Technical Report Documentation Page

1. REPORT No.

2. GOVERNMENT ACCESSION No.

3. RECIPIENT'S CATALOG No.

4. TITLE AND SUBTITLE

Recommended Structural Design Procedure for Estimating Required Thickness of Pavements and Bases

5. REPORT DATE

July 1951

6. PERFORMING ORGANIZATION

7. AUTHOR(S)

8. PERFORMING ORGANIZATION REPORT No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

State of California
Department of Public Works
Division of Highways
Materials and Research Department

10. WORK UNIT No.

11. CONTRACT OR GRANT No.

13. TYPE OF REPORT & PERIOD COVERED

12. SPONSORING AGENCY NAME AND ADDRESS

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

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In general, the concepts, test methods and formulas are an extension and logical development of those set forth in the article, "The Factors Underlying the Rational Design of Pavements," by F.N. Hveem and R.M. Carmany. However, additional experience indicates that certain modifications are in order and the detailed steps outlined herein represent the result of additional work and development over the past three years.

The primary departure from past practice is the substitution of the Stabilometer Test for the California Bearing Ratio, and the resistance value R derived from the Stabilometer Test should be used to indicate the relative quality of basement soils and all granular bases and subbases.

The methods and relative values used for estimating the equivalent wheel loads are revised as it has become evident that greater emphasis should be placed upon the destructive effect of the heaviest axle loads, and on the other hand, there are many cases where the EWL values should be reduced on frontage highways and other roads where heavy trucking is not expected.

The design procedure will evaluate (1) the supporting capacity of the basement soil in terms of Resistance Value, (2) the magnitude and number of individual wheel loads to be carried by the road, and (3) the slab strength of the paving and/or base material proposed for use.

17. KEYWORDS

18. No. OF PAGES:
28

19. DRI WEBSITE LINK
http://www.dot.ca.gov/hq/research/researchreports/1930-1955/51-01.pdf

20. FILE NAME
51-01.pdf

This procedure adopted by the California Division of Highways except portion relating to calculation of EWL.

July 30, 1951

STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS

MATERIALS AND RESEARCH DEPARTMENT

Recommended Structural Design Procedure for Estimating Required Thickness of Pavements and Bases

There is herewith submitted for general information and guidance a revised design procedure for estimating the required thickness and strength of pavements and bases.

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heaviest axle loads, and on the other hand, there are many cases where the EWL values should be reduced on frontage highways and other roads where heavy trucking is not expected.

The design procedure will evaluate (1) the supporting capacity of the basement soil in terms of the Resistance Value, (2) the magnitude and number of individual wheel loads to be carried by the road, and (3) the slab strength of the paving and/or base material proposed for use.

In applying this design procedure, the first step is to determine the Resistance Value of the soil. This "R" Value will be based upon Stabilometer and Expansion Pressure tests. (Early attempts to derive a comparable value from C.B.R. test data have not proven to be consistently reliable.) The "R" value of the soil will be indicated on Laboratory test reports.

The next step is to estimate the traffic to be sustained by the road, and as in the past, this traffic estimate will be expressed in terms of the total number of Equivalent 5000 lb. Wheel Loads anticipated for the ten year period immediately following construction. There is attached herewith a detailed outline of the procedure for estimating equivalent wheel loads, and the value derived from this procedure should be termed the EWL_{50} in order to distinguish the new values from those calculated by the older formulas. It will be noted that the values of EWL_{50} will in general be higher than those obtained from previous calculations, although this will not be true unless a substantial number of heavy axle loads are involved. It is proposed to discontinue the formal use of such designations as "light", "medium" or "heavy" industrial routes as these fixed classifications often result in an arbitrary selection of pavement types in lieu of careful consideration of all factors and the application of engineering principles. In lieu thereof, it is desired that in the future the weight of traffic to be carried on a given road be designated and referred to in terms of the Traffic Index. The Traffic Index is represented by simple numbers which will range between values of 2 and 10 for highway purposes and are the logarithm of the EWL_{50}. (It is, of course, necessary to convert the traffic data into an equivalent wheel load as a necessary step in assigning a Traffic Index value.) Both EWL's and Traffic Indexes are shown on the accompanying revised Design Chart. (Fig. II). The Traffic Index number will be more significant and more convenient to use, as the required thickness of any type of pavement over a given soil will vary directly in proportion to this number.

A District Map may be prepared on which the Traffic Index value for each route can be indicated and this index number will serve to indicate the structural design standard for each road and should be used in connection with the Design Chart to determine the thickness of the pavement and base combination required. Where ever the figures are available, the data from loadometer stations may be used as a basis for computing the EWL in assigning the Traffic Index number. However, on many routes such data are not available and the traffic index may be assigned on a more or less arbitrary basis according to available information concerning the general traffic conditions. These assigned Traffic Index values will be subject to modification and reconsideration whenever it appears desirable. A duplicate map may be retained in Headquarters Design Department for ready comparison.

Additional Points for Guidance

The final values derived from the revised design chart are subject to the following general restrictions or limitations as a matter of practical consideration and for reasons other than basic structural design.

A. The most economical, efficient and suitable type and thickness of pavement shall be selected by means of a design chart, Fig. II, with consideration being given to the effects of grades, speed of traffic, necessity for stopping and starting, etc. The type of pavement recommended should be based upon overall economic considerations and such other factors as may have a bearing on the individual case.

B. The thickness of all types of pavement, excluding Portland cement concrete, may be computed from the design chart, Fig. II, with due allowance for tensile strength or slab strength of the pavement and/or base. See typical values on instruction sheet accompanying chart, Fig. II

C. Portland cement concrete pavement may be proposed in thicknesses varying from 6 to 8", depending upon the weight of traffic to be carried. In general, a standard 8" depth of PCC pavement should be used for a traffic index value of 7.5 or greater; 7" for a traffic index of 7; and 6" with a traffic index of 6.5 or less. In any event, no PCC pavement should be considered less than 6" in depth. All concrete pavement shall be placed on a hardened or treated subgrade designed to resist displacement or erosion due to pumping action of the slabs.

D. Plant-mix bituminous surfacing will ordinarily range in thickness from 1-1/2" to 4" depending on weight of traffic, however, not less than 3" should ordinarily be proposed over cement treated bases as a safeguard against slippage.

E. Cement treated bases or lean concrete bases covered with a bituminous surface will not be considered in thicknesses less than 5" and a 6" minimum will generally be preferable. Cement treated bases more than 7" in thickness should be constructed in two or more layers, each of which should not be less than 4 nor more than 7" in thickness.

F. Crusher run bases should ordinarily not be proposed in layers less than 6" for average conditions although 4" layers will be approved where the underlying native material or sub-base is of unusually good quality and where only light traffic is anticipated.

G. When estimating the thickness of surfacing and base for borders adjacent to a pavement, assume that the EWL_{50} will be equal to 1% of the EWL calculated for the adjacent pavement lane, but not to exceed one million EWL for the average case.

July 30, 1951

PROCEDURE FOR ESTIMATING EQUIVALENT WHEEL LOADS BASED ON LOADOMETER DATA OR TRAFFIC CENSUS

As shown later in the design formula for calculating the thickness of pavements, the destructive effect of traffic is one of the three primary factors having an influence on structural design. Data from test tracks show that this traffic factor is a function of (1) the total wheel load, (2) the average unit pressure with which this load is applied and (3) the number of repetitions of this load. The combined influence of these factors on pavement structural design appears to be reasonably well expressed by the formula

$$T = m_1 \, p \sqrt{L} \, \log r \qquad (1)$$

Where T = Thickness of pavement and base

m_1 = A factor which includes all necessary conversion units and the other two primary factors namely strength of pavement, and ability of soil to support loads (these two variable factors are assumed to be fixed for purposes of comparing the effects of traffic)

p = Unit pressure of tire on pavement

L = Total load on wheel

r = Number of Axle load repetitions

In estimating the thickness of pavements required for highways, the number and weight of heavy trucks are the only elements of traffic that have any serious or important influence. As the tire pressures for these vehicles are rather consistently maintained to approximately the same tire pressure therefore, the unit pressure "p" may also be included in the factor "m" and we may then write the above relationship

$$T = m_2 \sqrt{L} \quad (\log r) \tag{2}$$

Where m_2 includes the pressure on the pavement.

The miscellaneous traffic over any highway consists of a wide variety of individual vehicles representing a range of sizes and weights. Probably no two trucks have exactly the same axle load pattern. Therefore, in order to evaluate this traffic, the Planning Survey Department has found it necessary to weigh the individual wheels of a certain number of trucks as a sample and from this sample to compute the relative percentages of axles falling in each load group. See Table 2.

The traffic recorded by the Planning Survey Department at any given time or estimated for the future is expressed as the axle load in pounds and, for convenience, is separated into groups, each covering a range of 1000 lbs.; for example, 4000 to 4999, 5000 to 5999 etc.

In order to convert the axle load data into a factor that can be used in the pavement design formula, it is necessary to convert the number of axles in each load group into some common denominator. A conversion of this sort has been made in the past expressed in terms of an equivalent number of 5000 lb. wheel loads.* Such a conversion is valid provided the proper factors are used. A large number of repetitions of a moderate load will equal the destructive effect of a much smaller number of heavy load repetitions.

In other words, a certain number of repetitions of a given wheel load will be the "destructive" equivalent of a different number of 5000 lb. wheel loads and available data indicates that within limits the relationships may be indicated by the expression

$$\sqrt{L_x} \log r_x = \frac{T}{m_2} = \sqrt{L_{5000}} \log r_{5000} \qquad (3)$$

Where L_x = Number of loads i.e. repetitions estimated to occur in a group L_x for the design life of the pavement

T = Thickness of pavement (including bases)

L_{5000} = wheel load of 5000 lbs.

r_{5000} = equivalent number of 5000 lb. loads

* "Designing Foundation Courses for Highway Pavements and Surfaces" by Fred J. Grumm, California Highways and Public Works, November 1941, p. 4.
Circular letter by A. M. Nash dated May 12, 1947

Therefore, to convert a given number of repetitions of a certain wheel load to an equivalent number of repetitions of a "standard" 5000 lb. wheel load, the above formula is rearranged into the following form for convenience.

$$\log r_{5000} = \frac{\sqrt{L} \times \log r_x}{\sqrt{5000}}$$

Chart I is drawn from this formula and any conversion of miscellaneous traffic data to equivalent 5000 lb. wheel loads is made by locating the intersection of the curve representing the particular wheel load with the vertical line representing the repetitions of this load, then proceeding horizontally to the curve representing the 5000 lb. wheel load. The vertical line at this point will indicate the equivalent number of repetitions of the 5000 lb. wheel load.

At the present time, in order to evaluate the traffic for any highway, it is necessary to have both the truck axle census and a loadometer survey of the road. From the census, it is possible to calculate and estimate the probable total number of heavy truck axles that will traverse a given highway during its life and from the loadometer survey it is possible to calculate the probable number or percentage of these axles falling within each of the various weight groups. The number of axles falling within each weight group is then converted into an equivalent number of 5000 lb. wheel loads and the sum of all these equivalent 5000 lb. wheel loads is the EWL_{50}*. The logarithm of the EWL_{50} is termed the Traffic Index and the thickness of pavement required varies directly in proportion to the Traffic Index values.

*EWL_{50} means the EWL calculated according to these instructions i.e. the 1950 method hence EWL50 to distinguish from previous EWL calculations

By way of illustration, following are data from the traffic census and loadometer survey and an example of the EWL_{50} calculation for Road I-Hum-1-E

TABLE I

TRAFFIC CENSUS DATA
I-Hum-1-E

		Average No. Daily	Percentage of Total Vehicles
No. Lanes	2		
Length in miles	.0771		
Total Vehicles (includes all trucks)		3759	100.0
Total Trucks (includes pick-ups)		447	11.9
Pick-ups[a]		195	5.2
2-Axle		180	4.8
3-Axle		23	.6
4-Axle		15	.4
5-Axle		19	.5
6 or more		15	.4

(a) (Not used in calculation of EWL)

FREQUENCY DISTRIBUTION OF COMMERICAL AXLE LOADS
Loadometer Data
District I

Weighing Station No. 75 Location Scotia, S

Table 2

Axle Load in Pounds	Axle Loads Per 100 Commercial Vehicles					
	Hum-1-E Northbound		Hum-1-E Southbound		Hum-1-E N & S	
	Number of Axles	Percentage	Number of Axles	Percentage	Number of Axles	Percentage
Under 8000	129.41	36.8	128.33	45.3	128.97	39.6
8000 - 9999	34.12	9.7	60.00	21.2	44.83	13.9
10000 - 11999	31.76	9.0	76.67	27.1	50.34	15.6
12000 - 13999	34.12	9.7	10.00	3.5	24.14	7.5
14000 - 15999	50.59	14.4	6.67	2.3	32.41	10.1
16000 - 17999	35.29	10.0	1.66	.6	21.38	6.6
18000 - 19999	22.35	6.4	--	--	13.10	4.1
20000 - 21999	7.06	2.0	--	--	4.14	1.3
22000 - 23999	1.18	.3	--	--	.69	.2
Over 24000	5.88	1.7	--	--	3.45	1.1
Total	351.76	100	283.33	100.0	323.45	100.0
Actual Number of Vehicles Weighed as a sample	85		60		145	

SAMPLE CALCULATION SHEET
Proposed Method
I-Hum-1-E (Northbound)*

	Axles per Truck		No. Trucks From Table 1	
Number of axles per day in each category =	2	x	180	360
	3	x	23	69
	4	x	15	60
	5	x	19	95
	6	x	15	90

Total Average Daily Axles - 2 Directions = 674

Total Average Yearly Axles = 674x365 = 246,000

Assuming a uniform increase reaching 50% at the end of 10 years, the estimated number of axles per 10 year period = $246{,}000 \; \frac{(1.0+1.5)}{2} \; 10 = 3{,}075{,}000$

For one direction - $\frac{3{,}075{,}000}{2}$ = 1,540,000
(Assuming equal traffic in both directions)

Wheel Load Group From Column 1 Table 2	% Axles Loads Per Load Group Table 2		Average Total Number of Axles Per 10 Years		Estimated Repetitions in 10 Years	Equivalent Repetitions of 5000# Wheel Load (From Formula (4) or Chart I)
3500	36.8	x	1,540,000	=	567,000	70,000
4500	9.7	x	"	=	149,000	80,000
5500	9.0	x	"	=	139,000	250,000
6500	9.7	x	"	=	149,000	790,000
7500	14.4	x	"	=	222,000	3,520,000
8500	10.0	x	"	=	154,000	5,820,000
9500	6.4	x	"	=	98,500	7,620,000
10500	2.0	x	"	=	30,800	3,230,000
11500	.3	x	"	=	4,600	360,000
12500	1.7	x	"	=	26,200	9,660,000
						31,400,000 = EWL_{50}

31.4 Million E.W.L. (One Way) = 7.5 Traffic Index

*This lane carries the heaviest traffic

The foregoing example represents a nominal two lane highway. It will be obvious that on multiple lane roadways the amount of traffic which will be carried on any one lane will be somewhat less than the total amount of traffic proceeding in one direction. The relative proportion will vary depending upon the amount of traffic on the road. For example, on a four lane divided highway, the outer lane may carry 85 percent of the traffic when the total volume is small. As the amount of traffic increases, the relative percentage will decrease until at peak capacity each lane will carry only 50 percent of the traffic. Therefore, when estimating the traffic to be carried on roads having four or more lanes, the estimate of EWL should be computed upon 75 percent of the anticipated amount of traffic. (Based upon the census and projected into the future).

It is also intended that the estimate of future traffic should be predicated upon the direction now showing the heaviest traffic. In many cases there is a considerable disparity in the weight of loads being carried in different directions on the highway. It is the intent that the design shall be based on the heaviest traffic that is being carried in one direction and not upon the average as in the past.

It will be noted in the example shown that the EWL_{50} value is approximately three times the EWL value obtained by the method described in the November 1941 issue of California Highways and Public Works and is approximately fifteen times that obtained by the simplified method based upon averages described in the circular letter of May 12, 1947. However, the new thickness design charts have been adjusted accordingly and the EWL_{50} value and corresponding traffic index number obtained by the method here shown should be used only in the revised design chart and without further modification. In order to avoid confusion, however, all wheel load estimates derived by the methods and charts described herein should be identified as EWL_{50} and preferably referred to in terms of the traffic index indicating that the 1950 procedure has been followed.

STATE OF CALIFORNIA

DIVISION OF HIGHWAYS

MATERIALS & RESEARCH DEPARTMENT

Procedure

From the intersection of the curve representing the particular wheel load with the vertical line representing the repetitions of this load, proceed horizontally to the curve representing the 5000 lb. wheel load. The vertical line at this point will indicate the equivalent number of repetitions of the 5000 lb. wheel load.

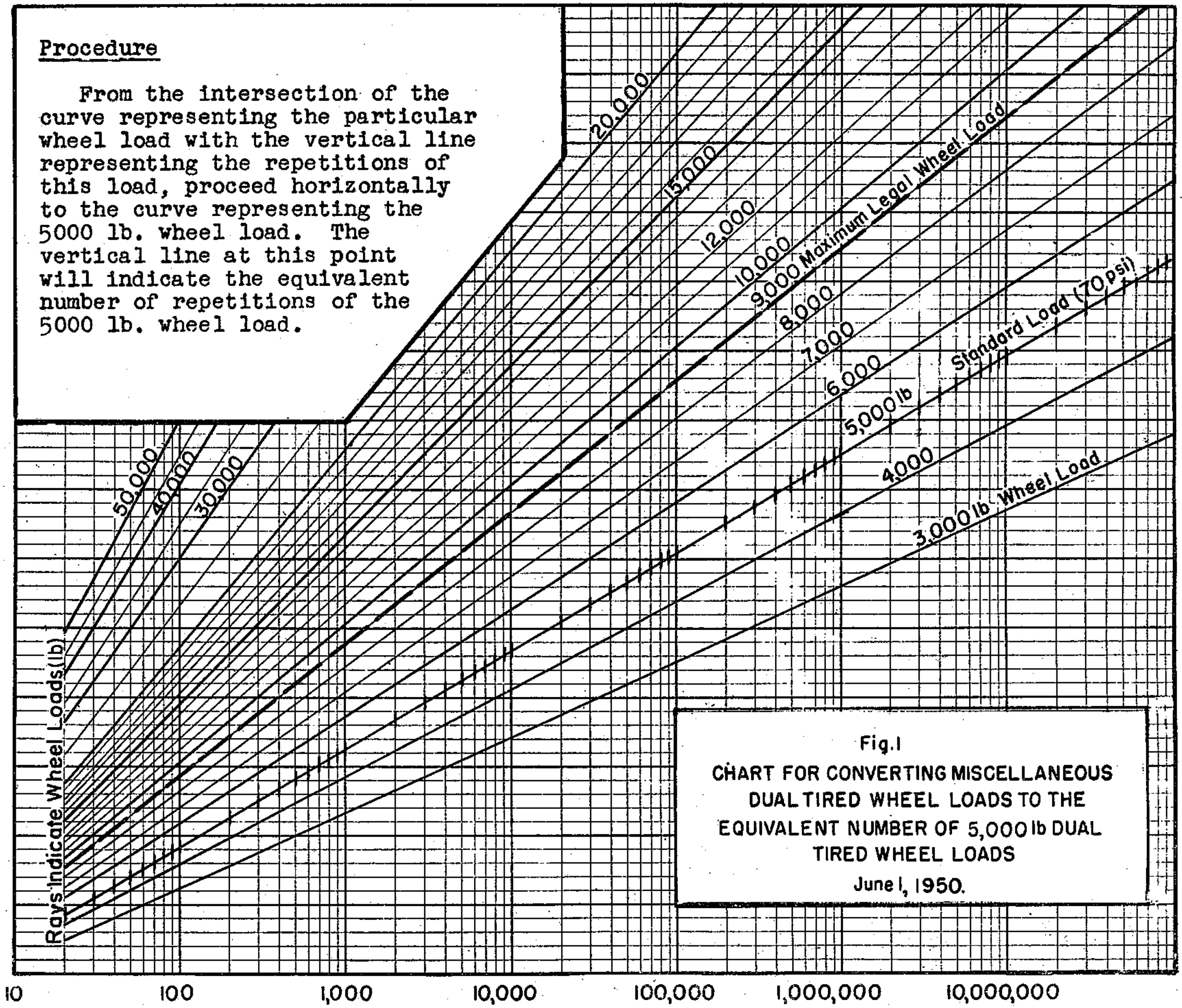


Fig. I

CHART FOR CONVERTING MISCELLANEOUS DUAL TIRED WHEEL LOADS TO THE EQUIVALENT NUMBER OF 5,000 lb DUAL TIRED WHEEL LOADS

June 1, 1950.

July 30, 1951

EXPLANATION AND INSTRUCTIONS FOR
USE OF PAVEMENT THICKNESS DESIGN CHART

The suitability of existing basement soils or materials proposed for subbases, bases and bituminous paving mixtures will be determined by Stabilometer tests. The Stabilometer test subjects the sample to a form of Triaxial Shear and has been a standard method in the Division of Highways for measuring "stability" of bituminous mixtures during the past eighteen years.

As stated in the previous instructions, all soils and granular base materials will be evaluated in a numerical scale ranging from 0 to 100; known as the Resistance Value, (designated by the letter "R") which primarily reflects the degree of friction between particles in the compacted soil material when the voids are filled with water. Test specimens are formed by compacting the samples in a special compactor which subjects the samples to a sort of kneading action, producing densities and structural arrangements closely simulating the condition of materials placed on the road by construction equipment.

The new design procedure is based upon the following relationship between the several factors that affect the structural performance of a pavement:

The type formula is as follows:

$$T = \frac{K\,D\,(90 - R)}{S} \qquad \text{(a)}$$

Where T = Combined thickness of Base and Surface

K = A Constant

D = The destructive effect of traffic represented by a calculated factor termed "Equivalent Wheel Load" derived by converting the actual number of axle loads of each magnitude to an equivalent number of 5000 lb. wheel loads having the same destructive effect

R = The Resistance Value of the soil while in a state of density and degree of saturation typical of the most adverse conditions to be expected on the road during the service life

S = A factor representing the tensile strength or slab strength of the pavement and base combination that is proposed for use

Each of the above components must be broken down or subdivided into measurable units. Therefore, the formula based on observed performance of test tracks and existing highways becomes:

$$T = \frac{K\,(P\sqrt{a}\ \log r)\,(P_h/P_v - 0.10)}{\sqrt[5]{c}} \quad \text{(b)}$$ [1]

Where T = Thickness of Cover (Base and Pavement) in inches

Where K = 0.0175 for best correlation but without any factor of safety

P_h = transmitted horizontal pressure in the Stabilometer test (psi)

P_v = applied vertical pressure in the Stabilometer test (typically 160 psi)

P = effective tire pressure (psi)

a = effective tire area (sq. in.)

r = number of load repetitions

c = tensile strength of the cover material as measured by the cohesiometer (approximately = modulus of rupture x 45.4)

In order to simplify the calculations and to permit utilization of available data, charts have been prepared for use in estimating the required thickness of any type or combination of pavement and base over any given soil to withstand various amounts of traffic.

(1) "The Factors Underlying the Rational Design of Pavements", by F. N. Hveem and R. M. Carmany, - Proceedings of the Highway Research Board, Vol. 28, p 101

The Design Chart, Fig. II, is prepared from the following simplified expression.

$$T = \frac{K' (\log EWL_{50}) (90-R)}{\sqrt[5]{c}} \qquad (c)$$

This expression is derived from equation (b) and contains a new constant K' = 0.095. The value assigned to K' is based upon an assumed tire pressure of 70 psi and includes the constant of the expression $\sqrt{a} = K''\sqrt{L}$ where L = the total load on a wheel

Then in the above equation (c)

$\log EWL_{50}$ = equivalent 5000# wheel repetitions* of traffic = $\sqrt{\frac{L}{5000}} \log r$

R = The resistance value of soil subbase or base as measured by the Stabilometer

c = Cohesion Value represents slab strength of cover material

T = Thickness of all layers above material represented by R

*This expression developed on p. 4 of the "Procedure for Estimating Equivalent Wheel Loads based on Loadometer Data or Traffic Census".

Cover material includes subbase, base and surface courses when the basement soil is being considered. "Cover" would include only base and surface when the subbase material is being tested. Similarly, when the base is being evaluated, "cover" would mean the bituminous surface or pavement alone. If the cover consists of a single layer, the appropriate Cohesiometer value may be selected from the following table.

Typical Cohesiometer Values, Representing Common Types of Pavement and Base Construction

	Cohesiometer Values
P.C.C. Pavement 5.0 Sacks (Class B)	15,000
P.C.C. Pavement 4.2 Sacks (Class C)	7,000
Cement Treated Base Class A	3,000
Cement Treated Base Class B	1,500
Plant Mix with Paving Grades of Asphalt or AC Surface Course 85 to 300 Penetration	400
Plant Mix with liquid asphalt SC-6	300
Plant Mix with liquid asphalt	200
Open Graded Mixes and RMS	150
Bituminous Surface Treatment, C.T. Bases Class C and Untreated bases or subbases	100

Correction for multiple layer construction involving materials of different slab strength

If the cover consists of a two-layer construction, the mean cohesiometer value may be determined from the formula

$$c_m = c_1 + \left(\frac{t_2}{t_1+t_2}\right)^2 (c_2-c_1)$$

t_1 = Thickness of layer A

t_2 = Thickness of layer B

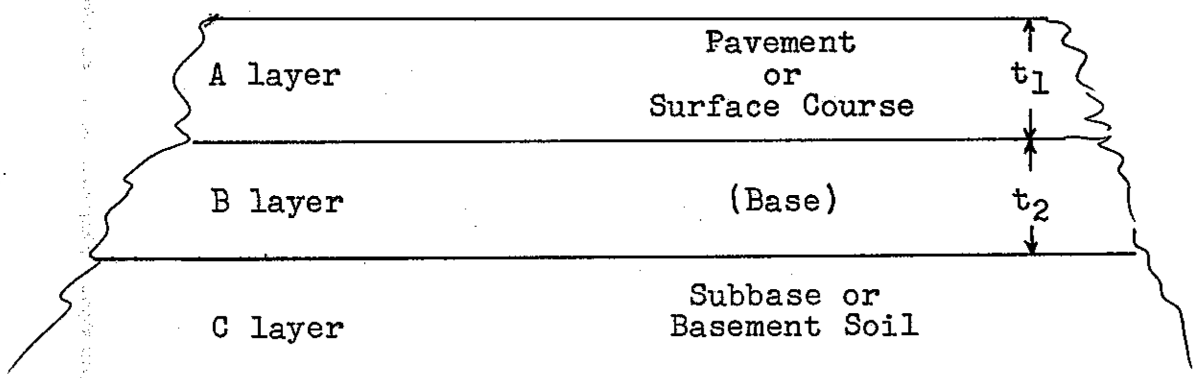
c_1 = Cohesiometer Value for layer A

c_2 = Cohesiometer Value for layer B

c_m = Equivalent Cohesiometer value of the layer combinations - <u>Value to use in structural design</u>

If the cover is a three-layer system, the cohesiometer value for the top two should first be determined from the above formula and the procedure repeated, treating the top two courses as a single layer.

Sketch Showing Relative Position of Elements Used in Calculating Combined Tensile Strength of Pavement and Base Combinations



A = Upper layer or course of pavement or bituminous surfacing

B = Second layer or base course of different tensile strength than surface course

C = Subbase or basement soil

Correction for Cover Materials having abnormal Unit Weight

In reporting stabilometer and expansion pressure tests of untreated materials and Class C cement treated bases, unless information is furnished to the contrary, test results are based upon the premise that cover material (bases and surfacing) to be placed over the tested soil will have an average unit weight of 130 lbs. per cu. ft.

In the event that light weight material such as tuff, pumice, diatomaceous earth etc. are used in one or all layers, corrections must be made which will increase not only the "indicated minimum thickness of cover" but may reduce the reported "R" value.

For purposes of preliminary estimating when light weight cover materials are being considered as an alternate, a table of factors is given below which may be used to predict approximately the total thickness necessary to compensate for marked variations in unit weight of surcharge.

Correction Factors for Weight of Cover Materials

Average Unit Weight of Cover Material (Lbs. per cu. ft.)	Multiply "thickness based upon 130 lbs. per cu. ft. Material" by factor below
150	0.9
140	1.0
130	1.0
120	1.0
110	1.1
100	1.2
90	1.3
80	1.4
70	1.5

The result obtained by multiplying the thickness of cover recommended in the test report (based upon 130 lbs. per cu. ft.) by the appropriate factor taken from the table will give a thickness approximating the maximum that would be obtained by the more lengthy and more exact method furnished to the District Materials Engineers.

The new design charts furnished herewith, revised June 1, 1950, are to supersede all design charts previously issued. These charts have been revised and adjusted downward to remove any theoretical "factor of safety". Any safety factors which will exist in the final calculated thickness are contained in the estimates for the weight and volume of traffic or in the assumption that the underlying soils will have access to water and will ultimately reach the completely saturated condition upon which the "R" value is based. Therefore, if the supporting soils or bases become saturated and if the estimated traffic develops, design based on these charts should be adequate but not extravagant.

It follows of course that much lighter designs may "stand up" and give good service as long as the supporting soils do not become saturated with water.

STATE OF CALIFORNIA DIVISION OF HIGHWAYS
MATERIALS & RESEARCH DEPT.

Fig. II

THICKNESS DESIGN CHART
FOR BASE AND/OR PAVEMENT

Revised June 1, 1950.

PROCEDURE

With a straightedge intersect Scale E at the value for R (as determined by the Stabilometer on specimens with H/D = 0.6) and Scale F at the traffic index for the total traffic load for the design life of the highway. The intersection of this line with Scale G is the thickness of gravel required to support the load (neglecting abrasion, etc). From this point intersect Scale H at the cohesiometer value of the surface. This line will intersect Scale I at the thickness of base and surface required to resist plastic flow of the basement soil.

If the cover consists of a two layer construction the mean cohesiometer value may be determined from the formula:

$$C_m = C_1 + \left(\frac{t_2}{t_1 + t_2}\right)^2 (C_2 - C_1)$$

t_1 = Thickness of top layer
t_2 = Thickness of bottom layer
C_1 = Cohesiometer value for top layer
C_2 = Cohesiometer value for bottom layer
C_m = Equivalent Cohesiometer value of the layer combinations. Value to use in structural design.

If the cover is a three layer system the cohesiometer value for the top two should first be determined from the above formula and the procedure repeated treating the top two courses as a single layer.