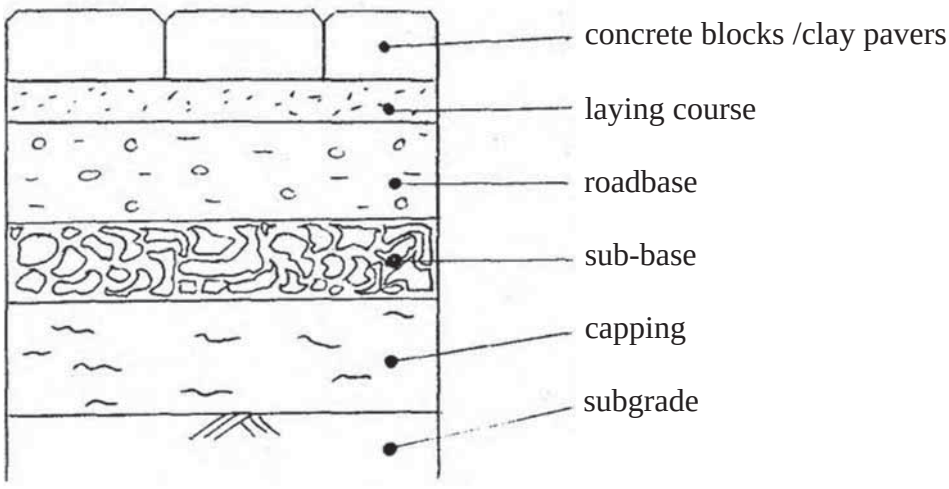
Good construction conditions result in the subgrade CBR never falling below the equilibrium value during construction

Special care is needed when partly constructed pavements are to be used as site access roads. It may be the case that drainage conditions during construction will be poorer than those obtaining after the road is built. Furthermore, once the CBR of fine grained soils has fallen as a result of poor site conditions, it may remain at the lower value throughout the life of the road. LR1132 (5) shows that on poorly drained fully wetted sites, CBR during construction is *1%* to *2%* for clays of all Plasticity Indices.

5.0 PAVEMENT COMPONENTS

The components of a concrete block/clay paver pavement are shown in Figure 1. One or more components may be absent from a specific pavement.

FIGURE 1. Pavement Components



The design methods presented in the forthcoming sections produce a specific design solution which may not employ materials favoured by the designed. The authors have found the material equivalence technique to be a practical means of transforming a design produced by a design chart into one employing the materials which the designer prefers. All commonly used pavement construction materials can be given a material conversion factor which is a relative measure of its contribution to a pavement. The values suggested in Table 4 can be used.

6.0 PAVEMENTS SUBJECTED TO HIGHWAY LOADINGS

It is important to recognise that most pavements falling into this category are not highway pavements. More commonly, concrete block and clay paver pavements comprise industrial hardstandings, petrol stations, parking areas, occasionally trafficked pedestrian areas and general infill which may be trafficked by cleaning and emergency service vehicles. In the UK, pavement construction specifications are usually based upon the D.Tp. Specification (6) and this has led to several failures for the following reasons. The D.Tp. Specification for granular material compaction is a method specification whereby various categories of compaction plant are permitted and the number of passes required for each category is specified for a certain material thickness.

The D.Tp. Specification was written with large trunk road projects in mind in which a full scale trial is undertaken prior to accepting a construction procedure. The purpose of the trial is to establish that the compaction method selected is capable of producing sufficiently dense material. In the case of concrete block and brick paver projects, the area is often too small to allow a trial area. Therefore, it is frequently the case that the

D.Tp. Method Specification is adopted without the safety check of a full scale trial. It is recommended that this practice be abandoned and in all cases, a performance specification should be adopted.

Subject to the above recommendation being implemented, the flow chart shown in Figure 2 can be used to proportion the thickness of pavements subjected to highway loadings. This flow chart has been developed by adopting the flexible pavement design method in LR1132 (6) and substituting concrete blocks or clay pavers for the equivalence thickness of asphalt. This is more conservative than some research would suggest but is considered to be appropriate for all types of pavements.

It is interesting to note that Figure 2 permits a granular sub-base to be used for pavements subjected to up to 1,5000,000 standard axles subject to some exclusions. For example, where there are more than twenty five commercial vehicles per day, it is recommended that a stabilized roadbase is provided. Also, where severe channelisation is anticipated, a roadbase should be provided. It is the authors' view that a fully granular pavement should be provided only when full engineering supervision is available, including ready access to a material testing laboratory. Also, on small areas where ii may be difficult to operate compaction equipment, granular material should be avoided. Care should also be exercised when severe dynamic loading is anticipated e.g. bus stops. In all of the above cases, the authors prefer a stabilized base since their experience suggests that there is less chance that such pavements will suffer premature degradation.

Figure 2 requires a knowledge of the cumulative number of standard axles which it is anticipated will use the pavement. When only the number of commercial vehicles per day is known, Table 5 can be used to determine the cumulative traffic for design lives of twenty years and forty years.

TABLE 5. Relationship between commercial vehicles per day and cumulative traffic

Commercial Vehicles per day	**Cumulative Traffic**			
	20 years design life		40 years design life	
	Zero growth	2% growth	Zero growth	2% growth
30	0.22	0.27	0.40	0.60
120	0.86	1.0	1.7	2.6
250	1.8	2.2	3.6	5.5
500	3.6	4.4	7.3	11.0
1000	7.2	9.6	15.0	24.0

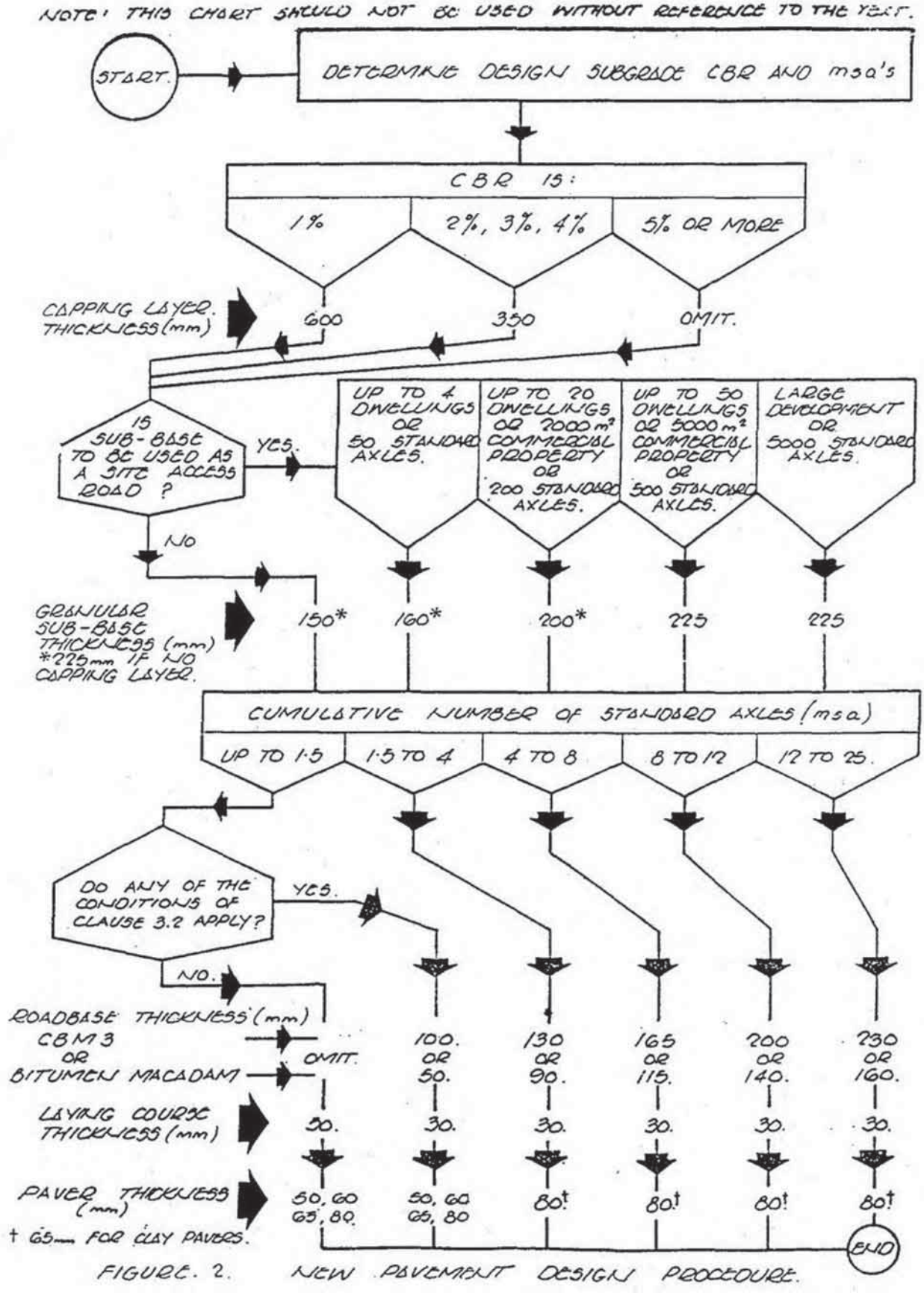


FIGURE. 2. NEW PAVEMENT DESIGN PROCEDURE.

TABLE 4 **Material Conversion Factors**

Category of Material	Commonly used as	Material Conversion Factor
65mm to 80mm concrete blocks or clay pavers on 30mm to 50mm laying course	Surfacing	1.0
Dense bitumen macadam	Roadbase/basecourse	1.0
Hot rolled asphalt	Surface/basecourse	1.0
Open textured macadam	Roadbase	0.7
Wet-mix or dry-bound macadam	Roadbase	0.45
Cement bound material 1 (CBM1)	Roadbase	0.4
Cement bound material 2 (CBM2)	Roadbase	0.5
Cement bound material 3 (CBM3)	Roadbase	0.7
Cement bound material 4 (CBM4)	Roadbase	0.7
Pavement quality concrete	Surface & roadbase	1.7
Type 1 granular sub-base material	Sub-base	0.3
Type 2 granular sub-base material	Sub-base	0.2
Crushed concrete	Capping	0.1
Selected hardcore	Capping	0.1
Selected fill	Capping	0.1

Note : that these factors should be used only in a manner whereby the final pavement comprises a combination of materials which is commonly specified in pavement engineering.

7.0 HEAVY DUTY INDUSTRIAL PAVEMENTS

The first requirement in the design of an industrial pavement is the Load Classification Index (LCI) of the equipment which the pavement is being designed to carry. Table 1 shows typical LCI values for different types of handling equipment and indicates that highway vehicles always fall into class A, i.e. the least damaging class. In order to use the design charts reproduced in this paper, the following information is required:

a) LCI of handling equipment
b) number of repetitions of that equipment
c) CBR of subgrade
d) strength of lean concrete base
e) elastic modulus of lean concrete base

Note : it is not essential to provide a lean concrete base. However, the design charts shown in Figure 3 to 7 are based upon lean concrete data. When designing a pavement with a base other than lean concrete, first obtain the thickness of a lean concrete base then use Table 4 to obtain the thickness of an alternative material.

Note also : all of the charts provide a 300mm thick sub-base. If a capping layer is provided or if a different thickness of sub-base is required, Table 4 can be used to assess the trade-off value of the change from the values produced by the design chart to the value used. By this means, lean concrete, or an alternative base material, can be added to or subtracted from the design value to accommodate the change in the thickness of other materials. Experience indicates that 80mm thick concrete blocks laid into 40mm sand will be suitable in all situations. In the UK, the widest experience is of the use of 200mm x 100mm x 80mm concrete blocks and 215mm x 112mm x 65mm clay pavers.In a few instances, 100mm thick concrete blocks have been specified. The authors can find no justification for this.

Firstly, use Figure 3 to determine the permissible radial tensile strain in the underside of the base. Figure 3 has four curves, one representing each of four strengths of lean concrete. It is recommended that the curve corresponding with $3N/mm^2$ flexural strength lean concrete is used unless particularly strong or weak lean concrete is specified.

When the permissible radial tensile strain has been determined from Figure 3, select one of Figures 4 to 7 according to subgrade CBR and determine the base thickness as follows. The permissible radial microstrain is shown on the left hand vertical axis. From the appropriate position on that axis, project a line horizontally to meet one of the eight LCI curves in the chart. From this intersection point, project a line vertically downwards into the lower box of the chart. This vertical line meets a series of four horizontal lines, each corresponding with a different strength lean concrete. The vertical and horizontal lines intersect in a family of base thickness curves. This intersection point represents the base thickness required.

For a full description of the basis of the method, see Knapton (7). A complete range of design charts is available in the British Ports Federation/ American Association of Port Authorities heavy duty pavement design manual (3).

8.0 AIRCRAFT PAVEMENTS

The design method presented here is a modification of the Federal Aviation Administration (FAA) asphalt pavement design method (8). Aircraft pavements designed according to the FAA rules usually have either four inches or five inches (100mm or 125mm) asphalt as the surfacing. By replacing that asphalt course with 80mm pavers laid into 40mm sand, a pavement is designed which is equally strong. This substitution has been discussed with FAA engineers responsible for the development of pavement specifications and they have agreed to consider favourably any proposal to use concrete blocks (not clay pavers) on all types of aircraft pavement except high speed runways. This is important since 75% of all paving expenditure at US airports is funded by the FAA.

In the UK, the first and most important application of pavers on aircraft pavements is at Luton International Airport where their use on aircraft stands, taxiways and turning circles is described fully by Emery (9). Following this experience, Emery and Knapton adopted the FAA method as follows, using the flexible pavement design charts with pavers replacing asphalt.

Pavements can be designed for commercial aircraft weighing 13,000kg or more. Figures 8 to 13 apply to individual types of aircraft. Figures 8, 9 and 10 apply to single wheel, dual wheel and dual tandem undercarriage configurations respectively whilst Figures 11, 12 and 13 apply to Boeing 747's McDonald Douglas DClOs and Tristars respectively. Each of these figures provides the overall thickness of the pavement for the appropriate type of aircraft. Pavement thickness depends upon the CBR of the subgrade, the gross weight of the aircraft and the number of departures of that aircraft.

In most aircraft pavement situations, a mix of aircraft types has to be accommodated and the pavement designer has to select the Design Aircraft from the mix so that he can select the appropriate design chart. The Design Aircraft is the one which requires the greatest pavement thickness, bearing in mind the number of annual departures of that aircraft. Therefore, as a preliminary to the main design exercise, Figures 8 and 13 are used to determine the thickness which would be required if a pavement were being designed for one type of aircraft.

Once the design aircraft has been found, the effects of all aircraft must be accounted for in terms of the design aircraft as follows. First, all aircraft must be converted to the same type of undercarriage as the design aircraft, using the factors shown in Table 6.

TABLE 6 Undercarriage Conversion Factors

To Convert from	to	Multiply No. of Departures by
single wheel	dual wheel	0.8
single wheel	dual tandem	0.5
dual wheel	dual tandem	0.6
double dual tandem	dual tandem	1.0
dual tandem	single wheel	2.0
dual tandem	dual wheel	1.7
dual wheel	single wheel	1.3
double dual tandem	dual wheel	1.7

Second, convert the number of annual departures to those of the Design Aircraft using the equation:

$$\log R1 = \log R2 \times \frac{W2}{W1}$$

where R1 = equivalence number of annual departures by the design aircraft

R2 = number of annual departures expressed in design aircraft undercarriage units

W1 = wheel load of design aircraft (kg)

W2 = wheel load of aircraft being equivalenced (kg)

When applying this equation to wide body aircraft, each such aircraft should be treated as a 136,000kg dual tandem undercarriage aircraft. In all calculations assume that 95% of the gross weight is carried by the main landing undercarriage.

Once the total pavement thickness has been found Figure 14 is used to determine the thickness of the base as follows.

Start with the total pavement thickness on the left side vertical axis and project a line horizontally until it meets the appropriate subgrade CBR curve. Then project a line vertically to obtain the base thickness in centimetres along the top of the chart or inches along the bottom.

In addition to pavement thickness selection, the aircraft pavement designer has several special factors to consider, all of which relate to the non-vertical forces applied by aircraft. Emery (9) has dealt with these factors. In particular, care has to be taken to ensure that paver jointing sand is not removed by jet blast. A liquid polymer sealer has been in service at Luton International Airport for many years and has been found to keep jointing sand in place.

9.0 CONCLUSIONS

The design methods presented in this paper can be used to design virtually any type of concrete block or clay paver pavement. They have each been in service for several years and have produced consistently correct pavements. Where pavements have failed, the authors have found the following to be the usual causes

1. inadequate drainage leading to reduction in subgrade CBR
2. insufficient care when sub-base is used as an access road
3. using non-soaked CBR values for clays
4. laying course sand degrading or washing away
5. overloading of industrial pavements
6. loss of jointing sand

It should be recognised that British highway engineers have pioneered the development of rigorous design methods and these methods are now accepted worldwide. The move towards rectangular pavers has been a result of the experience in The Netherlands and the UK and is now accepted in many countries.

Debate will probably continue regarding the equivalence between concrete blocks/clay pavers and asphalt. Because concrete blocks/clay pavers comprise a collection of rigid articulated units the use of an elastic constant must be seen as an expedient rather than a statement of true behaviour. However, because the technique allows well tried flexible pavement design procedures to be adopted, it is considered that it should continue to be used.

It will be interesting to observe whether concrete blocks gain widespread acceptance on aircraft pavements in the way they have done on highway and industrial pavements. There is no technical reason why they should not and Emery’s experience (9) points to

many benefits, both during the construction phase and throughout the life of the pavement.

It is hoped that this paper will constitute a ready reference for concrete block/clay paver pavement design. It is self contained and the user need only turn to the references for detailed specification.

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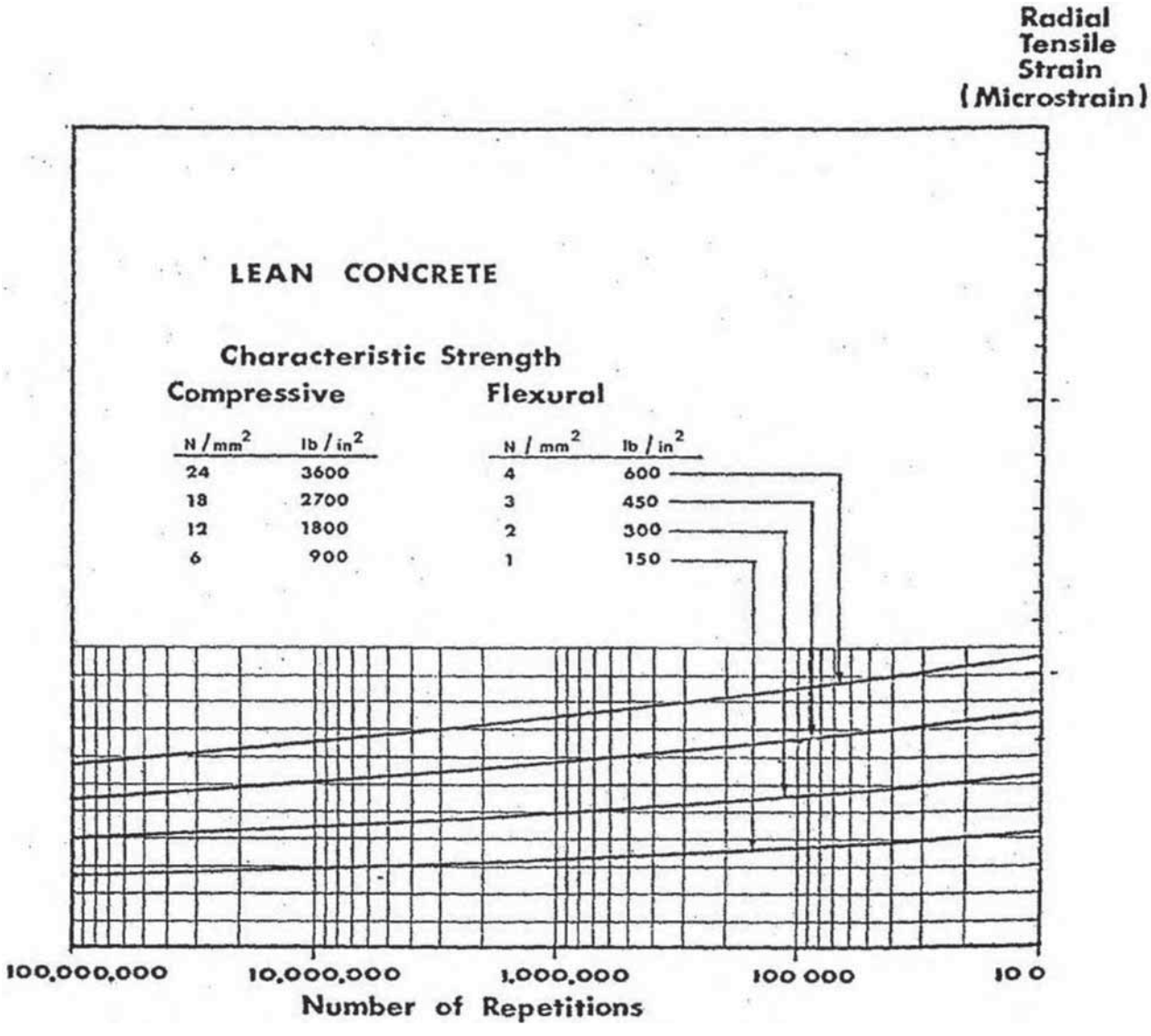


FIGURE 3: Permissible Tensile Strain for Cement Stabilized Bases

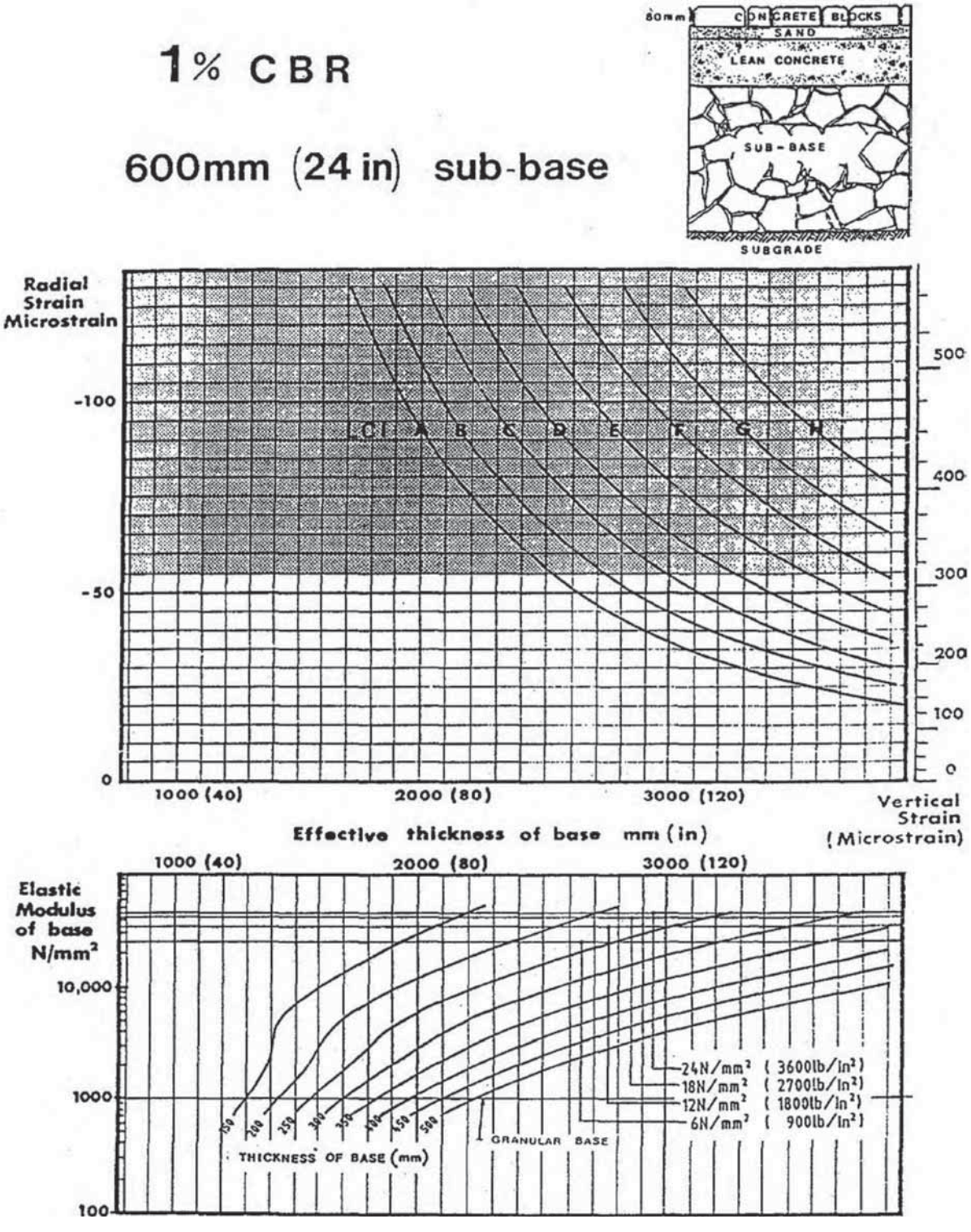


FIGURE 4- Industrial Pavement Design Chart for 1% CBR Subgrade

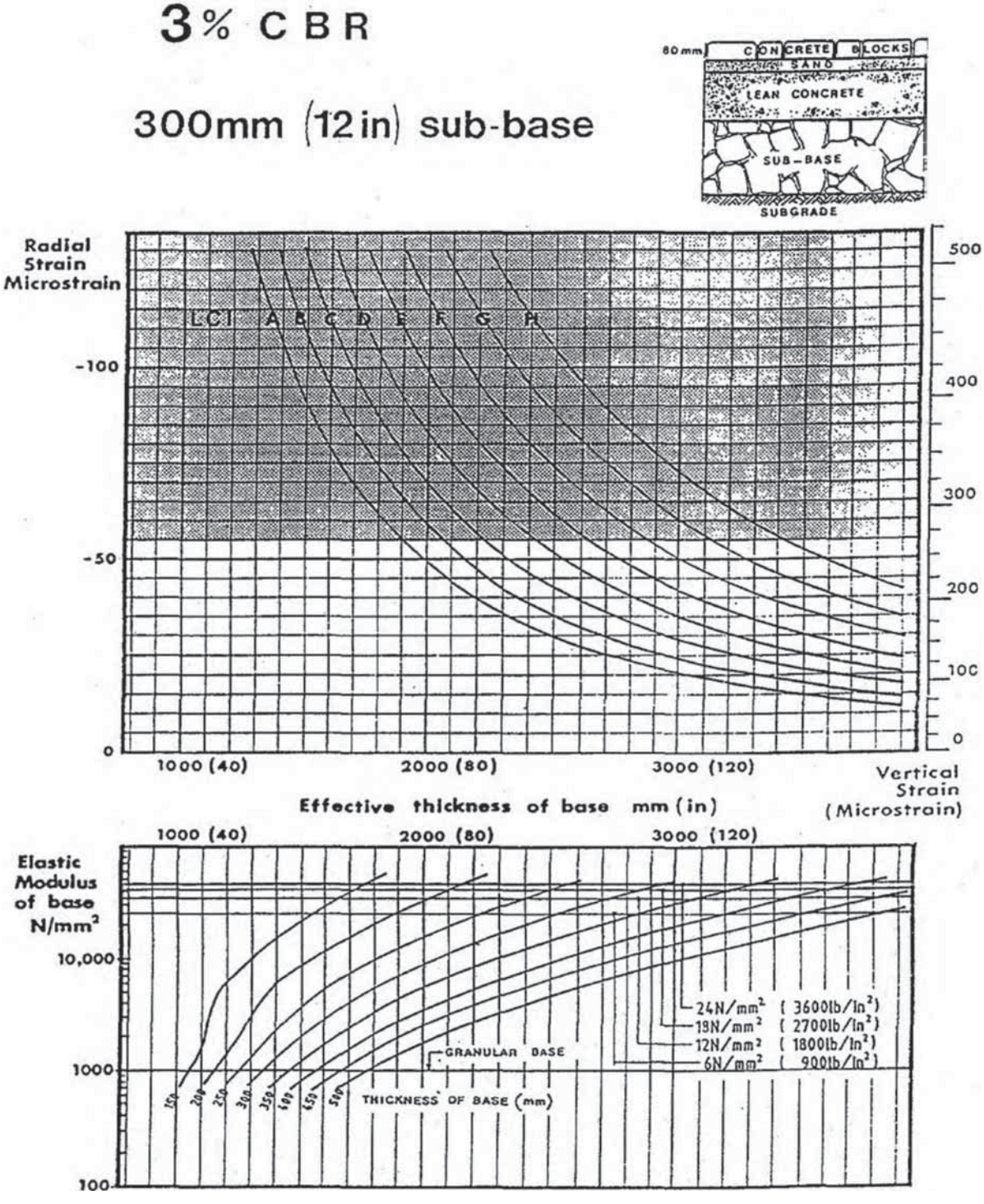


FIGURE 5: Industrial Pavement Design Chart for 3% CBR Subgrade

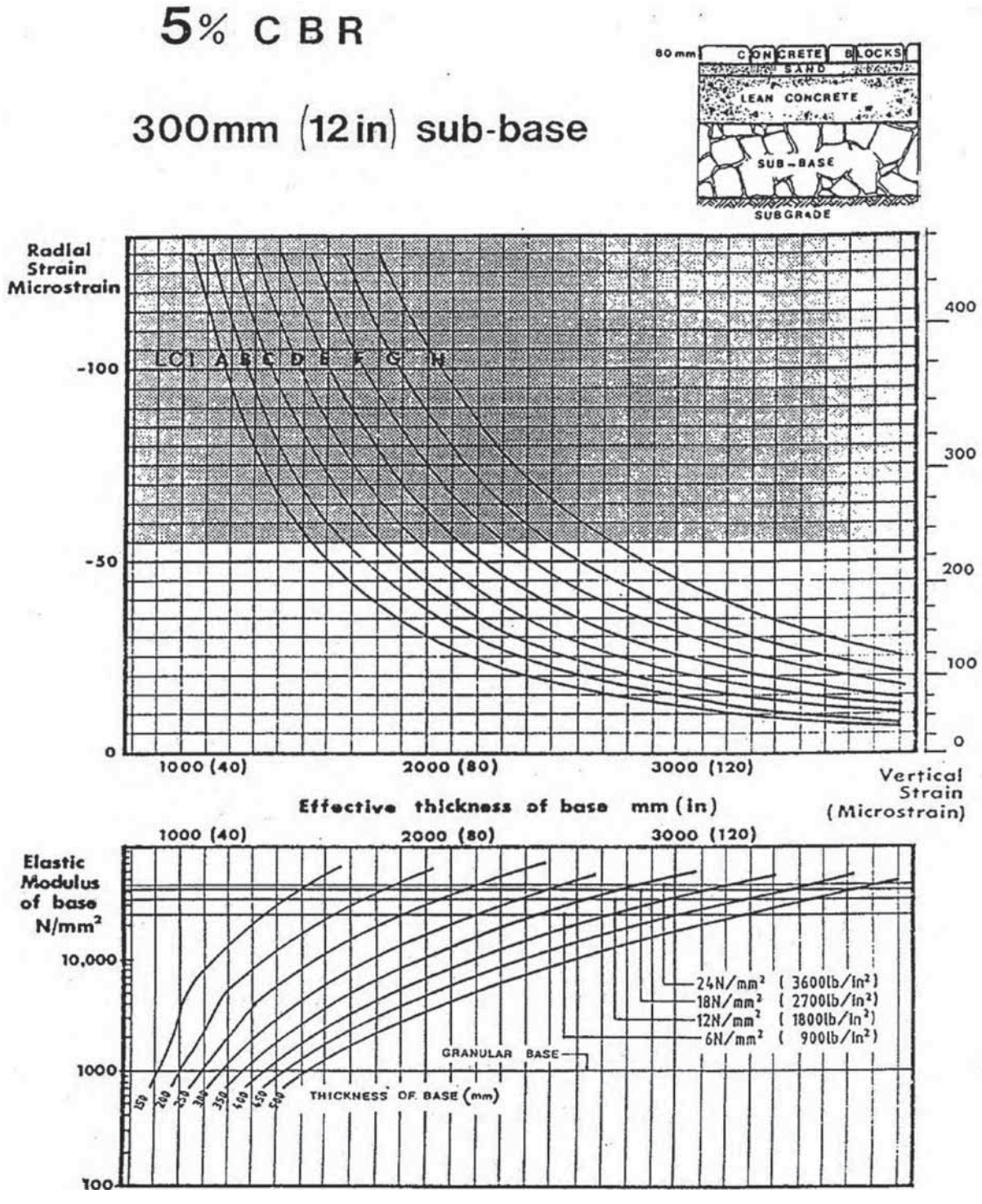


FIGURE 6: Industrial Pavement Design Chart for 5% CBR Subgrade

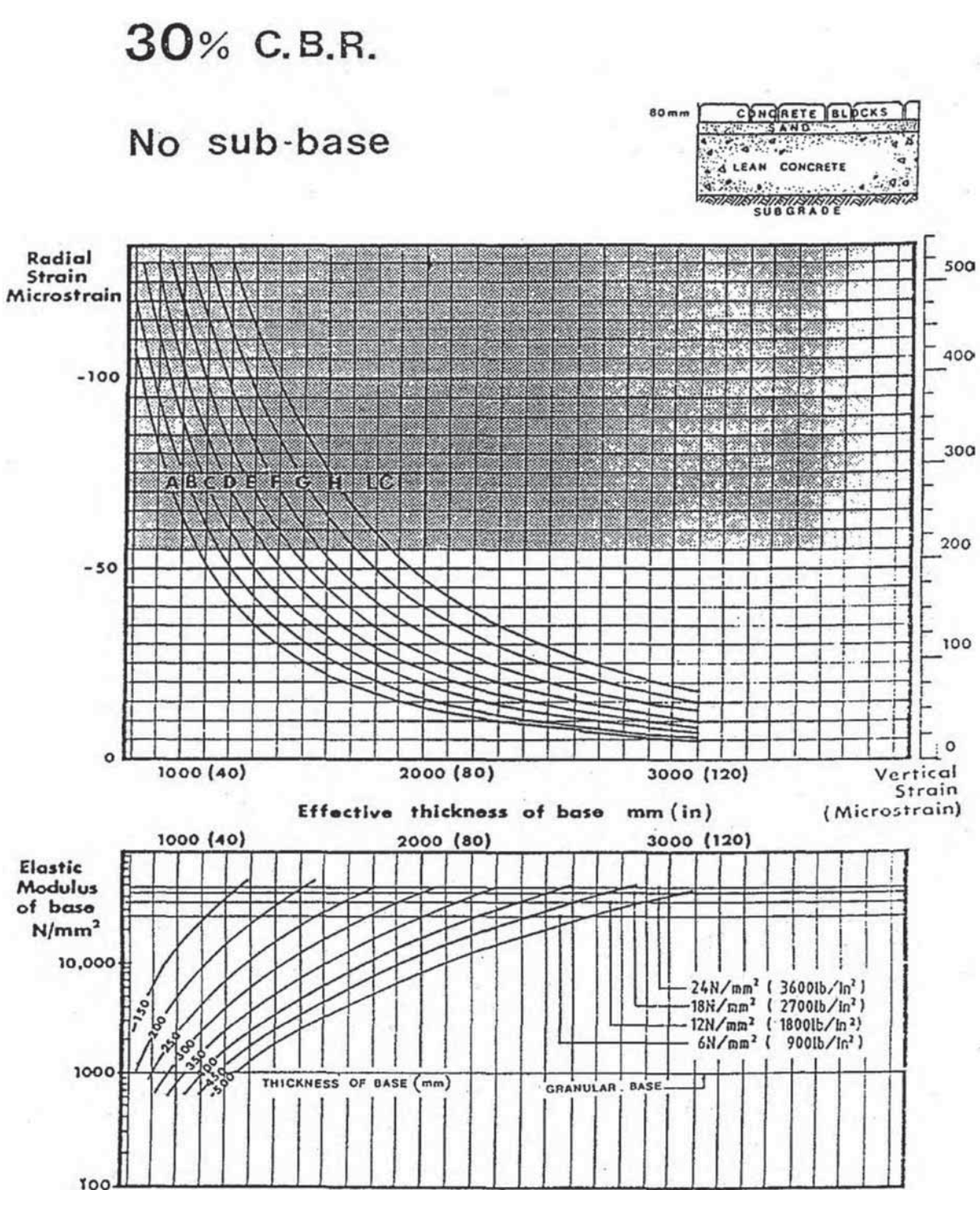


FIGURE 7 Industrial Pavement Design Chart for 30% CBR Subgrade

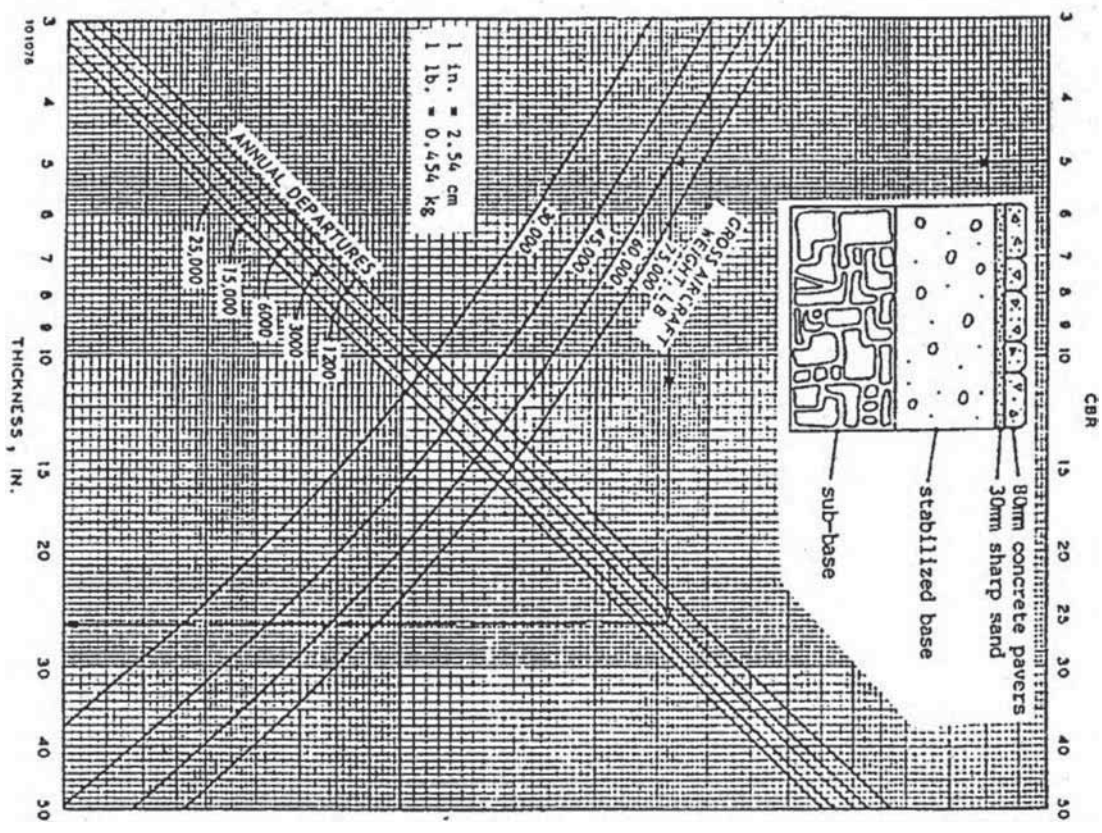


FIGURE 8: Flexible Pavement Design Curves For Critical Areas
Single Wheel Gear

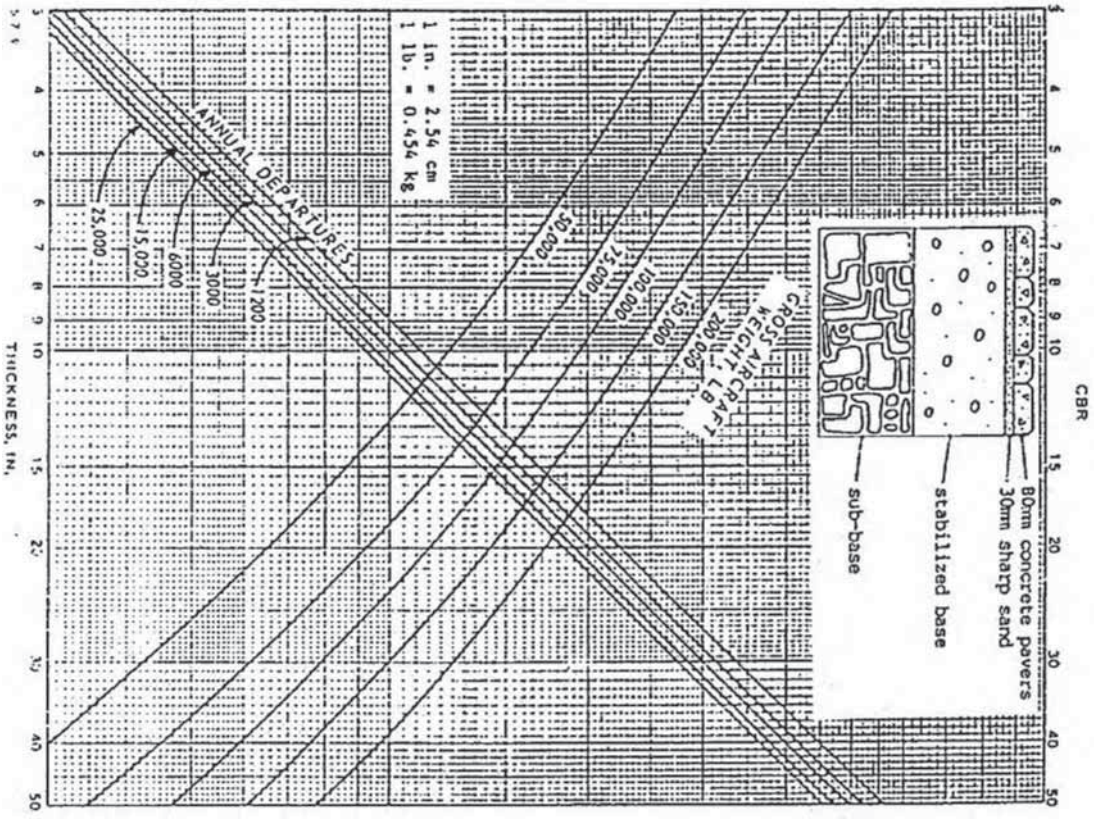


FIGURE 9 Flexible Pavement Design Curves For Critical Areas
Dual Wheel Gear

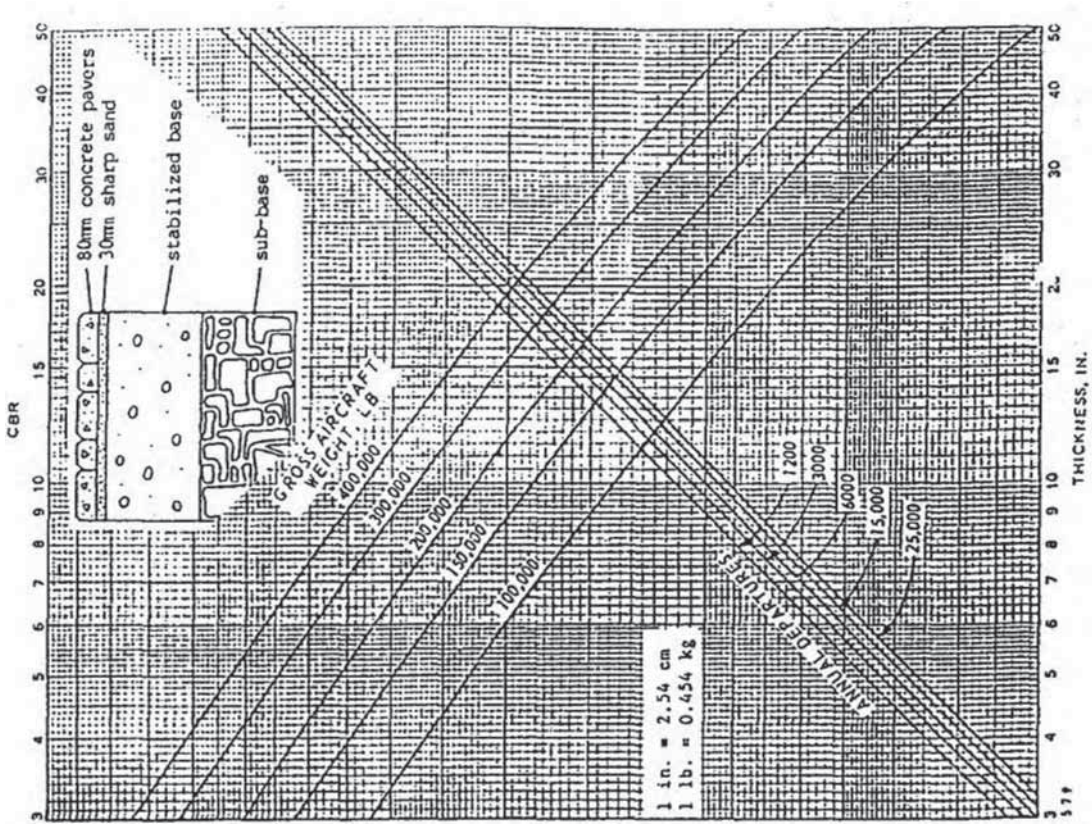


FIGURE 10: Flexible Pavement Design Curves For Critical Areas
Dual Tandem Gear

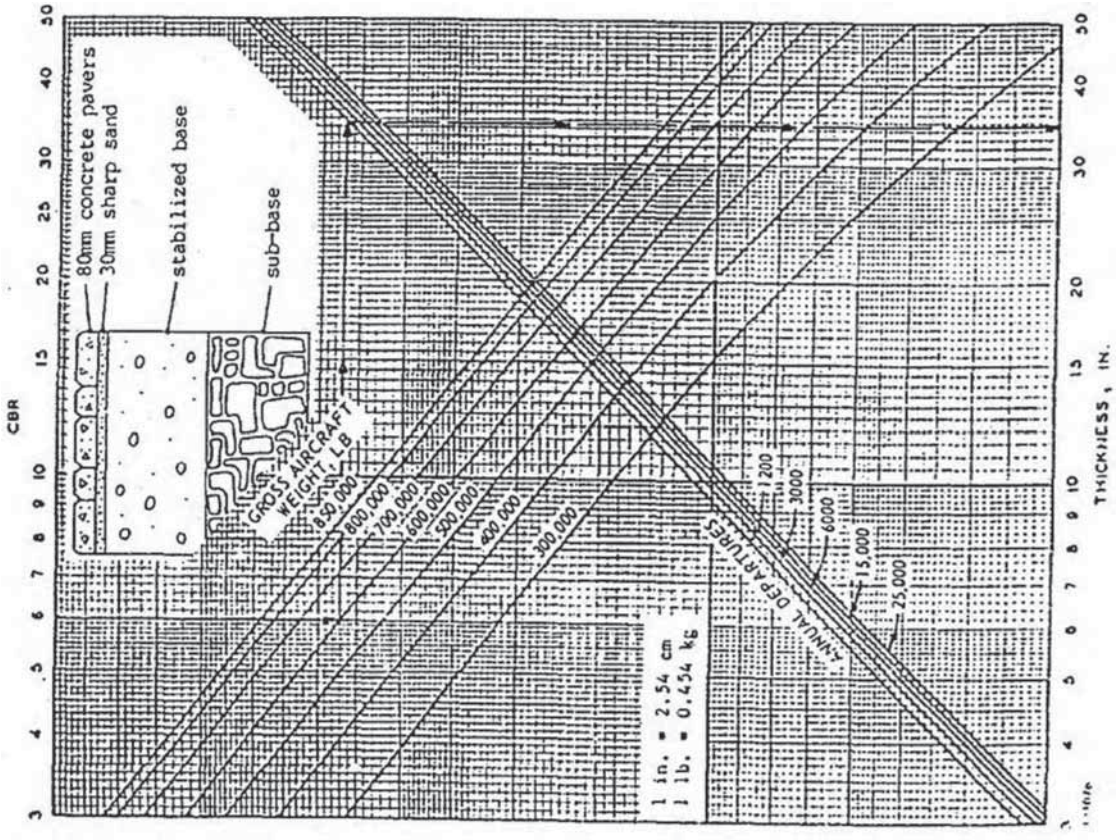


FIGURE 11: Flexible Pavement Design Curves For Critical Areas
B-747-100, SR, 200 B, C, F

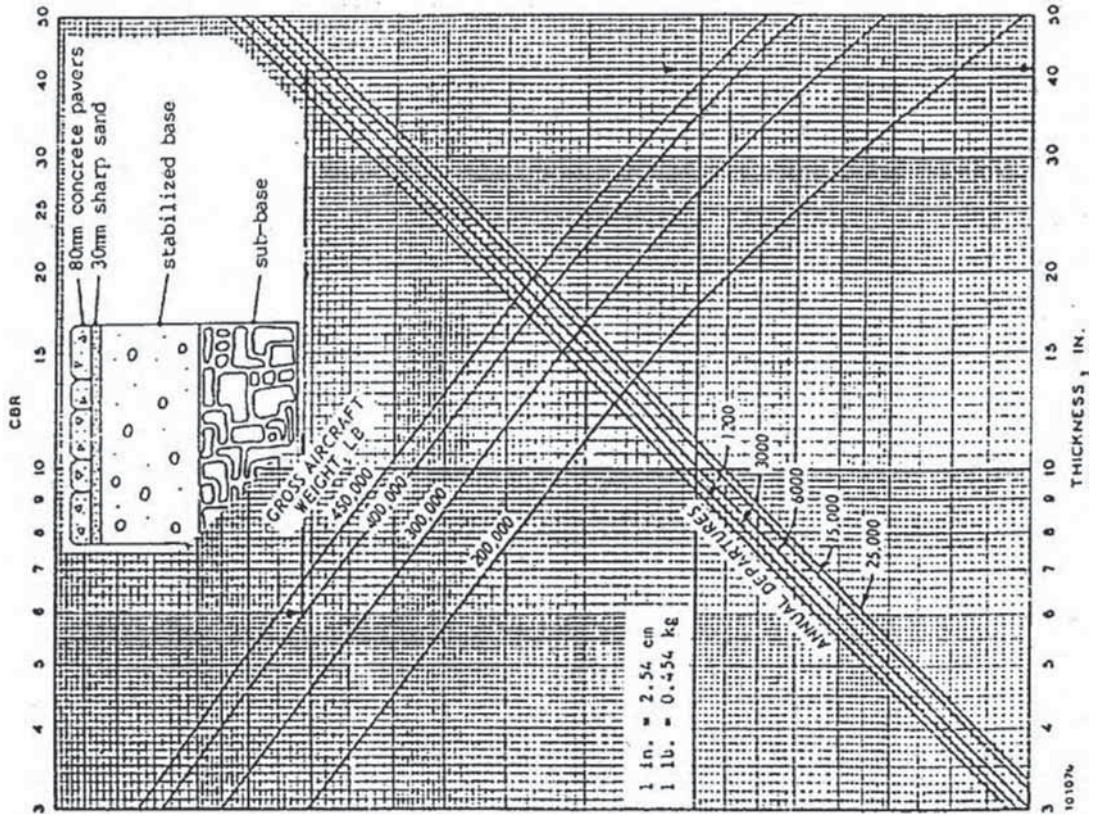


FIGURE 12: Flexible Pavement Design Curves For Critical Areas
DC 10-10, 10CF

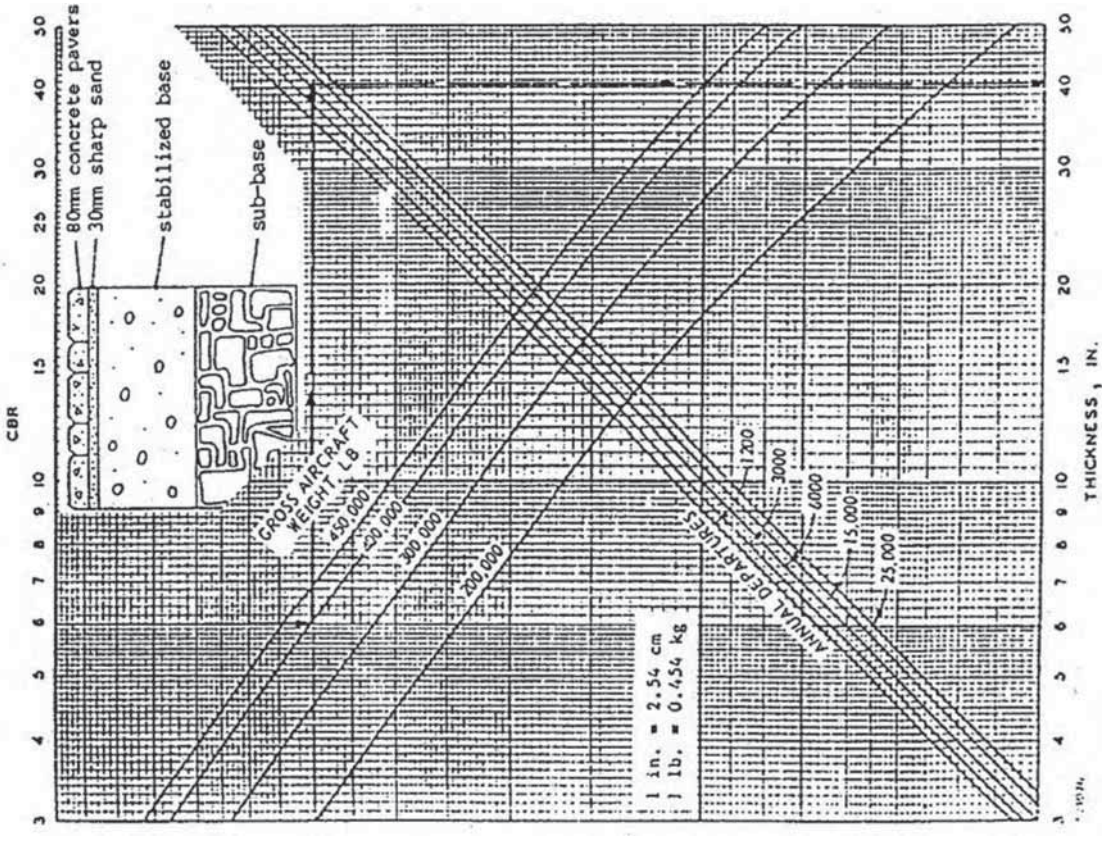


FIGURE 13: Flexible Pavement Design Curves For Critical Areas
L—1011—1, 100

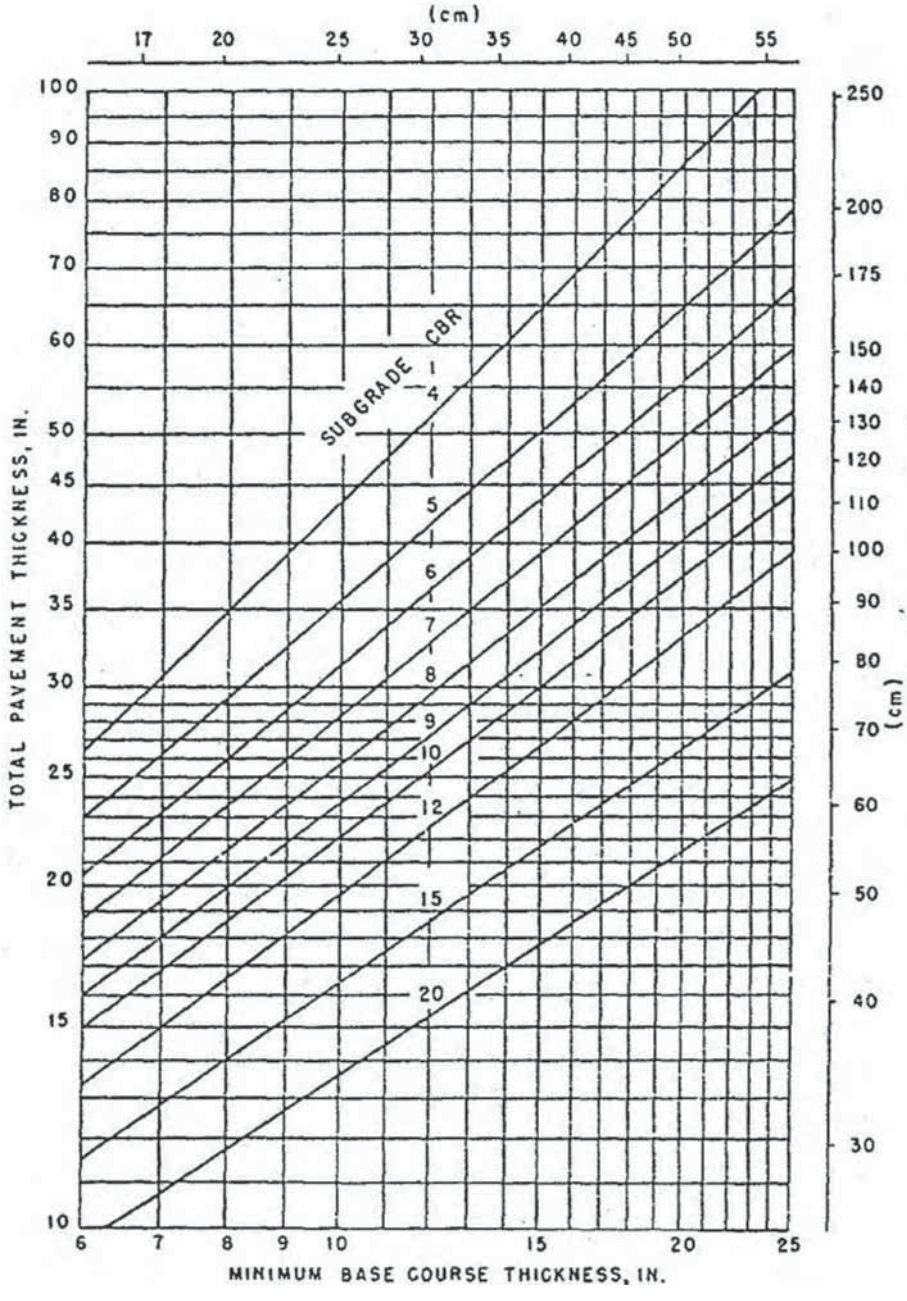


FIGURE 14: Minimum Base Course Thickness Requirements