Shell

Design Charts

for

Flexible Pavements

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When these charts were originally produced in 1963 they were dated accordingly as it was thought they would need amending from time to time, in the light of further understanding and experience. Although considerable progress has been made in these aspects, the developments have not so far resulted in any significant changes being necessary in the simplified design charts presented. The charts are therefore as valid today as when they were first issued, but the date '1963' has been omitted from the title in this reprinting.

SHELL INTERNATIONAL PETROLEUM COMPANY LIMITED . LONDON

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DESIGN CHARTS

Introduction

Bitumen-coated stone was used for base courses in the early days of the asphalt industry. Interest revived in Europe in the middle 1950's and this revival was given impetus by the publication, in 1957, of very good results obtained with thicker asphalt layers in the WASHO Road Test in the United States.

The development of bituminous bases raised an acute problem of thickness design. Existing design procedures, including the CBR method, were all largely empirical and rested essentially on extensive full-life experience of conventional constructions. They could not therefore cater for 'new materials'. Only a design system based on theory is capable of application outside current experience, i.e. able to predict the life under traffic of constructions which have not been built before.

The starting-point in the evolution of such a design system must be the consideration of the properties of the bituminous base course, and of the road structure as a whole, under the dynamic loading of traffic. Since 1945, a main objective of ' Shell ' research on bitumen has been to obtain a full understanding of the properties of bitumens, and of asphaltic mixtures, in engineering terms. This has included extensive work on the dynamic moduli of mixes and studies of their fatigue behaviour. A road vibration machine has been constructed which has been used for testing complete road structures in many countries. We have therefore been very well placed to attempt thickness design, which is, after all, a logical end product of such research. In addition to using the results of our own work we have taken full advantage of data published in the literature.

In all its aspects the subject is complex and information on some points is still incomplete. Nevertheless we feel that a stage has been reached when we are able to make fairly comprehensive design recommendations for flexible constructions; in particular, for those with thick bitumen-bound layers. These recommendations are comprised in the charts that form this booklet. Wherever possible, checks have been made against practical experience, including results of major road experiments, and general agreement has been found. We think that these thickness design charts, being based on engineering theory, are in advance of anything now available; they are wide in scope and have a potential for further development and refinement.

In applying the designs full consideration should be given to any special local conditions concerning materials or environment which may be of over-riding importance.

Because this booklet is written for the practical engineer rather than for the research worker, the explanations given of the basis of the design method are not extensive. Those wishing to know more are referred to the publications listed on pages 16-17.

Principles of Design

It is assumed that well designed structures behave elastically under the dynamic loads applied by traffic, and that elastic theory for layered systems may be used to calculate the distribution of stresses and strains. Although the road may be constructed with many layers, it is, for design purposes, considered to consist of only three layers, each layer consisting of a number of courses of materials of a similar type:

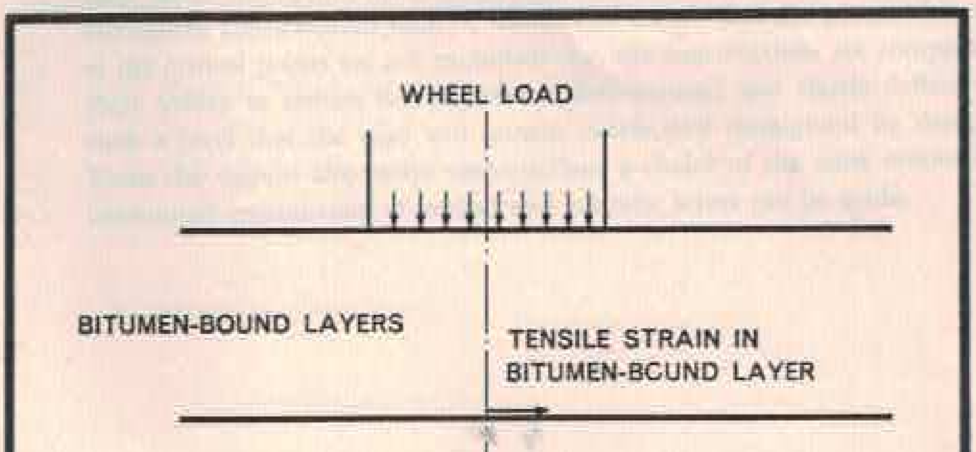
1 A bitumen-bound layer or layers.

2 A granular (unbound) layer or layers.

3 The soil formation or subgrade.

This system is illustrated in Fig. 1 which also shows the location and nature of the strains which are considered to be critical.

Fig. 1 FLEXIBLE PAVEMENT



Eventual failure of the road under traffic occurs when there is:

Excessive deformation of the surface. This occurs as a result of the accumulation of small permanent deformations in the structure. In well designed structures these are primarily dependent on the vertical compressive strain in the surface of the subgrade (Fig. 1). When the deformation is great it may also lead to cracking of the surface layer.

Cracking of the asphalt layer. This may occur as a result of repeated flexing of the asphalt layer under the repeated traffic loads (fatigue). The initiation of such cracks is governed by the tensile strain at the underside of the asphalt layer.

The design procedure is to select the thickness of each of the layers so that the strains developed at the critical points (Fig. 1) under traffic are acceptable.

The design charts have been drawn up on this basis and cover a wide range of conditions of subgrade and traffic. It is only necessary for the engineer to supply information on the subgrade and the expected traffic in order that he may select the appropriate design chart. The design curve gives a range of alternative constructions each of which will ensure that the permissible strains at the critical points are not exceeded—i.e. the constructions are comparable in their ability to reduce the permanent deformations and elastic deflections to such a level that the road will remain satisfactory throughout its design life. From the various alternative constructions a choice of the most economic and convenient combination of asphalt and granular layers can be made.

Design Procedure

There are four stages in the design procedure.

Stage 1
THE PROPERTIES OF THE SOIL SUBGRADE

The design calculations are based on the dynamic elastic modulus of the soil. This is not easy to measure directly but an approximate guide can be obtained from the results of conventional tests such as the CBR or plate-bearing tests. Chart 1 gives conversion factors to enable the dynamic modulus (E) of the soil to be deduced. For practical purposes E can be taken as equal to 100 CBR kg/cm^2 or 1,500 CBR psi (lb./in.^{2}). The test should preferably be carried out at the moisture content which the soil is likely to have in service under an impermeable surface. This 'equilibrium moisture content' is usually similar to that found at a depth of about 3 ft. (1 m.) in the natural soil. If the soil is liable to be subjected to frost penetration then it should be tested in a saturated condition. Particular care should be taken with silty soils, since these are likely to give rise to larger elastic deflections than would be indicated by the approximate conversion from the CBR. In these circumstances it is desirable to use constructions with asphalt layers thicker than the minimum given by the charts.

Stage 2
TRAFFIC REQUIREMENTS

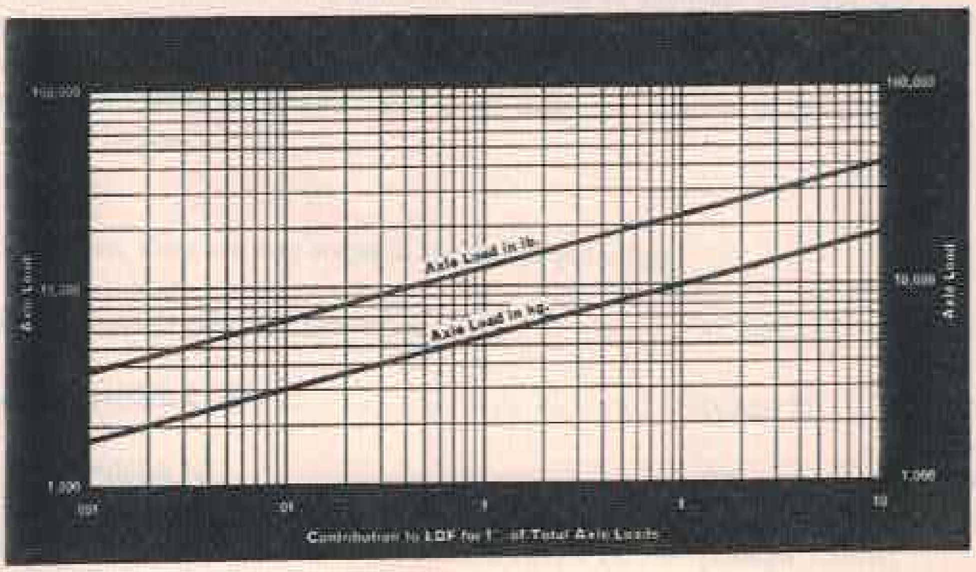
An estimate must be made of the total number of axle loads per lane to be carried during the design life of the road and of the frequency distribution of the different groups of axle load. For multi-lane roads only the lane carrying the greatest number of heavy axle loads is usually considered.

The contributions to failure made by light vehicles such as cars and vans may virtually be ignored, whilst only a relatively small number of heavy axle loads may be very important. For design the actual mixed traffic is expressed as an equivalent number (N) of 10 ton (22,000 lb./10,000 kg.) axle loads. This is a convenient basis because it is the maximum legal limit in many countries. The choice is quite arbitrary, however, and does not affect the use of the charts or the results obtained in any way.

The equivalent number of 10-ton axle loads used for design is calculated using Chart 2 in conjunction with Chart 3. Chart 2 is used to calculate the number of equivalent 10-ton axles per 100 axles, termed the Load Distribution Factor (LDF) from estimates of the frequency distribution of axle loads. This figure is then used, together with the estimated number of axle loads per lane per day and the design life, to calculate the Design Number (N) from Chart 3. The use of the charts is illustrated in detail in Example 1. If, when assessing traffic requirements, information on the likely axle-load distribution is not available the guide given on page 8 may be helpful.

NOTE: The axle-load groups included in Chart 2 have been selected as suitable and convenient. Lines for specific axle loads or representative of other axle-load groups can be added to the Chart if required, using Fig. 2. The contribution to LDF is plotted on the chart and the load line drawn at 45° to the axes. Alternatively the contribution to LDF may be obtained directly from Fig. 2 as % Total Axle Loads × Contribution to LDF for 1% Total Axle Loads.

Fig. 2



Stage 3
CONSTRUCTION THICKNESS

When the modulus (E) of the soil and the traffic requirement (N) have been established the appropriate design chart and design curve may be selected.

Alternative series of charts are provided.

SERIES I

Each chart is for a particular value of E, and each design curve on a chart applies to a particular value of N (Charts 4-8).

SERIES II

Each chart is for a particular value of N, and each design curve on a chart applies to a particular value of E (Charts 9-12).

Either series may be used depending on convenience. For example, Series II may be preferred when considerable variation in the soil properties (E) is found over the length of the proposed road, or when designs on soils with different properties from those given are required.

For any particular design curve a suitable construction is indicated by the co-ordinates of *any point* on the curve. The vertical axis co-ordinate gives the total thickness of dense asphalt wearing and base courses, and the horizontal axis co-ordinate gives the total thickness of granular base and sub-base layers.

Stage 4
QUALITY REQUIREMENTS FOR GRANULAR MATERIALS

Although deformation of the pavement is governed to a large extent by the properties of the subgrade, care must be taken that any unbound granular materials used in the base are capable of developing an adequate modulus and resistance to shear in place. In order to help in this respect, dashed lines are included in the design charts indicating the minimum CBR required for the material in any particular granular layer in the structure. The use of these lines is illustrated in Example 1.

To summarize, there are four stages in the design procedure:

STAGE 1	Establish subgrade properties	(Chart 1)
STAGE 2	Establish LDF	(Chart 2)
	Establish N	(Chart 3)
STAGE 3	Select alternative constructions	(Design Charts)
STAGE 4	Determine quality requirements for granular materials	(Design Charts)

In using the design charts consideration should be given to the notes which follow in the section 'Work Points'.

Execution

The design curves in this booklet require that the workmanship, materials and control of construction are such that the normally accepted standards, particularly of compaction, are attained.

Load Distribution Factor

When details of the expected axle-load distribution are not available the following figures may be used as a guide.

Type of Road	LDF
Motorways and other roads with 'slow lane'	5
Two- and three-lane main roads	2-3
Local/residential roads	less than 1

Climatic Conditions

The design calculations are based on severe conditions and it is probable that constructions will tend to be over-designed in temperate areas, particularly for the thicker bitumen-bound layers. It is felt undesirable, however, to apply a theoretical correction for such conditions until there is more confirmation from experience.

Thickness of Granular Layers

If a granular sub-base is used under an asphalt base it should have a minimum thickness of 4 in. (10 cm.), since thinner layers are not practicable.

Asphalt Wearing Courses

A surface course (or courses) of good quality asphaltic concrete must be used and this should generally be a minimum of 2 in. (5 cm.) thick, or 4 in. (10 cm.) on those roads carrying heavy wheel loads (say, when $N=10^6$ or greater). This course will form part of the total bitumen-bound thickness given in the charts.

Asphalt Base Courses

The dense asphalt-base layers should consist of well compacted high stone content mixes (40% or more, > ⅛ in. (3 mm.)) having a voids content of less than 10% and a bitumen content (40—100 pen. at 25°C) of not less than 3½% wt.

Open Graded Mixes

The charts in this booklet apply to constructions with dense bitumen-bound mixes of good quality. Mixes that are more open may be suitable but there is not yet sufficient experience with them to draw up mix specifications or design charts. They are, however, less effective than dense bitumen-bound mixes and it is doubtful whether in practice they would often afford an economic advantage.

Construction Phasing

These design charts make it possible to plan a 'stage construction'—building up over a period of years, in accordance with the expected increase in traffic activity, to full design thickness with successive layers of asphaltic mix. This is an important advantage of bituminous construction but the procedure should be used conservatively. Each stage should be built well before the estimated design life of the preceding stage is reached in order that structural deterioration does not occur.

A similar procedure is the practice of delaying the laying of the final wearing course for some months. This allows traffic compaction of local weak spots, and the good riding qualities which are restored by the wearing course will have greater permanence. Whenever a base-course mix is to be exposed to traffic, it should be dense and of high stability.

The design of overlays for old roads must be based on a reliable system for measuring their existing structural strength, but this subject is not dealt with in the present booklet. However, the design charts show that an additional 3 in. (7-8 cm.) of asphaltic concrete would correspond usually with an increase of ten times or more in the design number (N). The minimum thickness of overlay practicable on an old irregular surface is probably 2 in. (5 cm.) and this should be adequate unless the existing road is badly cracked.

Cement-Bound Bases

Failure of relatively strong constructions of the lean concrete type may occur when cracks in the cement-bound layer have propagated through the asphalt wearing course and allowed water to enter the construction. Experience shows that the use of thicker asphalt layers delays the appearance of surface cracks and the trend at present is to use thicker asphalt layers in such constructions. In effect this places the cement-bound layer at a lower level in the structure where the stresses are lower. The risk of cracking is then less likely but should cracks occur they will be less harmful to the structure.

Weak cement-bound layers such as soil cement tend to disintegrate under high traffic stresses, and the modulus of the material becomes effectively only slightly greater than that of the underlying layer. For design purposes such layers should therefore be considered as consisting of unbound granular material. A particular example of this occurs when the top of a low CBR subgrade is stabilized to provide a 'working platform' to permit compaction of the first granular or asphalt layer.

It follows that CBR or modulus measurements alone on cement-bound materials are not suitable for use in the design procedure directly, since no allowance for cracking or disintegration is made.

Examples of Design Procedure

EXAMPLE 1

A major road is to be constructed on a subgrade having a CBR of 5. It is expected that the traffic volume on the most heavily trafficked slow lane will be 15,000 axle loads per day, and the design life is to be 20 years. The expected axle-load distribution in this lane is:

less than 8,000 lb.	75%
8,000–16,000 lb.	20%
16,000–20,000 lb.	4%
20,000–24,000 lb.	1%
more than 24,000 lb.	0%
	100%

STAGE 1 The modulus (E) of the subgrade is obtained using Chart 1 which shows that for a CBR of 5, E=7,000 psi.

STAGE 2 The Load Distribution Factor (LDF) is obtained from Chart 2 by adding up the values on the horizontal axis for each axle-load category.

Axle Load Group lb.	Percentage	Contribution to LDF
Less than 8,000	75	0.4
8,000–16,000	20	1.8
16,000–20,000	4	1.6
20,000–24,000	1	0.9
More than 24,000	0	0.0
		Total 4.7

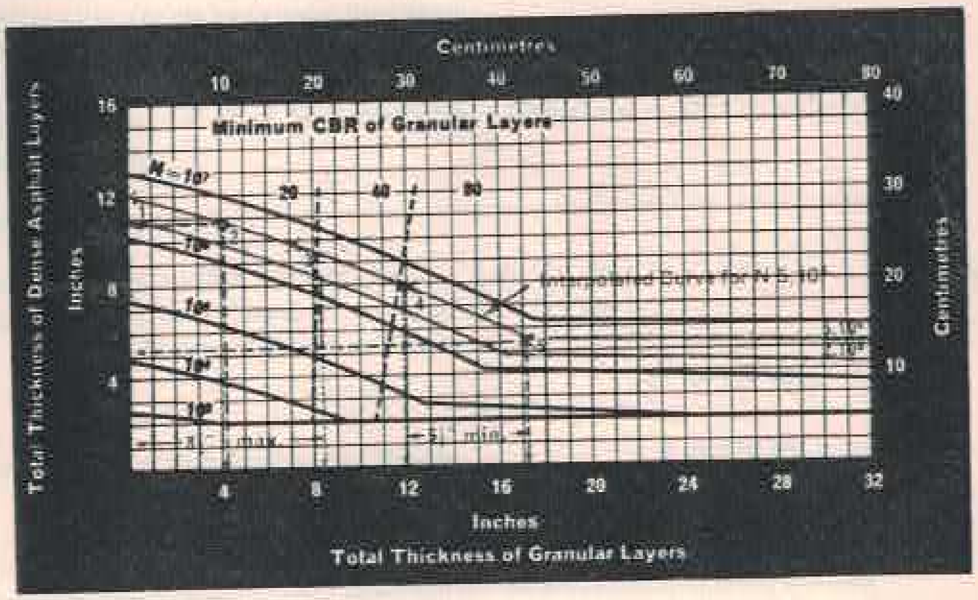
The design number of equivalent 10-ton axle loads (N) is obtained from Chart 3 as indicated in the inset diagram, $N=5\times10^8$.

STAGE 3 Using Chart 5 for E=7,500 psi and the interpolated curve for $N=5\times10^{6}$*, as illustrated in Fig. 3, the following alternative constructions are obtained.

* Interpolations are logarithmic.

Construction	Total Thickness of Dense Asphalt Layers		Total Thickness of Granular Layers		Overall Thickness	
	in.	(cm.)	in.	(cm.)	in.	(cm.)
1	12	30	—	—	12	30
2	11	28	4	10	15	38
3	10	25	7	18	17	43
4	8	20	12	30	20	50
5	5½	14	17	43	22½	57

Fig. 3 SUBGRADE MODULUS
E=7,500 psi/530 kg/cm² (Approx. CBR 5)



STAGE 4 Considering as an example construction 5, further reference to Fig. 3 shows how the charts give minimum quality requirements for the granular materials. From the points of intersection of the design-curve with the dashed lines denoting granular material properties, lines are drawn vertically to meet the horizontal axis of the chart. The intercepts given are the thickness requirements

for each CBR material and are a maximum for the low CBR materials and a minimum for the high CBR materials.

Dense Asphalt Wearing Course	1½ in. (4 cm.)	
Dense Asphalt Base Course (high stability)	4 in. (10 cm.)	
Total Thickness of Dense Asphalt Layers		5½ in. (14 cm.)
Granular Layer with Minimum CBR80	6 in. (15 cm.) (see note 1)	
Granular Layer with Minimum CBR40	4 in. (10 cm.)	
Granular Layer with Minimum CBR20	7 in. (18 cm.) (see note 2)	
Total Thickness of Granular Layers		17 in. (43 cm.)
Overall Thickness		22½ in. (57 cm.)

NOTE 1: 5½ in. (14 cm.) or greater from chart.
NOTE 2: 8½ in. (21 cm.) or less from chart.

Alternatively, if a typical black base construction (construction 2) is considered this would consist of:

Dense Asphalt Surface Courses	4 in. (10 cm.)	
Dense Asphalt Base Course	7 in. (18 cm.)	
Total Thickness of Dense Asphalt Layers		11 in. (28 cm.)
Granular Layer with Minimum CBR20		4 in. (10 cm.)
Overall Thickness		15 in. (38 cm.)

Comparing these two designs, 13 in. of granular base in construction 5 is replaced in construction 2 by 5½ in. of dense asphalt base.

EXAMPLE 2

A heavily trafficked road (single lane in each direction) is to be constructed on a subgrade of CBR 10. The design life is 15 years, and the expected traffic is 8,000 axle loads per lane per day with the following axle-load distribution:

less than 8,000 lb.	87½%
8,000–16,000 lb.	11%
16,000–20,000 lb.	1%
20,000–24,000 lb.	½%
more than 24,000 lb.	0%
	100%

STAGE 1 Subgrade modulus $E=15{,}000$ psi (Chart 1)

STAGE 2 $LDF=.44+1.0+.41+.45=2.3$ (Chart 2)
$N=10^8$ (Chart 3)

STAGE 3 Alternative designs (Chart 7)

Construction	Total Thickness of Dense Asphalt Layers in.	(cm.)	Total Thickness of Granular Layers in.	(cm.)	Overall Thickness in.	(cm.)
1	9	23	—	—	9	23
2	6	15	7	17	13	32
3	4½	12	10	25	14½	37

STAGE 4 The granular base will consist of a maximum thickness of 6 in. of a material of CBR 40 or greater, the remaining base material having a CBR of 80 or greater.

Comparing constructions 1 and 3, 4½ in. dense asphalt base replaces 10 in. of granular base.

EXAMPLE 3

A design is required suitable for a lightly trafficked road in a residential area, in which there is mainly car traffic with occasional delivery vans and trucks.

The LDF for traffic of this type, which will probably have axle loads of less than 4,000 lb., will be considerably lower than that even for axle loads of 8,000 lb., the lowest axle-load group shown on Chart 2. For an LDF of 0.1, for example, the value of N for a design life of 20 years with 150 axle loads per day will be about 10^5. Even, however, on very weak subgrades (say, CBR 3) 4in. (10 cm.) of dense asphalt or 2 in. (5 cm.) of dense asphalt with a granular base of 10 in. (25 cm.) will be adequate.

The design charts are based on a criterion of riding quality applicable to roads carrying fast-moving traffic. For relatively low-cost local roads where the traffic is slow moving and a lower standard of evenness is acceptable, higher subgrade stresses and shear stresses in the granular material are permissible. The designs given by the charts will in these circumstances be conservative, and a thinner impermeable surfacing will often suffice.

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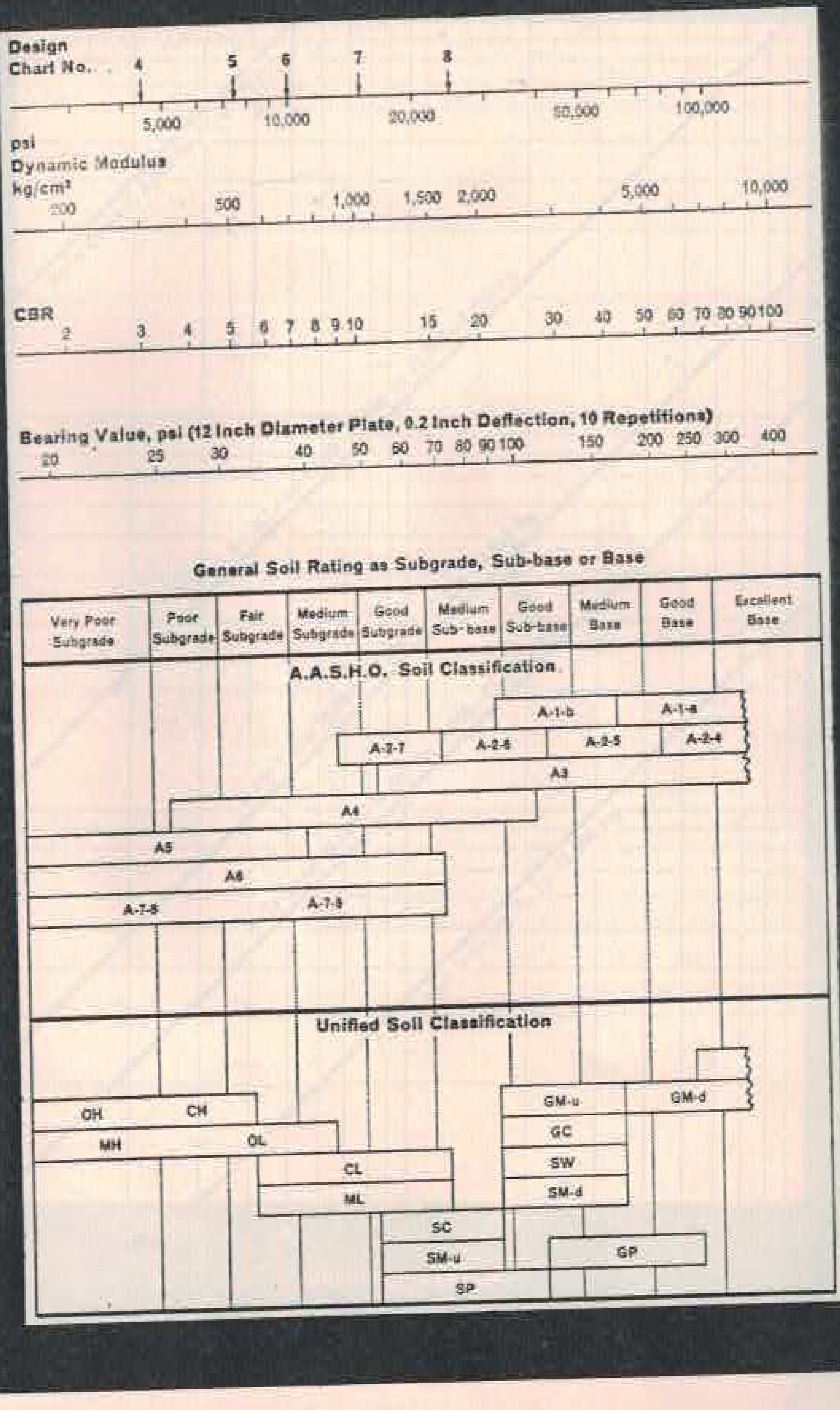
$E = 100$ CBR (kg/cm^2)

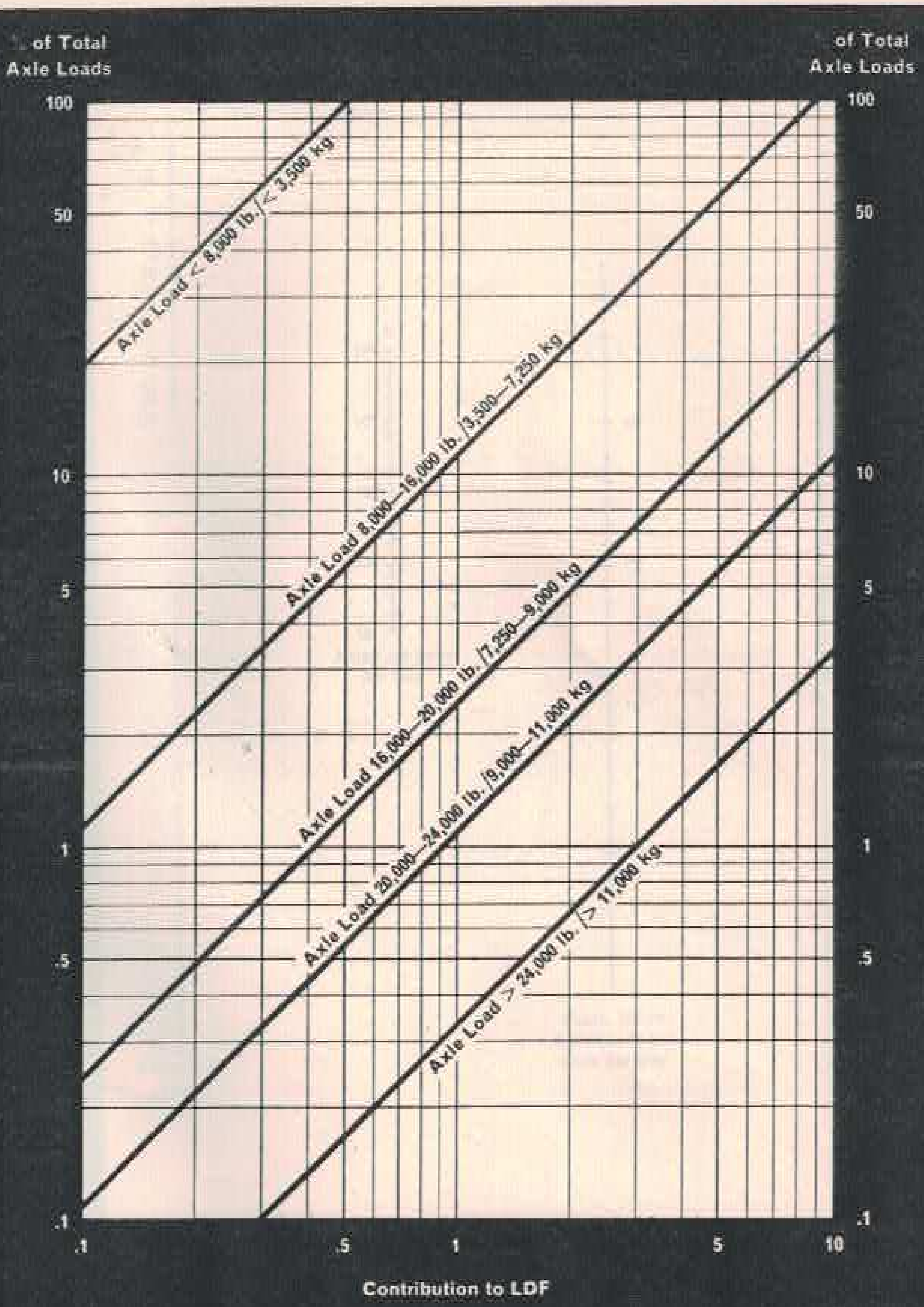
Chart 1

ESTIMATION OF DYNAMIC SOIL MODULUS (E)



CALCULATION OF THE LOAD DISTRIBUTION FACTOR (LDF)

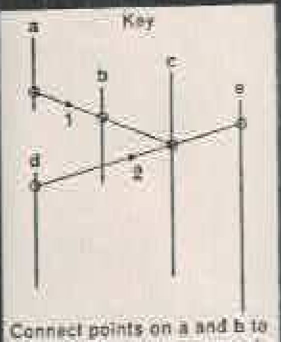
Chart 2



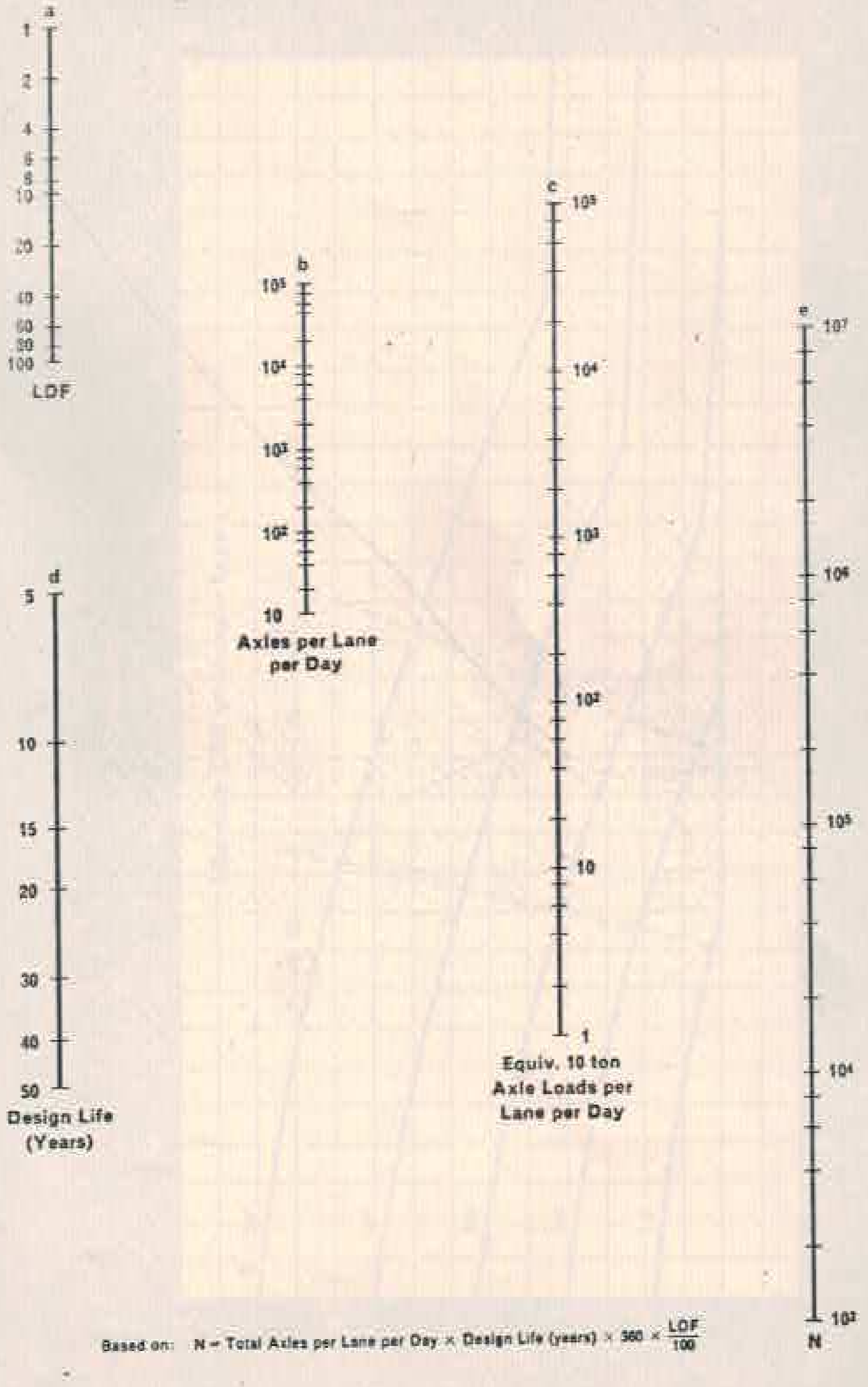
Note : Lines for specific axle loads or other axle-load groups can be added if required as indicated on page 5

DETERMINATION OF EQUIVALENT NUMBER OF 10 TON AXLE LOADS FOR DESIGN (N)

Chart 3



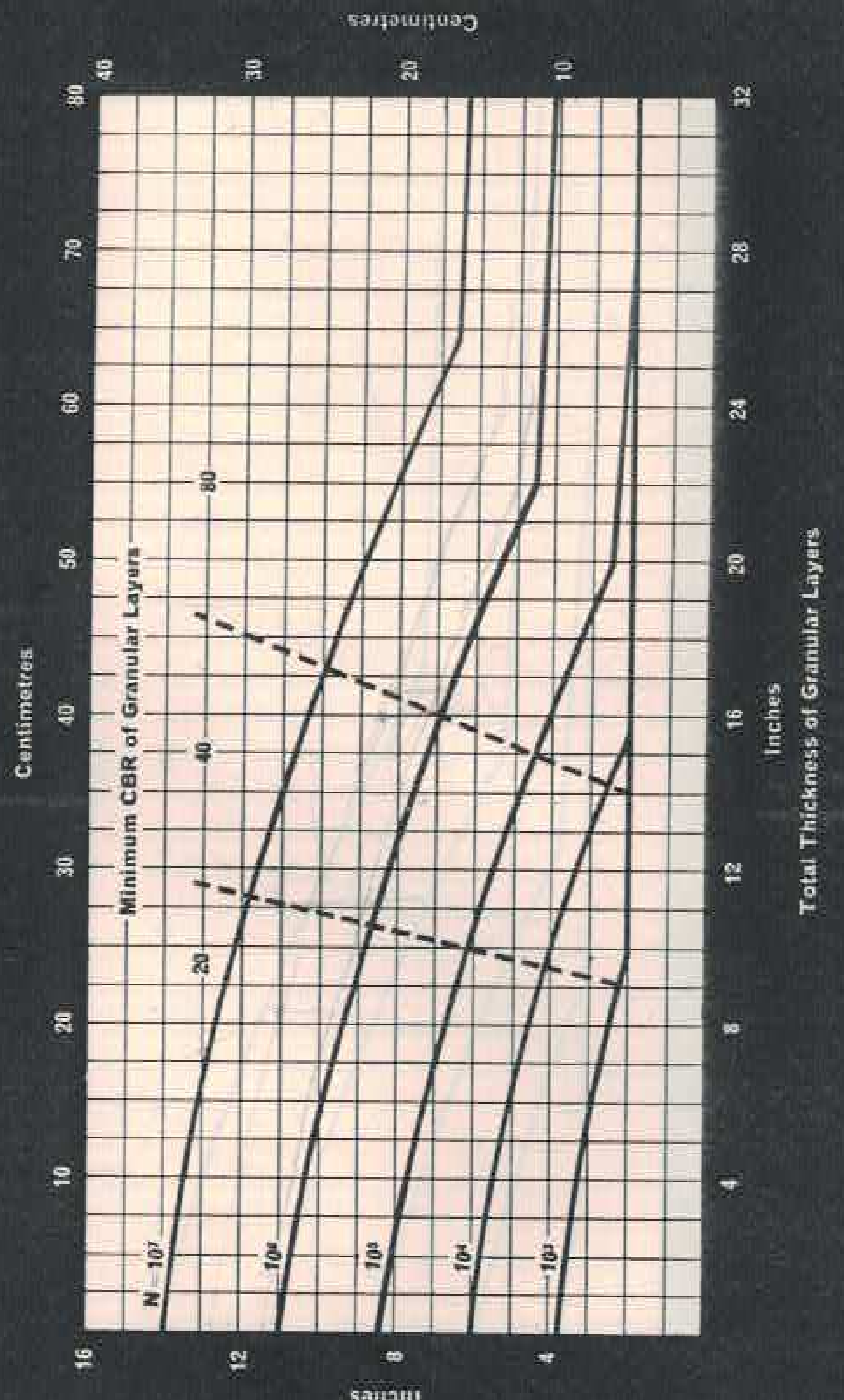
Connect points on a and b to find point on c then connect with point on d to find N



Based on: $N = \text{Total Axles per Lane per Day} \times \text{Design Life (years)} \times 360 \times \frac{LDF}{100}$

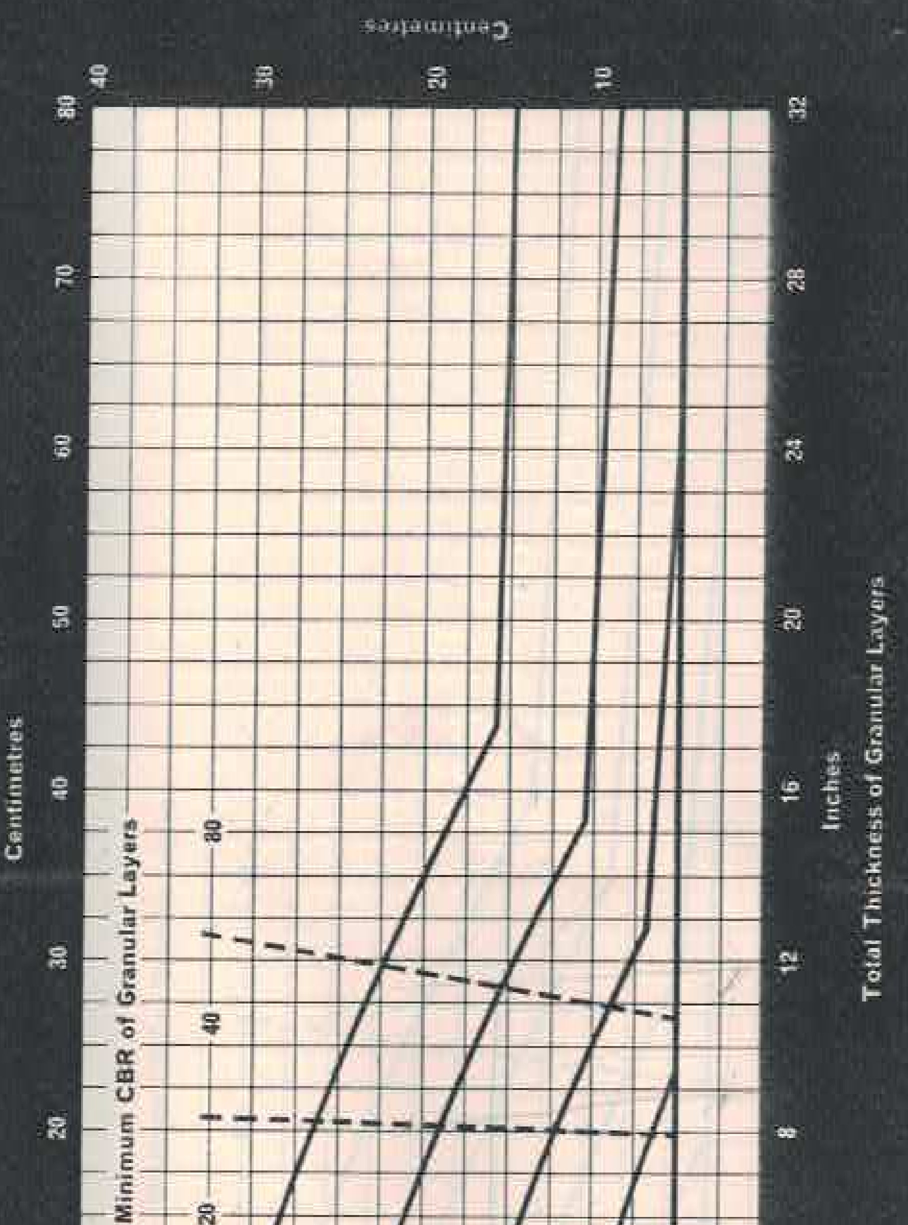
UBGRADE MODULUS $E=4{,}500$ psi/320 kg/cm^2 (Approx. CBR 3)

Chart 4



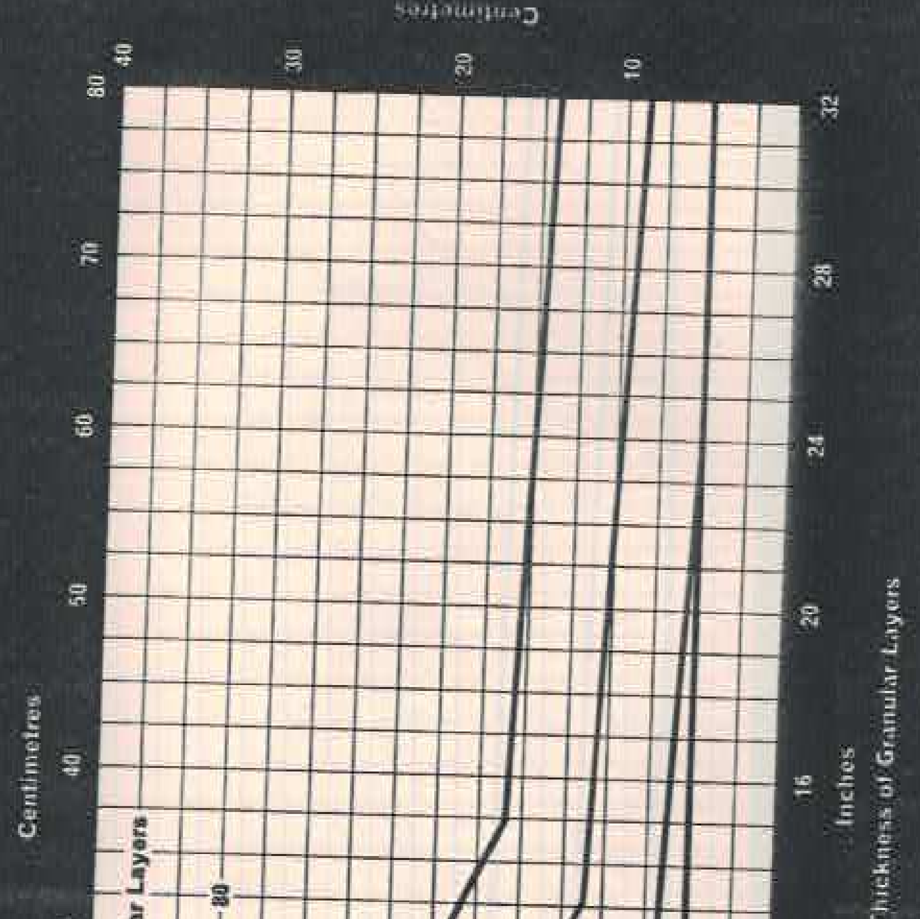
SUBGRADE MODULUS E=7,500 psi/530 kg/cm² (Approx. CBR 5)

Chart 5



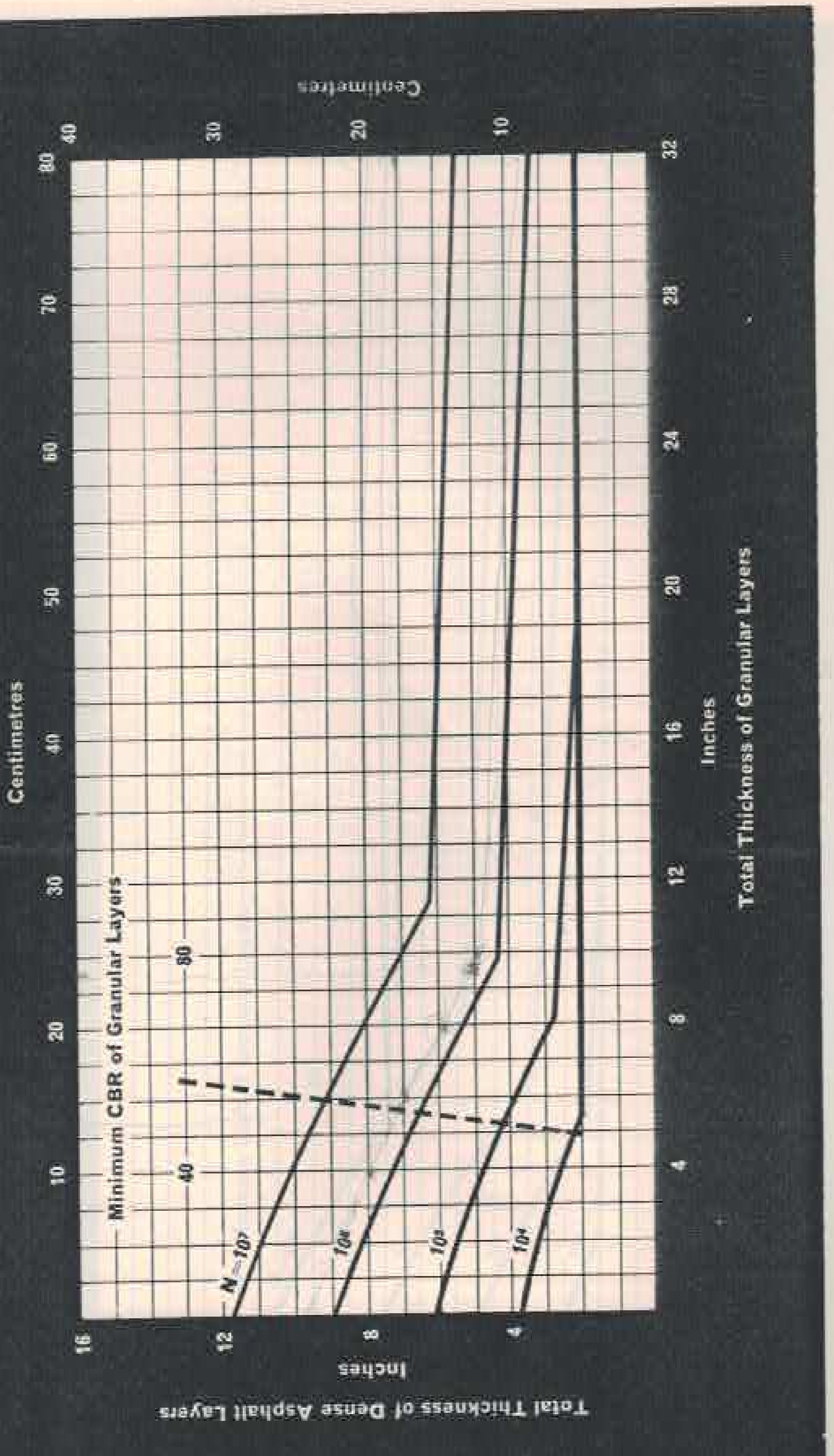
SUBGRADE MODULUS E=10,000 psi/710 kg/cm² (Approx. CBR 7)

Chart 6



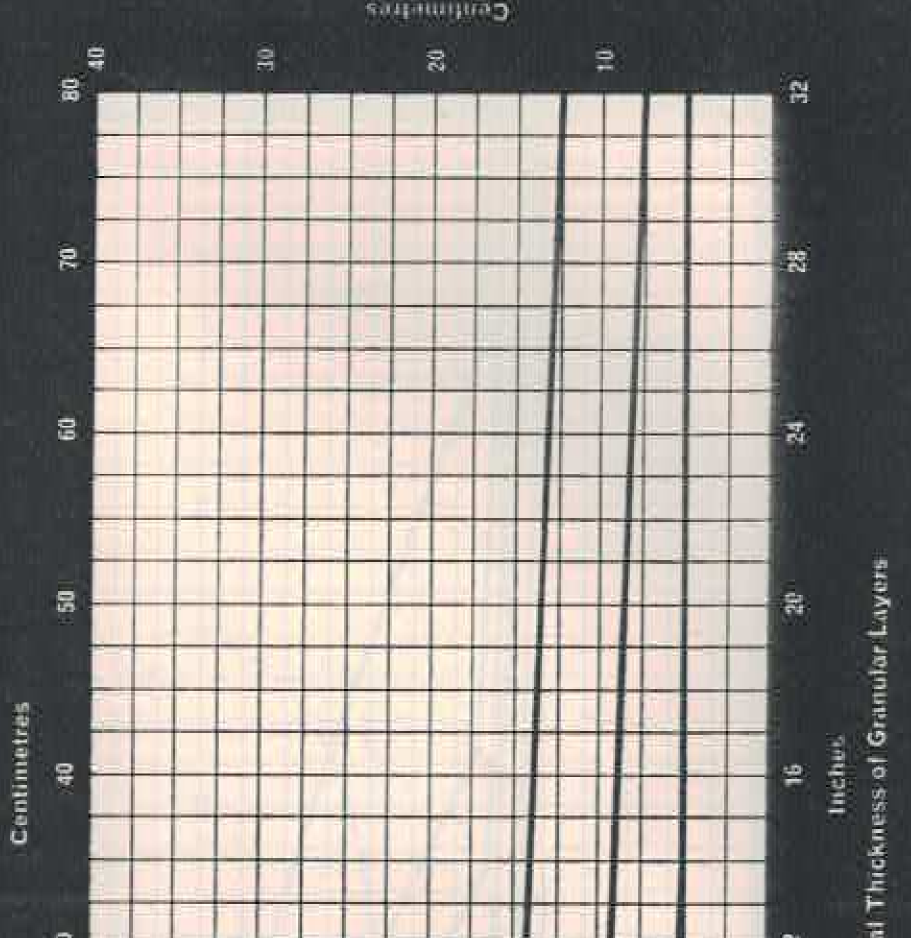
SUBGRADE MODULUS E = 15,000 psi/1,060 kg/cm² (Approx. CBR 10)

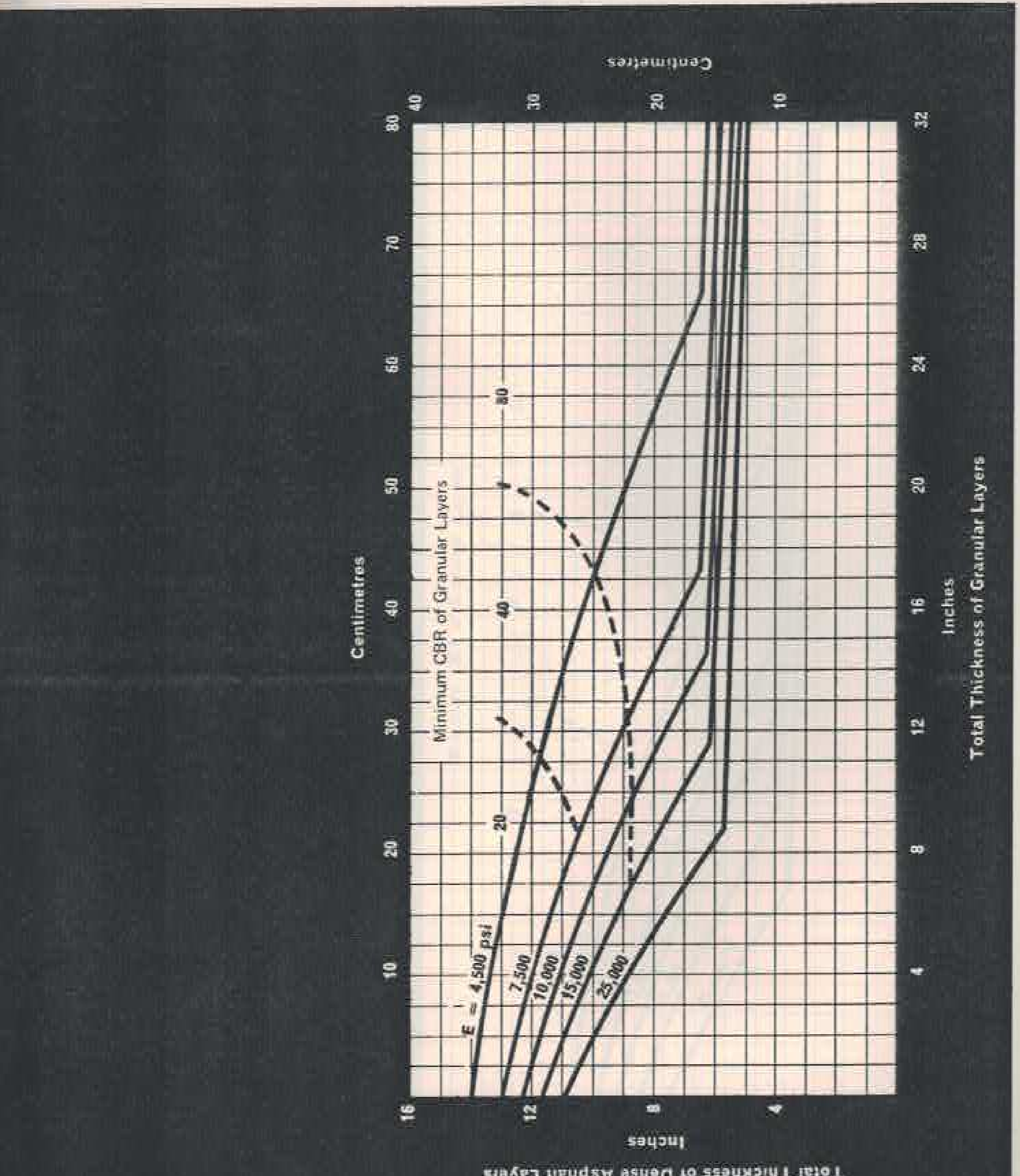
Chart 7

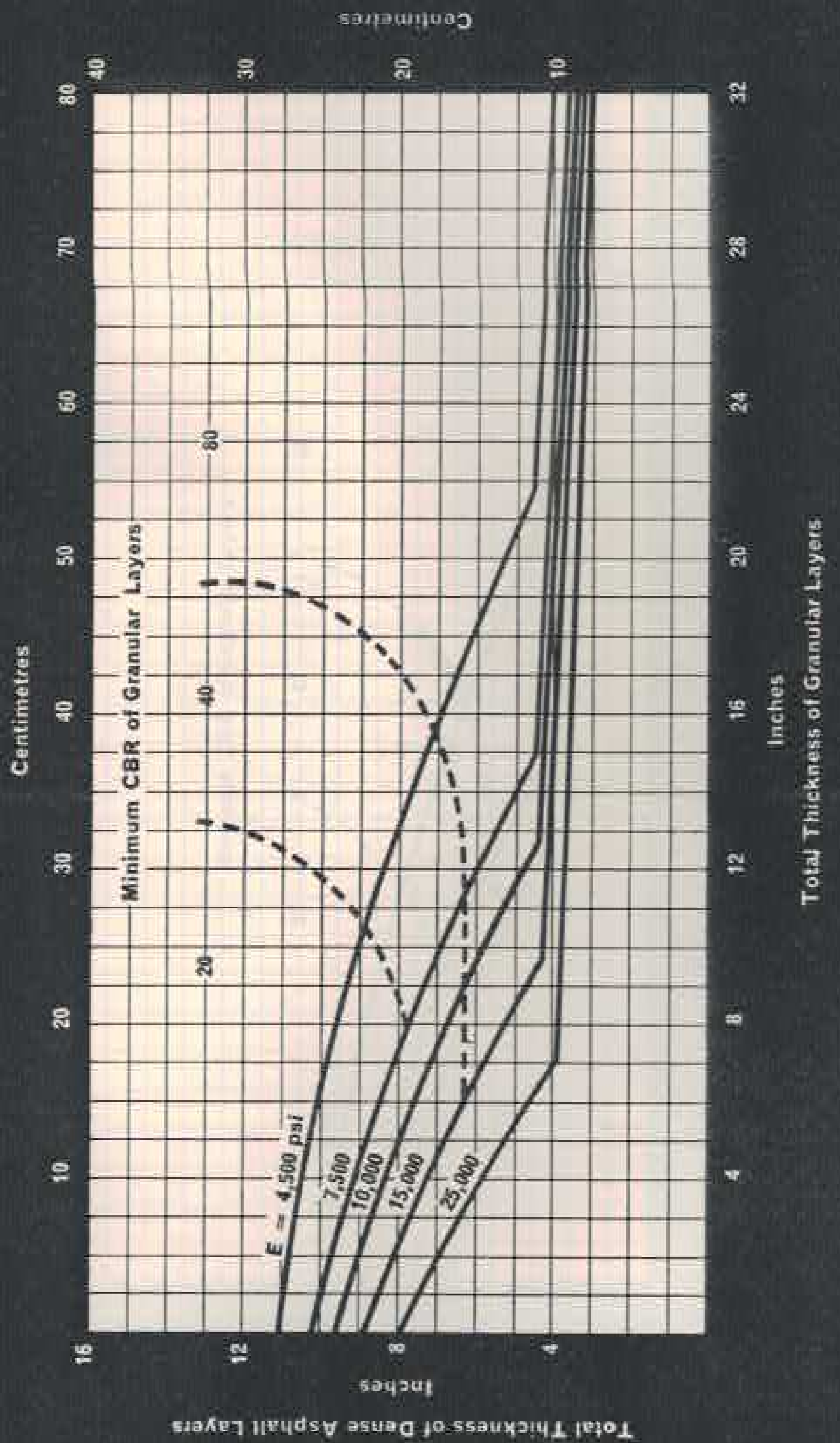


SUBGRADE MODULUS E=25,000 psi/1,770 kg/cm² (Approx. CBR 17)

Chart 8

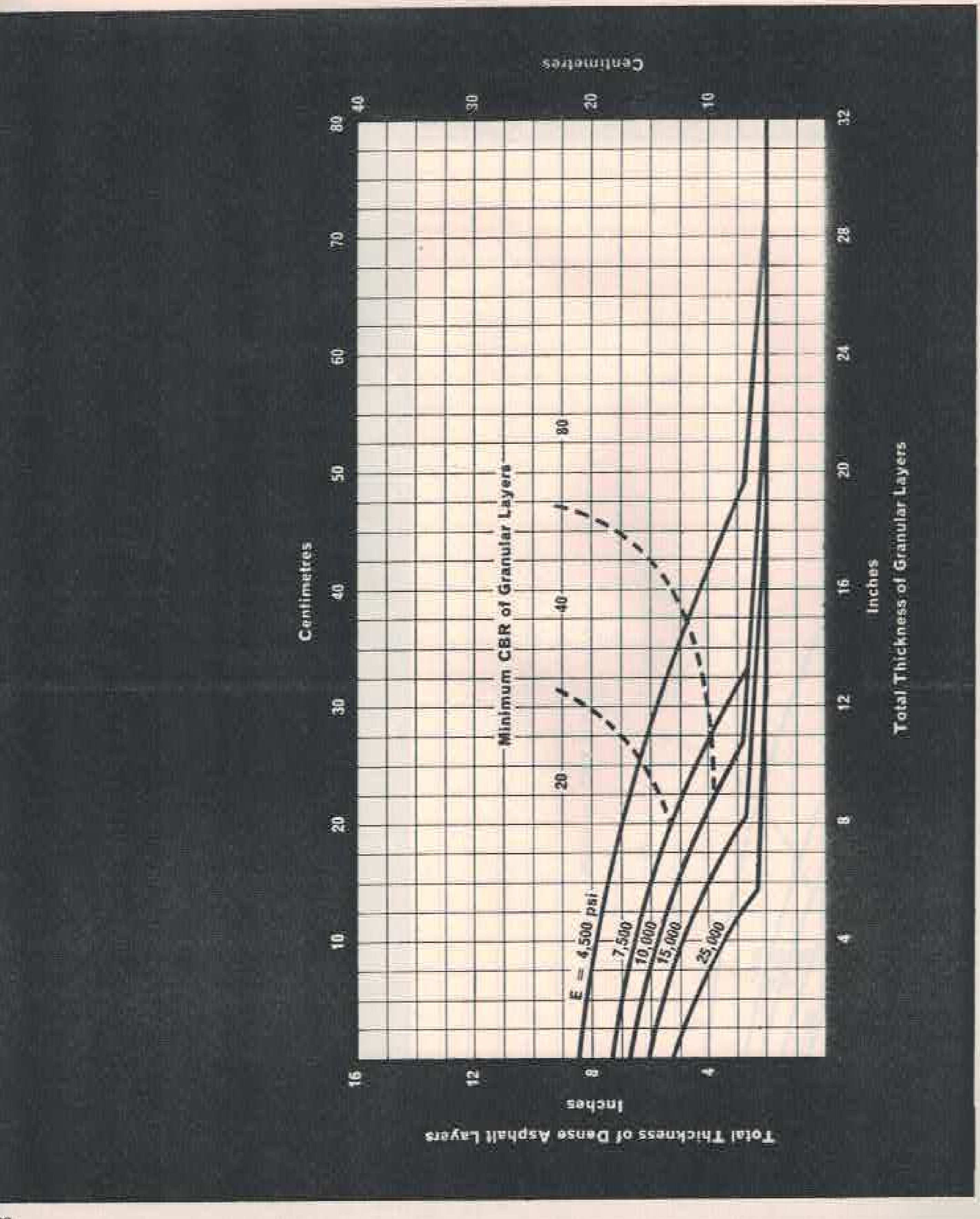



Total Thickness of Granular Layers
Inches
4
8
12
16
20
24
28
32
Centimetres
10
20
30
40
50
60
70
80
Total Thickness of Dense Asphalt Layers
Inches
4
8
12
16
Centimetres
10
20
30
40
E = 4,500 psi
7,500
10,000
15,000
25,000
Minimum CBR of Granular Layers
20
40
80


Centimetres
10
20
30
40
50
60
70
80
Inches
4
8
12
16
20
24
28
32
Total Thickness of Granular Layers
Total Thickness of Dense Asphalt Layers
Inches
4
8
12
16
Centimetres
10
20
30
40
Minimum CBR of Granular Layers
20
40
80
E = 4,500 psi
7,500
10,000
15,000
25,000

DESIGN NUMBER $N=10^5$

Chart 11



DESIGN NUMBER $N = 10^4$

Chart 12