ZERO-MAINTENANCE DESIGN FOR PLAIN JOINTED CONCRETE PAVEMENTS

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INTRODUCTION

Design procedures for heavily trafficked jointed concrete pavements have been developed to provide "zero-maintenance" performance over a specified design period. The term "zero-maintenance" refers only to structural maintenance, which includes such activities as crack repair, joint repair, slab replacement, slab grinding, patching, and overlay. The purpose of this paper is to present some major aspects of the development of these procedures and some of the results obtained. Complete details of the development are given in References 1-3.

Many highways in urban and suburban areas are being subjected to heavy traffic volumes and weights which cause rapid deterioration and premature failure. Hence, considerable maintenance is required, but scheduling of remedial and preventive maintenance is almost impossible without closing lanes and producing massive traffic jams, accidents, and delays to the public. Hence, there is a great need for pavements that can withstand heavy traffic volumes and weights and provide long term maintenance-free performance.

The research approach used to develop zero-maintenance design procedures is as follows:

1. Field survey: An extensive field survey was conducted on 70 pavements in 17 highway agencies (states, cities, tollways, etc.). Extensive data were collected and interviews conducted with practicing highway engineers (Ref. 1).
2. Analytical studies: Analyses were conducted using the data and information obtained from the field studies, previous research results, and mechanistic pavement analysis models. Adequacy of existing design procedures, types and causes of distress, maintenance performed, limiting design criteria, and maximum maintenance-free lives of various types of pavements were determined (Ref. 1). Plain jointed concrete pavements were selected for development of detailed zero-maintenance design procedures.
3. Design approach: Two different yet complimentary approaches were derived for structural design. A new serviceability/performance model was developed using 16 years of data from 25 plain jointed sections from the original AASHO Road Test that have been in service on I-80. The model was extended to other regions using data from 10 additional projects ranging in age from 9 to 25 years and heavily trafficked. A mechanistic fatigue analysis procedure was developed using a finite element model that permits consideration of traffic load and thermal curling of the slab. The models were verified using data collected from the field survey. A computer program, called JCP-1, was developed to assist in the design analysis. The design approach is illustrated in Figure 1. The procedure is comprehensive, yet practical, and a design manual has been developed for use by practicing pavement engineers (Ref. 2). This study is sponsored by the Federal Highway Administration.

STRUCTURAL DESIGN BASED ON SERVICEABILITY/PERFORMANCE

New Serviceability/Performance Equation

A new serviceability/performance equation was developed that relates the loss in serviceability index of the pavement to the number of equivalent 18-kip single axle loads (ESAL) and various pavement parameters, including: slab thickness, modulus of rupture and modulus of elasticity of concrete, modulus of foundation support (k), and a climatic regional factor (Ref. 3). The equation was obtained through extensive regression analyses using 25 original sections from the AASHO Road Test that from 1962 to 1974 were under regular

traffic as part of I-80 in Illinois.

Measurements of cracking, patching, spalling, faulting, and rougnness were taken periodically from 1962 to 1974 by the Illinois Department of Transportation and serviceability indices computed. The slab thicknesses included 8, 9-1/2, 11, and 12-1/2 inches over granular subbases from 3 to 9 inches in thickness. Slabs had 15 foot joint spacings and all had dowel bars. Therefore, these 25 sections provided extensive long term performance data (1958 - 1974 = 16 years). Data were obtained from 10 additional projects located in other states ranging in age from 9 to 25 years to help verify the models and determine climatic adjustment factors.

A stepwise multiple regression technique was used to develop the basic equation:

$$W'_{18} = [\rho \ln(\frac{3}{y} - 1) + \beta]10^6 \qquad (1)$$

where

W'_{18} = Total equivalent 18-kip single axle loads to reduce the serviceability index from p_i to p_t

$\beta = -50.08826 - 3.77485H + 30.64386 \sqrt{H}$

$\rho = -6.69703 + 0.13879H^2$

$y = p_t + \frac{3.0}{(e)^{-\beta/\rho} + 1} - p_i$

p_t = terminal serviceability index

p_i = initial serviceability index

H = PCC slab thickness, inches

This expression permits only an evaluation of the effect of the PCC slab thickness, terminal and initial serviceability index on equivalent 18-kip load applications. Therefore, the equation was extended so that other variables could be included, such as the k-value and PCC modulus of rupture. The model was extended using the Westergaard edge stress model similar to the way in which the Spangler corner equation was incorporated into the original AASHO Road Test model as described in the AASHTO Interim Guides (Ref. 5). The edge stress equation was used because fatigue analysis and field observations of distress show that the slab edge is the critical loading point. The following model was obtained which is used in the serviceability/performance design:

$$\log_{10}W_{18} = \log_{10}W'_{18} + (3.892 - 0.706\ p_t) \log\left[\frac{F28}{690} \times \frac{4 \log[\frac{8.789H^{0.75}}{M}] + 0.359}{4 \log[\frac{(Z)^{0.25}(0.540H^{0.75})}{M}] + 0.359}\right] \qquad (2)$$

in which:

$M = \sqrt{1.6a^2 + H^2} - 0.675H$

a = radius of applied edge load, inches

F28 = modulus of rupture used in design (28 day, 3rd point loading adjusted for variability) = $FF - C(\frac{Fcv}{100})FF$

FF = mean modulus of rupture at 28 days, 3rd point loading, psi

Fcv = coefficient of variation of modulus of rupture, percent

C = 1.03, a constant representing a confidence level of 85 percent

Z = E/k

E = modulus of elasticity of PCC, psi

k = modulus of foundation support on top of subbase, pci

The standard error of the estimate of $\log_{10}W_{18}$ is 0.22 based upon 150 data points which is similar to the error of the equation developed at the AASHO Road Test (Ref. 4).

Climatic Regional Factor

Pavement data were collected from 10 plain jointed concrete projects located in eight states. These projects ranged in age from 9 to 25 years and in total 18-kip ESAL in the heaviest traveled lane up to 33 million. Analyses were conducted to determine if the pavements from climatic regions different from Illinois showed differing performance. Four general climatic regions were chosen based upon precipitation and potential evapotranspiration, and frost heave and freeze thaw damage as defined in Table 1. A "climatic regional factor" is defined as follows:

$$RF = \frac{W_{18(computed)}}{W_{18(actual)}} \quad (3)$$

where

RF = climatic regional factor

W_{18} (computed) = total computed number of equivalent 18,000 pound single axle load applications to reduce serviceability index from an initial value to a terminal value determined from performance Equation 2.

W_{18} (actual) = total accumulated number of equivalent 18,000 pound single axle load applications to pass over pavement, determined from traffic data.

If RF equals 1.0, then there is no significant climatic effect for a given pavement. The RF could theoretically range from almost zero to more than 1.0. A computation of RF for each of the 10 sections plus the four slab thicknesses of AASHO was made according to Equation 3. The values for each of these projects is shown below. There is considerable scatter in each climatic region, but the results indicate that pavements perform significantly different in the four general climatic regions.

Region	RF Values	Mean RF	Design RF
Wet/Freeze	0.71, 0.82, 1.01, 1.02, 1.34	0.98	1.0
Dry/Freeze	0.56, 0.85, 1.24	0.88	0.9
Wet/Non-freeze	0.34, 1.30	0.82	0.9
Dry/Non-freeze	0.24, 0.43, 0.60	0.42	0.6

These data indicate, for example, that similar plain jointed concrete pavements constructed in dry/non-freeze climates would last about twice as long as those in wet/freeze climates.

Terminal Serviceability Index

The terminal serviceability index of 2.5 currently used in design procedures is for major rehabilitation. A serviceability index greater than 2.5 must be selected for zero-maintenance design which represents the point at which the project should receive routine maintenance which would end its zero-maintenance life. Analysis of results from the 35 sections indicates that pavements having serviceability indices of 3.5 or higher all showed maintenance-free performance, but projects having serviceabilities of less than 2.5 all received structural maintenance. Between 2.5 and 3.5, some did and some did not receive maintenance. A limiting value for zero-maintenance design of 3.0 was chosen based upon these data and recommendations received during the field visits.

Estimation of 18-kip Equivalent Loads

The total accumulated 18-kip ESAL in the design lane over the analysis period is computed using the following expression:

$$W_{18} = (ADT)(T/100)(DD/100)(LD/100)(TY)(365)(A)(\Sigma PE/100) \quad (4)$$

where

W_{18} = total accumulated 18-kip equivalent single axle loads from the time the pavement was opened to traffic to end of the analysis period.

TY = analysis period in years

ADT = average daily traffic (two directions) over period TY

T = percent trucks of ADT

DD = percent traffic in direction of design lane

LD = lane distribution factor, percent trucks in design lane in one direction

A = mean number of axles per truck

ΣPE = sum of the product of the percent of axles (both single and tandem in each load group) and the corresponding load equivalency factor (for terminal serviceability of 3.0)

Detailed guidelines on obtaining each of these parameters are given in Reference 2.

Design Chart

A graphical solution of Equation 2 was prepared and is shown in Figure 2. An example is given to illustrate the use of this chart in design. Assume the following parameters and solve for the required slab thickness:

Climatic region = wet/freeze

Total 18-kip ESAL = 20.0 million

k-value on top of subbase = 100 pci

Working stress of PCC = 600 psi

Required PCC Slab Thickness = 11 inches

If the pavement was located in a dry/non-freeze climatic region the required slab thickness is as follows:

Total 18-kip ESAL for design = 20.0 x 0.6 = 12.0 million

Required slab thickness = 9.5 inches

A sensitivity analysis of the serviceability/performance structural design procedure indicates that all of the design parameters have a significant effect. An example of the effect of each parameter is shown in Table 2 where the change in 18-kip ESAL to a serviceability index of 3.0 is determined due to a change in each of the four other parameters. A significant change in each parameter produces a significant change in the 18-kip ESAL applications. Since a typical lane loading for a heavily trafficked pavement is one million 18-kip ESAL/year, these could be considered as years of pavement life.

STRUCTURAL DESIGN BASED ON PCC FATIGUE

Fatigue Analysis

A fatigue analysis procedure was developed to provide a method of estimation of traffic damage that could result in cracking of the slabs. The basic fatigue design philosophy for zero-maintenance plain jointed pavements is that linear cracking must be prevented. This is possible through direct consideration of traffic loadings, slab curling, joint spacing, and foundation support. The PCC slab is subjected to many applications of heavy traffic loads. At the same time, it is also experiencing stresses due to climatic factors such as temperature and moisture gradients and shrinkage. Curling of the slab also results in "gaps" between the slab and the subbase which increase the stress under loads.

The major steps in the comprehensive fatigue analysis are as follows:

1. Determine axle applications in each single and tandem axle load group.
2. Select trial slab/subbase structure, transverse joint spacing, and other required factors.
3. Compute fatigue damage occurring at the slab edge for a given month, both day and night using the Miner's accumulative damage model (Ref. 6) and sum monthly over the entire design period.

$$DAMAGE = \sum_{k=1}^{k=p} \sum_{j=1}^{j=2} \sum_{i=1}^{i=m} \frac{n_{ijk}}{N_{ijk}} \quad (5)$$

where

DAMAGE = total accumulated fatigue damage over the design period occurring at the slab edge

n_{ijk} = number of applied axle load applications of i^{th} magnitude during the day or night (j) for the k^{th} month

N_{ijk} = number of allowable axle load applications of i^{th} magnitude over day or night for the k^{th} month determined from PCC fatigue curve

i = a counter for magnitude of axle load, both single and tandem axle

j = a counter for day and night (j = 1 day and j = 2 night)

k = a counter for months over the design period

m = total number of single and tandem axle load groups

p = total number of months in the design period

The fatigue damage is computed at the slab longitudinal edge because results from comprehensive fatigue analysis definitely showed this to be the critical point. Also, observed transverse cracking in actual pavements during the field survey and other research results confirm this result (Ref. 1, 5).

Applied Traffic, n_{ijk}

The n_{ijk} is computed using the traffic data for the month under consideration. It is computed using the following expression:

$$n_{ijk} = (ADTm)(T/100)(DD/100)(LD/100)(A)(30)(P/100)(C/100)(DN/100)(TF/100)(CON/100) \quad (6)$$

where

ADTm = average daily traffic at the end of the specific month under consideration

T, DD, LD, A = as defined for Equation 4

P = percent axles in i^{th} load group

C = percent of total axles in the lane that are within 6 inches of edge

DN = percent of trucks during day or night

TF = factor to either increase or decrease truck volume for the specific month

CON = 1 for single axles, 2 for tandem axles

Allowable Traffic, N_{ijk}

The N_{ijk} is computed from PCC fatigue considerations. First the total stress occurring at the edge of the slab for a given axle load is computed considering both traffic load and slab curling for the given month for either day or night conditions. The stress is computed for edge loading of both single and tandem axles using models developed from a finite element program that realistically considers both load stress and slab curling (Ref. 7). The models were derived using multiple stepwise regression techniques using a factorial of data obtained from the finite element program over a wide range of the design variables. The total stress at the bottom of the slab edge with the load located at the edge is computed as follows:

$$STRT = STRL + (R)STRC \quad (7)$$

where

STRT = total resultant stress in the longitudinal direction at the bottom of the

PCC slab edge when the wheel load is located at the slab edge (load is single axle or tandem axle)

STRL = stress at bottom of PCC slab edge when load is located at slab edge (no thermal curling stress)

STRC = stress at bottom of PCC slab edge caused by curling of slab due to thermal gradient (no traffic load)

R = adjustment factor for STRC so that it can be combined with STRL to give correct STRT

The regression equations determined for these stresses are as follows:

Load stress for single axle load:

$$STRL = [LOAD/(18.0H^2)][17.35783 + 0.7801E - 0.05388H^3/k + 7.41722 \log_{10}(H^3/k)] \quad (8)$$

Load stress for tandem axle load:

$$STRL = [LOAD/(36.0H^2)][14.09599 + 0.10522E - 0.09886H^3/k + 6.2339 \log_{10}(H^3/k) + 1.95266 (\log_{10}(H^3/k))^2 - 0.71963 \log_{10}(E + 1.0)] \quad (9)$$

Curl stress:

$$STRC = [(G)(ET)/(5 \times 10^{-6})][0.06712k + 79.07391 \log_{10}k + 11.72690L - 0.00720kL - 3.22139L \log_{10}k - 0.06883LE - 0.59539E \log_{10}k - 204.39477H/k - 38.08854L/H - 8.36842H \log_{10}k + 0.07151EH + 0.95691LE \log_{10}k + 0.20845LH \log_{10}k + 0.00058LHk - 0.00201LEH \log_{10}k] \quad (10)$$

R adjustment factor

$$R = 0.48039 + 0.01401H - 0.00427E - 0.27278G - 0.00403L + 0.19508 \log_{10}k + 0.45187G \log_{10}H - 0.00532G^2 + 0.01246GL - 0.00622GL \log_{10}k + 8.7872 \log_{10}(H^3/k)/H^2 + 0.00104GE - 0.11846G \log_{10}(H^3/k) + 0.07001 \log_{10}(E + 1.0) - 0.01331G \quad (11)$$

where LOAD = total load on single or tandem axle, pounds

H = PCC slab thickness, inches

G = thermal gradient through slab, °F/in.

k = modulus of foundation support (top of subbase, pci)

L = slab length, ft.

E = erodability along slab edge, inches

ET = thermal coefficient of contraction of PCC/°F

Standard estimate of error based on 426 data points:

Single axle of STRL = 7.65 psi

Tandem axle of STRL = 4.59 psi

Curling stress STRC = 15.36 psi

Total stress STRT = 18.97 psi

The load stress equations were verified using results from the AASHO Road Test (Ref. 4).

The flexural fatigue life of PCC varies as a function of the stress/strength ratio. PCC does not have a fatigue limit, i.e., there is no limiting repeated stress below which the life will be infinite (Ref. 8). Data from several PCC fatigue studies were used to develop a relationship between the number of applications to flexural failure of PCC and the stress/strength ratio (Ref. 3). The relationship used for design purposes is as follows:

$$\log_{10} N = 16.61 - 17.61 \left(\frac{STRT}{F}\right) \quad (12)$$

where

n = number of load applications to flexural failure of the PCC

STRT = total stress at bottom of PCC slab (Equation 7)

F = modulus of rupture of PCC (Equation 15)

This expression is not the mean fatigue curve, but provides for a confidence level in determining mean fatigue life of approximately one decade of load applications. The F in Equation 12 is determined monthly over the design period as shown below and given in Equation 15.

The 28-day mean modulus of rupture adjusted for concrete variability that is used in design, is obtained from the following expression (Ref. 25, 26):

$$F_{28} = FF - C * \frac{Fcv}{100} * FF \quad (13)$$

where

FF = mean modulus of rupture of the PCC at 28 days, 3rd point loading, psi

Fcv = coefficient of variation of modulus of rupture, %

C = 1.03, a constant representing a confidence level of 85%

A time-modulus of rupture relationship is used in this procedure to obtain the modulus of rupture of the Portland cement concrete at any time so that a time-dependent fatigue analysis can be conducted. Fatigue damage is computed on a monthly basis over the design analysis period.

The ratio F_A between the modulus of rupture at any time within the zero-maintenance design period and F_{28} is given by the following equation:

$$F_A = 1.2676 + 0.227 \log T_2 - 0.04437 (\log T_2)^2 \quad (14)$$

where

T_2 = time since the pavement slab was constructed, years

Consequently, the modulus of rupture used to determine fatigue damage in Equation 12 at any time is given by the relationship:

$$F = F_A * F_{28} \quad (15)$$

The fatigue damage is computed monthly for both day and night conditions and traffic. The JCP-1 program prints out this damage monthly for each year specified by the designer and the final accumulated damage over the design analysis period. This data can then be used to evaluate and design the pavement for zero-maintenance as discussed in the next section.

SELECTION OF DESIGN PARAMETERS

Guidelines for selection of certain critical design inputs are provided. More detailed recommendations for all required inputs are given in Reference 2.

Axle Load Distribution

The axle load distribution for heavy loads is very critical in the fatigue analysis. A summary of typical heavy axle load distributions for heavily traveled freeways is given in Table 3. Spot enforcement weight tickets can be used to establish the maximum single

and tandem axle loads for use in design as illustrated in Column 2 of Table 3 for Chicago, Illinois.

Mean Truck Lateral Distance

The mean distance from slab edge to the outside of truck dual tires can be estimated from visual observations. Considerable evidence exists that with paved shoulders and no lateral obstructions, the mean distance varies from 12 to 21 inches from the slab edge. Results from BPR measurements in 1956 indicated 11 inches (Ref. 9) and studies by Emery in 1975 (Ref. 10) show 16-18 inches. The lateral distribution is approximately normally distributed with a standard deviation of 10 inches. This parameter is important in determining the number of "edge" loads for the PCC slab.

Modulus of Foundation Support (k-value)

The elastic k-value is used in this design procedure and can be obtained through direct measurement with repetitive static plate loading tests performed in accordance with AASHO designation T-221 using a 30 inch diameter plate. The direct measurement of k is expensive and time-consuming and therefore new procedures were developed to estimate the k-value as a function of soil classification type and degree of saturation.

1. k-value of subgrade: Procedures were developed using a realistic finite element characterization of a soil mass loaded with a rigid plate and using stress dependent soil properties. The soil structural response to repeated load was developed for the AASHTO classification types in a previous extensive study conducted at the University of Illinois (Ref. 11).

The k-value of the soil over a year's time may be estimated by first determining its AASHTO classification and its probable degree of saturation during the year of the top 1-5 feet of soil. The k-value can then be estimated using the graphs provided in Figures 3 and 4 for all AASHTO classifications, except A-1 and A-3. A-2 soils are divided into "gravelly" and "sandy" types. "Gravelly" soils contain 50 percent or more gravel (percentage retained on No. 10 sieve), and "sandy" soils contain 50 percent or more sand (percentage passing No. 10 sieve). The k-value determined for A-1 granular materials is 400 pci and for A-3 sand materials is 215 pci. In frost regions the subgrade soils will be frozen for one or more months each year. A k-value of 500 pci may be used during these months for all soil classifications.

2. k-value on top of subbase: The placement of a subbase will usually increase the k-value of the total foundation (i.e., subbase and subgrade). After the k-value of the subgrade is determined, the k-value on top of a given subbase can be estimated using Figure 5 for non-stabilized granular materials, Figure 6 for asphalt-treated granular materials, and Figure 7 for cement-treated granular materials. These curves were developed using elastic layer theory. The thickness of the subbase should be such as to provide a k-value of at least 100 pci and preferably 200 pci throughout the year to provide adequate structural support and to minimize deflection of the slab to reduce joint faulting potential.

PCC Slab Thermal Gradients for Each Month

The thermal gradient in the PCC slab is defined as follows:

$$G = \frac{T_{top} - T_{bottom}}{H} \qquad (16)$$

where

G = thermal gradient, °F/in.

T_{top} = temperature at the top of the slab, °F

T_{bottom} = temperature at the bottom of the slab, °F

H = PCC slab thickness, inches.

A positive gradient indicates the top of the slab is warmer than the bottom which normally always occurs during daytime. A negative gradient indicates that the bottom is warmer than the top which normally occurs during the nighttime. A positive gradient re-

sults in tensile stress at the bottom of the slab at the center, and a negative gradient results in compressive stress at the bottom of the slab at the center. During times when the gradient is positive (usually daytime) the total combined stress at the bottom of the slab edge midway between the joints under traffic load will be much greater than when the gradient is negative (usually nighttime).

An average monthly positive gradient (called daytime gradient) and an average monthly negative gradient (called nighttime gradient) are used in design. A summary of thermal gradients for three geographically different regions is given in Table 4. A definition of the climatic regions is given in Table 1. These mean monthly gradients were computed using an accurate temperature model developed by Dempsey (Ref. 12, 13) which has been verified with actual data from several sources. The mean values were determined by averaging the gradients calculated every three hours throughout the day and throughout the night for these locations over a year's time.

Slab Length

Transverse contraction joint spacing is a very important input because of its effect on transverse cracking of the slab. Since plain jointed concrete pavements do not contain reinforcing steel to hold cracks tight, the design procedure for plain pavement must attempt to prevent such cracks. Joint spacing affects the curling and shrinkage of the slab. Daytime gradients (i.e., surface warmer than bottom of slab) result in tensile stresses in the bottom of the slab, that is additive (not directly, however) to traffic load stresses at the edge of the slab. The recommended joint spacing for plain concrete varies from 10 to 20 feet. If a random joint pattern is used, the length of the longest slab should be input for design.

Mean PCC Modulus of Rupture

High quality concrete must be used in the PCC slab. The mean modulus of rupture at 28 days as determined by the test procedure specified in AASHO Designation T-97, using the third-point loading, is the basis for determining concrete flexural strength. Current practice for conventional pavements indicates that this value ranges from 550 to 700 psi. A minimum cement factor of approximately six sacks per cubic yard is recommended for most regions for durability, which would give modulus of rupture values towards the high side of this range. The use of high strength concrete is also recommended. It will provide a greater wear resistance and a much greater resistance to fatigue damage and spalling (Ref. 16).

Joint Design

Only contraction type transverse joints are recommended. These joints should be spaced 10 to 20 feet apart, preferably in a random pattern. Dowel bars are strongly recommended for all transverse joints for pavements located in almost all climatic regions. The only exception may be for pavements located in dry-warm climates as defined by Table 1. Complete details on joint design are given in Reference 2 (Ref. 17, 18, 19, 20).

SELECTION OF STRUCTURAL DESIGN

The basic structural design philosophy to provide zero-maintenance plain jointed concrete pavements is to prevent linear (transverse) cracking of the slab and excessive pavement roughness caused by joint faulting and other factors. The fatigue analysis provides a direct comprehensive procedure that is used to minimize the possibility of transverse cracking. The serviceability/performance analysis provides a direct procedure that is used to minimize the possibility of occurrence of excessive roughness. The selected design must meet the limiting design criteria of both serviceability and fatigue.

1. Limiting Fatigue Consumption: A maximum allowable fatigue consumption (or DAMAGE) as accumulated monthly over the entire design analysis period at the slab edge midway between joints is 100. The actual limiting value of DAMAGE as computed from Equation 5 is 10^{-5}. However, since this value is very small and inconvenient to use in design, it was multiplied by a scale factor of 10^{7} so that the limiting value is 100. This value was set based upon fatigue analyses of 35 in-service pavements ranging in age from 9 to 25 years to give a high reliability that linear cracking from fatigue would be prevented. The computed fatigue consumption for each of these pavements, prior to any cracks that

occurred, was greater than this specified limiting value.

2. Limiting Terminal Serviceability: The minimum allowable terminal serviceability index is 3.0. This value was set based upon observations on the 35 in-service pavements and other information. Use of this minimum value provides a high reliability that the pavement will not require maintenance due to excessive roughness over the design analysis period.

A computer program, called JCP-1 was developed to make the numerous calculations required to assist the engineer in conducting the design. An example of zero-maintenance design of a project is provided to illustrate the method.

ZERO-MAINTENANCE DESIGN EXAMPLE

This design example is for a 6-lane freeway located in Chicago, Illinois. The freeway was originally constructed 15 years ago, and has reached a point of severe deterioration requiring complete reconstruction. The desired zero-maintenance design period is 20 years.

Structural Design

The design criteria, slab properties, traffic, foundation support, and environmental inputs determined for this project are given in Table 5 for a 13 inch slab trial. The program outputs a complete listing and results for each trial slab thickness. Trial analyses were run for 9, 11, 13, and 15-inch PCC slabs. Results at the end of the 20 year design period, for the 13 inch slab, are shown in Table 6. Fatigue damage accumulated for the 13-inch slab is summarized monthly, day/night, and also totals for each. The total fatigue damage is 11.60. The month during which the most fatigue damage occurred was July, when 3.364 accumulated. This is due to the high daytime thermal gradients in the slab and the increased track volume during July.

Results of the serviceability analysis are also given in Table 6. The serviceability index at the end of 20 years is 3.04 and the total number of accumulated 18-kip equivalent single axle loads is 30.23 million in the design lane. Similar outputs are obtained for Years 1, 5, 10, 15, 20, and a summary of results for the entire design period is given in Table 7 for a 9, 11, 13, and 15 inch slab, which will be used to select the design structure. The minimum design slab thickness is determined by plotting these data as shown in Figure 8 and selecting slab thickness considering limiting serviceability and fatigue criteria:

Fatigue Minimum Thickness = 12.2 inches
Serviceability Minimum Thickness = 12.8 inches

A slab thickness of nominally 13 inches is therefore selected for this design.

The previous structural design selection was obtained for a specified subbase, joint spacing, and concrete strength. There are other alternatives, however, which could be analyzed in order to obtain the most economical structural design. A summary of a few alternatives is shown in Table 8. The other design inputs were held constant for each of these alternatives and a single parameter was varied as shown. Required slab thickness varies from 11.0 to 13.2 depending upon the values of the design parameters controlled by the designer. Each alternative should be further designed and economical analyses conducted to determine the most economical alternative.

Another important consideration which should be evaluted is changing slab thicknesses across the lanes. In certain instances, this may provide for a more economical design. The design inputs can be changed to reflect the center lane and then the inside lane and the required thickness of each determined. A uniform varying thickness could then be specified as illustrated in the following analysis.

The design inputs for the inside and center lanes are identical to those shown in Table 5 for the outside lane with the exception of lane truck distribution:

Inside Lane = 7 percent
Center Lane = 35 percent

Required slab thicknesses for each lane are as follows:

Outside Lane (outer edge) = 12.8 inches
Center Lane (either edge) = 12.0 inches
Inside Lane (inside edge) = 11.4 inches

Therefore, the slab could vary in thickness from 13 inches on the outside edge to 11.5 inches at the inside edge.

Design of Other Components

The design of pavement joints, shoulders, and subsurface drainage is briefly given. Joint design includes the specification of transverse joint spacing, load transfer at transverse joints, joint shape and sealant, longitudinal joints, transverse construction joints, and transverse expansion joints at bridge ends. Values selected for these components are given in Table 9. A randomized transverse joint spacing is selected to prevent rhythmic vehicle response. Two random joint spacings are selected for trial analysis. Load transfer at the joints includes both aggregate interlock and corrosion proof dowels (Ref. 17, 18, 19). Dowels are considered necessary due to the heavy traffic and the wet/freeze climate.

Previous experience with PCC shoulders in the area indicates long term maintenance-free performance. The project is located in a wet/freeze region and shoulder separation may occur if AC shoulders are used. Therefore, PCC shoulders are selected for this design. A thickness equal to the slab thickness for a transverse distance of 12 inches, and then tapering to a thickness of 8 inches is selected. Tie bars of identical size to those placed for the traffic lanes are to be used (Ref. 21, 22).

Since the project is located in an area of high rainfall (35 inches annual precipitation), a subsurface drainage system is considered necessary (Ref. 14, 21, 23, 24). An open-graded subbase layer consisting of either granular material or asphalt stabilized granular material will be used. A filter layer is required between the subbase layer and the clay subgrade to prevent infiltration of fines that would clog the drainage system. A collector pipe and outlet piping system is also required. A minimum thickness of at least 12 inches granular and 6 inches asphalt stabilized subbase is required to increase the k-value above 100 pci as recommended. These thicknesses also meet that required for subsurface drainage as specified in Ref. 14.

Final Design Selection

A complete cost analysis of the alternative designs that meet the limiting criteria must be conducted. Since no pavement structural maintenance is expected over the 20-year analysis design period, the cost analysis can be based upon the first cost of the pavement. The design alternative providing the lowest initial construction cost should be chosen as the optimum zero-maintenance design alternative.

Justification for the construction of a zero-maintenance pavement is determined by comparing the construction cost of providing the zero-maintenance pavement with the total cost of a conventional pavement. Total cost of a conventional pavement includes initial construction, user delay, maintenance, and any rehabilitation costs (such as overlays), while the total cost of a zero-maintenance pavement includes only initial construction. Procedures to estimate user delay, maintenance, and rehabilitation of conventional pavements are provided in Reference 15. When the total cost of the conventional pavement equals or exceeds that of the zero-maintenance pavement, economic justification exists for construction of the zero-maintenance pavement.

Sensitivity Analysis

A sensitivity analysis is conducted to illustrate the effect of changes in several of the design parameters on required slab thickness. The average conditions are set as described in the design of the example project, and then one parameter at a time is varied over a reasonable range that might exist in actual situations. Joint spacing is the first parameter varied from 15 to 22 feet as shown in Figure 9. The curve labeled with an F is the slab thickness required for fatigue considerations, and the curve labeled S is the required slab thickness for serviceability considerations. The S curve is simply a horizon-

tal curve since there is no way to adjust for joint spacing and the empirical equation was based on a 15-foot joint spacing. The slab thickness required for fatigue increases from 12.2 to 13.8 inches as joint spacing increases from 15 to 22 feet. A change in the mean 28-day modulus of rupture from 550 to 800 psi produces a change of about 3 inches in PCC slab thickness as shown in Figure 9. A change in foundation conditions as shown in Figure 9 from a granular subbase/clay subgrade to a granular subgrade reduces the required slab thickness by about 1 inch. A change in subbase type from 12" granular to 6" asphalt treated results in a 1/2-inch reduction in PCC slab thickness. The variation in PCC strength shown in Figure 9 as indicated by the coefficient of variation from excellent quality control (5 percent) to poor (20 percent) causes an increase in required slab thickness of approximately 1 inch.

The effect of increasing the mean average daily traffic (ADT) from 40,000 to 120,000 in Figure 10, produces a change in required slab thickness of 2-1/3 inches. The change is very large for serviceability considerations as compared to fatigue considerations. A change in the mean lateral displacement of trucks nearer the edge from 24 to 12 inches in Figure 10, results in an increase in slab thickness of about 0.7 inches for fatigue considerations.

The effect of time from PCC slab placement to opening of traffic is shown in Figure 10. The sooner the pavement is opened to traffic, the greater the fatigue damage, and hence the greater the required thickness of slab as shown. The effect of varying climates is shown in Figure 10. Serviceability analysis shows a considerable difference in required slab thickness while fatigue analysis shows only minor differences for the pavements studied. Overall required slab thickness varies from 12.8 to 12.0 inches in changing from a typical wet/freeze (Chicago) to a dry/non-freeze (Los Angeles) climate.

The effect of axle load distribution is shown in Figure 11. The three axle load distributions are defined as follows:

Distribution	% SA > 18 kips	Max. SA	% TA > 32 kips	Max. TA
Moderate	1	30 kips	5	54 kips
Heavy	3	34 kips	10	56 kips
Very Heavy	3	38 kips	10	66 kips

There is a change in required slab thickness from 11.7 to 12.9 inches in changing from moderate to very heavy axle load distribution. The difference between the heavy axle load distribution and the very heavy distribution is only in the maximum load. The very heavy distribution maximum load goes up to 38 and 66 kips for single and tandem axles, respectively. The change in thickness based on serviceability is only 0.1 inch, but the change in thickness based on fatigue is 0.4 inches. The maximum axle load is very important in this design procedures and should be carefully estimated using spot state enforcement weighing information.

CONCLUSIONS

Design procedures for heavily trafficked plain jointed concrete pavements to provide "zero-maintenance" performance have been developed. The term "zero-maintenance" refers only to structural maintenance, such as patching, crack repair, slab replacement, grinding of faults, and overlay. Procedures are included for designing the concrete slab, subbase, shoulders, joints, and subsurface drainage. A computer program (JCP-1) is used to provide serviceability/performance and fatigue data for the structural design of the pavement. These procedures were developed based on nationwide field studies, long term performance data of in-service pavements, comprehensive mechanistic analyses, and results from laboratory studies. A detailed design example for a heavily trafficked freeway pavement is provided, including a sensitivity analysis of the major design factors. A design manual (Ref. 2) was developed which gives detailed recommendations for conducting the zero-maintenance design.

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Table 1 Definition of the Four General Climatic Regions.

Climatic Region	Annual Precipitation (P) and Potential Evapo-transpiration (E)	Frost Heave and/or Freeze-Thaw Damage
Wet/Freeze (WF)	$P \geq E$ or $P \geq 30$ ins.	Occurs in pavements in region
Wet/Non-freeze (W)	$P \geq E$ or $P \geq 30$ ins.	Does not occur in pavements in region
Dry/Freeze (DF)	$P < E$	Occurs in pavements in region
Dry/Non-freeze (D)	$P < E$	Does not occur in pavements in region

Table 2. Example Sensitivity Analysis of New Performance Design Equation 2.

Design Parameter	Change in Parameter *	Change in 18-kip ESAL (million)
Modulus of Rupture, psi	600 to 800	9.2 to 15.5
k-value of Foundation, pci	100 to 500	9.2 to 14.5
Slab Thickness, ins.	9 to 11	9.2 to 20.0
Climatic Region	WF to D	9.2 to 15.3

*Values are computed assuming a standard section of 9 in. slab, k-value of 100 pci, modulus of rupture of 600 psi, located in a wet-freeze region.

Table 3 Typical Heavy Axle Load Distributions.

Axle Load Groups (kips)	Axle Load Distribution as Percent of 100* (1)	(2)	(3)	(4)
Single Axles:				
18-20	58.5	35.4	40.0	45.3
20-22	16.5	41.1	27.1	27.2
22-24	16.0	17.0	18.3	17.1
24-26	7.2	3.5	10.1	6.9
26-28	1.1	1.4	2.0	1.5
28-30	0.7	0.2	1.0	0.6
30-32	---	---	0.7	0.5
32-34	---	0.7	0.5	0.4
34-36	---	---	0.3	0.3
36-38	---	0.7	---	0.2
	100.0	100.0	100.0	100.0
Tandem Axles:				
32-34	23.0	44.2	40.1	35.8
34-36	22.1	34.0	19.2	25.1
36-38	16.0	11.2	10.6	12.6
38-40	10.5	5.4	8.3	8.1
40-42	7.5	2.2	6.0	5.2
42-44	8.1	1.1	3.5	4.2
44-46	5.2	0.4	2.9	2.8
46-48	3.4	---	3.2	2.2
48-50	2.0	0.4	2.7	1.7
50-52	1.2	---	1.6	0.8
52-54	0.6	0.7	0.8	0.7
54-56	0.4	0.4	0.5	0.4
56-58	---	---	0.2	0.1
58-60	---	---	0.2	0.1
60-62	---	---	0.1	0.1
62-64	---	---	0.1	0.1
	100.0	100.0	100.0	100.0

* (1) Typical lighter axle load distribution from various states.

(2) Axle load distribution determined from spot enforcement weight tickets in Chicago freeways (1975).

(3) Typical heavier axle load distribution from various states.

(4) General average axle load distribution of heavy loads.

Table 4. Monthly Average Temperature Gradient (°F/inch)

	Wet/Non-Freeze Region*				Dry or Wet/Freeze Region**				Dry/Non-Freeze Region***			
	8 in.		12 in.****		8 in.		12 in.		8 in.		12 in.	
MONTH	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
JULY	1.87	-0.63	1.42	-0.39	2.08	-0.91	1.54	-0.54	1.83	-0.90	1.43	-0.56
AUGUST	1.47	-0.87	1.15	-0.56	1.73	-1.00	1.32	-0.63	1.62	-1.10	1.24	-0.76
SEPT	1.23	-0.91	0.83	-0.68	1.34	-1.13	0.92	-0.83	1.46	-0.87	0.97	-0.66
OCT	1.59	-1.12	1.10	-0.81	0.88	-0.80	0.56	-0.62	1.62	-0.91	1.01	-0.69
NOV	1.15	-1.00	0.81	-0.75	0.72	-0.79	0.43	-0.64	1.20	-0.81	0.78	-0.59
DEC	0.85	-0.65	0.55	-0.52	0.57	-0.50	0.40	-0.37	1.07	-0.69	0.71	-0.52
JAN	0.79	-0.49	0.55	-0.38	0.45	-0.84	0.27	-0.63	1.18	-0.68	0.76	-0.51
FEB	1.25	-0.93	0.79	-0.73	0.32	-0.78	0.18	-0.57	1.14	-0.57	0.73	-0.43
MARCH	1.53	-0.81	1.01	-0.61	0.86	-0.87	0.59	-0.62	1.27	-0.80	0.84	-0.60
APRIL	1.75	-1.02	1.29	-0.70	1.59	-0.62	1.11	-0.41	1.49	-0.99	1.12	-0.70
MAY	1.70	-1.01	1.33	-0.65	1.46	-0.72	0.99	-0.49	1.47	-0.89	1.13	-0.61
JUNE	1.63	-1.07	1.23	-0.74	1.58	-0.90	1.18	-0.57	1.59	-1.01	1.24	-0.68

* Data calculated for Atlanta, Georgia
** Data calculated for Chicago, Illinois
*** Data calculated for Los Angeles, California
**** PCC slab thickness

Table 5. Listing of Program Inputs for Example Design Problem for 13 Inch PCC Slab.

ZERO-MAINTENANCE PORTLAND CEMENT CONCRETE
PLAIN JOINTED PAVEMENT DESIGN PROGRAM (JCP-1)

PROBLEM # 3

ZERO-MAINTENANCE DESIGN -- EXAMPLE PROBLEM -- 13 INCH SLAB

INPUT DATA

DESIGN CRITERIA

PAVEMENT ZERO-MAINTENANCE DESIGN LIFE (YEARS)	20.00
INITIAL SERVICEABILITY INDEX AFTER CONSTRUCTION	4.50
TERMINAL SERVICEABILITY INDEX FOR ZERO-MAINTENANCE	3.00
TIME AFTER PCC SLAB PLACEMENT THAT PAVEMENT WILL BE OPENED TO TRAFFIC (YEARS)	0.16
MONTH PAVEMENT WILL BE OPENED TO TRAFFIC	OCT

YEARS DURING WHICH SUMMARY OF FATIGUE AND SERVICEABILITY DATA WILL BE PRINTED 1, 5,10,15,20,

YEARS DURING WHICH COMPREHENSIVE FATIGUE OUTPUT WILL BE PRINTED 1,

SLAB PROPERTIES

SLAB THICKNESS - INS.	13.00
SLAB LENGTH - FT.	15.00
MEAN PCC MODULUS OF RUPTURE (28-DAYS) - PSI	650.00
COEFFICIENT OF VARIATION OF PCC MODULUS OF RUPTURE - %	12.00
PCC COEF. OF THERMAL EXPANSION - PER DEG-F	5.000E-06
PCC MODULUS OF ELASTICITY	5.000E 06

TRAFFIC

AVERAGE DAILY TRAFFIC AT BEGINNING OF DESIGN PERIOD	70000.
AVERAGE DAILY TRAFFIC AT END OF DESIGN PERIOD	90000.
PERCENT TRUCKS OF ADT	10.00
PERCENT TRUCKS IN HEAVIEST TRAVELED OR DESIGN LANE	60.00
PERCENT DIRECTIONAL DISTRIBUTION	50.00
MEAN AXLES PER TRUCK	2.75
PERCENT TRUCKS DURING DAYLIGHT	60.00
MEAN DISTANCE FROM SLAB EDGE TO OUTSIDE OF TRUCK DUALS (IN)	18
NUMBER OF SINGLE AXLE LOAD INTERVALS	14
NUMBER OF TANDEM AXLE LOAD INTERVALS	18

Table 5. Continued

S.A.L. DISTRIBUTION TABLE

WEIGHT RANGE (POUNDS)	PERCENT
0. - 3000.	7.28
3001. - 7000.	16.28
7001. - 8000.	7.75
8001. - 12000.	15.01
12001. - 16000.	4.75
16001. - 18000.	1.94
18001. - 20000.	1.32
20001. - 22000.	1.02
22001. - 24000.	0.42
24001. - 26000.	0.14
26001. - 28000.	0.06
28001. - 30000.	0.02
30001. - 32000.	0.01
32001. - 34000.	0.01

T.A.L. DISTRIBUTION TABLE

WEIGHT RANGE (POUNDS)	PERCENT
0. - 6000.	0.37
6001. - 12000.	9.76
12001. - 18000.	4.36
18001. - 24000.	5.68
24001. - 30000.	8.92
30001. - 32000.	4.90
32001. - 34000.	4.30
34001. - 36000.	3.40
36001. - 38000.	1.40
38001. - 40000.	0.48
40001. - 42000.	0.19
42001. - 44000.	0.08
44001. - 46000.	0.06
46001. - 48000.	0.03
48001. - 50000.	0.02
50001. - 52000.	0.02
52001. - 54000.	0.01
54001. - 56000.	0.01

MONTHLY TRUCK PERCENTAGE

OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
8.33	8.33	8.33	7.00	7.00	7.00	8.36	9.33	9.33	9.33	9.33	8.33

Table 5. Continued

FOUNDATION SUPPORT

MODULUS OF FOUNDATION SUPPORT (K) FOR EACH MONTH - PCI

OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
160.	150.	150.	500.	500.	90.	120.	130.	160.	160.	160.	160.

ERODABILITY OF FOUNDATION AT BEGINNING OF DESIGN PERIOD (INS.) 0.0
ERODABILITY OF FOUNDATION AT END OF DESIGN PERIOD (INS.) 24.00

DESIGN MODULUS OF FOUNDATION SUPPORT (K) FOR SERVICEABILITY/PERFORMANCE ANALYSIS - PCI 142.00

ENVIRONMENTAL

PCC SLAB THERMAL GRADIENTS FOR EACH MONTH - DEG-F/INCH,

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
FOR THICKNESS OF 8.0 INCHES												
DAY	0.88	0.72	0.57	0.45	0.32	0.86	1.59	1.46	1.58	2.08	1.73	1.34
NIGHT	-0.80	-0.79	-0.50	-0.84	-0.78	-0.87	-0.62	-0.72	-0.90	-0.91	-1.00	-1.13
FOR THICKNESS OF 12.0 INCHES												
DAY	0.56	0.43	0.40	0.27	0.18	0.59	1.11	0.99	1.18	1.54	1.32	0.92
NIGHT	-0.62	-0.64	-0.37	-0.63	-0.57	-0.62	-0.41	-0.49	-0.57	-0.54	-0.63	-0.83
CALCULATED FOR THICKNESS OF 13.0 INCHES (BY INTERPOLATION)												
DAY	0.48	0.36	0.36	0.23	0.14	0.52	0.99	0.87	1.08	1.40	1.22	0.82
NIGHT	-0.57	-0.60	-0.34	-0.58	-0.52	-0.56	-0.36	-0.43	-0.49	-0.45	-0.54	-0.76

CLIMATIC REGIONAL FACTOR 1.00

Table 6. Summary of Results at End of Design Analysis Period

ZERO-MAINTENANCE PORTLAND CEMENT CONCRETE
PLAIN JOINTED PAVEMENT DESIGN PROGRAM (JCP-1)

PROBLEM # 3 ZERO-MAINTENANCE DESIGN -- EXAMPLE PROBLEM -- 13 INCH SLAB

RESULTS - ACCUMULATED FATIGUE DAMAGE OF P.C.C. SLAB AT OUTSIDE EDGE

SUMMARY FOR DESIGN PERIOD

	DAY	NIGHT	TOTAL
OCT	8.147E-01	2.819E-02	8.429E-01
NOV	3.700E-01	2.312E-02	3.932E-01
DEC	2.991E-01	3.713E-02	3.362E-01
JAN	5.079E-02	2.288E-03	5.308E-02
FEB	3.657E-02	2.715E-03	3.928E-02
MAR	3.779E-01	3.628E-02	4.142E-01
APR	1.148E 00	4.070E-02	1.188E 00
MAY	9.118E-01	3.474E-02	9.465E-01
JUN	1.431E 00	2.311E-02	1.454E 00
JUL	3.339E 00	2.490E-02	3.364E 00
AUG	1.942E 00	2.059E-02	1.962E 00
SEP	5.945E-01	1.192E-02	6.065E-01

SUM OF FATIGUE DAMAGE FOR DAY LOADING IS 1.131E 01
SUM OF FATIGUE DAMAGE FOR NIGHT LOADING IS 2.857E-01
TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD IS 1.160E 01

RESULTS - SERVICEABILITY/PERFORMANCE OF JCP DESIGN LANE

SERVICEABILITY INDEX AT END OF YEAR # 20 3.037E 00
NUMBER OF ACCUMULATED 18-KIP EQUIVALENT SINGLE AXLE LOADS AT END OF YEAR # 20 3.023E 07

Table 7. Summary of Fatigue and Serviceability Data for Example Problem Design for Granular Subbase.

Slab Thickness	Year	Fatigue Damage For Year	Serviceability Index	ESAL (10^6)
9	1	4.80×10^{7}	4.37	1.28
	5	8.34×10^{5}	3.52	6.56
	10	4.03×10^{5}	2.23	13.58
	15	3.28×10^{5}	*	*
	20	3.20×10^{5}	*	*
	TOTAL	6.21×10^{5}		
11	1	2.06×10^{3}	4.41	1.32
	5	1.27×10^{2}	4.01	6.79
	10	7.50×10^{1}	3.36	14.04
	15	6.20×10^{1}	2.79	21.76
	20	5.80×10^{1}	*	*
	TOTAL	4.04×10^{3}		
13	1	3.10	4.44	1.33
	5	0.50	4.18	6.85
	10	0.40	3.77	14.17
	15	0.30	3.36	21.97
	20	0.30	3.04	30.23
	TOTAL	11.60		
15	1	6.20×10^{-2}	4.46	1.34
	5	2.00×10^{-2}	4.28	6.87
	10	1.80×10^{-2}	4.01	14.21
	15	1.70×10^{-2}	3.77	22.03
	20	1.80×10^{-2}	3.44	30.32
	TOTAL	4.30×10^{-1}		

* Program will not compute since the serviceability index is below critical value for computation

Table 8. Summary of Zero-Maintenance Alternate Designs for Example Problem.

Alternative Number	Design Parameter			Design Thickness (ins)
	Slab Length (ft)	PCC Strength (psi)	Subbase Type	
1	15	650	Granular	12.8
2	20	650	Granular	13.2
3	15	800	Granular	11.3
4	20	800	Granular	11.7
5	15	650	Asphalt Stab.	12.3
6	20	650	Asphalt Stab.	13.1
7	15	800	Asphalt Stab.	11.0
8	20	800	Asphalt Stab.	11.5

Table 9. Summary of Joint Design Criteria for Example Problem.

Joint Component	Value
Transverse Joint Spacing	10-14-12-15 or 14-20-19-13 random
Load Transfer	Stainless steel dowels, 1-1/4"ϕ x 18" @ 12"
Transverse Joint Shape	Saw cut 1/4" wide x 3-1/4" depth
Longitudinal Joint Shape	Saw cut 1/4" wide x 3-3/4" depth between each traffic lane
Sealant	Preformed Neoprene Sealant, 11/16" width
Tiebars Across Longitudinal Joints	5/8 x 30" spaced at 30"
Transverse Expansion Joints	Place only at bridge ends

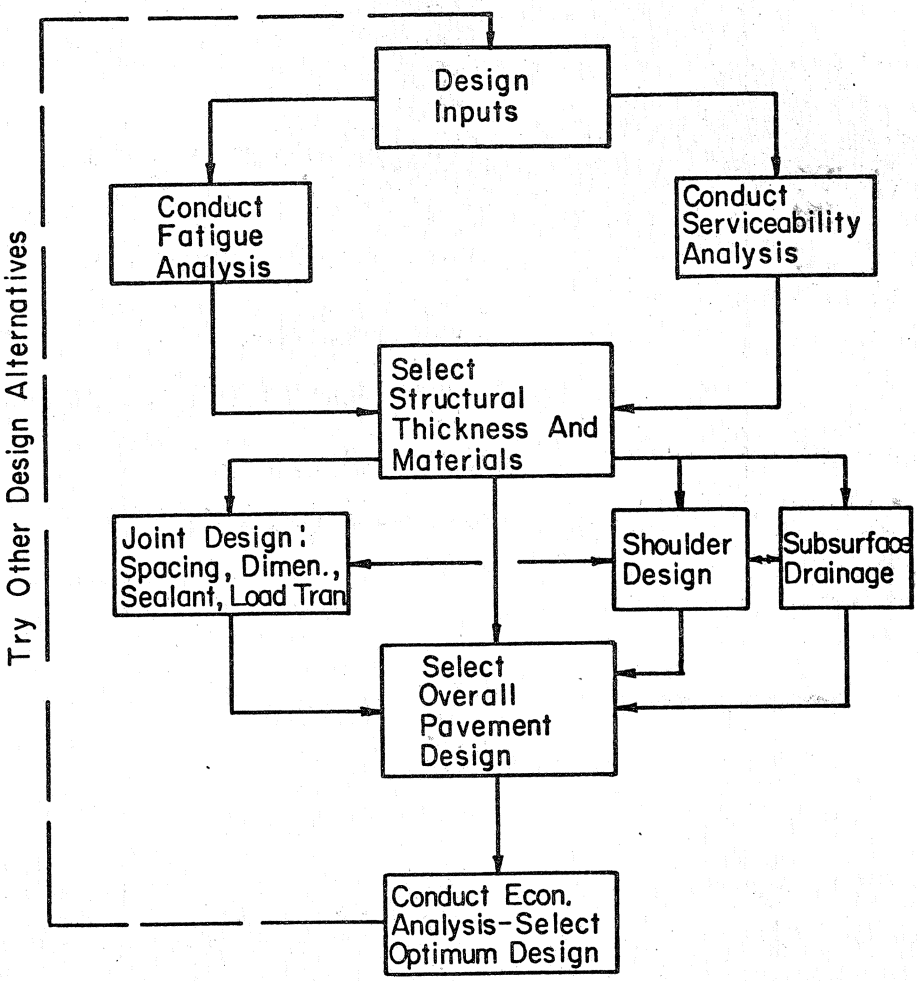


Figure 1. Zero-Maintenance Design Procedure for Plain Jointed Concrete Pavements.

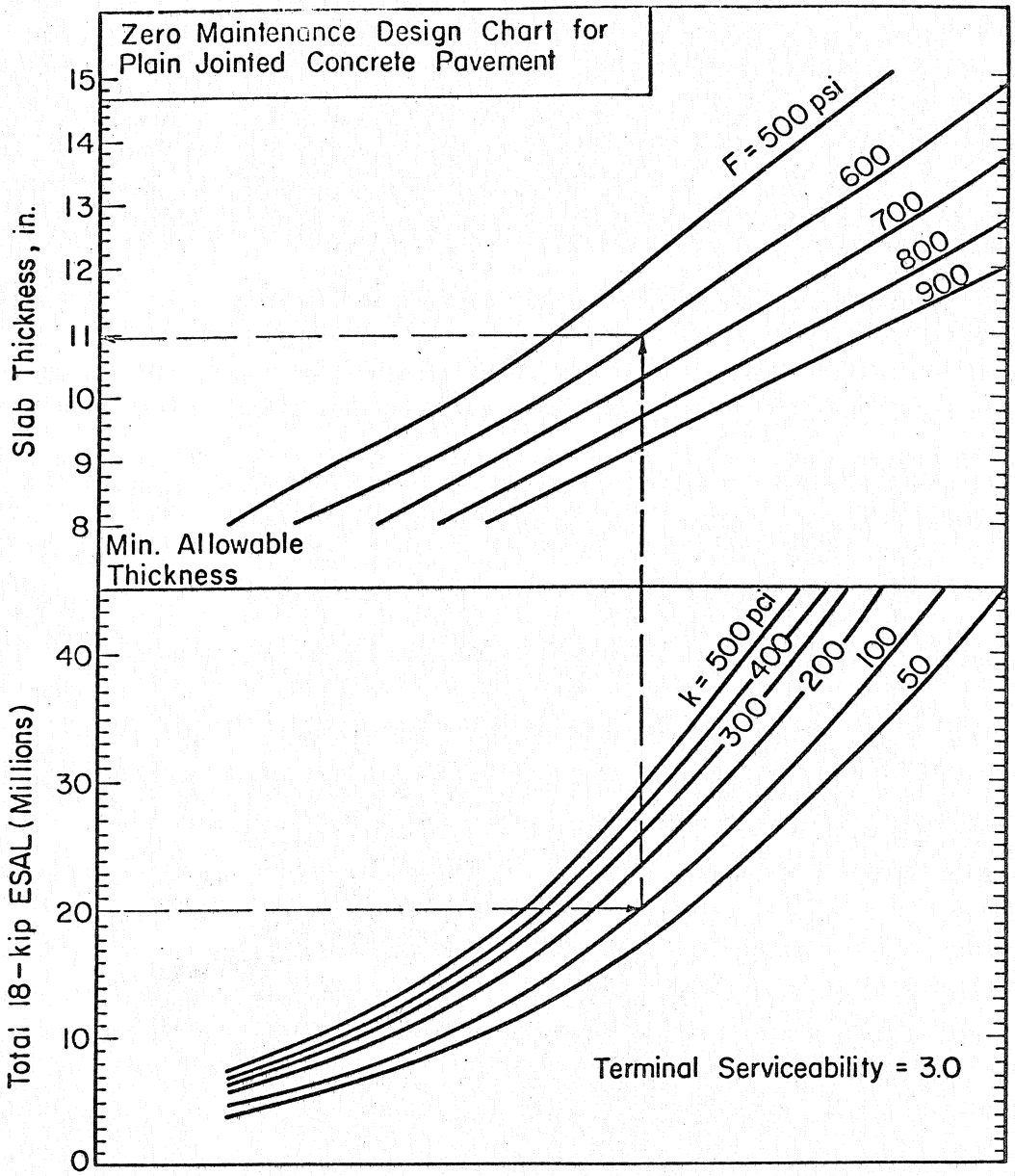


Figure 2. Serviceability/Performance Zero-Maintenance Design Chart for Plain Jointed Concrete Pavements.

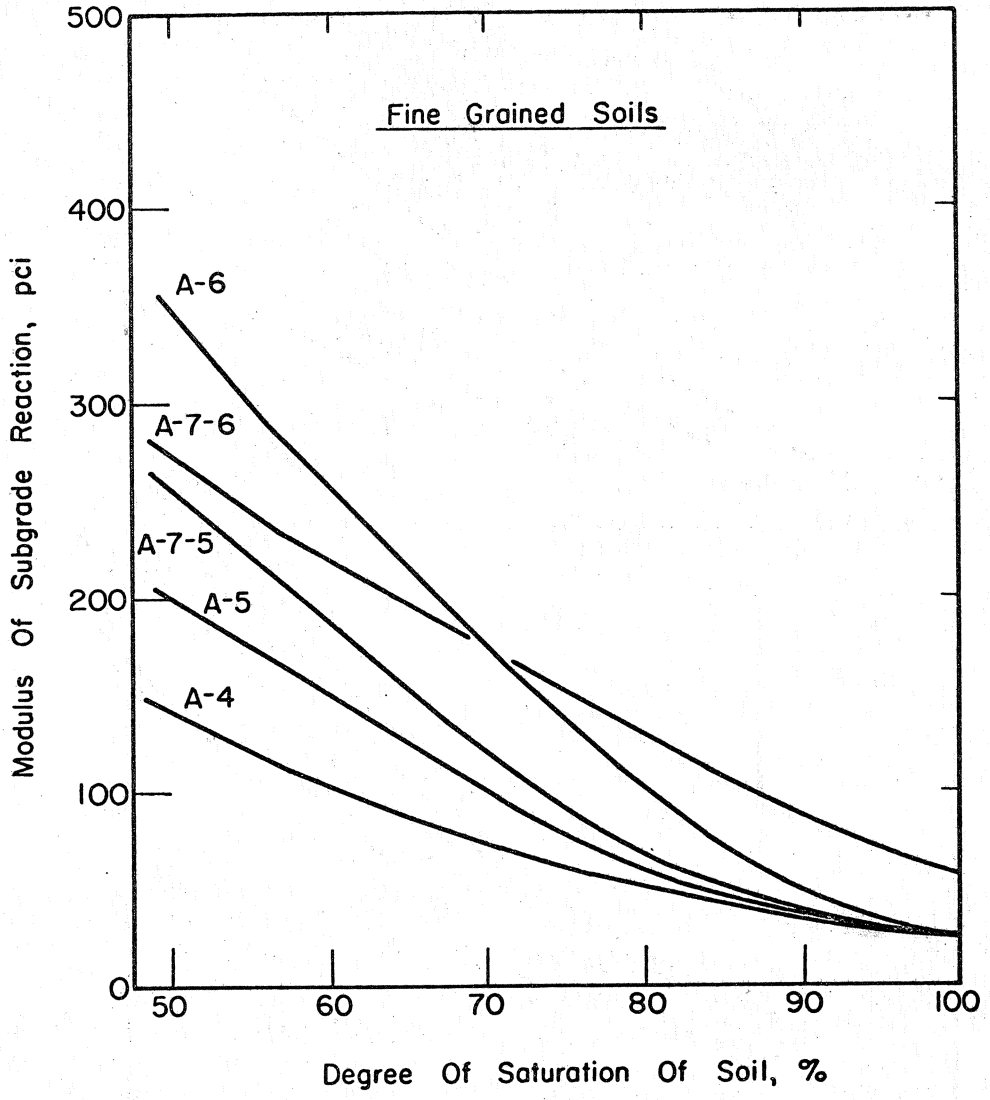


Figure 3. Elastic k-Values of AASHTO Classification Fine-Grained Soils.

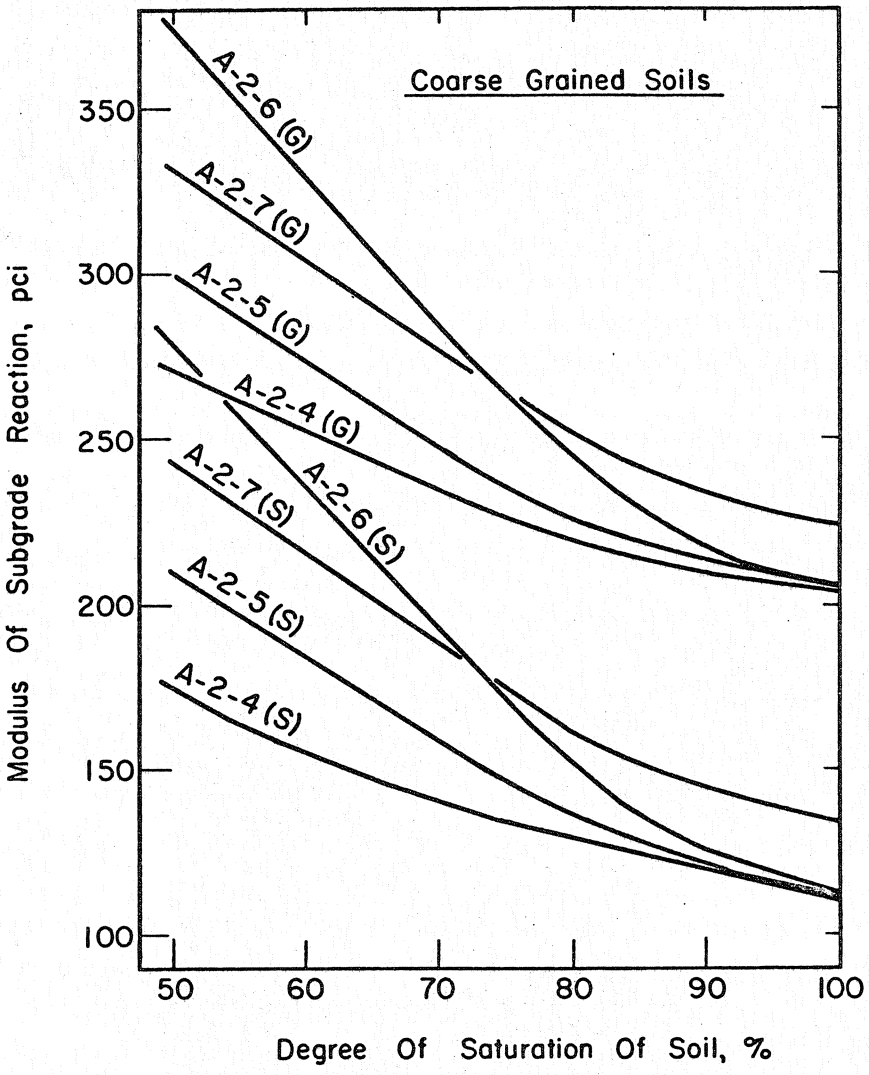


Figure 4. Elastic k-Values of AASHTO Classification Coarse-Grained Subgrade Soils (G refers to gravelly and S refers to sandy soils).

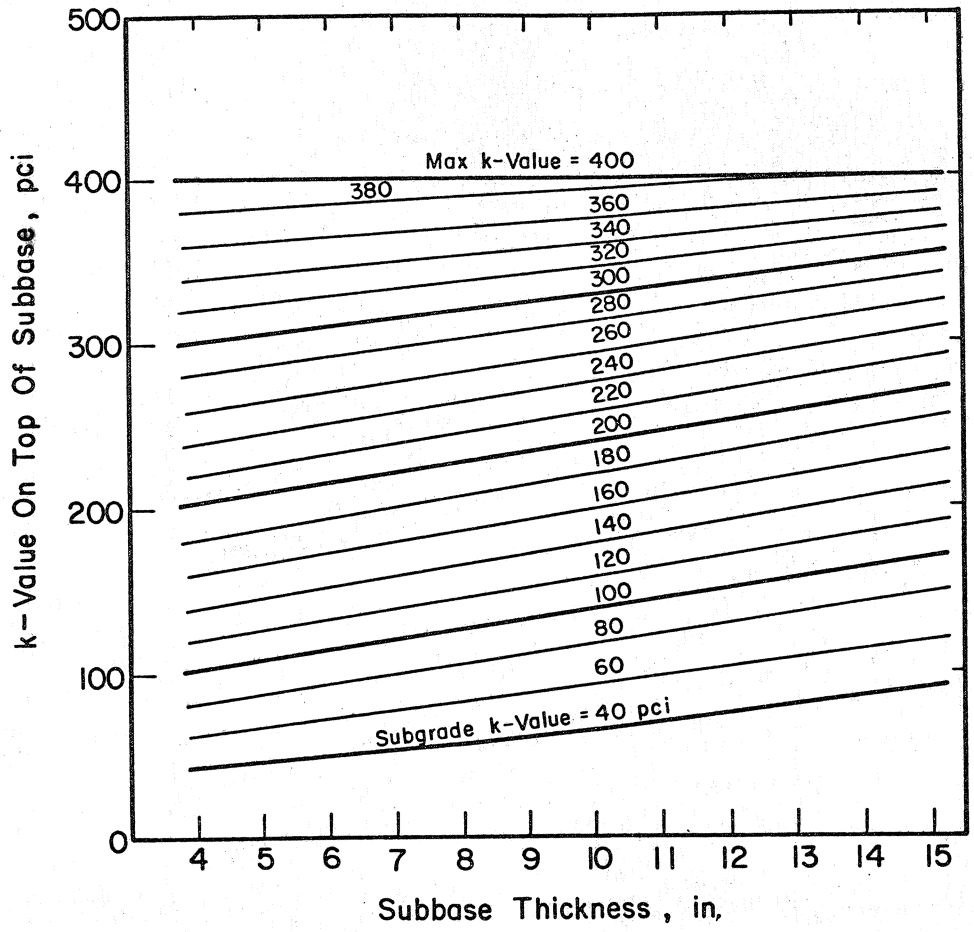


Figure 5. Elastic k-Value on Top of Granular Subbase.

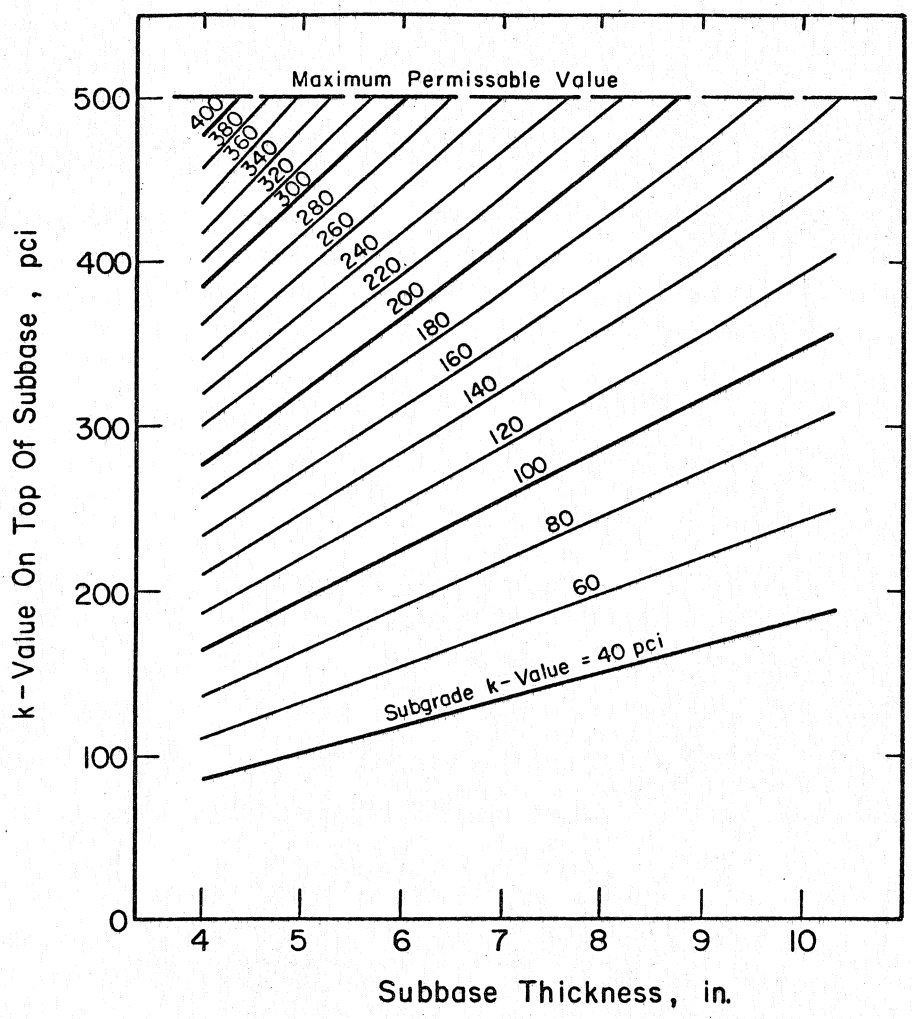


Figure 6. Elastic k-Value on Top of Asphalt Stabilized Granular Subbase.

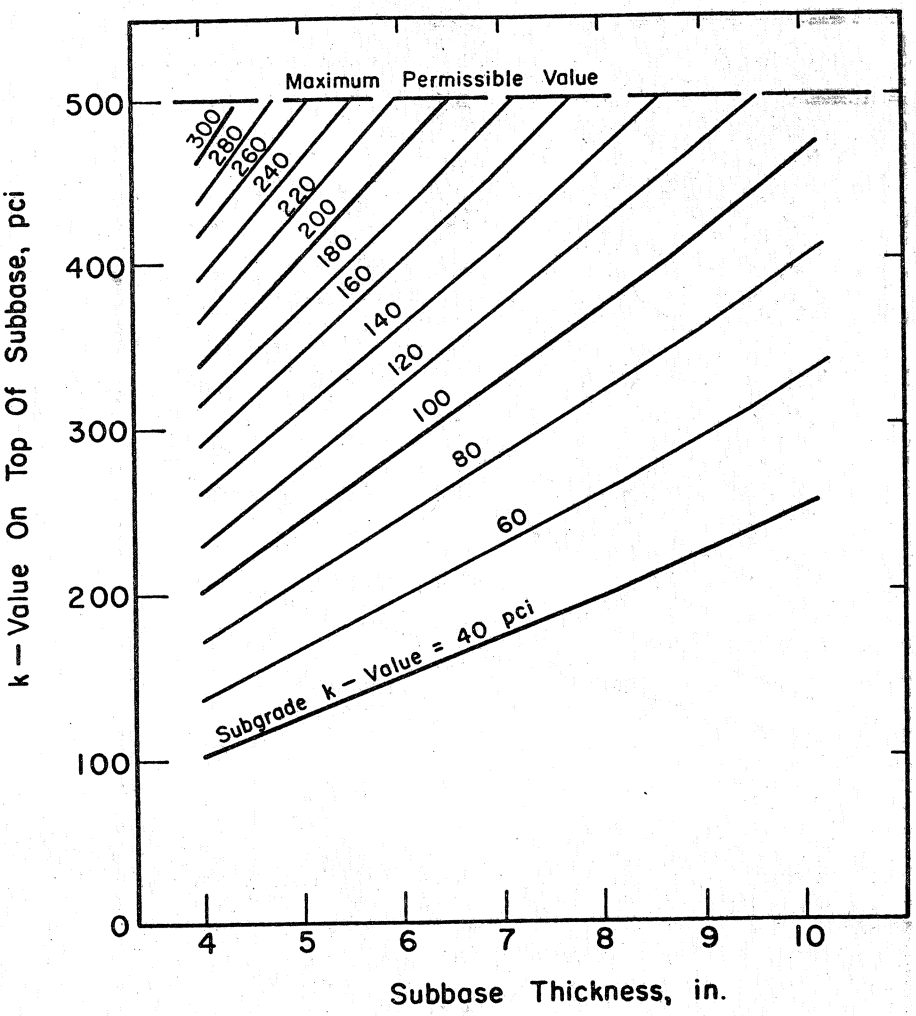


Figure 7. Elastic k-Value on Top of Cement Stabilized Subbase.

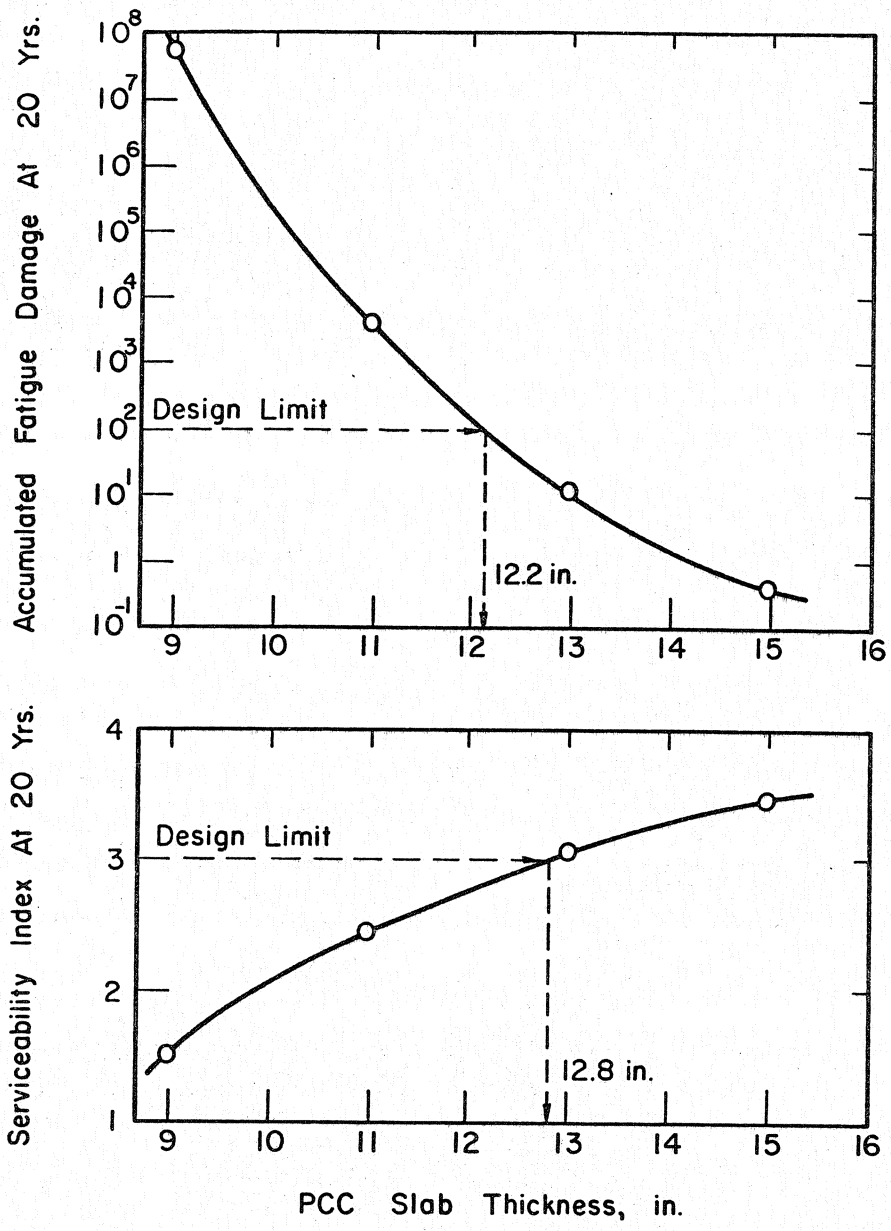


Figure 8. Fatigue Damage and Terminal Serviceability Plots Used to Determine Slab Design Thickness (for example given in Chapter 6).

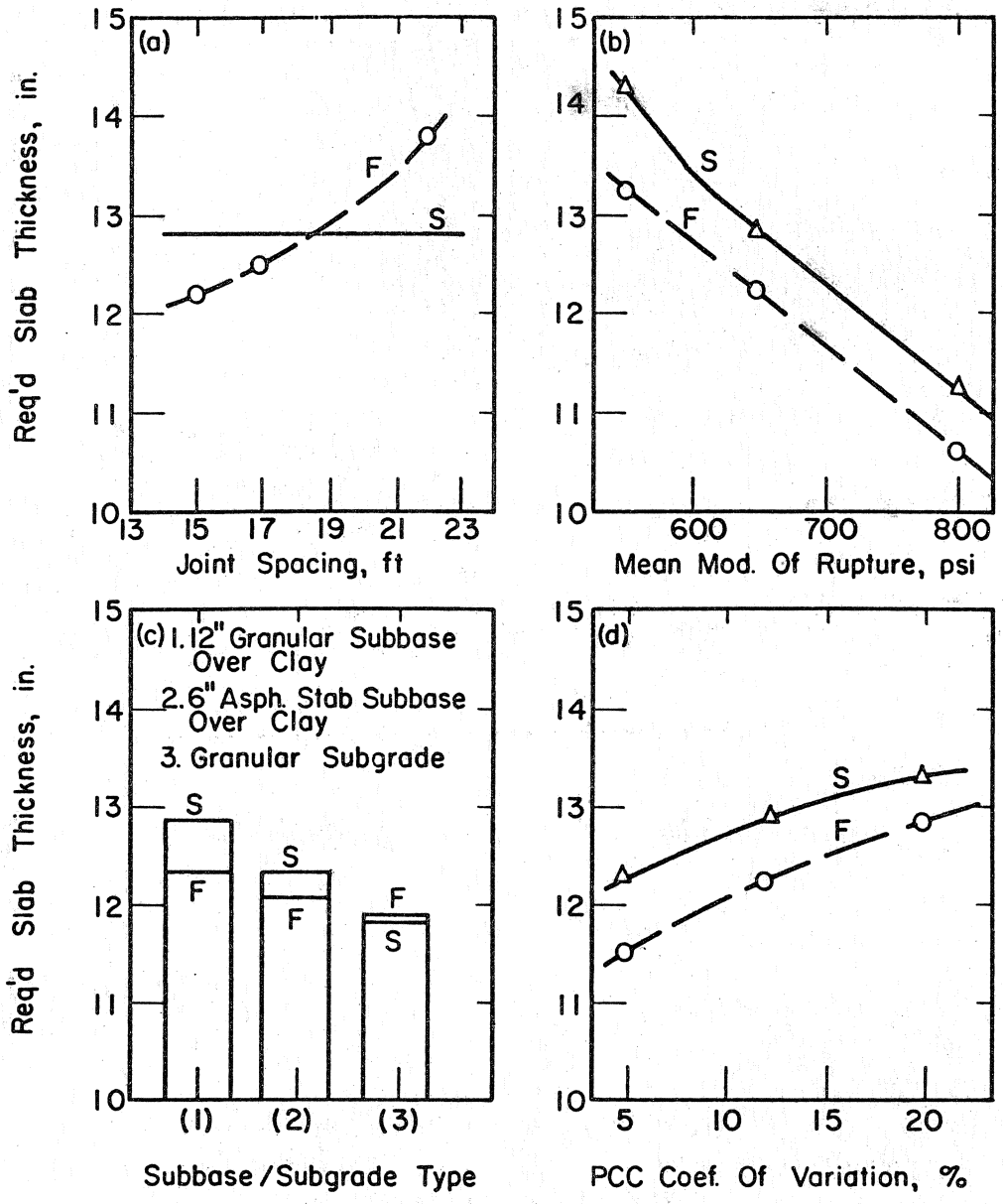


Figure 9. Sensitivity Analysis of Selected Design Parameters for Example Project (S = serviceability requirement, F = fatigue requirement).

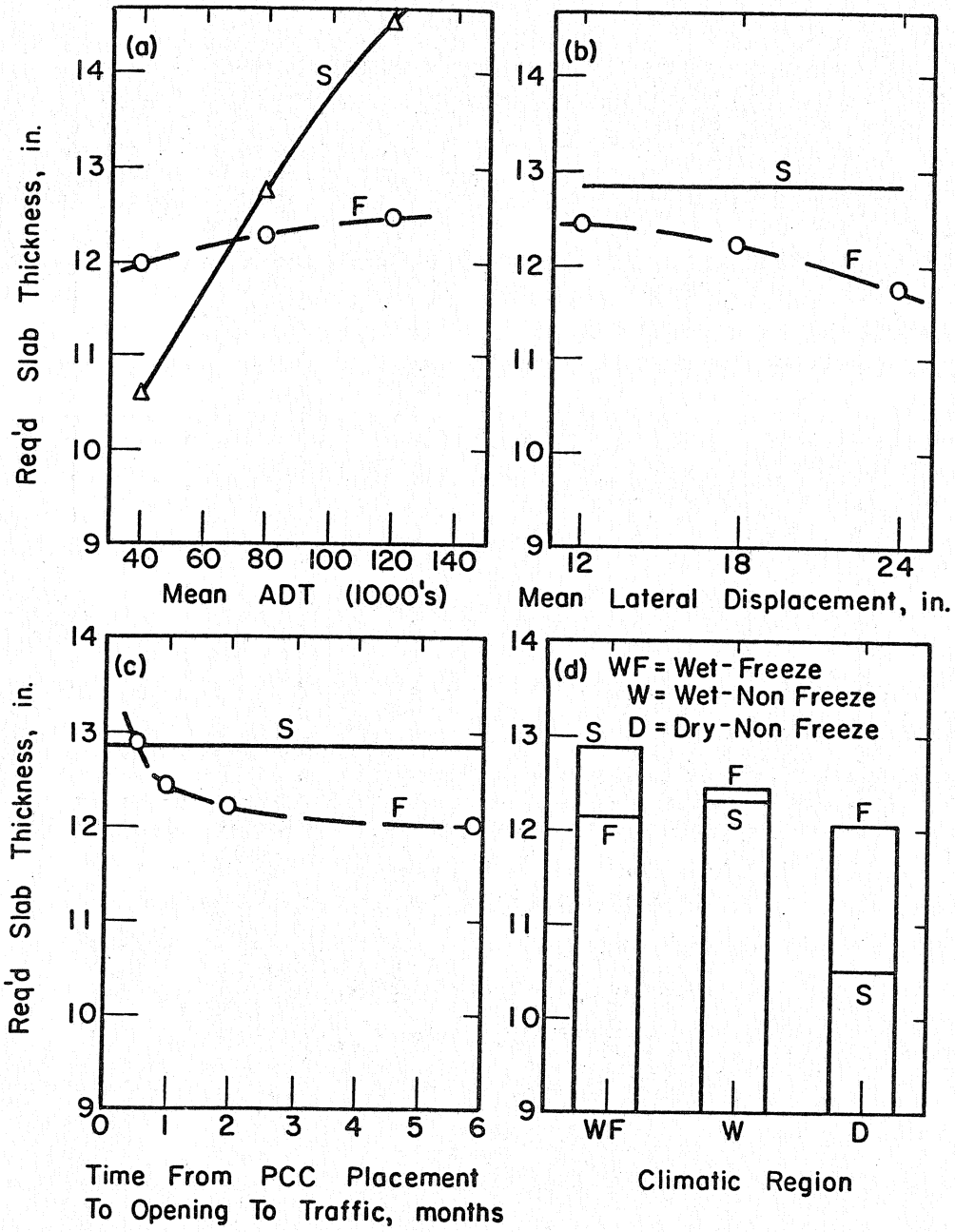


Figure 10. Sensitivity Analysis of Selected Design Parameters For Example Project (S = serviceability requirement, F = fatigue requirement).

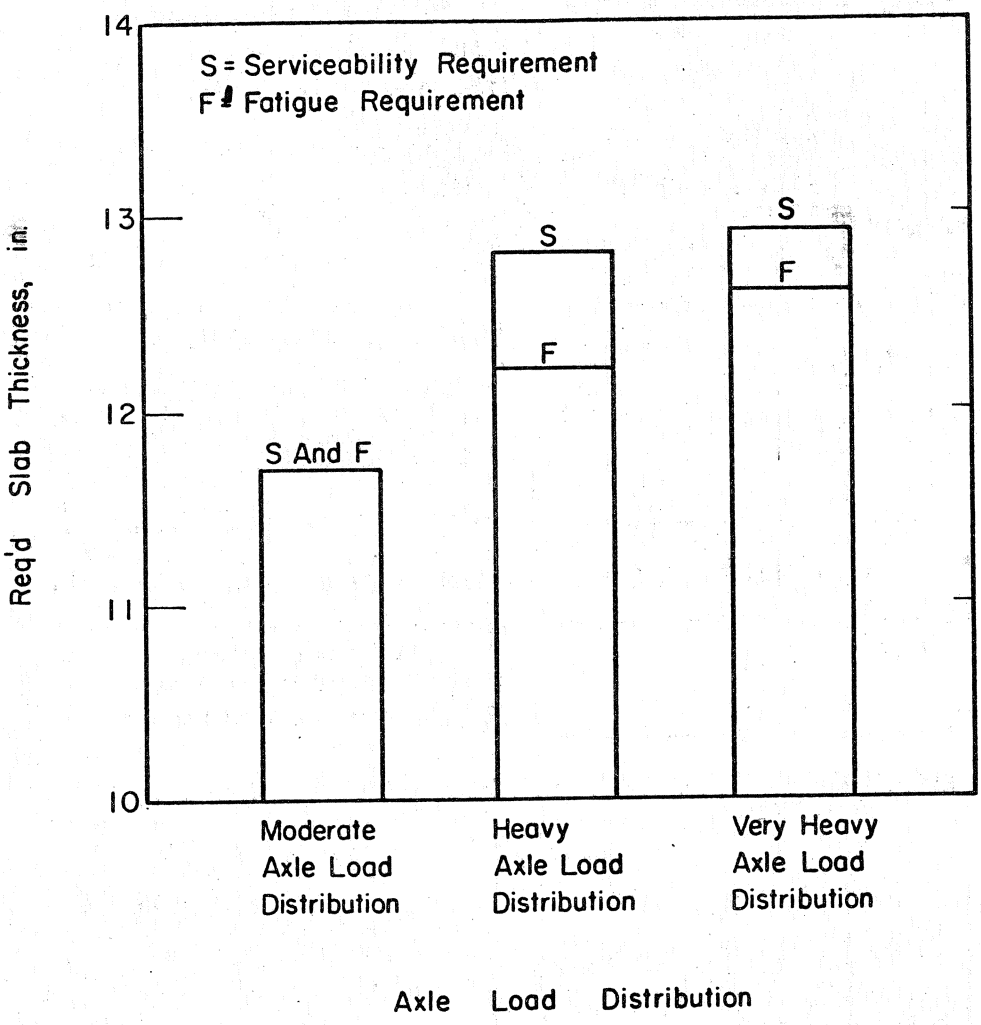


Figure 11. Sensitivity Analysis of Axle Load Distribution for Example Project.