Report No. FHWA-RD-77-112

DESIGN OF ZERO–MAINTENANCE PLAIN JOINTED CONCRETE PAVEMENT

Vol. II - Design Manual

DEPARTMENT OF TRANSPORTATION ★ UNITED STATES OF AMERICA ★

June 1977

Final Report

Prepared for

FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Washington, D.C. 20590

FOREWORD

Volume II presents an engineering guide for the design of heavily trafficked plain jointed concrete pavements to provide "zero-maintenance" performance over a selected design period. Procedures are included for designing the concrete slab, subbase, shoulders, joints, and subsurface drainage. These procedures were developed based on nationwide field studies, long-term performance data of inservice pavements, comprehensive mechanistic analysis, and results from laboratory studies.

This report completes a set of three prepared by the University of Illinois under research contract with the Structures and Applied Mechanics Division, Office of Research of the Federal Highway Administration. The first report is FHWA-RD-76-105, "Zero-Maintenance Pavements: Results of Field Studies on the Performance Requirements and Capabilities of Conventional Pavement Systems."

Development of the design procedures of this report are presented in FHWA-RD-77-111, Volume I, Development of Design Procedures.

The report is intended primarily for research and development audiences. Copies are being distributed accordingly by transmittal memorandum.

Charles F. Scheffey

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Director, Office of Research
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NOTICE

Technical Report Documentation Page

1. Report No. FHWA-RD-77-112	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Design of Zero Maintenance Plain Jointed Concrete Pavement, Vol. II - Design Manual		5. Report Date 8 June 1977
		6. Performing Organization Code
7. Author(s) Michael I. Darter and Ernest J. Barenberg		8. Performing Organization Report No. FHWA-RD-77-112
9. Performing Organization Name and Address Department of Civil Engineering University of Illinois at Urbana-Champaign Urbana, Illinois 61801		10. Work Unit No. (TRAIS) FCP 35E2012
		11. Contract or Grant No. DOT-FH-11-8474
12. Sponsoring Agency Name and Address Federal Highway Administration U.S. Department of Transportation Office of Research Washington, D.C. 20590		13. Type of Report and Period Covered Final, 1975-1976
		14. Sponsoring Agency Code S0788

15. Supplementary Notes

FHWA Project Monitors: Floyd J. Stanek, Contract Manager
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16. Abstract

This manual is an engineering guide for the design of heavily trafficked plain jointed concrete pavements to provide "zero-maintenance" performance over a selected design period. 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.

The manual includes specific recommendations for obtaining all necessary inputs and for performing the structural design. A detailed design example for a heavily trafficked freeway pavement is provided, including a sensitivity analysis of the major design factors. Input guides and output listings for the JCP-1 program are included.

17. Key Words Pavement, design, concrete, concrete pavements, concrete fatigue, serviceability, performance	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	161	

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PREFACE

"Design of Zero-Maintenance Plain Jointed Concrete Pavement, Vol. II-Design Manual," is an engineering guide for the design of heavily trafficked highway pavements. The objective of the design is to provide pavements which will perform relatively maintenance-free over a selected design period. The term "zero-maintenance" refers only to structural maintenance such as patching, crack filling, slab replacement, and overlay. Procedures are included for designing the following components of plain jointed concrete pavements: Portland cement concrete slab, subbase, shoulders, joints, and subsurface drainage. A computer program, called JCP-1, is used to provide serviceability/performance and fatigue damage data for structural design of the pavement. Manual procedures are also included to structurally design the pavement based on serviceability/performance.

This manual was developed at the Department of Civil Engineering, University of Illinois at Urbana-Champaign under sponsorship of the U. S. Department of Transportation, Federal Highway Administration. The principal investigators of the study are Dr. Michael I. Darter and Dr. Ernest J. Barenberg. The authors wish to sincerely thank the several persons who contributed directly to the development of this manual, including: Mr. Jihad Sawan, Miss H. S. Yuan, Mr. Amir M. Tabatabaie, Mr. Clive Campbell, Professor Marshall R. Thompson, and Professor Barry J. Dempsey. Thanks are also due to numerous state highway engineers from many states for providing considerable data and other assistance. Thanks are also due the FHWA project monitors Mr. William J. Kenis, Mr. Thomas Pasko, and Dr. Floyd Stanek, for their assistance and encouragement throughout the study. A special note of thanks to Mrs. Carol Ewing for typing and editing this manuscript.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

MULTIPLY	BY	TO OBTAIN
inches	2.54	centimeters
feet	0.3048	meters
square inches	6.4516	square centimeters
square yards	0.83612736	square meters
knots	0.5144444	meters per second
pounds	0.45359237	kilograms
kips	0.45359237	metric tons
pounds per cubic foot	16.018489	kilograms per cubic meter
pounds	4.448222	newtons
kips	4.448222	kilonewtons (kN)
pounds per square inch	6.894757	kilopascals
pounds per cubic inch	2.7144712	kilopascals per centimeters
gallons (U. S. liquid)	3.785412	cubic decimeters
Fahrenheit degrees	5/9	Celsius degrees of Kelvins*

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F-32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F-32) + 273.15$.

CHAPTER 1

INTRODUCTION

This design manual contains comprehensive procedures for the design of "zero-maintenance" plain jointed Portland cement concrete (PCC) pavements. The term "zero-maintenance" as used in this manual is restricted to the structural adequacy of the pavement travel lanes and shoulder system. Activities such as mowing, guard rail repair, striping, providing skid resistance, wear from studded tires, geometric obsolescence, and subsequent widening to increase capacity are not included in the definition of maintenance in this manual. Procedures are included for designing the following pavement components: PCC slab, subbase, shoulders, joints, and subsurface drainage.

1.1 BACKGROUND

The design procedures contained herein were developed at the University of Illinois under sponsorship of the U. S. Department of Transportation, Federal Highway Administration. The overall study title is "Zero-Maintenance Pavement: Performance Requirements and Capabilities of Conventional Pavements." Two technical reports document the development of the design procedures included herein.

1. "Zero-Maintenance Pavement: Results of Field Studies on the Performance Requirements and Capabilities of Conventional Pavement Systems," by M. I. Darter and E. J. Barenberg, Technical Report prepared for Federal Highway Administration, April, 1976.

2. "Design of Zero-Maintenance Plain Jointed Concrete Pavement, Vol. I- Development of Design Procedures," by M. I. Darter, Technical Report prepared for Federal Highway Administration, June, 1977.

The research approach used to develop the design procedures in this manual is illustrated in Figure 1.1. Field studies were conducted and plain jointed concrete pavements were examined in 10 highway agencies and extensive data collected. The types, causes, and ways to eliminate or minimize the significant distresses were identified based upon the experience of local pavement engineers and project staff, previous research studies, and analytical studies conducted as part of the project. Existing design procedures were critically evaluated as to their ability to provide zero-maintenance pavements and their limitations determined. Limiting criteria were determined for zero-maintenance design (including terminal serviceability and allowable fatigue consumption). All available long term performance data of plain jointed concrete pavements were compiled which included 25 sections from the original AASHO Road Test that have been under regular traffic since 1962 on I-80 in Illinois and 12 other projects located in various climatic regions which vary in age from 9 to 34 years. Analytical models and procedures for slab stress/strain computation and fatigue damage were developed, and a new serviceability/performance model was derived. A comprehensive fatigue analysis procedure was developed and verified that gives accumulated fatigue damage at the most critical point in the slab considering both traffic load applications and curling of the slab. A comprehensive yet practical design procedure was developed

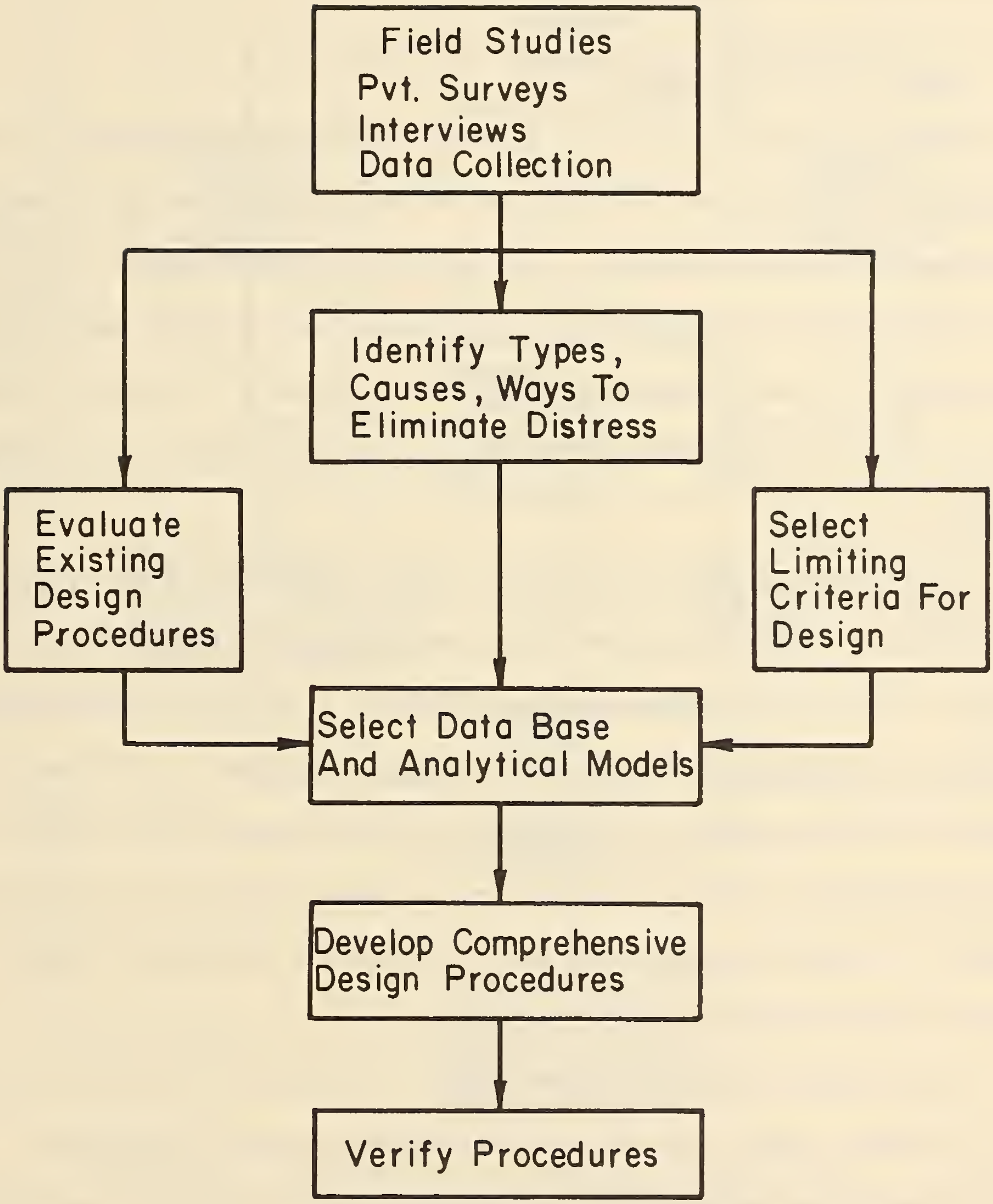


Figure 1.1. Research Approach to Develop Zero-Maintenance Design Procedures for Plain Jointed Concrete Pavements.

that considers both fatigue damage and serviceability loss in selection of the final pavement structure. Design recommendations were also developed for other components of the pavement system, including shoulders, joints, subbase, and subsurface drainage based upon results from the overall study and other research results.

1.2 GENERAL DESIGN APPROACH

The general design approach consists of (1) determination of material properties and structural thicknesses of the PCC slab and the subbase, (2) selection of joint spacing, configuration, load transfer, and sealant, (3) determination of shoulder type and dimensions, and (4) subsurface drainage provisions. These components are designed as a system to ensure compatibility. A flow diagram showing the major design steps is shown in Figure 1.2.

The structural design procedures consist of both a slab fatigue analysis and also a serviceability/performance analysis. The final structure design is based upon both of these considerations to ensure more comprehensive analysis of pavement performance. A computer program is included that provides fatigue damage and serviceability/performance data used for selection of the structural design. The program is named JCP-1 and is written in FORTRAN. A manual procedure is also included to determine structural design based on serviceability/performance.

The procedure shown in Figure 1.2 is iterative, indicating that there are, of course, more than one zero-maintenance design alternative. The design that gives the minimum construction cost is generally selected as the optimum design as long as it meets all of the limiting design criteria.

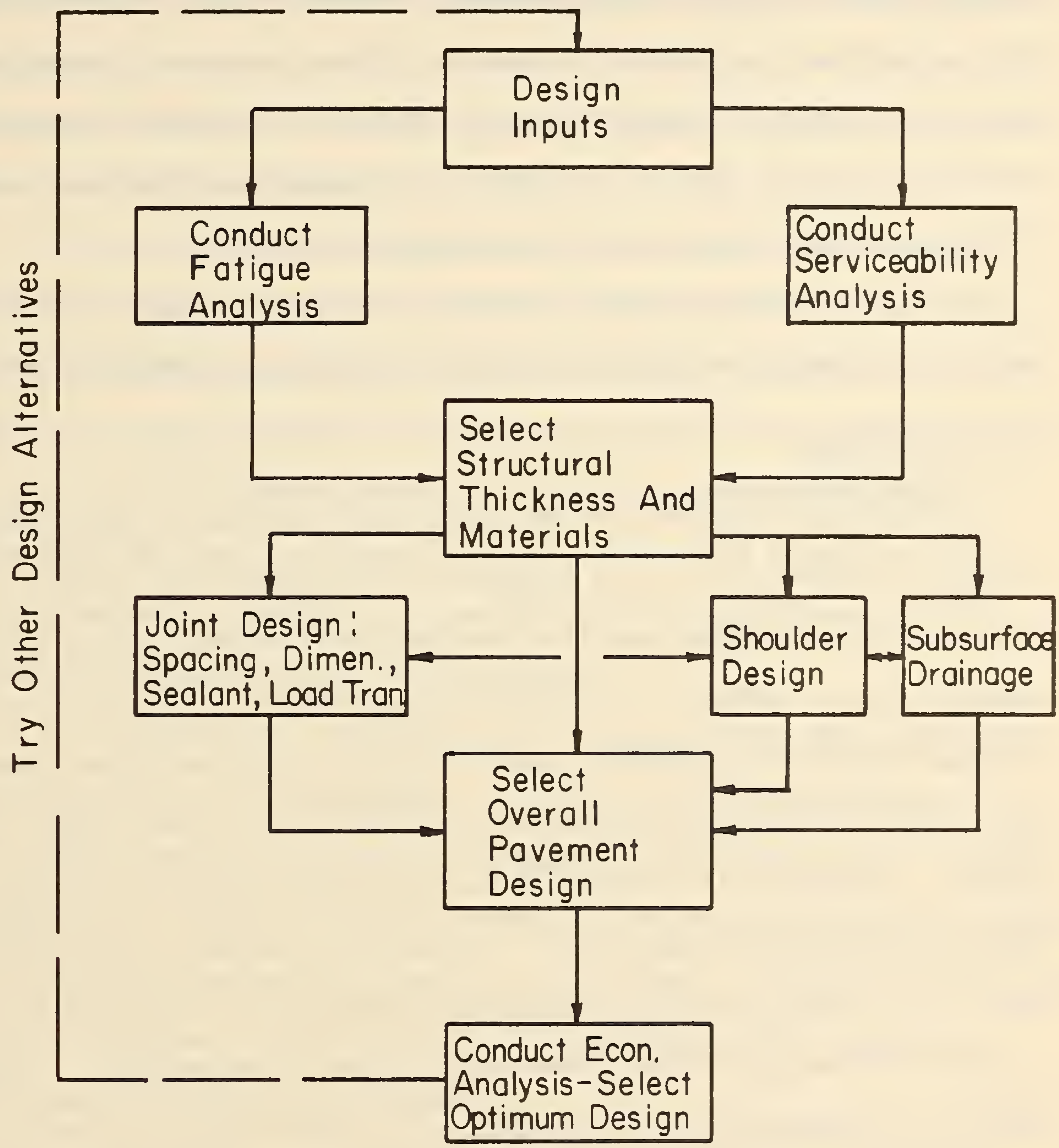


Figure 1.2. Zero-Maintenance Design Procedure for Plain Jointed Concrete Pavements.

The justification for construction of a zero-maintenance design is based upon an economic analysis. The increased costs to construct a zero-maintenance pavement over that of a conventional pavement must be compared with the costs resulting from maintenance, rehabilitation, and user delay if a conventional pavement is constructed. These costs must be computed over a given analysis period such as 20-40 years. Procedures have been developed by Butler (Ref. 4) for FHWA to estimate the maintenance, rehabilitation, and user delay costs of conventional pavements.

A detailed design example is provided in Chapter 6 that illustrates the design approach and results achieved, including a sensitivity analysis.

1.3 LIMITATIONS

An important question that was posed many times during the development of these procedures is: Can a pavement be constructed that actually lasts 20 or more years without requiring structural maintenance such as crack repair, overlay, grinding, joint repair, patching, etc? The field survey revealed that there are several plain jointed concrete and other pavement types that have performed maintenance-free for 15 to 27 years under heavy traffic. Therefore, it is possible to design and construct a pavement with this performance requirement. It requires, however, a most comprehensive and thorough design approach that considers all significant details to tailor the design to local conditions unique to the project. Although detailed recommendations are provided in this manual which are useful to most design situations, there is no substitute for engineering experience, which in certain instances may overrule specific recommendations given herein.

The design procedures contained herein have been developed using the most comprehensive mechanistic models available, and also long term measured pavement performance data. They have been verified using all data available to the project staff and found to give reasonable results as documented in Reference 3. However, there are several aspects that are not as fully verified or developed due to lack of data as others, and these limitations must be carefully considered.

1. PCC Durability - The deterioration of PCC from any of several causes will cause a reduction of pavement maintenance-free life. Although specific recommendations are given to minimize the occurrence, it may not be possible in some regions to prevent deterioration with existing materials.

2. Pavement Growth - The infiltration of a considerable amount of incompressibles into the joints may result in pavement growth at bridge ends. Therefore, high type joint sealants with long performance life must be provided to minimize this occurrence.

3. Joint Faulting - Recommendations herein specify that dowel bars must be used in most all pavements, even when stabilized subbases are used, with the possible exception of pavements with very low truck volumes and pavements located in warm dry climates. The use of a stabilized subbase will reduce faulting but not prevent its occurrence. If dowels are not used in other conditions, joint faulting will occur which will reduce the maintenance-free life of the pavement.

4. Construction - The failure to achieve construction quality as required in the specifications may have a serious effect on reducing the maintenance-free life of the pavement. A thorough inspection of the pavement should be conducted after construction to ascertain if any deficiencies exist, which would result in a reduce maintenance-free life. These should be corrected, if possible.

5. Design in Various Climates - Results from field surveys indicate that plain jointed concrete performs differently in different climates. Some climatic effects can be quantified directly herein, but an empirical climatic regional factor is still needed to help adjust for the difference in performance. This factor is not sufficiently verified and should be adjusted if it does not provide reasonable results in certain climates.

6. Traffic Estimation - A considerable effort has been made to specify how to obtain reasonable traffic estimates for design, the most crucial factor being the axle load distribution. The designer must carefully estimate all traffic inputs using the best sources of data available. Underestimation of traffic to a significant degree may result in a pavement structure not capable of lasting throughout the design period in a maintenance-free condition.

CHAPTER 2

MATERIAL PROPERTIES AND SPECIFICATIONS

2.1 PCC SLAB

The materials in the concrete slab include Portland cement concrete, joint sealing materials, dowels, and tie bars. A high degree of quality control is essential to ensure that the materials conform to the applicable specifications.

2.1.1 Portland Cement Concrete. The mix design and material specifications for the concrete should be in accordance with, or equivalent to, the requirements of AASHO "Guide Specifications for Highway Construction," and "Standard Specifications for Highway Materials."

The concrete mixture must be of high quality due to the relatively severe climatic conditions that the slab must endure over a long time period, and because of the large volumes of traffic that a zero-maintenance pavement is expected to carry. Any significant deterioration of the concrete will result in premature reduction of the maintenance-free life of the pavement. The use of high quality concrete cannot be overemphasized. Many conventional concrete pavements have been observed to have significant concrete disintegration which seriously reduced their maintenance-free life. Current practice for conventional pavements shows minimum cement factors ranging between 5.0 and 6.7 sacks/cubic yard, and maximum water cement ratio of 0.44 to 0.58. Concrete mixture design for zero-maintenance pavements should approach or exceed the most desirable limit of both of these factors to ensure high quality concrete.

Strong consideration should be given to the use of high-strength concrete to minimize durability problems and wear from studded tires, and provide greater strength to reduce fatigue damage. Current practice for conventional pavements shows design flexural strength for 28-day, 3rd point loading ranging between approximately 550 and 700 psi. High strength PCC having approximately 6000 to 9000 psi compressive strength at 56 days (or 750 to 925 psi flexural strength at 28 days) has been used in the U. S. for several years (Ref. 5). Some highway agencies have used high strength concrete, such as the plain jointed concrete pavements constructed in Belgium, which average about 9000 psi compressive strength after 90 days which is roughly equivalent to 900 psi 3rd point modulus of rupture at 28 days. The following recommendations are given with the objective of providing high quality concrete:

Factor	High Quality Recommended Values	High Strength Recommended Values
Maximum water/cement ratio:		
freeze climate	0.47	0.34 - 0.40
non-freeze climate	0.51	0.34 - 0.40
Minimum cement factor:		
freeze climate	6.0 sacks/cubic yard	6.0+
non-freeze climate	5.5 sacks/cubic yard	6.0+
Minimum 28-day, 3rd point loading, mean modulus of rupture	600 psi	

Another factor which must be carefully considered in certain regions is "D" cracking of the concrete pavements. Aggregates that are known or suspected to cause "D" cracking should be avoided. The maximum size of aggregate in these regions should be less than 1 inch and preferably 5/8 inch. Only sound high quality aggregates should be used in the concrete mixture.

Air-entrained concrete should be used in all regions to provide resistance to surface deterioration from freezing and thawing or from deicing salts or to improve workability of the mix. Consideration should be given to use cements other than Type I if materials in the area result in adverse reactions.

2.1.2 Joint Sealing Materials. Only the most durable sealants should be used for sealing joints. The primary, and by far the most important characteristic of the sealant, is to prevent the infiltration of incompressible materials into the joint over a long time period. Another purpose is to minimize the infiltration of surface water into the joint. The infiltration of incompressibles may result in widening of the joint over many years and result in loss of aggregate interlock and pavement growth. Since recommended joint spacing is relatively short (equal to or less than 20 feet) the joint movement is much less than for reinforced concrete pavements. Therefore, the sealant is not required to withstand as great of joint movement.

Two general types of sealants are available: liquid and preformed. Liquid sealants are placed in the joint in liquid form and allowed to set. These include both hot and cold poured types. Field data show that many of these types previously used have given poor performance (1-4 years life) and would not be suitable for use in zero-maintenance pavements. However, newer improved types (particularly thermosetting elastomer types) may be capable of providing longer service lives required for long term maintenance-free performance. Preformed sealants are extruded neoprene seals having internal webs that exert an outward force against the joint face. Long term performance (8-12 years+) of this type of sealant has been found on major highways even with long joint spacings when installation practice is adequate. Preformed seals must be selected to fit the joint shape and joint spacing. This type of sealant was the most recommended type for zero-maintenance pavements by engineers interviewed during the field visits. A major advantage of either the preformed sealants or the newer elastomer thermosetting sealants is that they do not soften at higher temperatures, and consequently do not entrap incompressibles as easily as do the hot poured (or thermoplastic) sealants which soften at warm temperatures. Improved sealants and sealant application techniques are being developed continually. The type available at the time of design that provides the longest term performance in terms of prevention of infiltration of incompressibles should be selected for use in zero-maintenance plain jointed concrete pavements.

2.1.3 Load Transfer Devices. Round dowel bars are recommended for use in transverse contraction joints to prevent faulting. Two types of dowel bars are recommended including plain round steel bars and corrosion proof round steel bars. Their usage and dimensions are discussed in Section 5.1, and depends on climate and traffic.

The conventional plain round steel dowel should conform to AASHO Designation M-227, Grade 70 or higher. It should be coated over its full length with a suitable coating (i.e., grease, asphaltic material, etc.) that inhibits corrosion and reduces friction so that the dowel can move freely. Use of inhibiting paints is not recommended.

Corrosion proof round dowel bars are presently available and are recommended for use as specified in Section 5.1. Stainless steel and Monel clad dowels have been used with success for many years by New Jersey and also in New York (Ref. 6, 7). Joint corrosion and subsequent lockup problems were eliminated through use of these dowels. Specifications for the dowels used in New Jersey are given in Figure 2.1. It is recommended that stainless steel or Monel coatings should extend over the entire dowel to control any joint cracking due to dowel corrosion.

Other methods of rendering dowels corrosion proof are available, but without long term performance data as for the stainless or Monel clad dowel. These methods include pretreatment with various plastic coatings (Ref. 8) and fiberglass dowels.

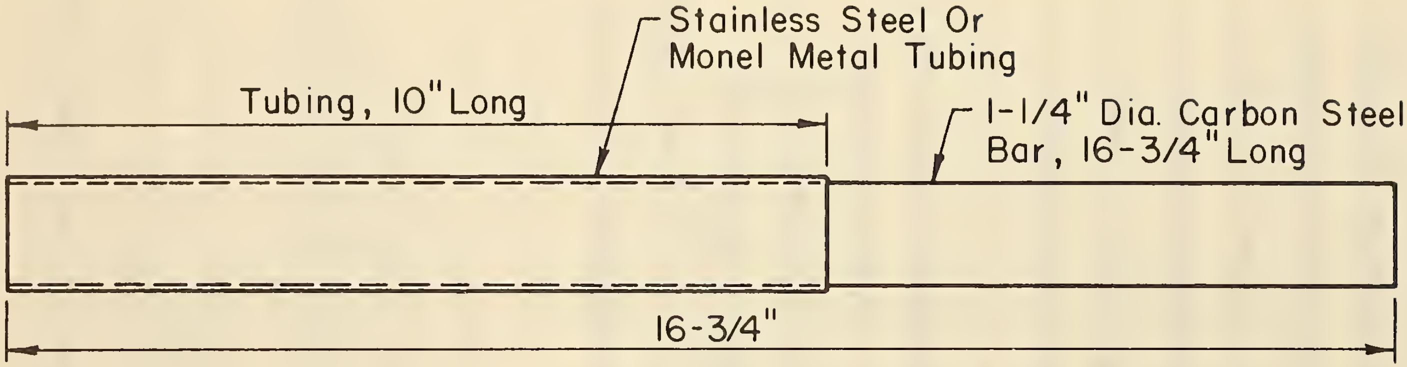
Misalignment of the dowels will reduce joint movement and can result in joint spalling and blowups. Since the joints are spaced relatively close, the misalignment problem is not as serious as with longer joint spacings. Tolerance should be limited to ± 1/4 inch in any direction.

2.1.4 Tiebars. Deformed tiebars should be used to tie lanes together and to tie PCC shoulders to the mainline. Tiebars should be deformed steel bars conforming to AASHO M-31 or M-53, Grade 40.

2.2 SUBBASE

The subbase of the pavement structure consists of one or more compacted layers of granular or stabilized material placed between the subgrade and PCC slab for the following purposes:

- provide uniform, stable, and permanent support
- increase the modulus of subgrade reaction (k-value)
- provide open graded subsurface drainage layer (in wet climatic regions)
- provide an erosion-proof surface



The dowels shall consist of either (a) 1-1/4" diameter solid stainless steel bars, (b) 1-1/4" diameter carbon steel bars encased in stainless steel or Monel metal, or (c) 1-1/4" diameter carbon steel bars that have been impregnated with chromium throughout their exposed surface. The stainless steel shall contain not less than 12 percent chromium. If encased in stainless steel or Monel metal, the thickness of the stainless steel or Monel shall be not less than .01 inches, and the tightness of fit shall be such as to preclude the occurrence of corrosion between the stainless steel or Monel and the underlying carbon steel. If rendered corrosion-resistant by impregnation with chromium, the layer of metal which has been so impregnated shall have (a) an average thickness of not less than .009 inch, (b) at no point a thickness of less than .008 inch, and (c) an average chromium content of not less than 20 percent, by weight. The Contractor shall furnish the Engineer with a certification showing that the means employed for rendering the dowels corrosion-resistant complies with the foregoing specification.

The dowels shall not vary in straightness throughout their length in excess of 1/32". The sliding portion of the dowel shall be of uniform cross section, free from burrs, projections, and any other irregularities that would interfere with free movement in the concrete.

Figure 2.1. Corrosion Proof Dowel Specified by New Jersey.

- prevent pumping of fine-graded soils at joints, cracks, and edges of slab
- minimize the damaging effects of frost action
- provide a working platform for construction equipment to minimize pavement roughness

The types of subbases recommended for zero-maintenance design are as follows when placed directly beneath the concrete slab.

(1) Open graded high quality granular material

(2) Open graded asphalt stabilized granular material

(3) Dense graded cement stabilized granular material

(4) Low cement content Portland cement concrete

(5) Dense graded asphalt concrete

The design philosophy is to use the minimum subbase thickness consistent with satisfying the listed purposes of the subbase. Hence, for a given type of subbase, the minimum thickness that provides a suitable working platform, uniform minimum support, provides erosion resistant surface, and prevents frost action damage, should be selected. The minimum allowable thickness is 4 inches, however. A summary of recommended specifications for the various types of subbases is shown in Table 2.1 and further information is contained in References 9, 10, and 11 for open-graded subbases.

When an open-graded subbase is used, it is necessary to provide a means for preventing the intrusion of the underlying fine-grained roadbed soils. Preventive measures usually consist of providing a layer of suitable material to act as a barrier between the roadbed soils and the susceptible subbase or base course. A minimum thickness of 4 inches of granular filter is usually considered as adequate for this purpose. The need for

Table 2.1. Recommended Specifications for Subbase Materials

Specification	Type A Open-Graded Granular	Type B Open-Graded Asphalt Stabilized****	Type C Dense-Graded Asphalt Stabilized	Type D Dense-Graded Cement Stabilized
Sieve Analysis:				
% passing				
1-1/2"	100		*	100
1"		100		
3/4"	60-90	90-100		
3/8"		30-50		
No. 4	25-50	0-5		65-100
No. 8		0-2		
No. 40	0-20			25-50
No. 200	0-1			5-20
Compressive Strength:				
psi at 28 days				800 min.
Stability:				
Hveem Stabilometer			35 min.	
Marshall-stability			1500 min.	
Marshall-flow			20 max.	
Soil Constants:				
Liquid Limit	25 max.		***	***
Plasticity Index**N.P.	N.P.		10 max.	10 max.

* To be determined by complete laboratory analysis, taking into consideration the ability of the stabilized mixture to resist erosion beneath the slab.

** As performed on samples prepared in accordance with AASHO Designation T-87.

*** These values apply to the mineral aggregate prior to mixing with the stabilizing agent.

**** Approximate asphalt content is 1-1/2-2 percent of 85-100 penetration grade.

preventive measures, as well as the suitability of materials to act as a barrier, may be evaluated by criteria established by the U. S. Corps of Engineers. These criteria suggest that detrimental intrusion may occur when the ratio (D_{15}/D_{85}) is greater than about 5, where

D_{15} = particle size wherein 15 percent of the base or subbase course particles are smaller than this size

D_{85} = particle size wherein 85 percent of the roadbed soil particles are smaller than this size

Several other types of barriers are also available such as special bituminous membranes and lime stabilization of the subgrade.

In areas subject to frost action, special consideration should be given to the requirements for subbase and base materials to reduce their susceptibility to detrimental frost action. Local experience is usually the best means for establishing suitable special criteria for subbase and base materials in such areas. One of the most common special criteria consists of modification of the grading requirements to reduce the percentage of fines, or treatment with a suitable admixture.

The following is provided as a guide to specification requirements for compaction of subbase courses:

1. Untreated aggregate subbase courses should be compacted to a minimum density of 105 percent of AASHO Designation T-99 or 98 percent of AASHTO T-180 density.

2. Cement-treated subbases should be compacted to a satisfactory density determined by the standard method of test, AASHO Designation T-134. The surface must not contain erodable material which generally occurs due to trimming of the subbase.

3. Dense-graded asphalt-treated subbase should be compacted to a satisfactory density based on the test method used to determine the stability of the mixutre, i.e., the Hveem Stabilometer, Hubbard-Field or Marshall.

The subbase width should extend beyond the PCC traffic lane slab in accordance with the subsurface drainage criteria as specified in Section 5.3.

2.3 SUBGRADE

The design procedures in this manual use the elastic modulus of subgrade reaction (k-value) to evaluate the support of the subgrade. The PCC slab thickness is therefore a direct function of the subgrade support. However, there are many soils that can cause serious roughness problems such as those that are excessively expansive, frost susceptible, non-uniform, and that may consolidate. The non-uniformity of subgrade soils is perhaps the most important single factor. For example, the 11 and 12-1/2 inch thick plain concrete slabs at the AASHO Road Test which have been under regular traffic since 1962, and before that heavy Loop 6 traffic, did not show any cracking or joint faulting, but the roughness increased enough over the 16-year period (1958-1974) to cause a loss in serviceability from approximately 4.5 to 3.5. Reasons for this loss may be non-uniform settlement of the foundation (i.e., subbase and/or subgrade).

The following guidelines are recommended for general consideration:

1. The basic criteria for compaction of roadbed soils should include an appropriate density requirement. Inspection procedures should be adequate to assure that the specified density is attained during construction.

2. Soils that are excessively expansive or resilient should receive special consideration. One solution is to cover these soils with a sufficient depth of selected material to overcome the detrimental effects of expansion or resilience. Expansive soils may often improved by compaction

at water contents somewhat over the optimum. In many cases, it may be more economical and effective to treat expansive or resilient soils by stabilizing with a suitable admixture, such as lime, or to encase a substantial thickness in a waterproof membrane to stabilize the water content (Ref. 28).

3. In areas subject to frost, pockets of frost-susceptible soils may be removed and replaced with selected non-susceptible material. Where such soils are too extensive for economical removal, they may be covered with a sufficient depth of suitable material to overcome the detrimental effects of freezing and thawing. The need for such measures and the type and thickness of material required must be determined on the basis of local experience and types of materials economically available.

4. Problems with highly organic soils are related to their extremely compressible nature, and are accentuated when deposits are extremely non-uniform in properties or depth. Local deposits, or those of relatively shallow depth, are often most economically excavated and replaced with sutiable selected material. Problems associated with deeper and more extensive deposits have been alleviated by placing surcharge embankments for preconsolidation, sometimes with special provisions for rapid removal of water to hasten consolidation.

5. Special provisions for unusually variable soil types and conditions may include: scarifying and recompacting; treatment of an upper layer of roadbed soils with a suitable admixture; using appreciable depths of more suitable roadbed soils; overexcavation of cut sections, and placing a uniform layer of selected material in both cut and fill areas; or adjustment in the thickness of subbase at transitions from one soil type to

another, particularly when the transition is from cut to fill section.

6. Although the design procedure is based on the assumption that provisions will be made for surface and subsurface drainage, unusual situations may require that special attention be given to design and construction of drainage systems. Drainage is particularly important where heavy flows of water are encountered (i.e., springs or seeps); where detrimental frost actions are present; or where soils are particularly susceptible to expansion or loss of strength with increase in water content. Special subsurface drainage may include provision of additional layers of permeable material beneath the pavement for interception and collection of water, and pipe drainage for collection and transmission of water. Special surface drainage may require such facilities as dikes, paved ditches, and catch-basins. Drainage provisions are specified in Section 5.3.

7. Certain roadbed soils pose difficult problems in construction. These are primarily the cohesionless soils, which are readily displaced under equipment used to construct the pavement; and wet clay soils, which cannot be compacted at high water contents because of displacement under rolling equipment and require long periods of time to dry to a suitable water content. Measures that have been applied to alleviate such construction problems include: blending with other soils or adding suitable admixtures to sand to provide cohesion, or to clays to hasten drying or increase shear strength; and covering with a layer of more suitable selected material to act as a working platform for construction of the pavement.

CHAPTER 3

STRUCTURAL DESIGN INPUTS

The zero-maintenance structural design procedure requires the selection and/or determination of several important factors related to the PCC slab, traffic, environment, and foundation support. Specific guidelines for the determination of each required input are provided in this chapter. An input guide is given for the JCP-1 computer program in Appendix A. Since the results from the design depend directly upon the inputs, the importance of accurate determination of each input factor is obvious.

3.1 DESIGN CRITERIA

3.1.1 Pavement Zero-Maintenance Design Life. The actual pavement life in years over which it is desired to provide structural maintenance-free performance is input. This time period may range from 1 to 40 years. Normally, the design would range from 15 to 40 years, but in certain instances a shorter interval may be desired. The program cannot accept fractions of years, such as 20.5 years. Only whole years should be input.

A design life can be separated into two or more analysis periods if conditions warrant. For example, consider a pavement under design for 30 years. If it is expected that legal load limits will increase significantly after 10 years, the program could be run for the first 10 year period with one axle load distribution, and then the program could be re-run for the next 20 years with a modified axle load distribution, and other necessary changes in input parameters.

3.1.2 Initial Serviceability Index After Construction. A value of 4.5 is typical for good construction practice. However, poor construction could result in a mean serviceability index ranging from 4.5 to less than

4.0. Serviceability index measured on other newly constructed jointed concrete pavements could be used as a guide. A value of 4.5 is recommended as a typical value for usual construction practice.

3.1.3 Terminal Serviceability Index for Zero-Maintenance. This serviceability index is for terminating maintenance-free life, not major rehabilitation. Field data indicate that plain jointed concrete pavement generally receives maintenance on heavily trafficked highway if the serviceability index is less than 3.0. A value of 3.0 is recommended for zero-maintenance design.

3.1.4 Time After PCC Slab Placement that Pavement is Opened to Traffic. This time input is very significant in affecting fatigue damage of the slab. The sooner the pavement is opened to regular traffic, the lower the modulus of rupture, and therefore, fatigue damage is higher. This time period is for opening to regular mixed traffic and not to construction traffic. If the pavement will be used as a haul road by the contractor soon after placement, an analysis can be made over the haul period to determine if significant fatigue damage occurs. This damage can then be added to that accumulated during the regular design period.

3.1.5 Month Pavement is Opened to Traffic. The month must be specified during which the pavement is expected to be opened to traffic. This input keys in other monthly data such as the k-value, seasonal truck traffic percentage, and thermal gradients. The following coding key should be used:

January	1	July	7
February	2	August	8
March	3	September	9
April	4	October	10
May	5	November	11
June	6	December	12

3.1.6 Years During Which Summary of Fatigue Damage and Serviceability Data Will be Printed. A summary of fatigue damage and serviceability data for any desired year of the design analysis period can be obtained. Damage is printed out for each month, day/night, and total for the given year. The summary also gives the serviceability index at the end of the year under consideration, and the total accumulated 18,000 pound equivalent single axle loads to the end of the year under consideration. All these results relate only to the specific design lane under consideration.

3.1.7 Years During Which Comprehensive Fatigue Output Will be Printed. A comprehensive summary of fatigue damage for each month of any desired year can be obtained. This output provides the following data for each month of the year, day and night: load stress for each axle load group, curl stress, flexural strength, number of applications to failure (from PCC fatigue curve), number of applied axle applications, and fatigue damage for each axle load. This information is not required for design and therefore the designer would usually not print out this information in routine design. It may be desirable to obtain this detailed fatigue information, however, for determining which loads are causing the most fatigue damage, magnitude of strength, etc.

3.2 SLAB PROPERTIES

3.2.1 Slab Thickness. Any number of trial slab thicknesses can be selected for analysis. Based upon the results of this trial, other thicknesses can be tried if needed until limiting design criteria are met (maximum fatigue damage and minimum serviceability index). Slab thicknesses required for zero-maintenance will normally range between 9 and 14 inches, depending on many factors. The program is set up so that the designer can input several slab thickness values and obtain complete results for each thickness by adding appropriate cards at the end of the original data deck to specify other trial thicknesses as indicated in Appendix A, input guide.

3.2.2 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 of the slab in that during the daytime thermal gradients through the slab may range as high as 3.0°F/inch. 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 joint spacing for plain concrete may vary from 10 to 20 feet, but 15-17 ft. (4.6-5.3 m) is the recommended maximum. If a random joint pattern is used, the length of the longest slab should be input for design. Complete joint design details are provided in Section 5.1.

3.2.3 Mean PCC Modulus of Rupture. The mean modulus of rupture at 28 days as determined by the test procedure specified in AASHO Designation T-97, using 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. As recommended in Chapter 2.0, a minimum cement factor of approximately six sacks per cubic yard is required for most regions for durability, which would give modulus of rupture values towards the high side of this range. Alternate designs using a range of concrete strengths may be developed to compare the economics of design. Agencies using compressive strength for design and construction control can use the following relationship to determine the modulus of rupture from compressive strength. This relationship was derived from strength correlation studies (Ref. 3):

$$FF = 10.0\ (CS)^{0.5}$$

where FF = modulus of rupture, 3rd point loading, psi

CS = compressive strength, psi

3.2.4 Coefficient of Variation of PCC Modulus of Rupture. The modulus of rupture of the concrete varies from point to point in the slab and this variation has significant effect on pavement performance (Ref. 13, 14). Therefore, it is important to consider this variability in zero-maintenance design where a high degree of reliability must be obtained. The coefficient of variation is defined as follows:

$$\text{coefficient of variation (\%)} = \frac{\text{standard deviation}}{\text{mean modulus of rupture}} \times 100 \qquad (3.1)$$

Many transportation agencies have studied the quality control of concrete and have information available for their construction procedures and specifications. Field data indicate that the coefficient of variation ranges from approximately 5 to 25 percent for excellent to poor quality control, respectively. A mean of about 12 percent can be considered typical for highway paving, and most projects range between 10 and 15 percent. It is recommended that construction control be adequate to limit the coefficient of variation to 15 percent or less. A general guide relating the coefficient of variation of concrete to descriptive quality control levels is as follows:

Level of Quality Control	Coefficient of Variation - %
Excellent	less than 10
Good	10 - 15
Fair	15 - 20
Poor	greater than 20

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

$$F_{28} = FF - C * \frac{Fcv}{100} * FF \tag{3.2}$$

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:

$$F_A = 1.22 + 0.17 \log T_2 - 0.05(\log T_2)^2 \tag{3.3}$$

where T_2 = time since the pavement slab was constructed, years

Consequently, the modulus of rupture used to determine fatigue damage at a given time is given by the relationship:

$$F = F_A * F_{28} \tag{3.4}$$

3.2.5 PCC Coefficient of Thermal Expansion. The coefficient of thermal expansion of the Portland cement concrete is used in the analysis of curling stresses. A typical range is 4×10^{-6} to 6×10^{-6} ins./°F, with a mean of approximately 5×10^{-6} ins./°F.

3.2.6 PCC Modulus of Elasticity. The modulus of elasticity of the concrete is used in the serviceability/performance and fatigue analysis, and ranges from approximately 4 to 6×10^6 psi. It is approximately related to the concrete strength by the following expression (Ref. 3):

$$E_c = 14.4\, W^{1.5} FF^{0.77} \tag{3.5}$$

where W = unit weight of the concrete slab, pounds per cubic foot

FF = modulus of rupture, psi

A typical value of 5×10^6 psi is usually used in design.

3.3 TRAFFIC

Traffic data are needed to estimate the number of applications of single and tandem axles for each load group throughout the design period. These data are used in PCC slab fatigue analysis and to compute the equivalent 18,000 pound single axle load applications and serviceability loss.

The prediction of traffic for design purposes must rely on information from past traffic, modified by factors for growth and other expected changes. Most states accumulate past traffic information in the format of the Federal Highway Administration W4 loadometer tables, which are tabulations of number of axles observed within a series of axle load groups. These tabulations are in a convenient form for use in fatigue analysis and for conversion to equivalent 18-kip single axle load applications. Special consideration must be given to "heavy" axle loads that are outside legal limits (overloads). The effect of the overloads on the life of the concrete slab is very serious and must be fully considered in zero-maintenance design.

3.3.1 Average Daily Traffic at Beginning of Design Period. The average annual number of vehicles (truck and automobile) that use the highway daily in both directions at the beginning of the design analysis period, when the highway is opened to regular traffic is input.

3.3.2 Average Daily Traffic at End of Design Period. The average annual number of vehicles that use the highway daily in both directions at the end of the design analysis period. The average daily traffic is assumed to increase uniformly from the beginning to end of the analysis period. If traffic projections indicate very definite non-linear increase with time, the design period may be divided into two or more periods and each analyzed separately, however this is normally not necessary as it will not usually affect the resulting design significantly.

3.3.3 Percent Trucks of ADT. The number of trucks expressed as a percent of average annual daily traffic over the entire design analysis period is required. If pick-ups and panel trucks are included in this percentage, their effect must be included in the axle load distribution.

3.3.4 Percent Trucks in Heaviest Traveled or Design Lane. The lanal distribution of trucks varies with many factors including number of lanes, urban/rural location, traffic volume, and percent trucks. This parameter can be best estimated through manual vehicle counts on the existing or similar highways in the area. The approximate lane distribution can be estimated using the following equations for the various types of highway. These equations were developed by the Georgia D.O.T. (Ref. 15), and were independently checked at a few locations and found to give reasonable predictions with measured data:

(a) Four Lane Rural

$$LD = 96.39 - 0.0004V \tag{3.6}$$

(b) Four Lane Urban

$$LD = 95.76 - 0.0005V \tag{3.7}$$

(c) Six Lane Urban

$$LD = 60.76 - 0.0004V + 1.3174T \tag{3.8}$$

where LD = percent total trucks in one direction in heaviest traveled lane (i.e., 100 percent indicates all trucks in heaviest traveled lane)

V = traffic volume in one direction (use average ADT over design period ÷ 2)

T = percent trucks of ADT

Eight and ten lane urban freeways have lane distribution values ranging from approximately 40 to 60 percent.

An important consideration with regard to the heaviest traveled lane is that the required structural design for the other lanes may be significantly less. <u>The lane distribution factor can be varied to design each lane separately, if desired</u>.

3.3.5 <u>Percent Directional Distribution</u>. The percent of all vehicles in one direction is normally always 50. This parameter converts the two-directional average daily traffic to one-directional traffic.

3.3.6 <u>Mean Axles Per Truck.</u> This parameter can be computed using data from manual counts of W4 loadometer tables by dividing the total number of truck axles that pass over a section of the highway (single axle plus tandem axles which are counted as one axle) by the number of trucks that pass the same section. The value of mean axles per truck range from 2.1

to 3.0 depending upon the traffic mix. When pick-ups and panels are excluded, it ranges from about 2.5 to 3.0 with a mean of 2.75 for major highways.

3.3.7 Percent Trucks During Daylight. If the same number of trucks uses the highway during daylight as during night, the value would be 50 percent. However, truck percentage is usually slightly greater in the daytime, ranging from 50 to about 65 percent. This value can be determined from manual counts.

3.3.8 Mean Distance from Slab Edge to Outside of Truck Dual Tires. The distance specified here is illustrated in Figure 3.1. This value can be estimated from visual observations taken on either the existing highway or on a similar highway as long as either has paved shoulders. The mean lateral distance has a significant effect on the number of "edge" loads and therefore fatigue damage of the PCC slab.

This parameter should be measured for local conditions, and only general guidelines are given as to the typical range of the mean distance. If heavy trucks travel on the average down the center of the lane, the mean distance would be 24 inches (for a 12 foot wide lane and an 8 foot wide truck). However, considerable evidence indicates that when there is a paved shoulder and no lateral obstructions, there is a definite shift of 3 to 12 inches toward the slab edge, which gives a mean value for D of 12 to 21 inches. Bureau of Public Roads measurements at 15 locations in 1956 for concrete traffic lanes and paved shoulders showed an average of 11 inches (Ref. 16) for two lane highways, and studies by Emery in 1975 (Ref. 17) showed a mean of approximately 16-18 inches on rural four lane interstate highways. The lateral distribution is approximately normally distributed with a standard deviation of 10 inches.

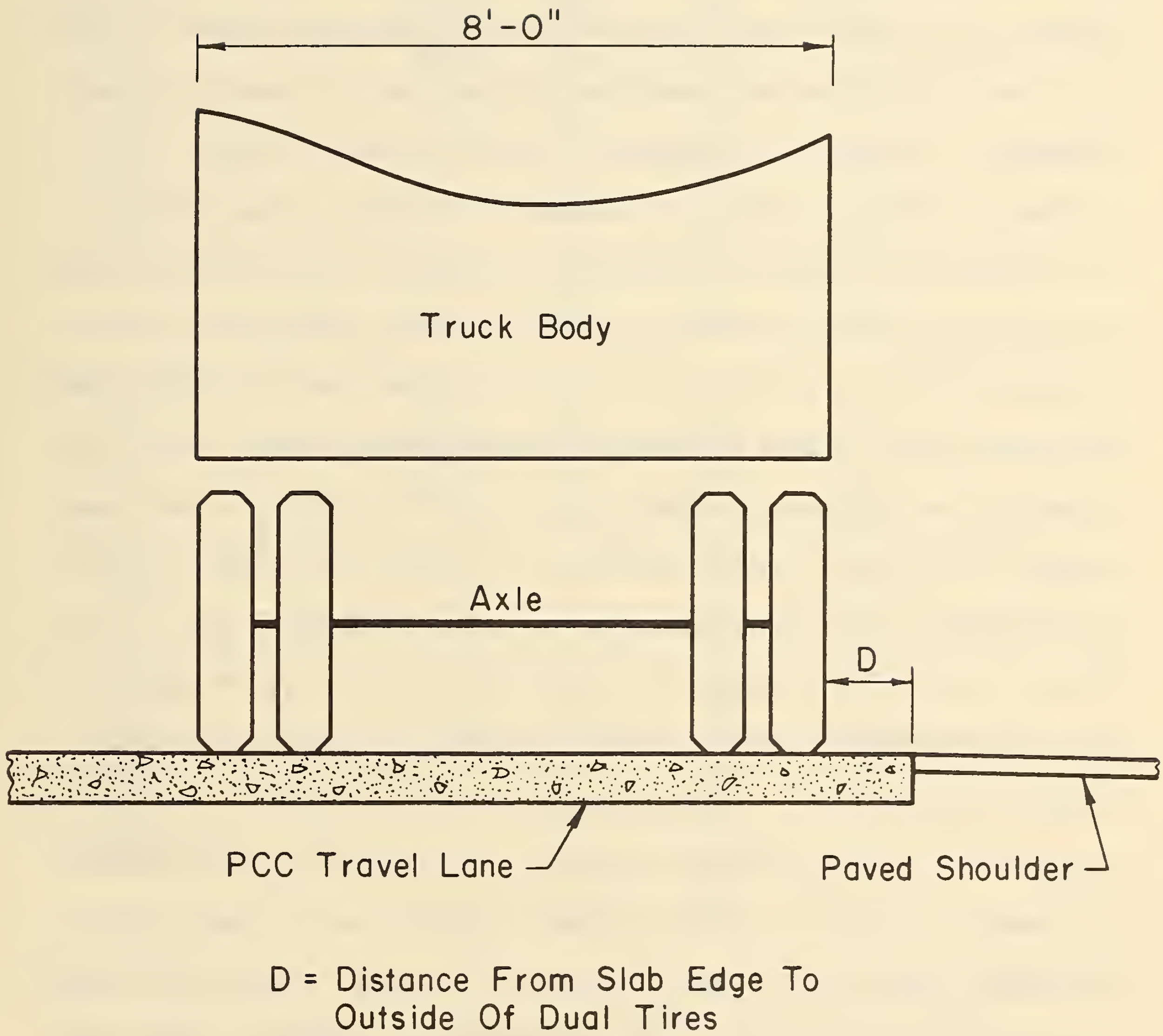


Figure 3.1. Illustration of the Mean Distance from Slab Edge to Outside of Dual Tires.

3.3.9 Axle Load Distribution. The average percent of total load applications occurring within specified load groups (usually 2000 pound ranges) must be estimated for the entire design analysis period. If a legal load limit change is expected, it should be included in the analysis. Most important by far is the distribution of loads in the heavy axle load groups (i.e., above 18,000 pound single and 32,000 pound tandem). Results from the field surveys and interviews indicate that for nearly all major highways, a significant percentage of axles are above the legal limits. Estimates indicate the total percentage of axles above these values at 3 to 20 percent. Data from loadometer stations do not usually give accurate estimates of the overload distribution due to enforcement, and an accurate estimation of the upper load distribution can only be obtained from spot weight studies or from police enforcement tickets. Data were obtained from enforcement weight tickets for a few months on the freeway system in Chicago, Illinois, during 1975. Single axle weights ranged up to 38,000 pounds and tandem axles ranged up to 56,000 pounds. Axle load data were also obtained from various states for urban freeways. The axle load distribution obtained from the Chicago weighings is shown in Column 2 of Table 3.1. Average heavier axle load distributions from other areas of the U. S. are shown in Column 3, and lighter load distributions are shown in Column 1. These axle load distributions are considerably different, especially in terms of maximum axle load. These distributions can be used as general guidelines in determining an estimated axle load distribution for a given pavement. An overall average distribution is shown in Column 4.

Table 3.1. 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.

The axle load distribution for axle loads above 18 and 32 kips for single axle and tandem axle, respectively, can be computed using any of these distributions. The percent of single axles and the percent of tandem axles over these limits must be specified, however. For example, if 3 percent single axle loads were greater than 18-kips, the percentage bewteen 22 and 24-kips is computed using, say, Column 4 as:

$$0.03 * 17.1 = 0.513 \text{ percent}$$

An example computation of the entire load distribution is given in Section 6.1.3.

It is recommended that spot weight studies be conducted on the existing or similar highways to establish the existing distribution, and then that this distribution be modified to account for any anticipated legal load increases or other load changes over the design analysis period.

3.3.10 Monthly Truck Percentage. The truck volume may vary from season to season and month to month over the year. This input requires that a percentage be assigned to each month within the year with the total summing to 100. For example, if truck percentage is equal in each month, the input percentage for each month is 100/12 = 8.33%. However, if the truck percentage was about 10 percent higher in four summer months and equal during the remainder of the year, the monthly truck percentage would be approximately 9.2 in four summer months and 7.9 during the remaining 8 months.

3.4 FOUNDATION SUPPORT

3.4.1. Modulus of Foundation Support (k) for Each Month. Westergaard's modulus of subgrade reaction (k) is used in this manual. It represents the load in pounds per square inch on a circular load area divided by the elastic deflection in inches of the plate. The elastic k-value may be obtained through direct measurement with repetitive static plate loading tests performed on the foundation soil in accordance with AASHO designation T-221 using a 30-inch diameter plate. The elastic k-value is used in this manual because when it is used in conjunction with the finite element stress program, the computed stress agrees well with "measured" stresses (computed from measured strains). Use of the gross k-value gives computed stress values that are considerably higher than "measured" stress values. However, direct measurement of k is expensive and time-consuming and normally can only be measured for one degree of saturation of the soil. Therefore, procedures are provided to estimate the k-value as a function of soil type and degree of saturation. The k-value must be input for each month of a typical year for use in the fatigue analysis.

(a) k-value of subgrade: The elastic k-value of the subgrade depends upon many factors including soil type, degree of saturation, distance to bedrock, water table level, etc. Procedures are included to obtain approximate k-values for use in design that are a function of soil classification type using the AASHTO method, and the degree of saturation of the soil. The values 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 were developed for the AASHTO classification types in a previous extensive study conducted at the University of Illinois (Ref. 18).

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 3.2 and 3.3 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 following approximate k-values may be used for design for A-1 and A-3 materials:

A-1   400 pci

A-3   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.

The degree of saturation of compacted subgrade soils ranges generally from 70 to 90 percent. The degree of saturation can be calculated from the following equation:

$$S = \frac{w100}{\left[\frac{62.4}{\gamma_d} - \frac{1}{Gs}\right]} \tag{3.9}$$

where S = degree of saturation, percent

w = water content of soil, percent of dry weight

γ_d = dry bulk density of soil, pcf

Gs = specific gravity of soil

(b) 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 determined using Figure 3.4 for non-stabilized granular materials, Figure 3.5 for asphalt-treated granular materials, and Figure 3.6 for cement-treated granular materials. These

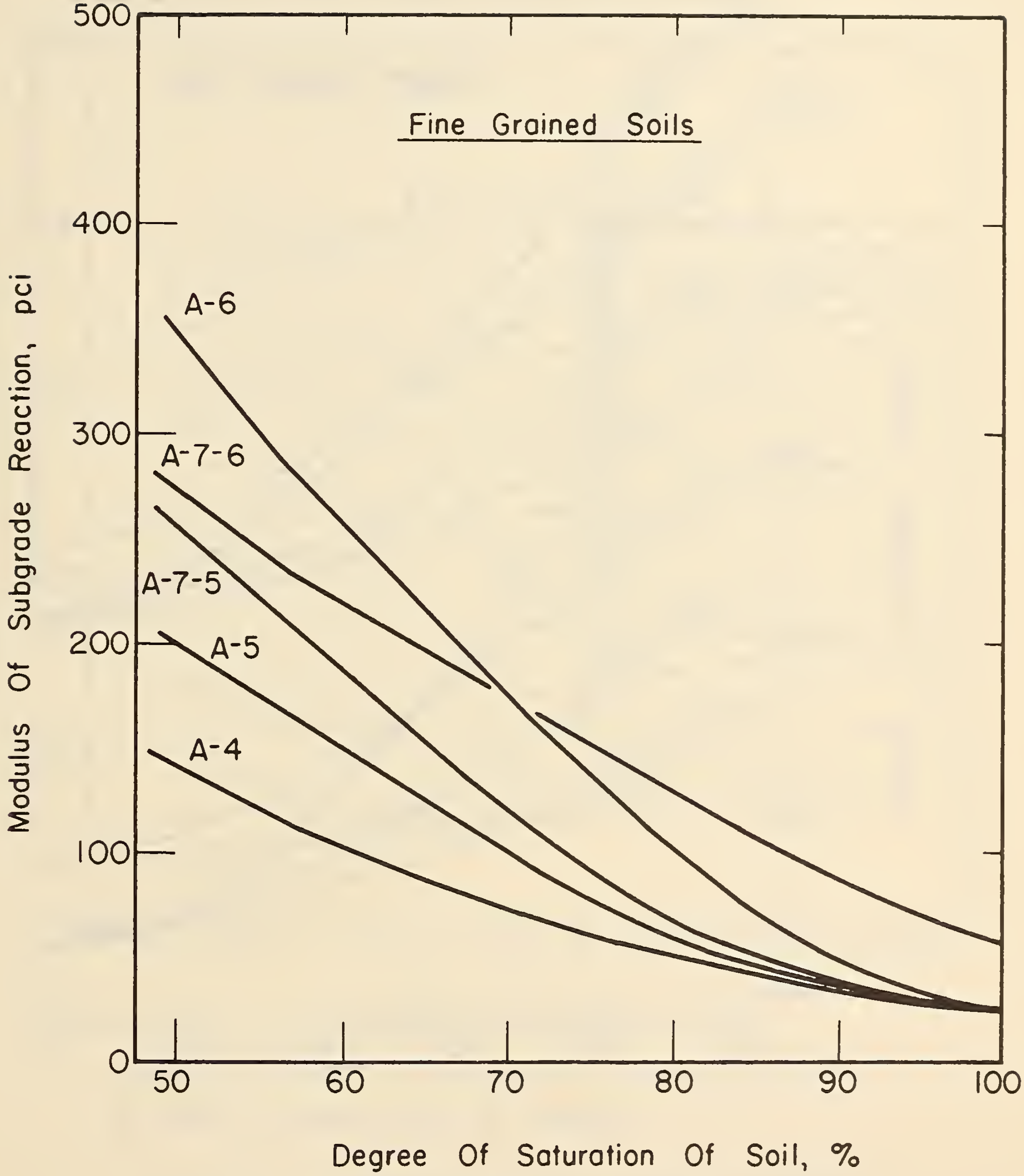


Figure 3.2. Elastic k-Values of AASHTO Classification Fine-Grained Soils.

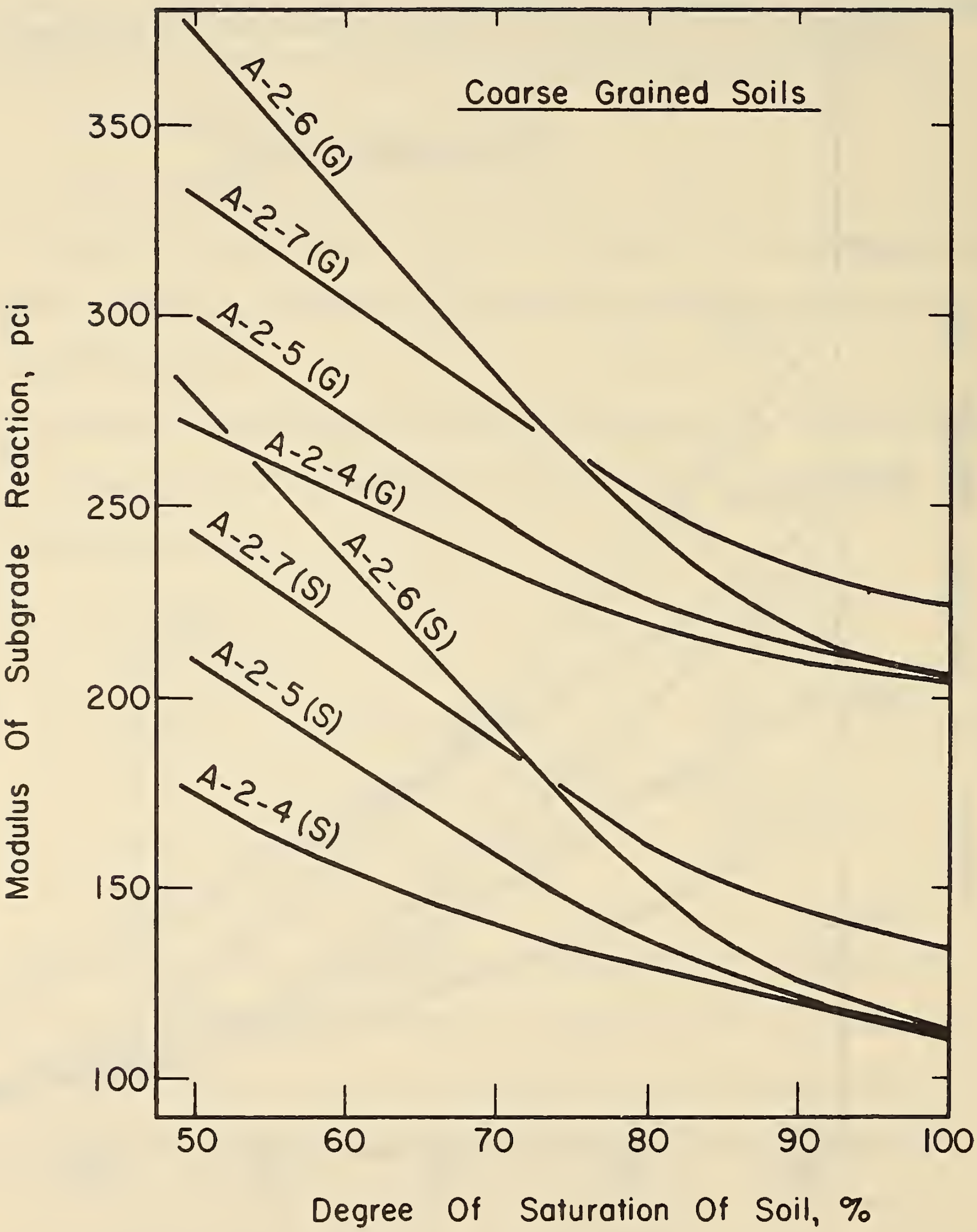


Figure 3.3. Elastic k-Values of AASHTO Classification Coarse-Grained Subgrade Soils (G refers to gravelly and S refers to sandy soils).

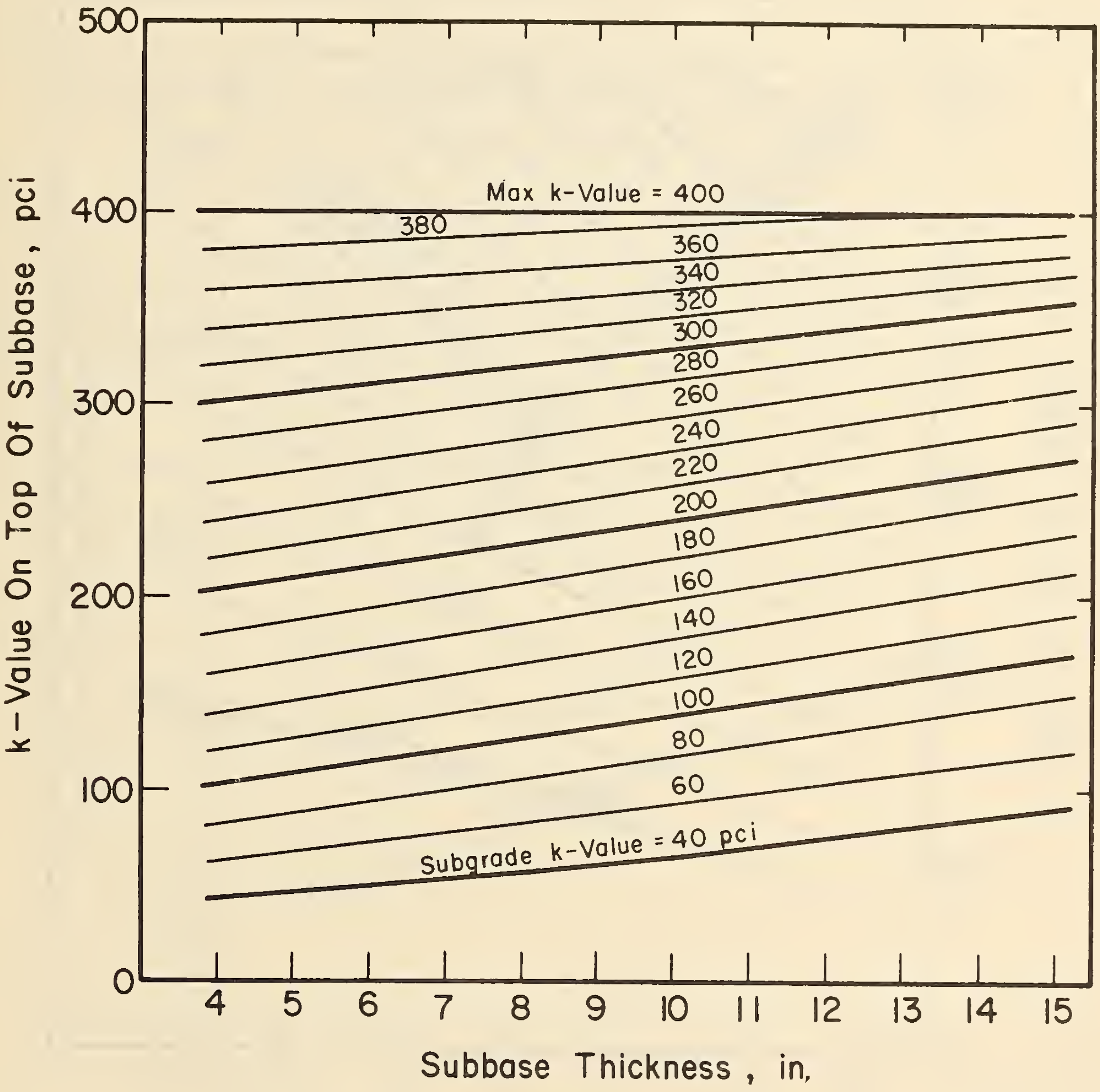


Figure 3.4. Elastic k-Value on Top of Granular Subbase.

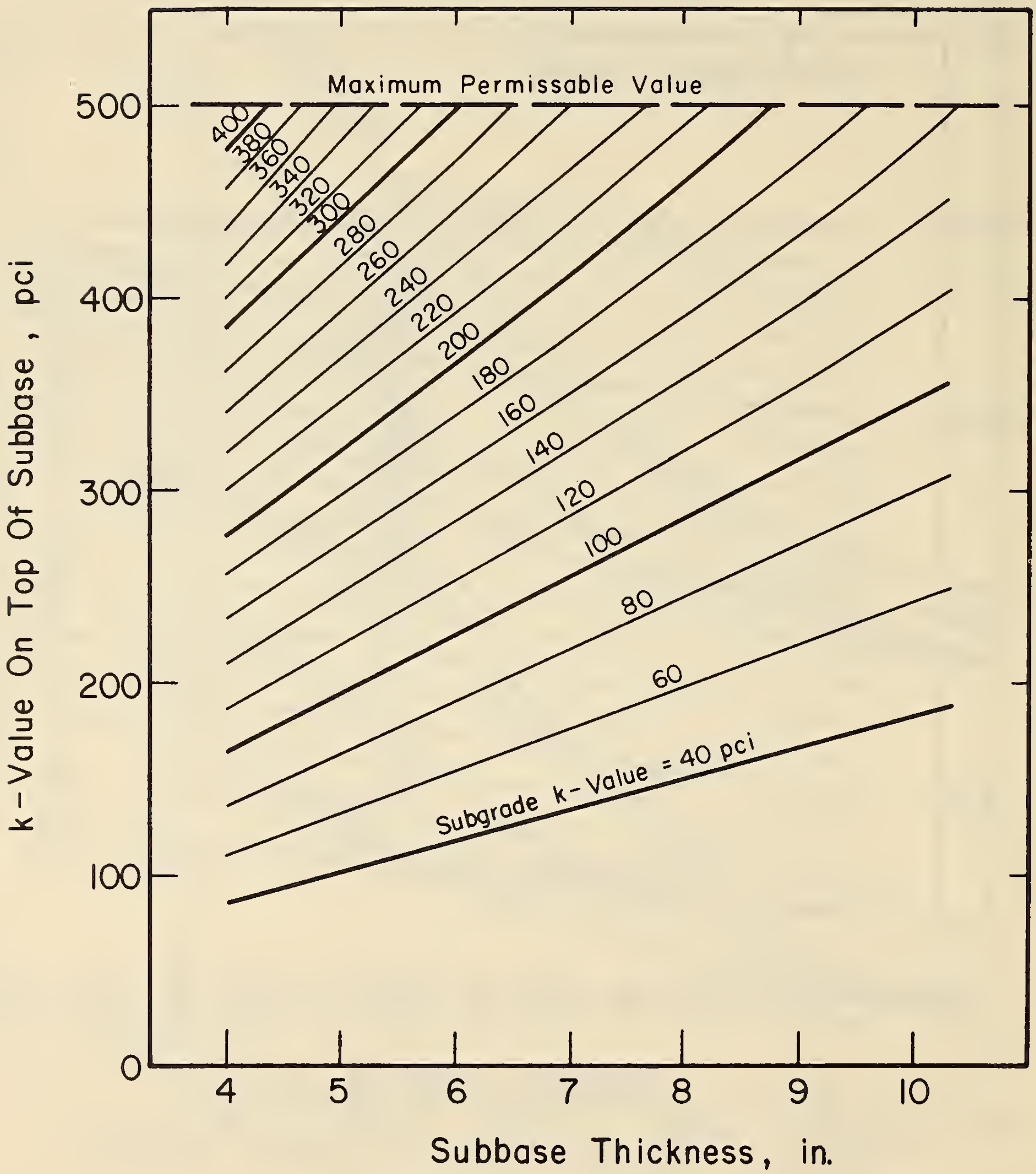


Figure 3.5. Elastic k-Value on Top of Asphalt Stabilized Granular Subbase.

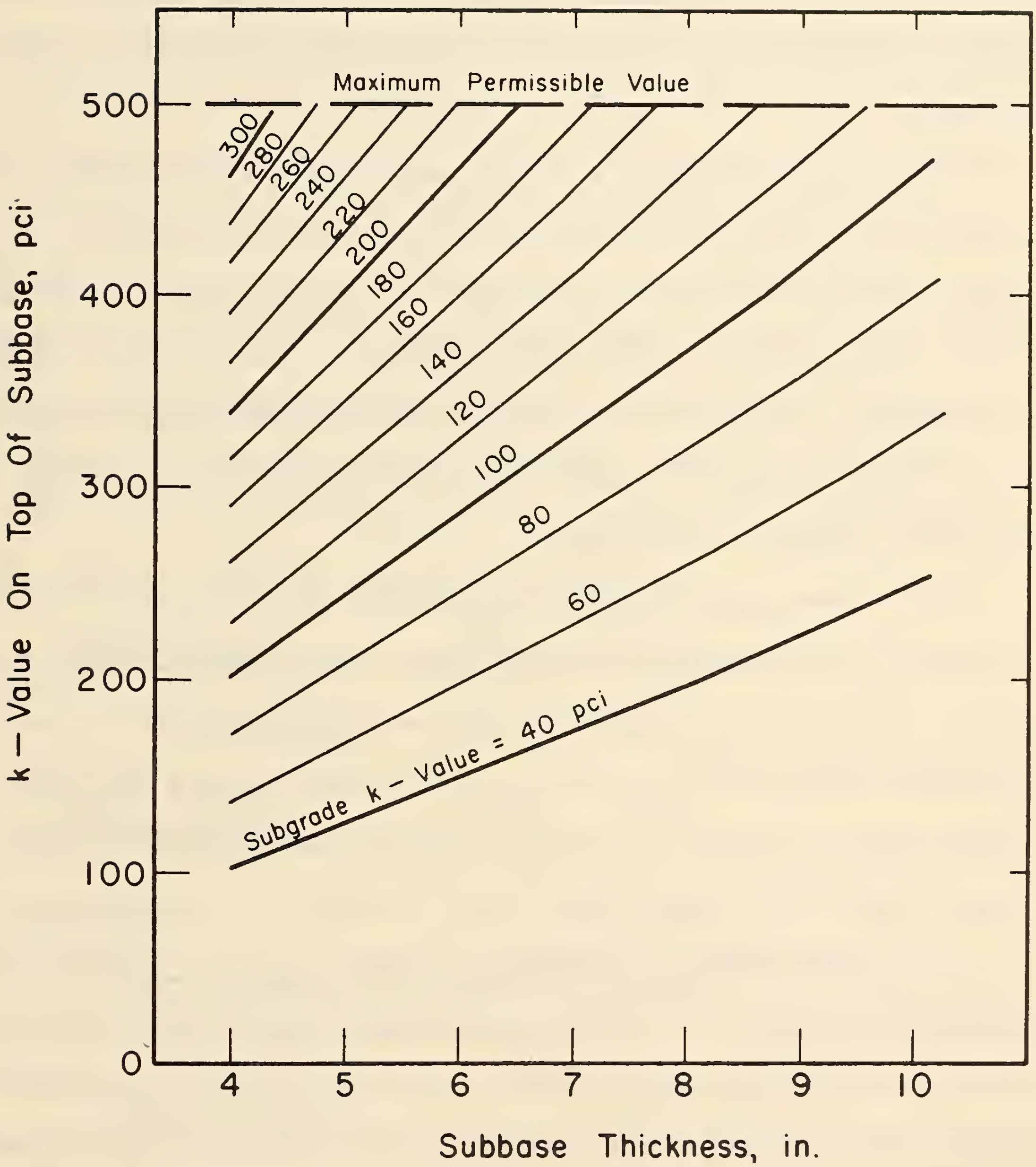


Figure 3.6. Elastic k-Value on Top of Cement Stabilized Subbase.

curves were developed using elastic layer theory. The k-value of the subgrade soil and the thickness and type of subbase must be known to determine the k-value on top of the subbase which is the value to be input on a monthly basis into the program. The thickness of the subbase should be such as to provide a k-value of at least 100 pci and preferably 200 pci during any month throughout the year to provide adequate structural support and to minimize deflection of the slab to reduce joint faulting potential.

The k-value determined in this manner should not be reduced to account for possible erodability and pumping, since any loss of support of the subbase is handled directly by the erodability factor described in Section 3.4.3. The k-values as determined using these procedures have been compared with available field measurements and the correlations developed by the Corps of Engineers and have been found to give similar values for typical degrees of saturation.

The designer can use Figures 3.4 - 3.6 to determine the k-value on top of two or more layers of subbase (where either both layers are granular or the lower layer is granular and the upper stabilized) by applying the same procedures over again using the k-value on top of the first subbase layer as the k-value of the "subgrade", and determining the k-value on top of the second subbase layer as before.

3.4.2 Design Modulus of Foundation Support (k) for Serviceability/Performance Analysis. A "design" k-value must also be selected for use in the serviceability loss procedure. This value should be selected by averaging the monthly k-values over the nine months that have the lowest values.

3.4.3 Erodability of Foundation. The amount of erosion of the subbase at any time is expressed as the width in inches of a rectangular strip parallel to the slab edge that has no contact with the pavement slab. An illustration of this situation is shown in Figure 3.7. The erodability in inches at the end of the design analysis period is input into the program. The erodability at the beginning of the design period when it is opened to traffic is assumed to be zero in the program. The amount of erodability at any time after the pavement is opened to traffic is linearly interpolated between the initial and final erodability factors.

The erodability of the subbase will depend on many factors, including subbase type, available moisture, subsurface drainage, shoulder type, etc. Subbases that are densely graded and contain considerable fines may pump significantly in a wet region. For example, an erodability of up to 60 inches was experienced for the dense graded granular subbase at the AASHO Road Test. Some estimated values that may be considered for design are as follows for PCC pavements having either full depth asphalt concrete or PCC shoulders tied to the pavement slab (provision of a totally non-erodable subbase is not believed to be possible):

Subbase Type	Climatic Region, inches			
	WF	W	DF	D
Granular - Dense Graded	36	36	24	12
Open Graded	24	24	12	6
Stabilized Granular (Asphalt or Cement)	12	12	6	6

3.5 ENVIRONMENTAL

3.5.1 PCC Slab Thermal Gradients for Each Month. The thermal gradient in the PCC slab is defined as follows:

$$G = \frac{T_{top} - T_{bottom}}{H} \tag{3.10}$$

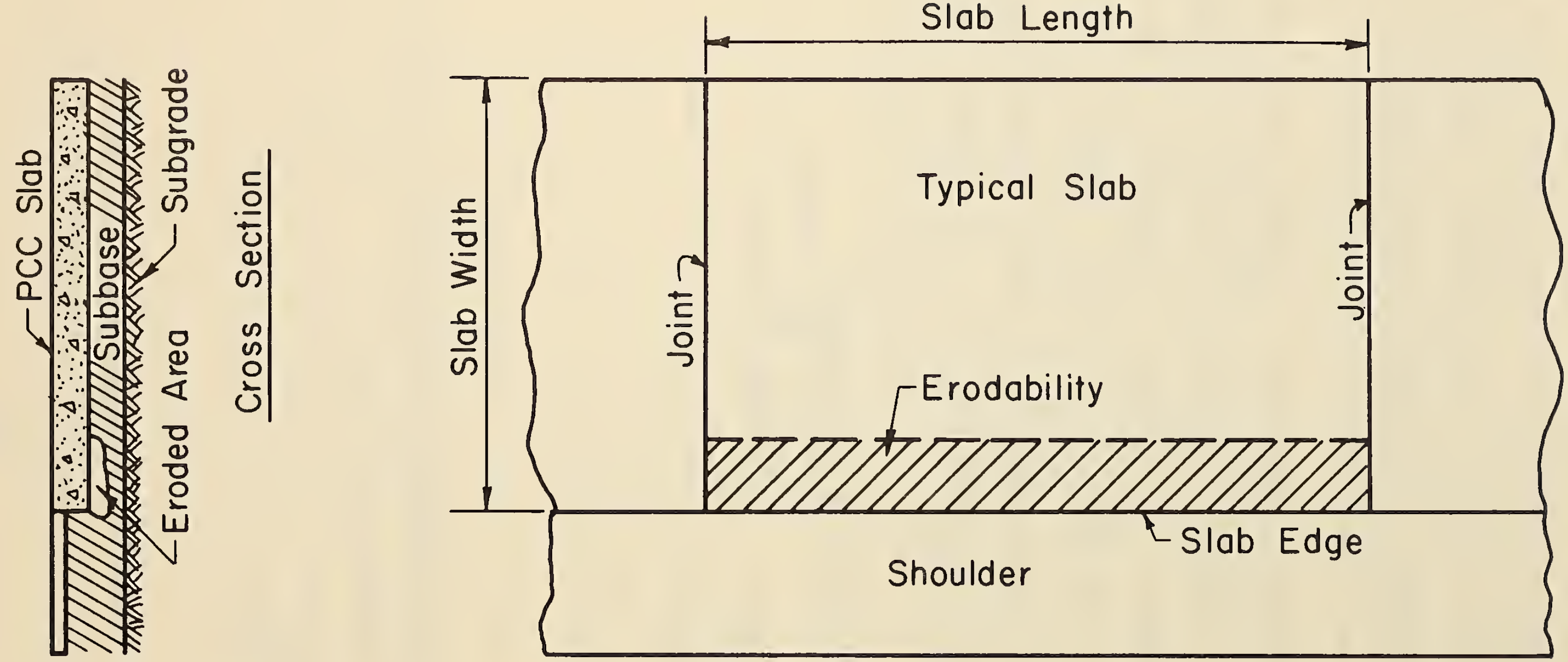


Figure 3.7. Illustration of Erodability of Slab.

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 is 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 results in tensile stress at the bottom of the slab, and a negative gradient results in compressive stress at the bottom of the slab. 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).

The temperature gradient varies continually throughout a 24-hour period and varies from month to month. An <u>average</u> monthly positive gradient (called daytime gradient) and an <u>average</u> monthly negative gradient (called nighttime gradient) are used in design. A summary of thermal gradients for three geographically different regions is given in Table 3.2. A definition of the climatic regions is given in Table 3.3. These mean monthly gradients were computed using an accurate temperature model developed by Dempsey (Ref. 19, 27) which has been verified with actual data from several sources. The mean values were determined by averaging the gradients calculated for every three hours throughout the day and throughout the night for three locations over a year's time. These values are <u>means</u>, and therefore less than the maximum values (of say, 3.0 °F/in.) commonly used. These values may be used for design if measured data are

Table 3.2. 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 3.3. 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

*Generally in areas having a mean Freezing Index > 0 (Ref. 64).

not available. Results show that the termal gradients can be linearly interpolated between 8 and 12 inch slabs for any desired thickness between, or for a greater thickness. Therefore, the inputs required for the program include the mean thermal gradients for each month, both daytime and nighttime, for two slab thicknesses such as 8 and 12 inches (102 and 305 mm). The program will then interpolate to compute the gradients for the slab thickness under consideration.

3.5.2 Climatic Factor. The climatic factor is a value ranging from 0.1 to somewhat greater than 1.0, and is defined as follows:

$$CF = \frac{W_{18(\text{computed})}}{W_{18\ (\text{actual})}} \tag{3.11}$$

where

CF = climatic 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 given in Appendix B.

W_{18} (actual) = total accumulated number of equivalent 18,000 pound single axle load applications to pass over pavement, determined from traffic data (1 pound = 4.45 newtons).

The analysis of performance of several plain jointed concrete pavements located in regions different from the site of the AASHO Road Test showed that those located in different climatic regions performed significantly different. A definition of climatic regions is given in Table 3.3. Those located in warm dry regions in particular (southern Arizona, southern California, etc.) showed much better performance than was predicted using the regression equation derived using pavements in Illinois. The climatic factor was developed to adjust for this difference in performance.

A summary of the climatic factors computed for the limited number of pavements available is given in Table 3.4. It is emphasized that these values are tentative and therefore somewhat conservative values are recommended for design as indicated. However, it is definitely felt that a climatic factor is necessary to adjust the serviceability/performance equation for regions different than the northern Illinois climate for which it was derived. The climatic factor is only used in the serviceability analysis and not in the fatigue analysis. The climatic factors for the fatigue analysis include the thermal gradients and the monthly foundation support modulus (k).

Table 3.4. Summary of Climatic Factors for Use in Design.

Region	CF Range	$\overline{CF}$	Recommended CF Design
Dry/Non-freeze	0.29 - 0.71	0.47	0.6
Wet/Non-freeze	0.56 - 1.12	0.84	0.9
Dry/Freeze	0.79 - 1.26	1.02	1.0
Wet/Freeze	0.64 - 1.45	1.02	1.0

CHAPTER 4

STRUCTURAL DESIGN

The structural design of zero-maintenance plain jointed concrete pavement involves two independent but complimentary approaches. The structural design is based upon both a serviceability/performance analysis and a PCC slab fatigue analysis. The structural design recommended for construction must meet the limiting criteria of both approaches. Structural design consists of the selection of PCC slab thickness and strength, subbase type and thickness, and joint spacing. The structural design must be compatible with shoulder and subsurface drainage design.

4.1 SERVICEABILITY/PERFORMANCE

A new serviceability/performance model was developed (Ref. 3) 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. 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 roughness 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 12 additional projects ranging in age from 9 to 34 years to help verify the models and determine climatic adjustment factors.

The Westergaard edge load model was used to extend the equation to other conditions similar to the procedure used to incorporate the Spangler corner equation into the original AASHO Road Test equation. The Westergaard edge load model was used since edge loading was found to be the critical loading condition of the slab. The full design model is given in Appendix B. This equation is used in the program to compute the loss in serviceability at the end of each year that the designer specified throughout the design analysis period.

The total accumulated 18-kip ESAL in the design lane is computed at the end of each year specified using the following expression:

$$W_{18} = (ADT)(T/100)(DD/100)(LD/100)(TY)(365)(A)(\Sigma PE/100) \qquad (4.1)$$

where

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

TY = time in years from opening of traffic to end of year under consideration

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

Load equivalency factors for a terminal serviceability index of 3.0 are given in Tables 4.1 and 4.2.

This value (W_{18}) is then used in the serviceability/performance model to compute the loss in serviceability over the period TY. Both the W_{18} and serviceability index is printed out for each year the designer specified, but always for the total accumulated over the design analysis period. These data can then be used to select the minimum PCC slab thickness for limiting serviceability index as described in Section 4.3.

A plot is shown in Figure 4.1 that can be used to solve the serviceability/performance equation manually. The graph can be used to solve for slab thickness for a given total 18-kip ESAL, k-value of foundation, and working stress of PCC concrete. The terminal serviceability for this plot is 3.0 which is recommended for design. To solve for required slab thickness, the chart is entered with total 18-kip ESAL (in millions) that has been adjusted for climatic region, which can be computed using Table 4.3.

Total 18-kip ESAL = (RF)(Total computed 18-kip ESAL/
(used to enter Figure 4.1) computed using Table 4.3)

The slab thickness is then determined as shown for a given modulus of foundation support (top of subbase) and working PCC stress. The working stress (F_{28}) is determined as:

$$F_{28} = FF - C * \frac{Fcv}{100} * FF \tag{4.2}$$

where

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

Fcv = coefficient of variation of PCC, %

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

Table 4.1. Traffic Equivalency Factors for Jointed Concrete Pavement with Terminal Serviceability Index of 3.0 - Single Axles*

Axle Load (kips)	Slab Thickness - Inches							
	8	9	10	11	12	13	14	15
2	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
4	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
6	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
8	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
10	0.09	0.09	0.08	0.08	0.08	0.08	0.08	0.08
12	0.18	0.18	0.18	0.17	0.17	0.17	0.17	0.17
14	0.36	0.34	0.34	0.34	0.34	0.34	0.34	0.34
16	0.62	0.61	0.60	0.60	0.60	0.60	0.60	0.60
18	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20	1.52	1.55	1.57	1.58	1.58	1.58	1.59	1.59
22	2.18	2.29	2.35	2.38	2.40	2.41	2.41	2.41
24	3.00	3.23	3.38	3.47	3.51	3.53	3.54	3.54
26	4.01	4.40	4.70	4.87	4.96	5.01	5.04	5.05
28	5.23	5.80	6.31	6.65	6.83	6.93	6.98	7.01
30	6.12	7.46	8.25	8.83	9.17	9.36	9.46	9.52
32	8.53	9.42	10.54	11.44	12.03	12.37	12.56	12.66
34	10.75	11.72	13.20	14.52	15.46	16.03	16.36	16.54
36	13.44	14.55	16.24	18.08	19.49	20.41	20.95	21.27
38	16.70	17.70	20.00	22.15	24.17	25.56	26.43	26.94
40	20.61	21.50	23.80	26.77	29.50	31.53	32.85	33.66

* Computed using equations derived at AASHO Road Test (Ref. 19).

Table 4.2. Traffic Equivalency Factors for Jointed Concrete Pavement with Terminal Serviceability Index of 3.0 - Tandem Axles*

Axle Load	Slab Thickness - Inches							
(kips)	8	9	10	11	12	13	14	15
10	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
12	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
14	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
16	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08
18	0.14	0.13	0.13	0.13	0.13	0.13	0.13	0.13
20	0.22	0.21	0.21	0.20	0.20	0.20	0.20	0.20
22	0.32	0.31	0.30	0.30	0.30	0.30	0.30	0.30
24	0.46	0.45	0.44	0.44	0.44	0.44	0.44	0.44
26	0.63	0.62	0.62	0.62	0.62	0.62	0.62	0.62
28	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
30	1.12	1.13	1.14	1.14	1.14	1.14	1.14	1.14
32	1.44	1.47	1.49	1.51	1.51	1.51	1.51	1.51
34	1.80	1.88	1.93	1.95	1.96	1.97	1.97	1.97
36	2.23	2.36	2.45	2.49	2.51	2.52	2.52	2.53
38	2.71	2.92	3.06	3.13	3.17	3.19	3.20	3.20
40	3.26	3.55	3.76	3.89	3.95	3.98	4.00	4.01
42	3.87	4.26	4.58	4.77	4.87	4.92	4.95	4.96
44	4.57	5.06	5.50	5.78	5.94	6.02	6.06	6.09
46	5.36	5.95	6.54	6.94	7.17	7.29	7.36	7.40
48	6.25	6.93	7.69	8.24	8.57	8.76	8.86	8.92
50	7.26	8.03	8.96	9.70	10.17	10.43	10.58	10.66
52	8.40	9.24	10.36	11.32	11.96	12.33	12.54	12.66
54	9.70	10.58	11.90	13.11	13.95	14.47	14.77	14.94
56	11.16	12.07	13.57	15.07	16.16	16.86	17.27	17.51
58	12.81	13.72	15.41	17.19	18.59	19.52	20.07	20.40
60	14.67	15.56	17.40	195.0	21.25	22.45	23.19	23.62
62	16.76	17.60	19.59	22.01	24.14	25.67	26.65	27.23
64	19.09	19.87	21.97	24.71	27.27	29.19	30.45	31.22
66	21.69	22.38	24.58	27.63	30.65	33.01	34.61	35.62
68	24.58	25.16	27.44	30.78	34.27	37.14	39.15	40.45
70	27.78	28.20	30.56	34.18	38.16	41.59	44.09	45.73

* Computed using equations derived at AASHO Road Test (Ref. 19).

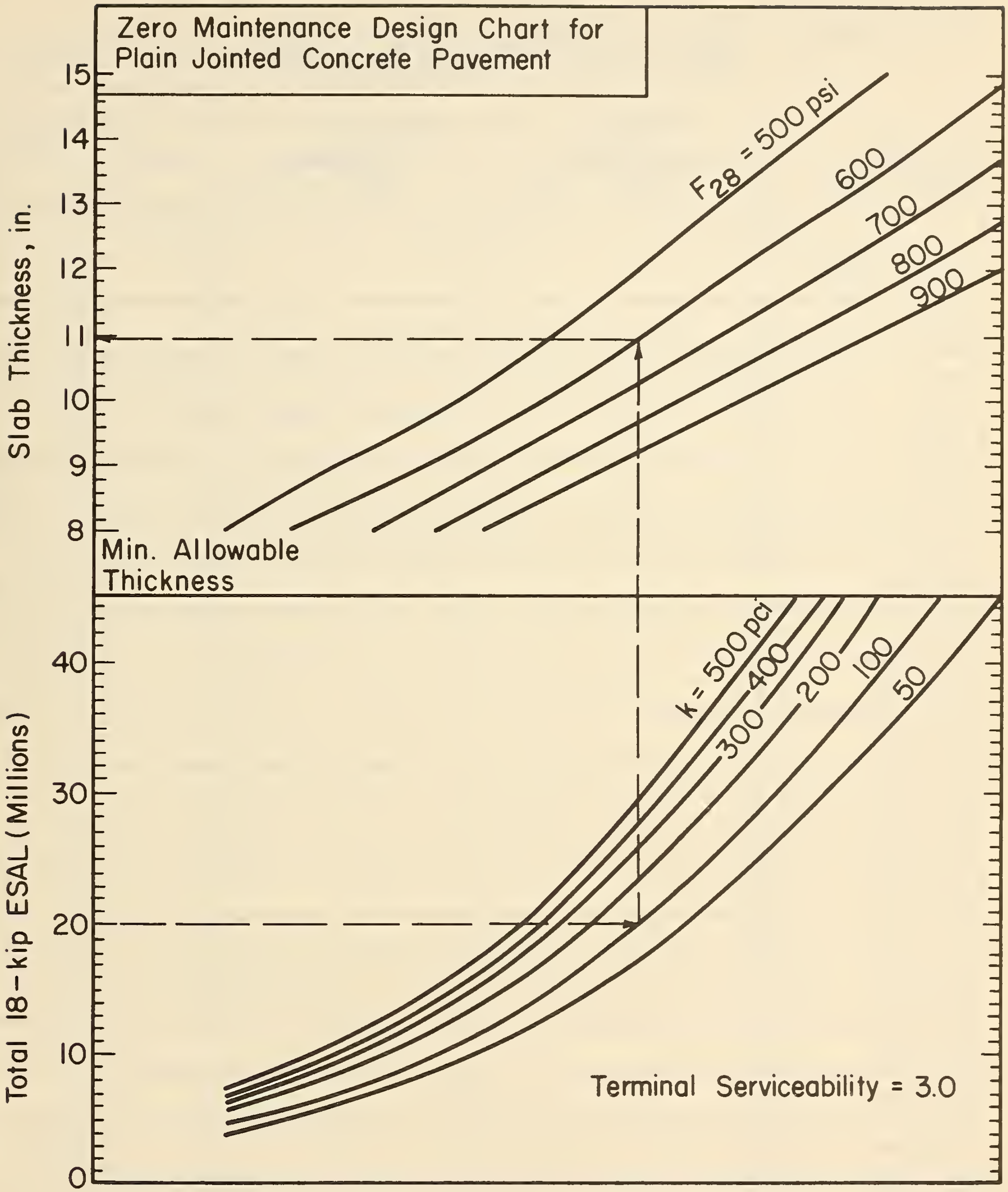


Figure 4.1. Serviceability/Performance Zero-Maintenance Design Chart for Plain Jointed Concrete Pavements.

Table 4.3. Calculation Sheet for Determining Equivalent Single Axle Load Applications in Design Lane Over Design Period.

AXLE LOAD GROUP - KIPS	EQUIVALENCY FACTOR - (E)	PERCENTAGE LOADS - (P)	P X E
Single Axles:			
0-2			
2-4			
4-6			
6-8			
8-10			
10-12			
12-14			
14-16			
16-18			
18-20			
20-22			
22-24			
24-26			
26-28			
28-30			
30-32			
32-34			
34-36			
36-38			
38-40			

Table 4.3. Calculation Sheet for Determining Equivalent Single Axle Load Applications in Design Lane Over Design Period (Continued).

AXLE LOAD GROUP - KIPS	EQUIVALENCY FACTOR - (E)	PERCENTAGE LOADS - (P)	P X E
Tandem Axles:			
0-6			
6-10			
10-12			
12-14			
14-16			
16-18			
18-20			
20-22			
22-24			
24-26			
26-28			
28-30			
30-32			
32-34			
34-36			
36-38			
38-40			
40-42			
42-44			
44-46			
46-48			
48-50			
50-52			
52-54			
54-56			
56-58			
58-60			
60-62			
62-64			

Table 4.3. Calculation Sheet for Determining Equivalent Single Axle Load Applications in Design Lane Over Design Period (Continued).

AXLE LOAD GROUP - KIPS	EQUIVALENCY FACTOR - (E)	PERCENTAGE LOADS - (P)	P X E
64-66			
66-68			
68-70			
TOTALS		100.0	ΣPE

Total accumulated equivalent 18-kip single axle loads over design period:

W_{18} = (ADT)(T/100)(DD/100)(LD/100)(TY)(365)(A)(ΣPE/100)

= ______________________________

Therefore, the required slab thickness for zero-maintenance design can be determined manually using Table 4.3 and Figure 4.1.

4.2 PCC FATIGUE

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, and other required factors as detailed in Chapter 3.

(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. 22) and sum monthly over the entire design period.

$$\text{DAMAGE} = \sum_{k=1}^{k=p} \sum_{j=1}^{j=2} \sum_{i=1}^{i=m} \frac{n_{ijk}}{N_{ijk}} \tag{4.3}$$

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 over day or night 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 damage (or cracking) in actual pavements during the field survey and other research results confirm this result.

The n_{ijk} is computed using the traffic data input to the program for the month under consideration. It is computed using the following expression (note: n_{ijk} is also denoted as NAAL in Chapter 6):

$$n_{ijk} = (ADTm)(T/100)(DD/100)(LD/100)(A)(30)(P/100(C/100)(DN/100)(TF/100)(CON/100) \quad (4.4)$$

where

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

T, DD, LD, A = same as Equation 4.1

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

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

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. 20). The models are documented in Appendix C. The models have been verified using "measured" stresses (computed from measured strains) at the AASHO Road Test. The computed results for load stresses compare well with the measured results using the measured elastic modulus of foundation support (k-value).

The total stress at the bottom of the slab edge with the load located at the edge is computed as follows:

$$STRT = STRL + (R)STRC \tag{4.5}$$

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 thermal curling of slab only

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

An illustration of the location of these stresses is given in Figure 4.2.

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. 21).

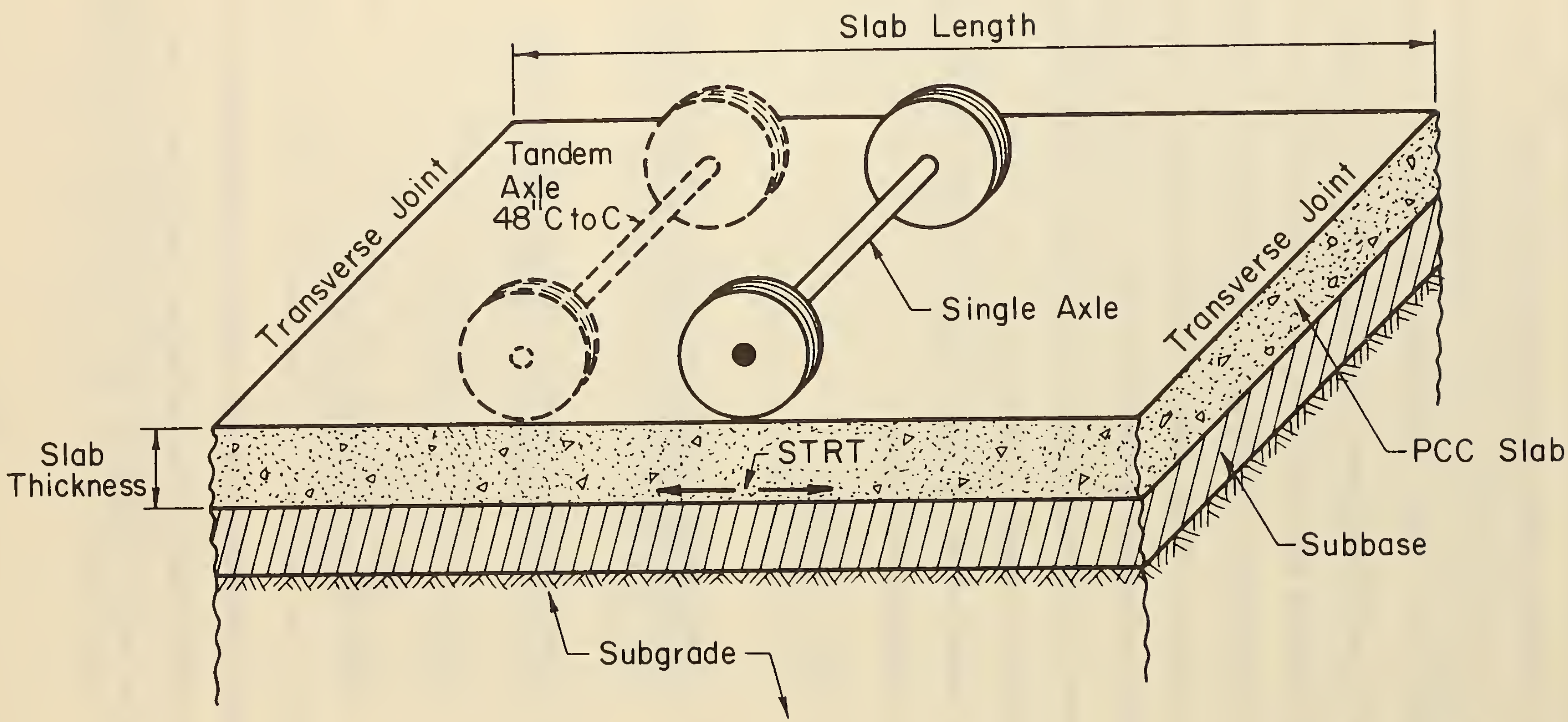


Figure 4.2. Illustration of Location of Loads and Stresses in PCC Slabs.

Data from several PCC fatigue studies were used to develop a relationship between the number of application to flexural failure of PCC and the stress/strength ratio (Ref. 3). The relationship used for design purposes is as follows:

$$\log_{10} N_d = 16.61 - 17.61 \left(\frac{STRT}{F}\right) \qquad (4.6)$$

where

N_d = number of load applications to flexural failure of the PCC used in design

STRT = total stress at bottom edge of PCC slab (Equation 4.5)

F = adjusted modulus of rupture of PCC used for computing fatigue (Equation 3.4)

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 (or 76 percent).

The fatigue damage is computed monthly for both day and night conditions and traffic. The 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 Section 4.3.

4.3 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 as indicated by the serviceability index which is an estimator of the user's acceptability of the pavement.

The procedures used to obtain the serviceability/performance data and fatigue damage data are described in Sections 4.1 and 4.2, respectively. This section describes how to use this data to select an adequate structural design that has a high reliability to provide zero-maintenance performance.

4.3.1 Limiting Design Criteria. Limiting criteria have been determined for zero-maintenance design for fatigue consumption and for serviceability index.

(a) 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.* This value was set based upon fatigue analyses of 37 in-service pavements ranging in age from 9 to 34 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.

(b) Terminal Serviceability: The minimum terminal serviceability index allowed is 3.0. This value was set based upon observations on the 35 in-service pavements. 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.

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* Note: The actual limiting value of DAMAGE as computed from Equation 4.3 is 10^{-4}. However, since this value is very small and inconvenient to use in design, it was multiplied by a scale factor of 10^6 so that the limiting value is 100.

4.3.2 Selection of Alternative Trial Designs. The designer must specify trial structural designs, determine the required inputs, run the JCP-1 computer program, and analyze the output fatigue and serviceability data. The program is written to analyze any number of slab thicknesses and provide outputs for each thickness, while holding all other inputs constant. The designer can therefore examine a range of slab thicknesses for a given traffic, foundation support, and environment with only one run of the program.

An example of fatigue and serviceability results has been plotted in Figure 4.3 for design of major freeway as described in Chapter 6. Trial slab thicknesses of 9, 11, 13, and 15 inches were analyzed, and the data as obtained from the JCP-1 program is plotted as shown, to select minimum slab thicknesses based upon both serviceability and fatigue limiting criteria. The minimum slab thicknesses allowed for a limiting fatigue damage of 100 is 11.7 inches, and the minimum slab thickness allowed for a limiting serviceability index of 3.0 is 12.5 inches. Slabs of any lesser thickness would exceed these limits. For example, if a 10-inch slab were constructed, a serviceability index of about 2.0 would occur at 20 years and a fatigue damage of over 10^4 would occur. These values indicate that considerable maintenance would be required long before the end of the 20 year design period and hence would not be acceptable for zero-maintenance design. A slab thickness of 12.5 inches, would be selected as an acceptable zero-maintenance design in this example.

The program requires the input of a specific structural section as well as material properties, joint spacing, foundation, traffic, and

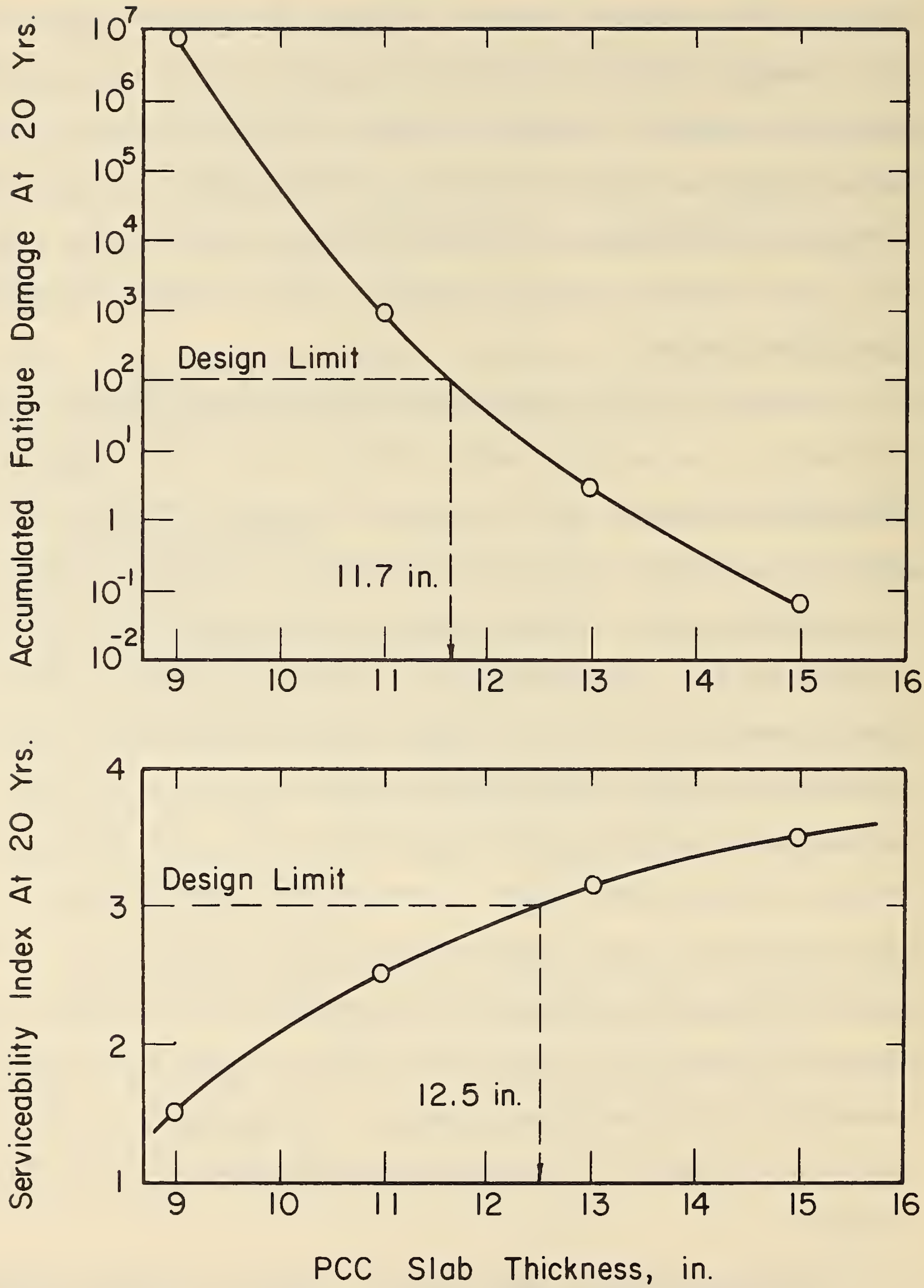


Figure 4.3. Fatigue Damage and Terminal Serviceability Plots Used to Determine Slab Design Thickness (for example given in Chapter 6).

climatic inputs. Parameters which are fixed for a given design situation include: traffic, subgrade support, environmental factors. Parameters which can be controlled by the designer and their typical ranges include:

a. PCC slab - thickness (8 to 14 inches)
modulus of rupture (600-900 psi)
joint spacing (10-20 ft)

b. Subbase - type (granular or stabilized)
thickness (4 to 24 inches)

There are many possible alternatives that can be developed that meet the zero-maintenance limiting design criteria, and several should be examined so that the least cost design that is also compatible with shoulder and subsurface drainage requirements can be selected.

For example, several trial alternatives could be developed for a given situation as shown in Table 4.4. The slab thickness that gives acceptable fatigue damage and terminal serviceability would be selected for each alternative. There are, of course, many other alternatives which may be tried. A detailed example design is provided in Chapter 6 to illustrate the design procedure.

Table 4.4. Example Illustration of Possible Alternate Trial Designs for Given Traffic, Foundation, and Climatic Conditions

Alternative	Joint Space (ft)	Subbase Type	Subbase Thick. (ins)	Strength*** (pci)
1	15	G*	12	600
2	15	G	12	800
3	15	S**	6	600
4	15	S	6	800
5	20	G	12	600
6	20	G	12	800
7	20	S	6	600
8	20	S	6	800

* G = Granular

** S = Stabilized (both cement and asphalt)

*** 28 day, 3rd point modulus of rupture

CHAPTER 5

DESIGN OF OTHER COMPONENTS

All components of the pavement must be designed as part of a system. The results from the structural design have important implications on joint, shoulder, and subsurface drainage design, and these components have significant implication on the structural design. These components must compliment the structural design so that the pavement can withstand both heavy traffic and severe environmental factors without the occurrence of distress. Many conventional pavements have adequate structural designs, but due to inadequate consideration of joints, shoulders, and subsurface drainage have exhibited premature distress and hence reduced maintenance-free life. Design recommendations are provided for joints, shoulders, and subsurface drainage.

5.1 JOINTS

Joints are placed in plain jointed concrete pavements to control transverse and longitudinal cracking. There are several aspects to joint design that must be considered to provide an adequate jointing system. Only contraction type joints are used for regular transverse and longitudinal joints. Expansion joints may be used at structures. Recommendations of major factors are included herein; however, excellent detailed information on joint design and construction can be found in References 24 and 2.

5.1.1 Transverse Joint Spacing. Results from several field tests have shown that as transverse joint spacing increases from 10 feet to 30 feet in plain concrete pavements, the amount of transverse cracking increases very significantly. Comprehensive analytical analyses have shown that the major reason for this increase in transverse cracking is the combination of traffic load stress and curling of the slab due to temperature gradients. Thermal curling stresses increase approximately two times as slab length increases from just 15 to 20 feet, for example. Therefore, transverse joint spacing is an input to the structural design procedure described in Chapter 4.0, so that the combined effects of load and curling can be provided for directly in design. It should also be noted that the PCC modulus of rupture also has a significant bearing on joint spacing, in that the use of higher strength concrete will permit the use of longer joint spacing for the same fatigue damage. A maximum limit for contraction joint spacing is 20 ft. but it is highly recommended to limit spacing to about 15-17 ft. if dowel bars are used and 12-15 feet or less if they are not used so that aggregate interlock can be maintained.

Random joint spacing has been used on many plain jointed concrete pavements and are recommended to prevent rhythmic or resonant responses in vehicles moving at normal freeway speeds. The first spacing pattern used in California was 13-19-18-12 ft intervals. Some states have modified this original spacing pattern such as 9-10-13-14 ft and 17-23-22-16 ft. If random joint spacing is used, the longest spacing should be input in the structural design procedure. A minimum slab length of 7 feet is recommended to minimize slab tilting, however.

5.1.2 Load Transfer at Transverse Joints. The transfer of load at transverse joints in zero-maintenance plain jointed concrete pavements is required to prevent faulting at the joint. It is recommended that load transfer be accomplished through a combination of aggregate interlock and dowel bars. Many heavily trafficked plain jointed concrete pavements have been constructed without dowels, but nearly all of these have shown serious faulting. Some pavements located in dry warm climates, however, have shown long term performance without development of serious faulting. Plain pavements constructed without dowels in wet climates under heavy traffic have nearly always shown serious faulting, however. Even some pavements constructed with dowels in wet regions have shown faulting.

The use of dowel bars is strongly recommended in all wet climates. In addition to dowel bars, the following recommendations are also given (See Ref. 3):

(1) Provide foundation of slab that has monthly k-values greater than 100 pci, and preferably greater than 200 pci. Stabilization of the subbase with asphalt or cement may be necessary to achieve this recommendation.

(2) Provide relatively thick PCC slab (i.e., greater than 10 inches)

(3) Use full depth PCC or asphalt concrete shoulders and subsurface drainage to minimize free moisture and pumpable material.

(4) Minimize joint spacing (less than or equal to 17 ft)

Dowel bars may not be necessary in dry-warm climates if the following recommendations are followed (See Ref. 3):

(1) Stabilized subbase with asphalt or cement having k-value greater than 200 pci.

(2) Skewed joints (1:6 or 1:5)

(3) Increase angularity of the coarse aggregate in the PCC.

(4) Provide relatively thick PCC slab (i.e., greater than 10 inches)

(5) Use full depth PCC or AC shoulders and <u>possibly</u> subsurface drainage

(6) Minimize joint spacing (12-15 ft. maximum)

(7) Provide erosion proof subbase surface

However, even if all of these recommendations are followed for dry climates, there is no guarantee that serious faulting will not occur. Additional research is needed to provide more data on the need for dowel bars to prevent faulting on heavily trafficked pavements. If dowel bars are not used on regular transverse joints, they should definitely be placed at a minimum of three joints next to an expansion joint.

Recommended sizes and spacing of dowel bars are given in Table 5.1. An increase in spacing of dowel bars may be acceptable for traffic lanes other than the heaviest traveled lane according to truck traffic volumes.

The use of corrosion proof round steel bars is recommended in wet/freeze climates where a significant amount of deicing salt will be applied. Plain round steel bars may be used in other climates or where corrosion of the plain steel dowel has not occurred. The various types available and specifications are discussed in Section 2.1.3.

5.1.3 Joint Shape and Sealant. Transverse and longitudinal contraction joints can be constructed through either sawing the hardened slab at the proper time or by inserting plastic tape in the slab surface while the concrete is plastic. Plastic tape inserts should only be used where previous long term performance experience has shown that subsequent spalling of the joint (requiring maintenance) does not occur. The use of a combination of plastic tape inserts for transverse joints and sawing of longitudinal joints joints to avoid spalling at the joint intersections may be an acceptable solution.

Dimensions of the joint width and depth for field molded (poured) and preformed sealants are provided and illustrated in Table 5.2 and Figure 5.1.

The width of joint sealant reservoir must be determined based upon the allowable extensibility of the sealant as illustrated in Table 5.2. Potential joint opening must be known to computed the required joint width. The following expression can be used to compute design joint opening:

$$\Delta L = CL[\alpha \Delta T + \varepsilon] \tag{5.1}$$

where

ΔL = joint opening caused by temperature change ΔT and drying shrinkage of PCC.

α = thermal coefficient of contraction of PCC (/°F) (generally 5-6 x 10^{-6}/°F)(9-10.8 x 10^{-6}/°C)

ε = drying shrinkage coefficient of PCC (approximately 0.50 to 2.50 x 10^{-4} in/in.)(cm/cm)

L = joint spacing (ins.)

ΔT = temperature range (for design use temperature at placement minus lowest mean minimum monthly temperature).

C = adjustment factor due to subbase/slab frictional restraint (0.65 for stabilized subbase, 0.80 for granular subbase).

The elastomers have an expansion-compression range of about ± 20 percent at temperatures from -40°F to +180°F. The preformed sealants are designed so that it will always be under at least 20 percent compression in the sawed joint (based upon its uncompressed width). The maximum allowed compression of the seal is 50 percent before a rubber or rubber situation is reached. Thus the seal working range is 20-50 percent.

Table 5.1. Recommended Dowel Bar Dimensions and Spacing

Slab Thickness (ins)	Dowel Diameter (ins)	Total Dowel Length (ins)	Lane Dowel Spacing, ins.* % Truck Lane Traffic < 20%	20 - 49%	> 50%
8	1-1/4	18	12-24	12-18	12
9	1-1/4	18	12-24	12-18	12
10	1-1/4	18	12-24	12-18	12
11	1-1/4	18	12-24	12-18	12
12	1-1/4	18	12-24	12-18	12
13	1-1/4	18	12-24	12-18	12
14	1-1/4	18	12-24	12-18	12
15	1-1/4	18	12-24	12-18	12

* Dowel spacing may be varied depending on percent truck traffic in lane. However, dowel must be placed within 6 inches of slab edge with a minimum spacing of 12 inches to the next dowel bar.

Table 5.2. Recommended Transverse Joint Dimensions for Field Molded (Poured) and Preformed Compression Sealants.

Slab Thickness (ins)	Joint Spacing (ft)	Sealant Reservoir Width (in.)	Sawed Depth (in.)
8	$\leq$ 20	*	2
9	$\leq$ 20	*	2-1/4
10	$\leq$ 20	*	2-1/2
11	$\leq$ 20	*	2-3/4
12	$\leq$ 20	*	3
13	$\leq$ 20	*	3-1/4
14	$\leq$ 20	*	3-1/2
15	$\leq$ 20	*	3-3/4

* Width of uncompressed preformed sealant should be 7/16 inch for a joint reservoir width of 1/4 inch recommended for all slab thicknesses for $\leq$ 20 ft. joint spacing. Width of joint reservoir for field molded (poured) sealant should be based upon design joint opening as illustrated:

Example: Joint Spacing = 15 ft.

Design temperature range = 100°F (temperature at placement munus lowest mean minimum monthly temperature)

Stabilized Subbase

Maximum allowable extension of sealant = 20%

Design joint movement (Eq. 5.1)

$$\Delta L = 0.65 \times 15 \text{ ft.} \times 12\frac{\text{in}}{\text{ft}} [5.5 \times 10^{-6}/°\text{F} \times 100°\text{F} + 1.0 \times 10^{-4}]$$

$$= 0.076 \text{ ins.}$$

Minimum joint sawed width $= \frac{0.076}{0.20} = 0.38$ in.

Use reservoir width = 0.5 in.

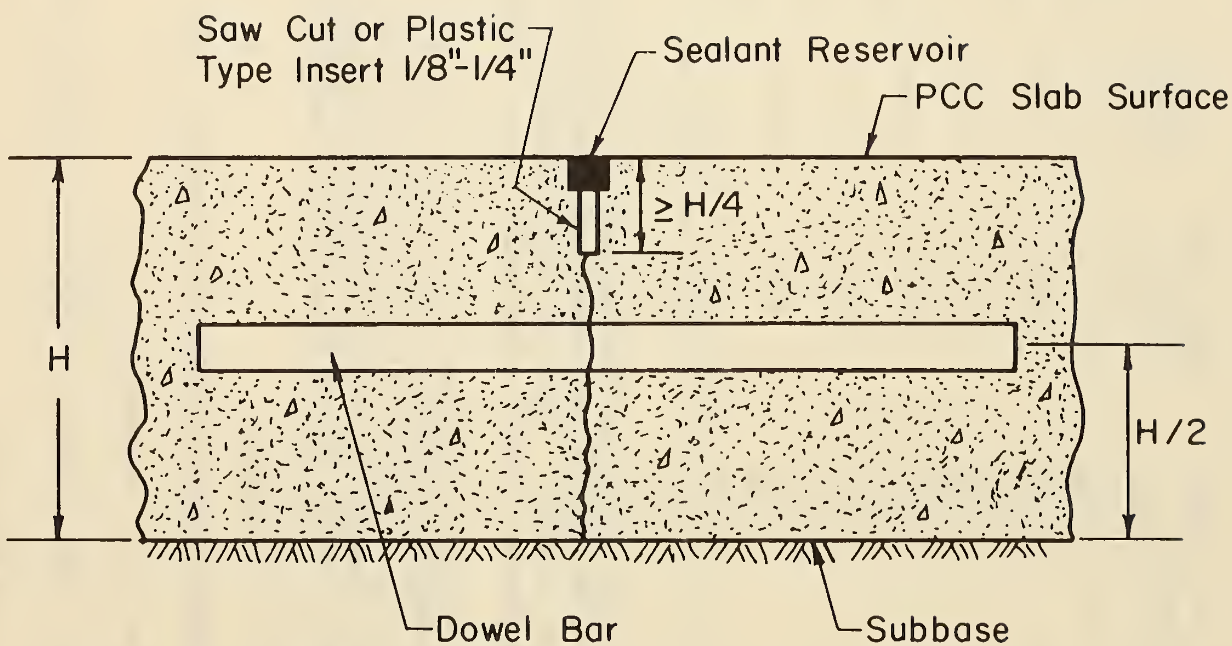


Figure 5.1. Transverse Contraction Joint.

Recommendations for joint sealing materials are given in Section 2.1.2. The following are recommended if plastic tape inserts are used for transverse joints:

(1) Plastic tape is approximately 13-mil. thickness

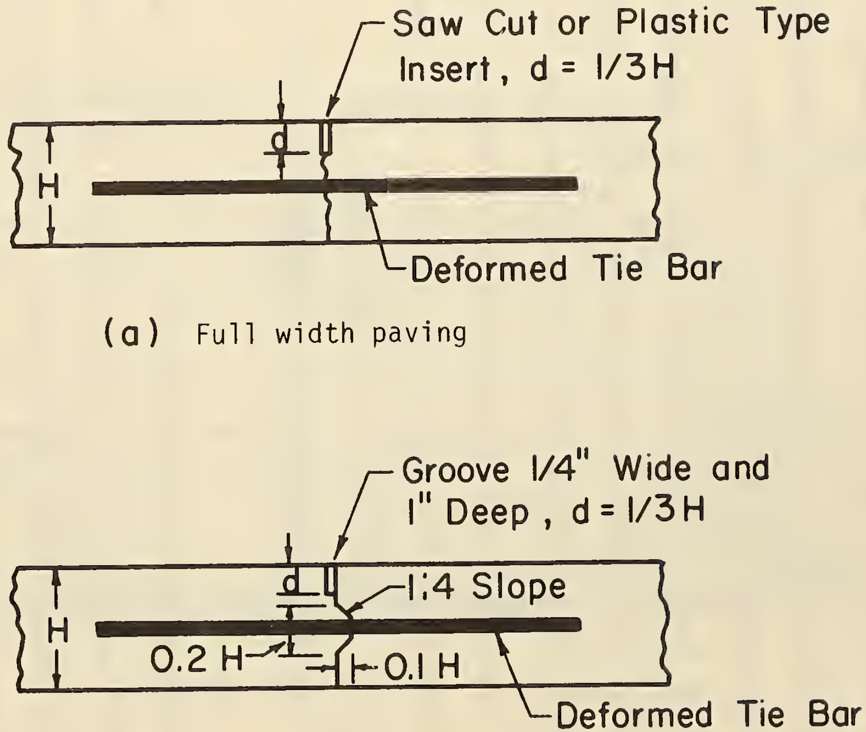
(2) Place tape by automatic machine vertically, and no deeper than 1/8 inch below the slab surface (some tension is needed during installation)

(3) Width of tape is at least 1/4 of the slab thickness.

5.1.4 Longitudinal Joints. Longitudinal joints are provided between traffic lanes to eliminate longitudinal cracking. A longitudinal joint may be of two general types as illustrated in Figure 5.2 depending on whether the paving is full width or less than full width. Recommended dimensions are indicated in Figure 5.2. When the paving is full width, longitudinal joints may be formed by sawing or by impressing a plastic tape (but only if long term performance indicates that the impressed tape will not cause joint spalling). The depth of the saw cut or insert must be at least 1/3 the slab thickness to control longitudinal cracking.

Deformed rebars are used in all longitudinal joints as recommended in Table 5.3. A maximum of four lanes (approximately 50 feet) may be tied together. If a greater width is designed, a longitudinal doweled joint must be provided so that excessive shrinkage stresses do not cause longitudinal cracking.

5.1.5 Transverse Construction Joints. These joints are provided at planned interruptions such as at the end of a day's paving, at leave-outs for bridges, and where emergency interruptions suspend paving for 30 minutes or longer. Construction joints should always be placed at



(a) Full width paving

(b) Lane(s) at a time

Figure 5.2. Longitudinal Joints Between Traffic Lanes.

Table 5.3. Tiebar Dimensions and Spacing.

Slab Thickness (ins)	Tiebar Size (ins)	Tiebar Spacing Distance to nearest free edge or to nearest joint where movement can occur 12.5 ft or less (ins)	16 ft (ins)	25 ft (ins)	30 ft (ins)
8	1/2 x 30	30	25	16	13
9	5/8 x 30	30	30	22	18
10	5/8 x 30	30	30	19	16
11	5/8 x 30	30	28	18	15
12	5/8 x 30	30	25	16	13
13	5/8 x 30	30	24	15	12
14	5/8 x 30	30	22	14	11
15	5/8 x 30	30	20	13	11

a regular transverse joint. A butt-type joint is recommended with dowel bars with dowel size as used at transverse joints.

5.1.6 Transverse Expansion Joints and Lugs. Transverse expansion joints are only used at fixed objects such as bridge ends. The expansion joint must always be doweled with the same size and spacings used for transverse contraction joints. In some areas, the infiltration of incompressibles into the transverse joints has resulted in pavement growth at the expansion joint. The major purpose of the sealant placed in the transverse contraction joints is to prevent infiltration of incompressibles, and therefore if the sealant performs its function, pavement "growth" should not occur. If this has occurred in the region where the zero-maintenance pavement is to be constructed, consideration may need to be given to use of a stabilized subbase or possibly even lugs similar to those used for CRCPs as described in Reference 25.

5.2 SHOULDERS

Shoulders must be designed to provide zero-maintenance performance, since repair of a shoulder failure usually requires closing of the adjacent traffic lane. Results from field studies indicate that the only shoulder types adjacent to jointed concrete pavements that have low maintenance performance are PCC and full depth asphalt concrete (AC). Full depth asphalt concrete shoulders have shown generally good performance in the various states, but have required longitudinal joint maintenance often and have exhibited some separation and cracking at the longitudinal lane shoulder joint in freeze areas (Ref. 11). PCC shoulders have been observed to give over 10 years of maintenance-free performance in Illinois (with no sign of distress) and equal performance in other states over shorter time periods. Recommendations from highway agency engineers indicated preference for PCC shoulders when the traffic lanes were PCC. However, full depth AC shoulders may provide maintenance-free performance in certain climatic regions.

5.2.1. PCC Shoulder Design. The following recommendations are based upon results of field studies in Illinois and other states:

(a) Slab thickness - preferably equal to the mainline slab thickness at the longitudinal joint and continuing at a constant thickness throughout. If a taper is more economical, begin taper 24 inches from joint. to a thickness of eight inches at shoulder edge.

(b) Tie bars - tie the shoulder to the mainline pavement by 30 inches long No. 4 or No. 5 deformed steel bars spaced at 30 inches on center.

(c) Transverse joint - space joints identical to the traffic lanes.

(d) Longitudinal joint - place at edge of traffic lane and seal (or preferably increase traffic lane width 1-2 ft. to decrease edge loads).

(e) Subbase - use same subbase as placed beneath PCC mainline pavement (See subsurface drainage, Section 5.3).

Further details on PCC shoulder design can be found in Reference 26.

5.2.2. Asphalt Concrete Shoulder Design. The following recommendations are based upon results of field studies in several states:

(a) Thickness - equal to slab thickness at the longitudinal traffic lane/shoulder joint for at least 24 inches and tapering to 10 inches at shoulder edge (to provide adequate thickness for parked trucks).

(b) Longitudinal joint - saw cut a 1 inch square joint and fill with high type joint sealant.

(c) Subbase - use same subbase as is placed under PCC mainline pavement (See subsurface drainage, Section 5.3).

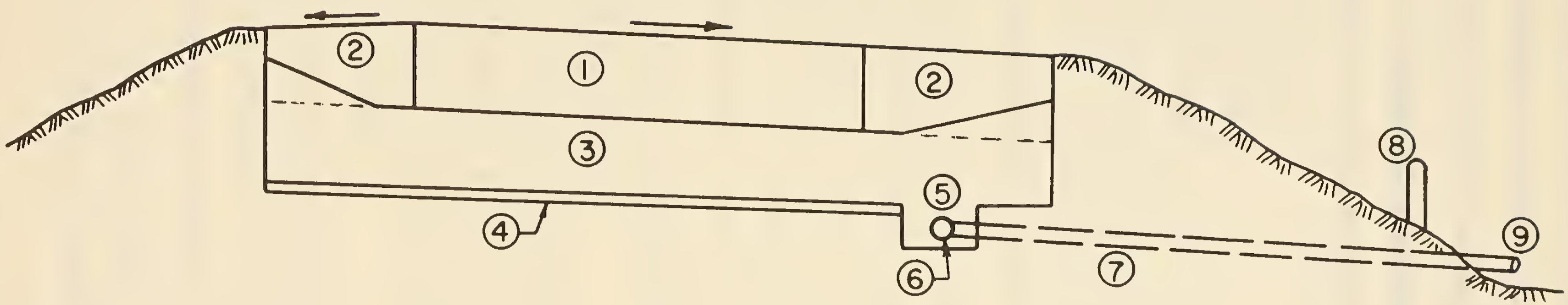
Further information on AC shoulder design can be found in Reference 11.

5.3 SUBSURFACE DRAINAGE

The presence of free water beneath the PCC slab can result in several distresses which would limit the maintenance-free life of the pavement. These distresses may include cracking, faulting, pumping, frost heave, and durability problems in PCC and subbase. Therefore, in regions where relatively high annual rainfalls exist, or where significant ground water exists, consideration should be given to providing subsurface drainage systems. The major components of a general subsurface drainage system are shown in Figure 5.3. The major purpose of the subsurface drainage system is to rapidly drain the roadbed to reduce the periods when the structure is exposed to excess moisture.

The general guidelines for the design of subsurface drainage systems, developed for the Federal Highway Administration by Cedergren (Ref. 12), are recommended. The basic procedure considers subsurface drainage layers as conveyors of water and considers in-flow rates from all significant sources. Seepage principles are then used to determine the permeability and thickness of a subsurface drainage layer that will accomodate the water flow. Hence, the drainage system is designed to have an out-flow rate equal to the rate of infiltration into the pavement during a one-hour design rainfall having a frequency of occurrence of one year. The infiltration rate for PCC is 0.50 to 0.67 of the total rainfall. This procedure, however, gives a drainage layer having a very high drainage capacity. This high capacity may not be required and a somewhat less porous drainage layer may be adequate, which would have greater stability in providing support for the PCC slab.

Pavements located in areas where subsurface moisture is not of sufficient



Description Of Components

1. PCC Slab - Traffic Lanes
2. PCC or AC Shoulders
3. Open Graded Subbase (Drainage Layer)
4. Filter Layer
5. Collector Trench
6. Perforated Collector Pipe
7. Outlet Pipe
8. Outlet Pipe Marker
9. Outlet Pipe Automatic Drainage Gate

Figure 5.3. Typical Subsurface Drainage System with Collector Pipe.

magnitude to provide subsurface drainage should not, however, be constructed in a "bathtub." The subbase should be daylighted to provide for some lateral drainage in these areas. The subbase should be constructed with high quality asphalt or cement stabilized granular materials to provide erosion proof subbase surface. Additional information on subsurface drainage is found in References 9-12.

CHAPTER 6

ZERO-MAINTENANCE DESIGN APPLICATION AND COST INCREMENT

6.1 DESIGN APPLICATION

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. Details on selection of structural design inputs, interpretation of program outputs, selection of structural design, and design of other components are described. A sensitivity analysis of some of the design parameters is given in Section 6.7 to illustrate their relative effects on the design.

The design criteria, slab properties, traffic foundation support, and environmental inputs are determined as recommended in Chapter 3.

6.1.1 Design Criteria.

(1) Pavement Zero-Maintenance Design Life: The desired period of maintenance-free life is 20 years. However, the pavement should perform for several additional years beyond 20 with maintenance before major rehabilitation is needed.

(2) Initial Serviceability Index After Construction: Reasonably good construction practice is expected, and therefore a value of 4.5 is selected as recommended in Section 3.1.2.

(3) Terminal Serviceability Index for Zero-Maintenance: A value of 3.0 is selected as recommended in Section 3.1.3.

(4) Time After PCC Slab Placement that Pavement is Opened to Traffic: The pavement is expected to be opened to regular traffic approximately 60 days after placement and therefore the value is 60/365 = 0.16 years.

(5) Month Pavement is Opened to Traffic: October, or the 10th month of the year, according to the key given in Section 3.1.5.

(6) Years During Which Summary of Fatigue and Serviceability Data Will be Printed: It is desired to observe the accumulation of fatigue damage and serviceability throughout the design period, hence the following years are selected for printout of this data: 1, 5, 10, 15, 20.

(7) Years During Which Comprehensive Fatigue Output Will be Printed: The first year is usually the most critical due to low concrete strength and hence a detailed fatigue analysis is desired to observe the critical loads, stresses, etc., for only Year 1.

6.1.2 Slab Properties.

(1) Slab Thickness: Reinforced jointed concrete pavements have been constructed in this area with a 10 in. (254 mm) slab. These pavements have generally required maintenance after only about 5 years, and hence the slab thickness for zero-maintenance design may be considerably greater than 10 in. (254 mm) for 20 year design. Trial thicknesses of 9, 11, 13, and 14 in. (229, 279, 330, 381 mm) are chosen to provide a range of results which should encompass the appropriate slab thickness.

(2) Slab Length: A random joint spacing of 10-14-12-15 ft. (3.0 -4.3-3.6-4.6 m) will be used as a first trial hence 15 ft. (4.6m) is used as the program input. A longer joint spacing will also be tried.

(3) Mean PCC Modulus of Rupture: The mean modulus of rupture, third point loading, at 28 days curing is 650 psi as determined from beam break tests for a cement factor of 6.0 sacks per cubic yard. Higher strength concrete will also be tried as another alternative.

(4) Coefficient of Variation of PCC Modulus of Rupture: Construction data for other projects in the area show an average coefficient of variation of 12 percent which will be used in this design.

(5) PCC Coefficient of Thermal Expansion: A typical average value of 5×10^{-6}/°F is selected.

(6) PCC Modulus of Elasticity: A typical average value of 5×10^{6} psi is selected.

6.1.3 Traffic.

(1) Average Daily Traffic at Beginning of Design Period: The initial ADT in both directions is estimated to be 70,000.

(2) Average Daily Traffic at End of Design Period: The final ADT after 20 years is estimated from transportation planning studies to be 90,000. The increase over the 20 year period is expected to be reasonably linear.

(3) Percent Trucks of ADT: The average percent of trucks, excluding panels and pickups, is 10 percent over the entire 20 year period as determined from planning studies.

(4) Percent Trucks in Heaviest Traveled Lane: Manual counts of lanal distribution of the existing freeway show approximately 58, 35

and 7 percent, respectively, in the outer, center, and inside traffic lane. The calculated percentage using the 6-lane urban equation as recommended in Section 3.3.4, is as follows:

$$LD = 60.76 - 0.0004\ (80{,}000/2) + 1.3174\ (10)$$

$$LD = 58 \text{ percent}$$

A value of 60 percent is selected for design.

(5) Percent Directional Distribution: Travel is approximately equal in each direction, and therefore a value of 50 percent traffic in the design direction is selected.

(6) Mean Axles Per Truck: Manual counts conducted on the existing freeway show an average of 2.75 axles per truck (excluding pickups and panels).

(7) Percent Trucks During Daylight: Manual counts show approximately 60 percent trucks during daylight hours.

(8) Mean Distance from Slab Edge to Outside of Truck Dual Tires: Visual observations indicate that the mean distance from the slab edge to the outside of truck duals is approximately 18 in. (457 mm) for pavement sections located between interchanges with paved shoulders.

(9) Axle Load Distribution: The freeway will carry a considerable amount of heavy industrial traffic and data obtained from state police spot weighings on this freeway indicate single axle loads up to 34 kips and tandem axles loads up to 56 kips. Ideally, the axle load distribution should be established from on-site weighings, but due to the high volume of traffic, this is impossible, and the closest loadometer station is several miles to the south. Therefore, the existing axle load distribution

was estimated using the recommendations for heavy industrial overload data given in Section 3.3.9, for loads above 18-kips single axle and 32-tandem axle. The percent of axle loads over these values are estimated to be 3 percent for singles and 10 percent for tandem axles. The estimated axle load distribution for heavy loads is given in Table 6.1. The distribution for axles of lesser weight was estimated using a distribution obtained from the closest loadometer station, and the final combined distribution is shown in Table 6.2. This axle load distribution represents the existing distribution and should be increased if conditions indicate future legal load changes during the 20 year period.

(1) Monthly Truck Percentage: The volume of trucks is expected to vary from season to season. The following variation over the year as a proportion of 100% is assumed based on traffic counts:

Sep, Oct, Nov, Dec,	8.33%
Jan, Feb, Mar,	7.00
April,	8.35
May, Jun, Jul, Aug	9.33
	100.00

6.1.4 Foundation Support.

(1) Modulus of Foundation Support for Each Month: The pavement will be placed on about two-four feet of fill soil and the average water table is located approximately two feet beneath the ground surface. The soil is an AASHO Classification A-6 clay with an average CBR of 3. The average degree of saturation of the upper portion of the subgrade is expected to vary from 79 to 90 percent throughout the year. The estimated monthly degree of saturation is shown in Table 6.3. The subgrade is expected to be

Table 6.1. Determination of Axle Load Distribution for Loads Greater than 18 and 32 for Single and Tandem Axles, Respectively.

Axle Load Group (kips)	Percent Load Distribution (Table 3.1)	Percent Load Distribution for 3% Singles and 10% Tandems
Single Axles:		
18-20	44.0	1.32
20-22	34.0	1.02
22-24	14.0	0.42
24-26	4.8	0.14
26-28	1.9	0.06
28-30	0.8	0.02
30-32	0.4	0.01
32-34	0.1	0.01
	100.0	3.00
Tandem Axles:		
32-34	43.0	4.30
34-36	34.0	3.40
36-38	14.0	1.40
38-40	4.8	0.48
40-42	1.9	0.19
42-44	0.8	0.08
44-46	0.6	0.06
46-48	0.3	0.03
48-50	0.2	0.02
50-52	0.2	0.02
52-54	0.1	0.01
54-56	0.1	0.01
	100.0	10.00

Table 6.2. Determination of Final Load Distribution for Use in Design of Project.

Axle Load Group (kips)	Design Axle Load Distribution (percent)
Single Axles:	
0-3	7.28
3-7	16.28
7-8	7.75
8-12	15.01
12-16	4.75
16-18	1.94
18-20	1.32
20-22	1.02
22-24	0.42
24-26	0.14
26-28	0.06
28-30	0.02
30-32	0.01
32-34	0.01
Tandem Axles:	
0-6	0.37
6-12	9.76
12-18	4.36
18-24	5.68
24-30	8.92
30-32	4.90
32-34	4.30
34-36	3.40
36-38	1.40
38-40	0.48
40-42	0.19
42-44	0.08
44-46	0.06
46-48	0.03
48-50	0.02
50-52	0.02
52-54	0.01
54-56	0.01
TOTAL	100.00

Table 6.3. Estimation of Modulus of Foundation Support - k-Value.

Month	Subgrade Degree of Saturation (%)	Subgrade k-value* (pci)	k-Value on top of Subbase: 12" Granular** (pci)	k-Value on top of Subbase: 6" Asphalt Stab*** (pci)
JAN	frozen	frozen	500****	500****
FEB	frozen	frozen	500	500
MAR	90	48	90	135
APR	85	72	120	178
MAY	84	78	130	190
JUNE	79	110	160	240
JULY	79	110	160	240
AUG	79	110	160	240
SEP	79	110	160	240
OCT	79	110	160	240
NOV	81	100	150	224
DEC	81	100	150	224

* From Figure 3.2, A-6 soil

** From Figure 3.4

*** From Figure 3.5

**** Recommended k-value for frozen soil frozen to a depth of 36 in. (914 mm) for two months during the year as indicated (based upon data from the State Geological Survey). The k-value on top of the subgrade is determined using Figure 3.2 for an A-6 soil and varying degrees of saturation as recommended in Section 3.4.1.

Two subbases are evaluated in this example: 12 in. (305 mm) of open-graded granular material, and 6 in. (152 mm) of open-graded asphalt stabilized granular material. The k-value on top of the subbase is determined from Figure 3.4 and 3.5 and given in Table 6.3. It should be noted that the k-value on top of the 12 in. (305 mm) granular subbase falls below the minimum recommended value of 100 pci during March, and hence a thicker granular subbase should be considered, or better still only stabilized should be considered, as recommended in Section 3.4.1.

(2) Design Modulus of Foundation Support (k) for Serviceability/Performance Analysis: The "design" k-value for use in the serviceability analysis is determined according to recommendations in Section 3.4.2 by selecting the average k-value over the 9 months that have the lowest values:

Subbase	Design k-Values
Granular	142 pci
Asphalt-Treated	212 pci

(3) Erodability of Foundation: The initial erodability is zero and the final erodability is estimated to be 24 in. (610 mm) for granular subbase and 12 in. (305 mm) for asphalt stabilized subbase according to the recommendations in Section 3.4.3.

6.1.5 Environmental.

(1) PCC Slab Thermal Gradients for Each Month: The mean thermal

gradients for an 8 and 12 in. (203-305mm) slab as recommended in Section 3.5.1, Table 3.2 for a freeze region are used.

(2) Climatic Regional Factor: The project is located in a wet/freeze climate, and therefore the design regional factor is 1.0.

6.2 INTERPRETATION OF PROGRAM OUTPUTS

The program outputs a complete listing of inputs and results for each trial slab thickness. Trial analyses were run for 9, 11, 13, and 15 in. (229, 279, 330, 381mm) PCC slabs placed on the asphalt stabilized subbase. A listing of program inputs for the 13 in. (330mm) PCC slab trial is shown in Table 6.4. The inputs should be carefully checked to eliminate any possible errors.

Results for Year One, as printed out for the 13 in. (330mm) slab, are shown in Table 6.5. Fatigue damage accumulated during the first year for a 13 in. (330 mm) slab is summarized monthly, day/night, and also totals for each. The total fatigue damage for Year One is 0.430. The month during which the most fatigue damage occurred was July, when a damage of 0.1496 accumulated. This is due to the high daytime thermal gradients in the slab and the increased truck volume during July. Total fatigue damage during the daytime is 0.4273 and during the nighttime is 3.138×10^{-3}. This is due to the reversal of thermal gradients during the nighttime resulting in a smaller total stress in the PCC slab under load.

Results of the serviceability analysis are also given in Table 6.5. The serviceability index at the end of Year One is 4.44, and the number of accumulated 18-kip equivalent single axle loads is 1.332 million in the design lane. Results are also shown for Year Ten in Table 6.6

Similar outputs as given in Tables 6.5 - 6.6 are obtained for Years

Table 6.4. 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 6.4. Listing of Program Inputs for Example Design Problem for 13 Inch PCC Slab (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 6.4. Listing of Program Inputs for Example Design Problem for 13 Inch PCC Slab (Continued).

FOUNDATION SUPPORT
****

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

OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
240.	224.	224.	500.	500.	135.	178.	190.	240.	240.	240.	240.

ERODABILITY OF FOUNDATION AT BEGINNING OF DESIGN PERIOD (INS.) 0.0
ERODABILITY OF FOUNDATION AT END OF DESIGN PERIOD (INS.) 12.00

DESIGN MODULUS OF FOUNDATION SUPPORT (K) FOR
SERVICEABILITY/PERFORMANCE ANALYSIS - PCI 212.00

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 6.5. Results from JCP-1 Program for Year 1 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

****

FOR YEAR #

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

	DAY	NIGHT	TOTAL
OCT	3.883E-02	5.296E-04	3.936E-02
NOV	1.366E-02	3.379E-04	1.400E-02
DEC	9.218E-03	5.732E-04	9.791E-03
JAN	1.366E-03	2.781E-05	1.393E-03
FEB	8.026E-04	3.136E-05	8.339E-04
MAR	1.144E-02	3.831E-04	1.182E-02
APR	4.436E-02	4.281E-04	4.479E-02
MAY	2.847E-02	3.136E-04	2.878E-02
JUN	4.864E-02	1.615E-04	4.880E-02
JUL	1.495E-01	1.714E-04	1.496E-01
AUG	6.791E-02	1.241E-04	6.803E-02
SEP	1.311E-02	5.632E-05	1.317E-02

SUM OF FATIGUE DAMAGE FOR DAY LOADING IS 4.273E-01

SUM OF FATIGUE DAMAGE FOR NIGHT LOADING IS 3.138E-03

TOTAL FATIGUE DAMAGE FOR YEAR # 1 IS 4.304E-01

RESULTS - SERVICEABILITY/PERFORMANCE OF JCP DESIGN LANE
****

SERVICEABILITY INDEX AT END OF YEAR # 1 4.444E 00
NUMBER OF ACCUMULATED 18-KIP EQUIVALENT
SINGLE AXLE LOADS AT END OF YEAR # 1 1.332E 06

Table 6.6 Results from JCP-1 Program 10 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

*******************************************************************************

FOR YEAR # 10
RESULTS - ACCUMULATED FATIGUE DAMAGE OF P.C.C. SLAB AT OUTSIDE EDGE
*******

             DAY         NIGHT        TOTAL
OCT      1.726E-03    5.688E-05    1.783E-03
NOV      1.267E-03    5.960E-05    1.326E-03
DEC      1.266E-03    1.197E-04    1.386E-03
JAN      3.361E-04    1.179E-05    3.479E-04
FEB      2.469E-04    1.454E-05    2.614E-04
MAR      2.472E-03    1.274E-04    2.600E-03
APR      9.267E-03    1.605E-04    9.428E-03
MAY      7.160E-03    1.350E-04    7.295E-03
JUN      1.259E-02    8.130E-05    1.267E-02
JUL      3.635E-02    9.060E-05    3.644E-02
AUG      1.960E-02    7.144E-05    1.967E-02
SEP      4.827E-03    3.637E-05    4.863E-03

SUM OF FATIGUE DAMAGE FOR DAY LOADING IS       9.711E-02
SUM OF FATIGUE DAMAGE FOR NIGHT LOADING IS     9.651E-04
TOTAL FATIGUE DAMAGE FOR YEAR # 10 IS          9.808E-02

RESULTS - SERVICEABILITY/PERFORMANCE OF JCP DESIGN LANE
*******

SERVICEABILITY INDEX AT END OF YEAR # 10       3.850E 00
NUMBER OF ACCUMULATED 18-KIP EQUIVALENT
   SINGLE AXLE LOADS AT END OF YEAR # 10       1.417E 07
```

1, 5, 10, 15, 20 and a summary of results for the entire design period is given in Table 6.7 for the 13 in. (330mm) slab. The total fatigue damage for the 20 year period for the 13 in. (330mm) slab is 2.498 and the terminal serviceability is 3.12. A summary of data for 9, 11, 13, and 15 in. (229, 279, 330, 381mm) slabs is given in Table 6.8 which will be used to select the design structure in Section 6.3.

Details and example calculations showing how these results are obtained are presented. The calculations for accumulated 18-kip single axle loads in the heaviest traveled lane at the end of the design period for a 13 in. (330mm) PCC slab are given in Table 6.9. The value of 30.23 x 10^6 corresponds exactly to that obtained from JCP-1 program as given in Table 6.8. The loss in serviceability index for the 13 in. (330mm) slab when it is subjected to 30.23 x 10^6 equivalencies can be computed using Eq. 3.5. The final serviceability index is calculated to be 3.12, which corresponds to the value given in Table 6.8.

A detailed summary of the fatigue analysis is shown in Table 6.10 for the first month after opening to traffic, which is October. The second column, D/N, represents day and night (Day = 1 and Night = 2). The load column represents the axle load of the upper range for single (3000 to 34,000 lbs.) and then tandem axles (6000 to 56,000 lbs.). The STRL column is the tensile stress at the bottom edge of the slab for the given axle load located at the edge of the slab. For example, the following edge stress results from these axle loads for a 13 in. (330mm) slab.

Table 6.7. 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	7.619E-02	1.748E-03	7.794E-02
NOV	4.086E-02	1.612E-03	4.247E-02
DEC	3.625E-02	3.118E-03	3.937E-02
JAN	8.385E-03	2.751E-04	8.660E-03
FEB	5.937E-03	3.353E-04	6.272E-03
MAR	6.400E-02	3.088E-03	6.709E-02
APR	2.414E-01	3.809E-03	2.452E-01
MAY	1.794E-01	3.149E-03	1.825E-01
JUN	3.134E-01	1.862E-03	3.152E-01
JUL	9.175E-01	2.061E-03	9.196E-01
AUG	4.779E-01	1.614E-03	4.795E-01
SEP	1.129E-01	8.172E-04	1.138E-01

SUM OF FATIGUE DAMAGE FOR DAY LOADING IS	2.474E 00
SUM OF FATIGUE DAMAGE FOR NIGHT LOADING IS	2.349E-02
TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD IS	2.498E 00

RESULTS - SERVICEABILITY/PERFORMANCE OF JCP DESIGN LANE
****

SERVICEABILITY INDEX AT END OF YEAR # 20	3.119E 00
NUMBER OF ACCUMULATED 18-KIP EQUIVALENT SINGLE AXLE LOADS AT END OF YEAR # 20	3.023E 07

Table 6.8. Summary of Fatigue and Serviceability Data for Example Problem Design for Asphalt Stabilized Subbase

Slab Thickness	Year	Fatigue Damage For Year	Serviceability Index	ESAL (10^6)
9	1	4.22×10^{6}	4.38	1.28
	5	2.72×10^{5}	3.53	6.56
	10	1.76×10^{5}	2.39	13.58
	15	1.64×10^{5}	*	*
	20	1.71×10^{5}	*	*
	TOTAL	8.87×10^{6}		
11	1	2.68×10^{2}	4.42	1.32
	5	3.81×10^{1}	4.01	6.79
	10	2.78×10^{1}	3.36	14.04
	15	2.58×10^{1}	2.88	21.76
	20	2.59×10^{1}	2.55	29.95
	TOTAL	9.06×10^{2}		
13	1	4.30×10^{-1}	4.44	1.33
	5	1.20×10^{-1}	4.18	6.85
	10	9.80×10^{-2}	3.85	14.17
	15	9.36×10^{-2}	3.44	21.97
	20	9.37×10^{-2}	3.12	30.23
	TOTAL	2.50		
15	1	7.71×10^{-3}	4.46	1.34
	5	3.38×10^{-3}	4.28	6.87
	10	3.06×10^{-3}	4.05	14.21
	15	3.05×10^{-3}	3.77	22.03
	20	3.13×10^{-3}	3.53	30.32
	TOTAL	6.96×10^{-2}		

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

Table 6.9. Calculation Sheet for Determining Equivalent Single Axle Load Applications in Design Lane Over Design Period.

AXLE LOAD GROUP - KIPS	EQUIVALENCY FACTOR - (E)	PERCENTAGE LOADS - (P)	P X E
Single Axles			
0-3	0.0011	7.28	0.0080
3-7	0.02	16.28	0.3256
7-8	0.03	7.75	0.2325
8-12	0.17	15.01	2.5517
12-16	0.60	4.75	2.8500
16-18	1.00	1.94	1.9400
18-20	1.58	1.32	2.0856
20-22	2.41	1.02	2.4582
22-24	3.53	0.42	1.4826
24-26	5.01	0.14	0.7014
26-28	6.93	0.06	0.4158
28-30	9.36	0.02	0.1872
30-32	12.37	0.01	0.1237
32-34	16.03	0.01	0.1603

Table 6.9. Calculation Sheet for Determining Equivalent Single Axle Load Applications in Design Lane Over Design Period (Continued).

AXLE LOAD GROUP - KIPS	EQUIVALENCY FACTOR - (E)	PERCENTAGE LOADS - (P)	P X E
Tandem Axles:			
0-6	0.001	0.37	0.0004
6-12	0.03	9.76	0.2928
12-18	0.13	4.36	0.5668
18-24	0.44	5.68	2.4992
24-30	1.14	8.92	10.1681
30-32	1.51	4.90	7.3990
32-34	1.97	4.30	8.4710
34-36	2.52	3.40	8.5680
36-38	3.19	1.40	4.4660
38-40	3.98	0.48	1.9104
40-42	4.92	0.19	0.9348
42-44	6.02	0.08	0.4816
44-46	7.29	0.06	0.4374
46-48	8.76	0.03	0.2628
48-50	10.43	0.02	0.2086
50-52	12.33	0.02	0.2466
52-54	14.47	0.01	0.1447
54-56	16.86	0.01	0.1686
TOTAL		100.00	62.7501

Total accumulated equivalent 18-kip single axle loads over design period:

W_{18} = (ADT)(T/100)(DD/100)(LD/100)(TY)(365)(A)(PE/100)

= (80000)(10/100)(50/100)(60/100)(20)(365)(2.75)(62.7501/100)

= 30.23×10^6

Table 6. 10. Comprehensive Fatigue Analysis Output for Month #1 (October) of First Year After Opening to Traffic.

FATIGUE DAMAGE SUBTOTALS FOR YEAR # 1

MONTH	D/N	LOAD	STRL	STRC	R	STRT	F	N	NAAL	DAMAGE
1	1	3000.	2.37E 01	2.36E 01	1.1554	5.096E 01	5.999E 02	1.300E 15	8.717E 02	6.704E-07
1	1	7000.	5.52E 01	2.36E 01	1.1554	8.252E 01	5.999E 02	1.540E 14	1.949E 03	1.266E-05
1	1	8000.	6.31E 01	2.36E 01	1.1554	9.041E 01	5.999E 02	9.035E 13	9.280E 02	1.027E-05
1	1	12000.	9.47E 01	2.36E 01	1.1554	1.220E 02	5.999E 02	1.070E 13	1.797E 03	1.679E-04
1	1	16000.	1.26E 02	2.36E 01	1.1554	1.535E 02	5.999E 02	1.268E 12	5.688E 02	4.487E-04
1	1	18000.	1.42E 02	2.36E 01	1.1554	1.693E 02	5.999E 02	4.363E 11	2.323E 02	5.325E-04
1	1	20000.	1.58E 02	2.36E 01	1.1554	1.851E 02	5.999E 02	1.501E 11	1.581E 02	1.053E-03
1	1	22000.	1.74E 02	2.36E 01	1.1554	2.009E 02	5.999E 02	5.168E 10	1.221E 02	2.364E-03
1	1	24000.	1.89E 02	2.36E 01	1.1554	2.166E 02	5.999E 02	1.778E 10	5.029E 01	2.828E-03
1	1	26000.	2.05E 02	2.36E 01	1.1554	2.324E 02	5.999E 02	6.121E 09	1.676E 01	2.739E-03
1	1	28000.	2.21E 02	2.36E 01	1.1554	2.482E 02	5.999E 02	2.107E 09	7.184E 00	3.410E-03
1	1	30000.	2.37E 02	2.36E 01	1.1554	2.640E 02	5.999E 02	7.250E 08	2.395E 00	3.303E-03
1	1	32000.	2.52E 02	2.36E 01	1.1554	2.798E 02	5.999E 02	2.495E 08	1.197E 00	4.799E-03
1	1	34000.	2.68E 02	2.36E 01	1.1554	2.955E 02	5.999E 02	8.587E 07	1.197E 00	1.394E-02
1	1	6000.	2.07E 01	2.36E 01	1.1554	4.798E 01	5.999E 02	1.590E 15	8.861E 01	5.572E-08
1	1	12000.	4.14E 01	2.36E 01	1.1554	6.867E 01	5.999E 02	3.927E 14	2.337E 03	5.952E-06
1	1	18000.	6.21E 01	2.36E 01	1.1554	8.936E 01	5.999E 02	9.696E 13	1.044E 03	1.077E-05
1	1	24000.	8.28E 01	2.36E 01	1.1554	1.101E 02	5.999E 02	2.394E 13	1.360E 03	5.681E-05
1	1	30000.	1.03E 02	2.36E 01	1.1554	1.307E 02	5.999E 02	5.912E 12	2.136E 03	3.613E-04
1	1	32000.	1.10E 02	2.36E 01	1.1554	1.376E 02	5.999E 02	3.709E 12	1.173E 03	3.164E-04
1	1	34000.	1.17E 02	2.36E 01	1.1554	1.445E 02	5.999E 02	2.327E 12	1.030E 03	4.425E-04
1	1	36000.	1.24E 02	2.36E 01	1.1554	1.514E 02	5.999E 02	1.460E 12	8.142E 02	5.578E-04
1	1	38000.	1.31E 02	2.36E 01	1.1554	1.583E 02	5.999E 02	9.159E 11	3.353E 02	3.661E-04
1	1	40000.	1.38E 02	2.36E 01	1.1554	1.652E 02	5.999E 02	5.746E 11	1.150E 02	2.001E-04
1	1	42000.	1.45E 02	2.36E 01	1.1554	1.721E 02	5.999E 02	3.605E 11	4.550E 01	1.262E-04
1	1	44000.	1.52E 02	2.36E 01	1.1554	1.790E 02	5.999E 02	2.261E 11	1.916E 01	8.472E-05
1	1	46000.	1.59E 02	2.36E 01	1.1554	1.859E 02	5.999E 02	1.419E 11	1.437E 01	1.013E-04
1	1	48000.	1.66E 02	2.36E 01	1.1554	1.928E 02	5.999E 02	8.901E 10	7.184E 00	8.071E-05
1	1	50000.	1.72E 02	2.36E 01	1.1554	1.997E 02	5.999E 02	5.584E 10	4.790E 00	8.577E-05
1	1	52000.	1.79E 02	2.36E 01	1.1554	2.066E 02	5.999E 02	3.503E 10	4.790E 00	1.367E-04
1	1	54000.	1.86E 02	2.36E 01	1.1554	2.135E 02	5.999E 02	2.198E 10	2.395E 00	1.090E-04
1	1	56000.	1.93E 02	2.36E 01	1.1554	2.204E 02	5.999E 02	1.379E 10	2.395E 00	1.737E-04
1	2	3000.	2.37E 01	-2.83E 01	1.0692	-6.579E 00	5.999E 02	6.355E 16	5.811E 02	9.145E-09
1	2	7000.	5.52E 01	-2.83E 01	1.0692	2.498E 01	5.999E 02	7.527E 15	1.300E 03	1.726E-07
1	2	8000.	6.31E 01	-2.83E 01	1.0692	3.287E 01	5.999E 02	4.416E 15	6.187E 02	1.401E-07
1	2	12000.	9.47E 01	-2.83E 01	1.0692	6.443E 01	5.999E 02	5.231E 14	1.198E 03	2.291E-06
1	2	16000.	1.26E 02	-2.83E 01	1.0692	9.599E 01	5.999E 02	6.196E 13	3.792E 02	6.120E-06
1	2	18000.	1.42E 02	-2.83E 01	1.0692	1.118E 02	5.999E 02	2.132E 13	1.549E 02	7.263E-06
1	2	20000.	1.58E 02	-2.83E 01	1.0692	1.275E 02	5.999E 02	7.338E 12	1.054E 02	1.436E-05
1	2	22000.	1.74E 02	-2.83E 01	1.0692	1.433E 02	5.999E 02	2.526E 12	8.142E 01	3.224E-05
1	2	24000.	1.89E 02	-2.83E 01	1.0692	1.591E 02	5.999E 02	8.692E 11	3.353E 01	3.857E-05
1	2	26000.	2.05E 02	-2.83E 01	1.0692	1.749E 02	5.999E 02	2.991E 11	1.118E 01	3.736E-05
1	2	28000.	2.21E 02	-2.83E 01	1.0692	1.907E 02	5.999E 02	1.030E 11	4.790E 00	4.652E-05
1	2	30000.	2.37E 02	-2.83E 01	1.0692	2.064E 02	5.999E 02	3.543E 10	1.597E 00	4.506E-05
1	2	32000.	2.52E 02	-2.83E 01	1.0692	2.222E 02	5.999E 02	1.219E 10	7.983E-01	6.546E-05
1	2	34000.	2.68E 02	-2.83E 01	1.0692	2.380E 02	5.999E 02	4.197E 09	7.983E-01	1.902E-04
1	2	6000.	2.07E 01	-2.83E 01	1.0692	-9.557E 00	5.999E 02	7.772E 16	5.907E 01	7.601E-10
1	2	12000.	4.14E 01	-2.83E 01	1.0692	1.113E 01	5.999E 02	1.919E 16	1.558E 03	8.119E-08
1	2	18000.	6.21E 01	-2.83E 01	1.0692	3.183E 01	5.999E 02	4.739E 15	6.961E 02	1.469E-07
1	2	24000.	8.28E 01	-2.83E 01	1.0692	5.252E 01	5.999E 02	1.170E 15	9.068E 02	7.750E-07
1	2	30000.	1.03E 02	-2.83E 01	1.0692	7.321E 01	5.999E 02	2.889E 14	1.424E 03	4.929E-06
1	2	32000.	1.10E 02	-2.83E 01	1.0692	8.011E 01	5.999E 02	1.813E 14	7.823E 02	4.316E-06
1	2	34000.	1.17E 02	-2.83E 01	1.0692	8.700E 01	5.999E 02	1.137E 14	6.865E 02	6.036E-06
1	2	36000.	1.24E 02	-2.83E 01	1.0692	9.390E 01	5.999E 02	7.135E 13	5.428E 02	7.608E-06
1	2	38000.	1.31E 02	-2.83E 01	1.0692	1.008E 02	5.999E 02	4.476E 13	2.235E 02	4.993E-06
1	2	40000.	1.38E 02	-2.83E 01	1.0692	1.077E 02	5.999E 02	2.808E 13	7.663E 01	2.729E-06
1	2	42000.	1.45E 02	-2.83E 01	1.0692	1.146E 02	5.999E 02	1.762E 13	3.033E 01	1.722E-06
1	2	44000.	1.52E 02	-2.83E 01	1.0692	1.215E 02	5.999E 02	1.105E 13	1.277E 01	1.156E-06
1	2	46000.	1.59E 02	-2.83E 01	1.0692	1.284E 02	5.999E 02	6.934E 12	9.579E 00	1.381E-06
1	2	48000.	1.66E 02	-2.83E 01	1.0692	1.353E 02	5.999E 02	4.350E 12	4.790E 00	1.101E-06
1	2	50000.	1.72E 02	-2.83E 01	1.0692	1.422E 02	5.999E 02	2.729E 12	3.193E 00	1.170E-06
1	2	52000.	1.79E 02	-2.83E 01	1.0692	1.491E 02	5.999E 02	1.712E 12	3.193E 00	1.865E-06
1	2	54000.	1.86E 02	-2.83E 01	1.0692	1.560E 02	5.999E 02	1.074E 12	1.597E 00	1.486E-06
1	2	56000.	1.93E 02	-2.83E 01	1.0692	1.629E 02	5.999E 02	6.739E 11	1.597E 00	2.369E-06

30,000 lb. single axle, edge stress = 237 psi

54,000 lb. tandem axle, edge stress = 186 psi

The STRC column is edge curling stress in the longitudinal direction. The mean daytime thermal gradient for October is 0.48°F/inch of slab for the 13 in. (330 mm) slab, which results in a tensile stress of 23.6 psi. The mean nighttime thermal gradient is -0.57°F/inch which produces a compressive stress of 28.3 psi. The R is an adjustment factor to multiply by the curling stress so that a correct total stress in the PCC slab under load can be calculated. Total stress, or STRT, is calculated for a 30,000 lb. single axle as follows:

$$\begin{aligned} STRT &= STRL + R^* \; STRC \\ &= 237 + 1.554^* \; 23.6 = 264.3 \text{ psi} \end{aligned}$$

The STRT is the total stress at the bottom edge of the PCC slab due to the combined effect of edge load and slab curling. Equations for STRL, STRC, and R are given in Volume I (Ref. 3).

The F is the mean monthly modulus of rupture that has been adjusted for material variability and is calculated as follows for October:

Mean 28-day Modulus of Rupture (FF) = 650 psi

Coefficient of Variation (F_{cv}) = 12 percent

Adjusted Modulus of Rupture for variability (F_{28}) $= FF - 1.03 \times \frac{F_{cv}}{100} \times FF$

$= 650 - (650 \times .12)\ 1.03$

$= 569.7$ psi

Modulus of Rupture at Beginning of October or 0.16 years from placement = 569.7 * FA where

$$FA = 1.22 + 0.17 \log_{10} 0.16 - 0.05(\log_{10} 0.16)^2 = 1.053$$

Therefore, Modulus of Rupture (or F) = 569.7 * 1.053
= 599.9 psi

The N is the number of load applications to fracture, calculated from the PCC fatigue equation as follows, for example, considering a 30,000 SAL:

$$STRT = 264.0 \text{ psi}, \quad F = 599.9 \text{ psi}$$

$$\text{Fatigue Ratio} = 264.0/599.9 = 0.44$$

$$\log N = 16.61 - 17.61\ (0.44) = 8.8616$$

$$N = 7.25 \times 10^8 \text{ applications}$$

The NAAL is the number of expected applications of the indicated axle load. It is calculated from the traffic data as follows for the 30,000 lb. single axle using Eq. 4. 4 (Vol. I):

$$NAAL = (ADTm)(T/100)(DD/100)(LD/100)(A)(30)(P/100)(C/100)(DK/100)(TF/100)(CON)$$

where

$$ADTm = \frac{90{,}000 - 70{,}000}{20 \times 12}(1.0) + 70{,}000 = 70.083$$

C = proportion of "edge" loads to total axles passing within 6 in. (152mm) of the slab edge, determined from normal distribution tables with a standard deviation = 10 in. (254 mm) and mean of 18 in. (454mm).

$$S = \frac{\bar{x} - 6}{\sigma} = \frac{18 - 6}{10} = 1.20$$

From normal distribution table with Z = 1.20 to Z = ∞, the proportion is 0.1151.

TF = 8.33 * 12.0/100.0 = 1.00 (for October)

CON = 1.0 for single axle

T, DD, LD, A, P, DK = as input

Therefore:

$$NAAL = 70083 * 10/100 * 50/100 * 60/100 * 2.75 * 30$$

$$* 0.02/100 * 0.1151 * 60/100 * 1.00 * 1.00$$

$$= 2.395 \text{ axles during daytime in October}$$

Fatigue damage for the daytime in October, or DAMAGE, therefore is calculated as follows:

$$DAMAGE = NAAL/N(10^7)$$

For a 28,000 - 30,000 lb. single axle load range:

$$DAMAGE = [2.395/7.25 \times 10^8](10^7)$$

$$= 3.303 \times 10^{-2}$$

The damage for all other axle load groups is computed similarly as given in Table 6.10. These damage values are then summed for the month and other months and printed out in the yearly and final summary as given in Tables 6.5 - 6.7.

6.3 SELECTION OF STRUCTURAL DESIGN

The results given in Table 6.8 are plotted as shown in Figure 6.1, and the minimum design slab thicknesses determined as indicated for the asphalt stabilized subbase:

Fatigue Minimum Thickness = 11.7 in. (297mm)

Serviceability Minimum Thickness = 12.5 in. (318mm)

Therefore, for these foundation, traffic, slab, and climatic conditions, a zero-maintenance design thickness would be 12.5 in. (318 mm) minimum of PCC, and 6 in. (152 mm) open-graded asphalt stabilized subbase over a "filter" and prepared subgrade as subsequently discussed.

These data were obtained form the JCP-1 program. It is possible to determine the required slab thickness manually using serviceability criteria. The total accumulated 18-kip equivalent single axle loads were computed in Table 6.9 to be 30.23 x 10^6. This value should be multiplied by the regional factor and the result used in Figure 4.1 to determine the required slab thickness:

$$\underset{\text{(for design)}}{\text{18-kip ESAL}} = 1.0 \times 30.23 \times 10^6 = 30.23 \times 10^6$$

$$\text{Working Stress} = 650 - (650)(.12)(1.03) = 570 \text{ psi}$$

$$\underset{\text{(9 lowest months)}}{\text{k-Value}} = (135 + 178 + 190 + 240 + 224 + 224 + 240 + 240 + 240)/9 = 212 \text{ pci}$$

Using these data and Figure 4.1 a slab thickness of 12.5 in. (318 mm) is obtained.

A plot of serviceability and fatigue damage with time is shown in Figure 6.2. The 9 in. (229mm) slab serviceability drops to 3.0 at 7 years, and the 11 in. (279 mm) at 12 years, while the 13 in. (330 mm) lasts longer than the 20 year design period. The yearly fatigue curves show that a considerable portion of the fatigue damage occurs during the first few years, especially for the thinner slabs. This is due to the relatively low PCC modulus of rupture early in the pavements' life.

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 6.11. The other design inputs were held constant for each of these alternatives as a single parameter was varied as shown. Required slab

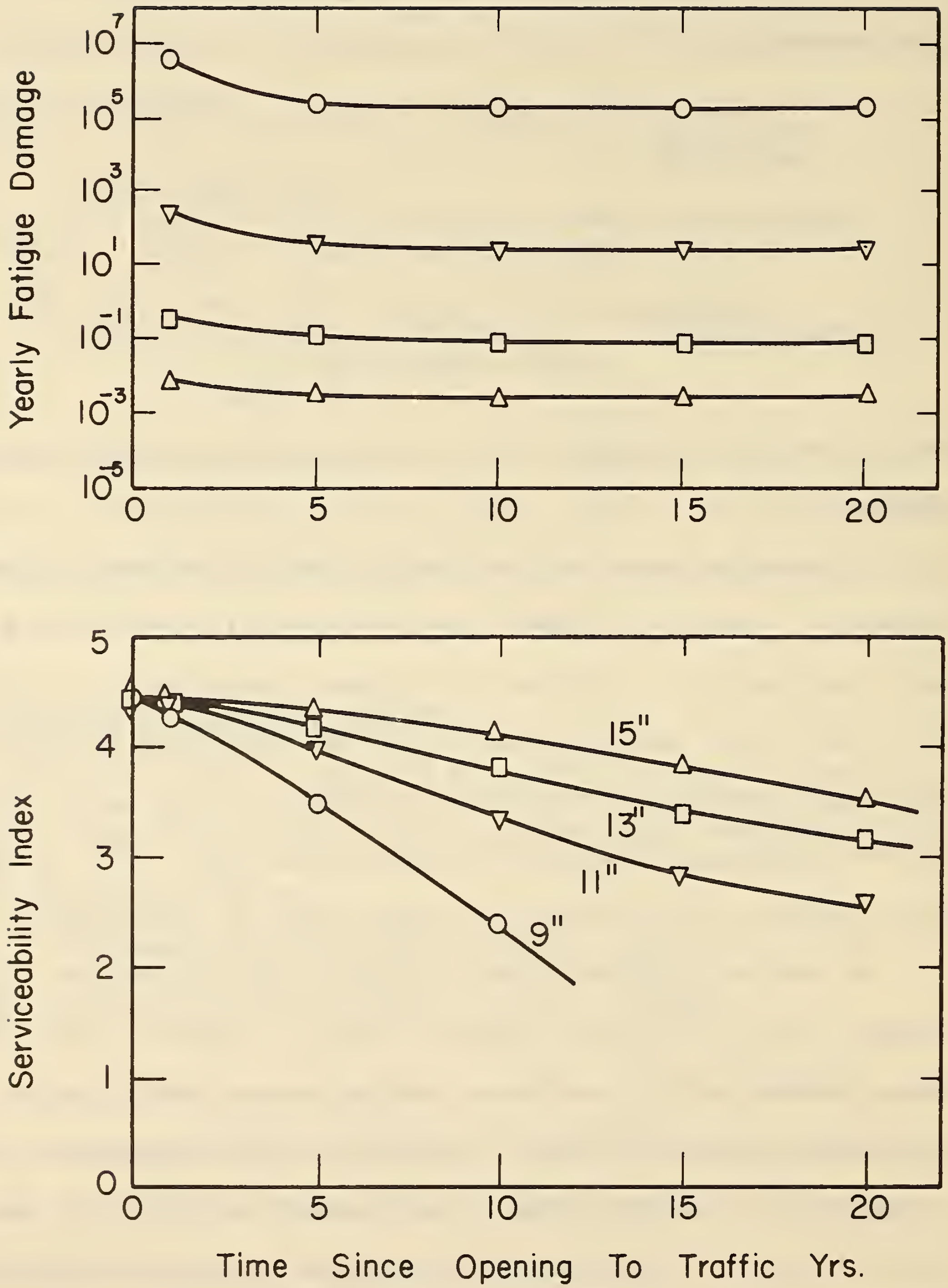


Figure 6.2. Illustration of Fatigue Damage and Serviceability History Over Design Life for Example Problem.

Table 6.11. Summary of Zero-Maintenance Alternate Designs for Example Problem.

	Design Parameter				
Alternative Number	Slab Length (ft)	PCC Strength (psi)	Subbase Type	Design Thickness (ins)	Controlling Criteria
1	15	650	Granular	12.9	S
2	20	650	Granular	12.9	S
3	15	800	Granular	11.2	S
4	20	800	Granular	11.3	F & S
5	15	650	Asphalt Stab.	12.5	S
6	20	650	Asphalt Stab.	12.6	F
7	15	800	Asphalt Stab.	11.0	S
8	20	800	Asphalt Stab.	11.1	F & S

F = Fatigue Criteria

S = Serviceability Criteria

thickness varies from 11.0 to 12.9 (279-328 mm) depending upon the values of the design parameters controlled by the designer. Each alternative should be further designed and economic analyses conducted to determine the most economical alternative.

Another important consideration which should be evaluated 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 6.4 for the outside lane with the exception of lane truck distribution:

Outside Lane = 60 percent

Center Lane = 33 percent

Inside Lane = 7 percent

Required slab thicknesses for each lane are as follows:

Outside Lane (outer edge) = 12.5 in. (318 mm)

Center Lane (either edge) = 11.4 in. (290 mm)

Inside Lane (inside edge) = 11.0 in. (279 mm)

Therefore, the slab could vary in thickness from 12.5 in. (318 mm) on the outside edge to 11.0 in. (279 mm) at the inside edge.

6.4 DESIGN OF OTHER COMPONENTS

The design of pavement joints, shoulders, and subsurface drainage is 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 6.12. A randomized transverse joint spacing is selected to prevent rhythmic vehicle response. Two random joint spacings are selected for trial analyses. Load transfer at the joints includes both aggregate interlock and corrosion proof dowels. Dowels are considered necessary due to the heavy traffic and 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 in. (305 mm), and then tapering to a thickness of 8 in. (203 mm) is selected. Tie bars of identical size to those placed for the traffic lanes are to be used.

Since the project is located in an area of high rainfall (35 in. annual precipitation), a subsurface drainage system is considered necessary. 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 in. (305 mm) granular and 6 in. (152 mm) asphalt stabilized subbase is required to increase the k-value above 100 pci. These thicknesses also meet that required for subsurface drainage as specified in Reference 12. Drainage calculations are as follows for a straight section

Table 6.12. 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, 7/16" width
Tiebars Across Longitudinal Joints	5/8 x 30" spaced at 30"
Transverse Expansion Joints	Place only at bridge ends

of highway situated on a 3 ft. (0.9 m) embankment and assuming no ground water exists. The cross slope is 0.02 and maximum longitudinal grade is 0.01. The 1 hour/1 year precipitation rate for the Chicago area is 1.2 in/hour. Therefore, the design infiltration rate is

$$I = 0.5 * 1.2 = 0.6 \text{ in./hour}$$

The permeability of the open-graded subbase course selected is estimated to be 4000 ft./day. The time to drain the layer after a rainstorm according to Reference 12 is 1.5 hours, which is acceptable for the 6 in. (152 mm) asphalt stabilized subbase. The 12 in. (305 mm) granular subbase would provide even faster drainage of excess moisture. Various drainage design values are summarized in Table 6.13.

6.5 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 design analysis 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

Table 6.13. Summary of Drainage Design Values.

Component	Design Value
Subbase Drainage Layer Thickness	6 inches asphalt stab. 12 inches granular
Time to Drain Layer	1.5 hours for asphalt stab.
Required Min. Permeability of Subbase	4000 ft/day
Min. Collector Trench Width	1.5 feet
Required Min. Permeability of Trench Backfill	310 ft/day
Min. Perforated Pipe Diameter	CMP - 6 inches ACP - 4.5 inches
Maximum Distance Between Outlets	500 feet

conventional pavements are provided in Reference 4. 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.

Pavement costs were computed for the recommended zero-maintenance design shown in Figure 6.3 using typical current costs (1976) for the Chicago area. A conventional pavement was designed using the Illinois Department of Transportation (IDOT) design manual (Ref. 29). The same traffic and soils data was used for the zero-maintenance design. The resulting design is summarized below:

Slab Thickness: 9 ins. (229 mm)

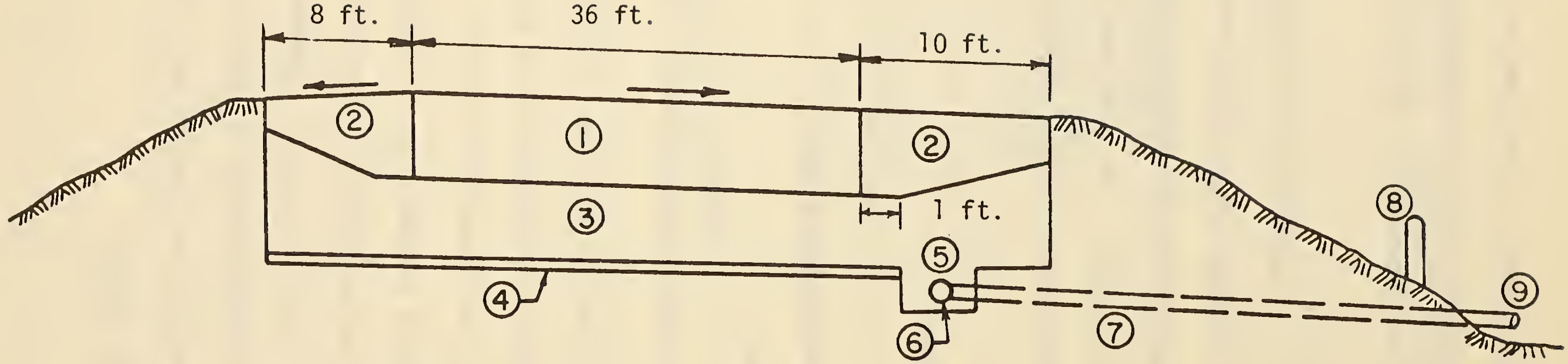
Continuously Reinforced

Subbase: 6 ins. (152 mm) asphalt stabilized

AC Shoulders: 8ins. (152mm)

Longitudinal edge drains with outlets spaced 500 ft. (152 m) maximum.

IDOT currently specifies subsurface longitudinal drainage as standard practice. Unit costs used in the analysis were obtained from various sources including IDOT, PCA, contractors, and materials suppliers. The expected 20 year costs for the conventional pavement due to maintenance and impacts resulting roadway occupancy by maintenance crews (extra user costs due to delay and accidents) were computed using the EAROMAR program (Ref. 4). A present worth cost value of $350,000 was obtained from the analysis. The complete cost analysis results are summarized as follows. All costs are expressed as present worth values.



Description of Components

1. PCC Slab - Traffic Lanes - 12.5 ins. (318 mm)
   Joint design: Trans. Jt. Spacing = 15 ft. (4.6m) preformed compression sealants, corrosion proof dowels, tie bars for longitudinal lane and shoulder joints.
2. PCC Shoulders - 12.5 ins. tapering to 8 ins. at edge
3. Open Graded Asphalt Stabilized Subbase (Drainage Layer) - 6 ins. (152 mm)
4. Filter Layer
5. Collector Trench - Width 1.5 ft (0.4m)
6. Perforated Collector Pipe - CMP g in. (152mm) or ACP 4.5 in (114mm) dia.
7. Outlet Pipe - Spacing of 500 ft. (152m)
8. Outlet Pipe Marker
9. Outlet Pipe (a non-clogging end must be provided).

Figure 6.3. Cross section of example zero-maintenance design.

1. Conventional Design (6 lanes plus shoulders)

Initial Construction	$1,050,522 / mi.
20-year Maintenance and User Cost	350,000 / mi.
Total 20-year Cost	$1,400,522 / mi.

2. Zero-Maintenance Design (6 lanes plus shoulders)

Initial Construction	$1,180,291 / mi.
20-year Maintenance and User Cost	-0-
Total 20-year Cost	$1,180,291 / mi.

The total present worth savings is $220,231/mi. The percent increase in construction cost of the zero-maintenance pavement is 12 percent. Therefore, economic justification exists for constructing the zero-maintenance pavement.

6.6 COST INCREMENT FOR ZERO-MAINTENANCE DESIGN

The additional "cost increment" for constructing a zero-maintenance pavement over that of a conventional pavement is very important in any economic study. This cost increment is expected to vary widely across the U. S. due to differing designs and costs of labor and materials. A study was made in two areas: Chicago and Los Angeles, since they have widely differing climates and construction costs.

The incremental costs of constructing zero-maintenance pavement was determined for two levels of traffic and two locations. Unit costs were determined for each location from state highway departments, the Portland Cement Association (who recently completed a comprehensive pavement cost study) and contractors. The procedure used is as follows:

1. Zero-maintenance designs were developed for a typical 6 lane freeway traffic and soils conditions in Chicago and Los Angeles. A traffic loading of "average and "heavy" was used. These are characterized as:

Traffic	Average Chicago	Average L.A.	Heavy Chicago	Heavy L.A.
Initial ADT	55,000	65,000	110,000	130,000
Final 20 year ADT	70,000	70,000	140,000	140,000

Percent trucks was 10 for Chicago and 13 for L.A.

The JCP-1 computer program was used to select the design structure and joint spacing.

2. Conventional designs were developed using the same design data. The IDOT design manual (Ref. 29) was used for the Chicago designs and the California Department of Transportation design procedure (Ref. 30) was used to design the pavements in Los Angeles.

3. Other components of the pavements were designed in accordance with the recommendations for zero-maintenance (for the zero-maintenance designs) and the standard practice of the states involved (for the conventional designs).

4. Initial construction costs of each pavement design was computed using the unit costs previously obtained. These costs are obviously only approximate, but since the same unit costs are used for both the zero-maintenance and the conventional design the comparison between the two should be reasonable.

5. Required slab thicknesses and other design data for each project are as follows:

a. Chicago Conventional Design - Average Traffic

Slab Thickness: 8 ins. (203mm)

Continuous Reinforcement

AC Shoulders: 8 ins. (203 mm)

Asphalt Stabilized Subbase: 6 ins. (152 mm)

b. Chicago Zero-Maintenance Design - Average Traffic

Slab Thickness: 12 ins. (305 mm)

Joint Spacing (skewed): 12-15 ft. (3.6-4.6 m)

PCC Shoulders: 12 to 8 ins. (304-203 mm) tied

Corrosion Proof Dowels

Open Graded Asphalt Stabilized Subbase: 6 ins. (152 mm)

Longitudinal Subsurface Edge Drains

Preformed Compression Joint Sealant

c. Chicago Conventional Design - Heavy Traffic

Same as average traffic except slab thickness of 9 ins. (229 mm)

d. Chicago Zero-Maintenance Design - Heavy Traffic

Same as average traffic except slab thickness of 14 ins. (356 mm)

e. Los Angeles Conventional Design-Average and Heavy Traffic

Slab Thickness: 9 ins. (229mm)

Joint Spacing (skewed): 12-19 ft. (3.6-5.8 m)

AC Surfaced Shoulders: 4 ins. (102 mm)

Cement Stabilized Subbase: 6 ins. (152 mm)

No dowels

f. Los Angeles Zero-Maintenance Design - Average and Heavy Traffic

Slab Thickness: 12 ins. (305 mm)

Joint Spacing (skewed): 12-15 ft. (3.6-4.6 m)

No dowels

PCC Shoulders: 12-8 ins. (305-203 mm) tied

Low Cement Content PCC Subbase: 6 ins. (152 mm)

Liquid Joint Sealant

6. Initial construction costs for these pavements are summarized in Table 6.14. The percent increase of costs for the zero-maintenance pavement ranges from 14 to 24. The large difference in pavement costs between California and Illinois is due to difference in labor and materials costs.

Table 6.14. Initial Construction Costs for Conventional and Zero-Maintenance Pavements in Two Locations Under Average and Heavy Traffic (6 lanes and shoulders).

LOCATION	Construction Costs - $/mile AVERAGE TRAFFIC	HEAVY TRAFFIC
Chicago		
Conventional	$1,003,002	$1,050,522
Zero-Maintenance	1,148,570	1,224,133
% Increase	14.5	16.5
Los Angeles		
Conventional (9 in. JCP)	524,750	
Zero-Maintenance (12 in. JCP)	651,470	
% Increase	24.1	

6.7 SENSITIVITY ANALYSIS

A sensitivity analysis is conducted to illustrate the effect of changes in several of the design parameters on required slab thickness and to show the reasonableness of the design procedure. 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 range that might exist in actual situations. Joint spacing is the first parameter varied from 15 to 23 ft. (4.6 - 7.0 m) as shown in Figure 6.4a. 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 horizontal curve since there is no way to adjust for joint spacing and the empirical equation was based on a 15 ft. (4.6 m) joint spacing. The slab thickness required for fatigue increases from 11.6 to 13.5 in. (295 - 343 mm) as joint spacing increases from 15 to 23 ft. (4.6 - 7.0 m . A change in the mean 28-day modulus of rupture from 550 to 800 psi produces a change of about 3 in. (76 mm) in PCC slab thickness as shown in Figure 6.4b. A change in foundation conditions as shown in Figure 6.4c from a granular subbase/clay subgrade to a granular subgrade reduces the required slab thickness by about 1 in. (25 mm) A change in subbase type from 12 in. (305 mm) granular to 6 in. (152 mm) asphalt treated results in a 1/2 in. (13 mm) reduction in PCC slab thickness. The variation of PCC strength shown in Figure 6.4d 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 in. (25 mm).

The effect of increasing the mean average daily traffic (ADT) from 40,000 to 120,000 in Figure 6.5a, produces a change in required slab

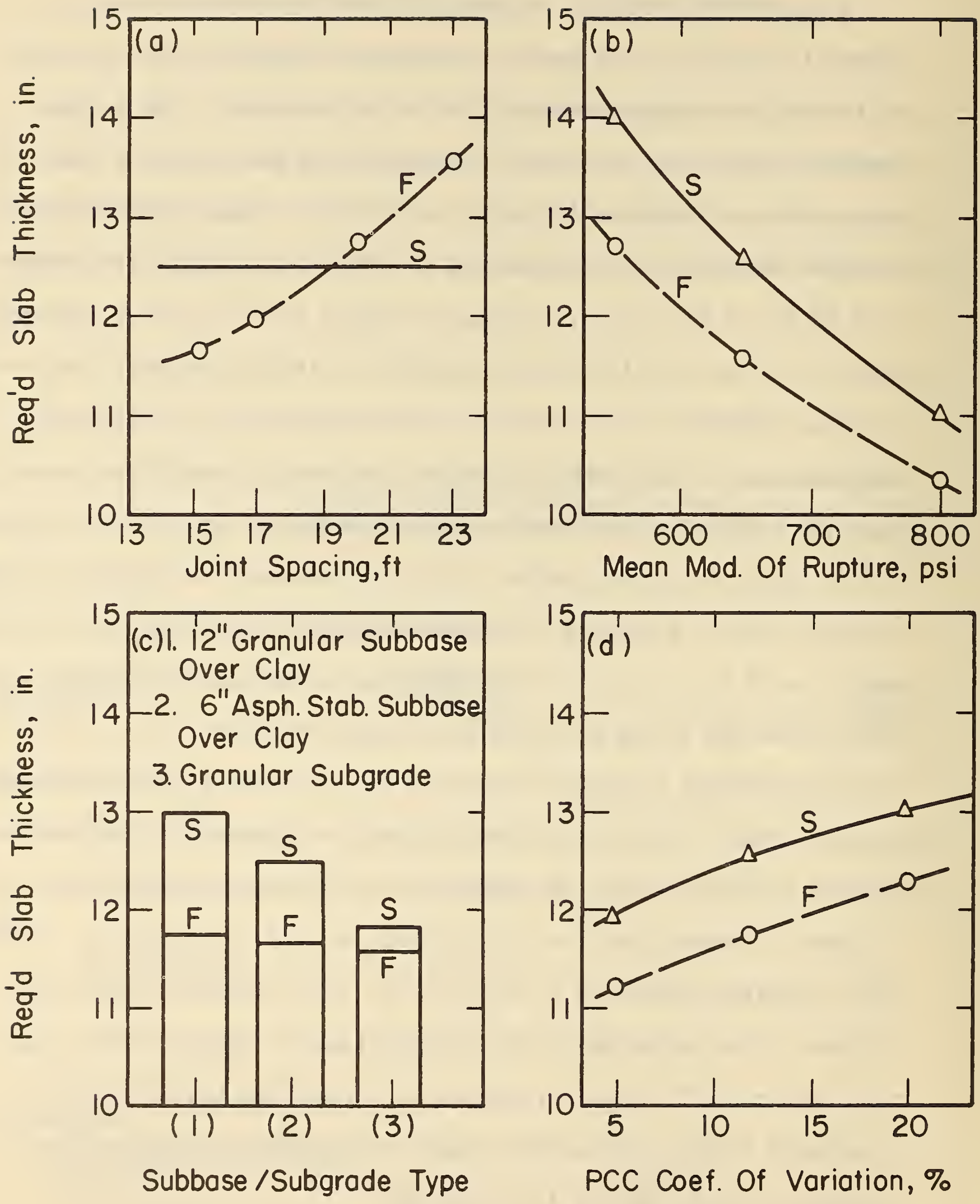


Figure 6.4. Sensitivity Analysis of Selected Design Parameters for Example Project (S = serviceability requirement, F = fatigue requirement).

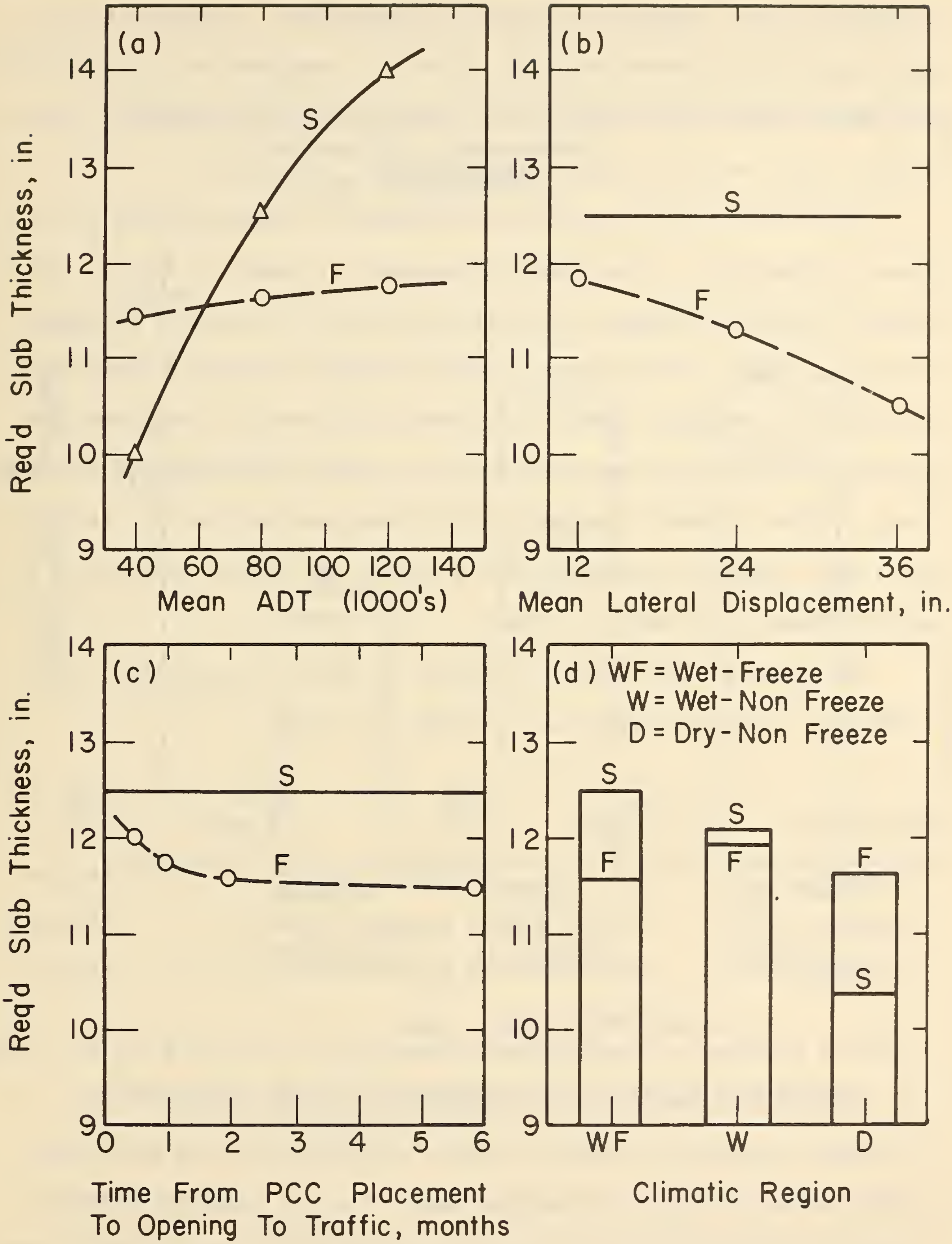


Figure 6.5. Sensitivity Analysis of Selected Design Parameters For Example Project (S = serviceability requirement, F = fatigue requirement).

thickness of 4 in. (102 mm). 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 36 to 12 in. (914 - 305 mm) in Figure 6.5b, results in an increase in slab thickness of about 1.3 in. (33 mm) for fatigue considerations.

The effect of time from PCC slab placement to opening of traffic is shown in Figure 6.5c. 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 6.5d. 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 12.5 to 11.7 in. (318 - 297 mm) 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 6.6. 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 of 11.4 to 12.6 in. (290 - 320 mm) 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 ranges to 38 and 66 kips for single and tandem axles, respectively. The

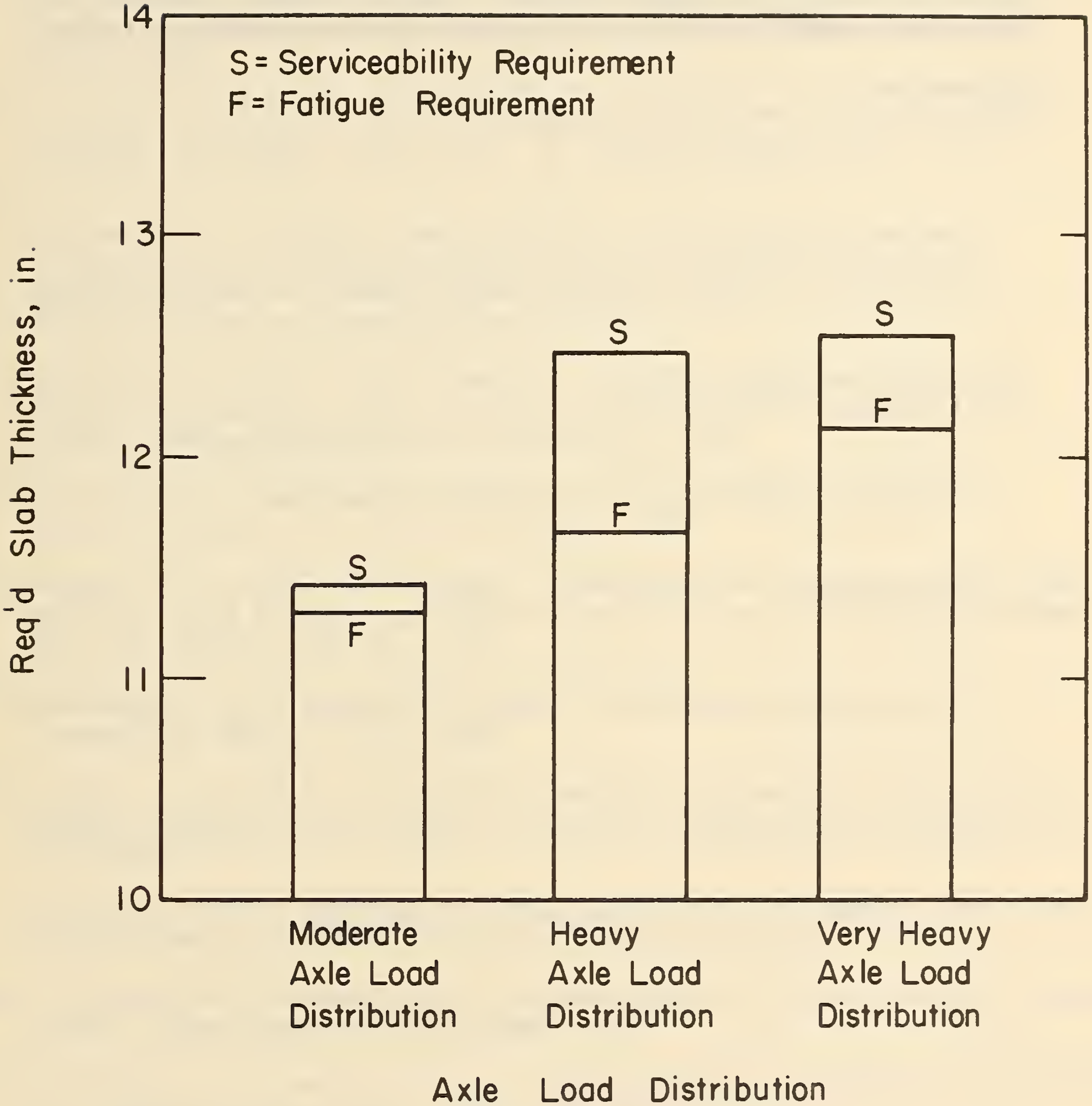


Figure 6.6. Sensitivity Analysis of Axle Load Distribution for Example Project.

change in required thickness considering serviceability is only 0.1 in. (2.5 mm), but the change in thickness considering fatigue is 0.5 in. (12.7 mm). The maximum axle load is very important in this design procedure, and should be carefully estimated using spot state enforcement weighing information.

REFERENCES

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APPENDIX A

A.1 INPUT GUIDE - JCP-1 PROGRAM

ZERO-MAINTENANCE DESIGN OF PLAIN JOINTED CONCRETE PAVEMENT

IDENTIFICATION OF PROBLEM

Three Cards

20A4
20A4
20A4

1 80

Enter descriptive identification of design project; date of run, project number, designer, etc. (Any or all of the cards may be left blank).

DESIGN CRITERIA DATA

One Card

F10.0	F10.0	F10.0	F10.0	I5	
1 — 10	20	30	40	45	80
DLIFE	SIC	PT	OPEN	KMONTH	

DLIFE = Pavement zero-maintenance design life (years)

SIC = Initial serviceability index after construction

PT = Terminal serviceability index for zero-maintenance

OPEN = Time after PCC slab placement that pavement will be opened to traffic (years)

KMONTH = Month pavement will be opened to traffic (right justify) (Input 1 through 12 according to the following key: Jan=1, Feb=2, Mar=3, Apr=4, May=5, Jun=6, Jul=7 Aug=8, Sep=9, Oct=10, Nov=11, Dec=12)

PRINTOUT DATA CONTROL

One Card

80I1	
1	80
DLIFE	

Enter 1 in the columns that correspond to the years during which summary of fatigue and serviceability data will be printed.

One Card

80I1

1 DLIFE 80

Enter 1 in the columns that correspond to the years during which comprehensive fatigue output will be printed.

SLAB PROPERTIES DATA

One Card

F5.0	F5.0	F5.0	F5.0	E10.3	E10.3	
1 5	10	15	20	30	40	80
H	L	FF	FCV	ET	E	

H = Slab thickness - inches

L = Slab length - feet

FF = Mean PCC modulus of rupture (28 days) - psi

FCV = Coefficient of variation of PCC modulus of rupture - percent

ET = PCC coefficient of thermal expansion (per degree - F)

E = PCC modulus of elasticity (psi)

TRAFFIC DATA

One Card

F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	I5	
1	10	20	30	40	50	60	70	75 80
ADTI	ADTF	T	LD	DD	A	PC	D	

ADTI = Average daily traffic at beginning of design period - two direction

ADTF = Average daily traffic at end of design period - two direction

T = Percent trucks of ADT

LD = Percent trucks in heaviest traveled or design lane

DD = Percent direction distribution

A = Mean axles per truck

PC = Percent trucks during daylight

D = Mean distance from slab edge to outside of truck duals (in.) (right justify)

One Card

I5	I5	

1 5 10 80

KK KSAL

KK = Number of axle load distribution groups (single plus tandem) (right justify)

KSAL = Number of single axle load distribution groups (right justify)

As Many Cards As Needed

F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0
F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0

1 10 20 30 40 50 60 70 80

LOAD(I)

[LOAD(I), I=1,KK]

LOAD(I) = The highest value of each axle load distribution group (first enter single axle loads (KSAL) and then tandem axle loads)(pounds)

As Many Cards As Needed

F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0
F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0

1 10 20 30 40 50 60 70 80

DIST(I)

[DIST(I),I=1,KK]

DIST(I) = The percentage axle loads in each of the KK axle load groups input in the previous card (first enter single axle percentage and then tandem axle percentage)

One Card:

F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	

1 5 10 15 20 25 30 35 40 45 50 55 60 80

TRUKPC(I)

[TRUKPC(I),I=1,12]

TRUKPC(I) = The monthly truck percentage over year (enter percentage for first month pavement will be opened to traffic in Columns 1-5, 2nd month in Columns 6-10, etc.)

FOUNDATION SUPPORT DATA:

One Card:

F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	

1 5 10 15 20 25 30 35 40 45 50 55 60 80

K(J)

[K(J),J=1,12]

K(J) = Modulus of foundation support (k-value at top of subbase) for each month in pci (enter k-value for first month pavement will be opened to traffic in Columns 1-5, 2nd month in Columns 6-10, etc.)

One Card:

F10.0	

1 10 80

ERODEF

ERODEF = The amount of erodability of foundation at the end of design life in inches.

One Card:

F10.0	

1 10 80

DK

DK = Design modulus of foundation support for serviceability/performance analysis in pci.

ENVIRONMENTAL DATA (TWO SETS OF FOUR CARDS):

Set One - Four Cards

F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	

1 10 20 30 40 50 60 70 80

H1 G1(1,1) G1(2,1) G1(3,1) G1(4,1) G1(5,1) G1(6,1)

	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	

1 10 20 30 40 50 60 70 80

G1(7,1) G1(8,1) G1(9,1) G1(10,1) G1(11,1) G1(12,1)

	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	

1 10 20 30 40 50 60 70 80

G1(1,2) G1(2,2) G1(3,2) G1(4,2) G1(5,2) G1(6,2)

	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	

1 10 20 30 40 50 60 70 80

G1(7,2) G1(8,2) G1(9,2) G1(10,2) G1(11,2) G1(12,2)

H1 = PCC slab thickness for relatively thin slab (usually 8 inches) - inches

G1(J,M) = Mean temperature gradients for slab of H1 thickness for each month, day, and night where
J = index for months
(J=1 for first month opened to traffic)
M = index for day (M=1) and night (M=2)

Set Two - Four Cards

F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	

1 10 20 30 40 50 60 70 80

H2 G2(1,1) G2(2,1) G2(3,1) G2(4,1) G2(5,1) G2(6,1)

	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	

1 10 20 30 40 50 60 70 80

G2(7,1) G2(8,1) G2(9,1) G2(10,1) G2(11,1) G2(12,1)

1–10	11–20	21–30	31–40	41–50	51–60	61–70	71–80
	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	
	G2(1,2)	G2(2,2)	G2(3,2)	G2(4,2)	G2(5,2)	G2(6,2)	

1–10	11–20	21–30	31–40	41–50	51–60	61–70	71–80
	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	
	G2(7,2)	G2(8,2)	G2(9,2)	G2(10,2)	G2(11,2)	G2(12,2)	

H2 = PCC slab thickness for relatively thick slab (usually 12 inches) - inches

G2(J,M) = Mean temperature gradients for slab of H2 thickness for each month, day, and night where
- J = index for months (J=1 for first month opened to traffic)
- M = index for day (M=1) and night (M=2)

One Card

1–10	11–80
F10.0	
RF	

RF = Regional factor

The cards shown on the following page may be added for each additional PCC slab thickness to be analyzed:

SIX CARDS SET FOR EACH ADDITIONAL TRIAL PCC SLAB THICKNESS:

IDENTIFICATION OF PROBLEM

Three Cards (Same as first trial thickness).

20A4
20A4
20A4

80

SLAB THICKNESS

One Card

F5.0	

1 5 80
H

H = New Slab Thickness, inches

CONTROL DATA

One Card

80I1	

1 DLIFE 80

Enter 1 in the columns that correspond to the years during which summary of fatigue and serviceability data will be printed.

One Card

80I1	

1 DLIFE 80

Enter 1 in the columns that correspond to the years during which comprehensive fatigue output will be printed.

FINAL CARD OF DATA DECK

/*

12 80

/* indicates end of data deck

A. 2 SAMPLE INPUT

IBM — FORTRAN Coding Form — GX28-7327-6 U/M 050** Printed in U.S.A.

PROGRAM: ZERO MAINTENANCE DESIGN - EXAMPLE PROBLEM (JCP-1)
PROGRAMMER: M. I. DARTER   DATE: 2 JULY 1976   PAGE 1 OF 2

```
     (BLANK CARD)
      ZERO-MAINTENANCE DESIGN -- EXAMPLE PROBLEM --  9-INCH SLAB
     (BLANK CARD)
 20.0     4.5       3.0       0.16      10
1000100001000010000 1
00000000000000000000
9.00 15.0 650. 12.      5.E-06    5.E+06
 70000.   90000.    10.       60.0      50.       2.75      60.       18
   32   14
  3000.   7000.     8000.     12000.    16000.    18000.    20000.    22000.
 24000.   26000.    28000.    30000.    32000.    34000.     6000.     2000.
 18000.   24000.    30000.    32000.    34000.    36000.    38000.    40000.
 42000.   44000.    46000.    48000.    50000.    52000.    54000.    56000.
 7.28     16.23     7.75      15.01     4.75      1.44      1.32      1.02
 0.42      0.14     0.06      0.02      0.01      0.01      0.01      9.76
 4.36      5.68     8.92      4.90      4.30      3.40      1.40      0.43
 0.19      0.08     0.06      0.03      0.02      0.02      0.01      0.01
 8.33 8.33 8.33 7.00 7.00 7.00 8.36 9.33 9.33 9.33 9.33 8.33
240. 224. 224. 500. 500. 135. 178. 190. 240. 240. 240. 240.
 13.0
212.0
  8.0 0.88      0.72      0.57      0.45      0.32      0.86
      1.59      1.46      1.58      2.08      1.73      1.34
     -0.80     -0.79     -0.50     -0.84     -0.78     -0.87
```

*A standard card form, IBM electro 888157, is available for punching statements from this form.

**Number of forms per pad may vary slightly

Coded input data for example problem design (Four trial slab thicknesses are run with this input).

IBM FORTRAN Coding Form

GX28-7327-6 U/M 050**
Printed in U.S.A.

PROGRAM: ZERO MAINTENANCE DESIGN - EXAMPLE PROBLEM (JCP-1)		PUNCHING INSTRUCTIONS — GRAPHIC / PUNCH	PAGE 2 OF 2
PROGRAMMER: M. I. D.	DATE 2 JULY 1976		CARD ELECTRO NUMBER*

```
C  STATEMENT  C  FORTRAN STATEMENT                                                    IDENTIFICATION
   NUMBER     O                                                                       SEQUENCE
              N
              T
         -0.62     -0.72     -0.90     -0.91     -1.00     -1.13
 12.0     0.56      0.43      0.40      0.27      0.18      0.59
          1.11      0.99      1.88      1.54      1.32      0.92
         -0.62     -0.64     -0.37     -0.63     -0.57     -0.62
         -0.41     -0.49     -0.57     -0.54     -0.63     -0.83
 1.0
      (BLANK CARD)
        ZERO-MAINTENANCE DESIGN -- EXAMPLE PROBLEM -- 11-INCH SLAB
      (BLANK CARD)
11.00
10001000010000100001
00000000000000000000
      (BLANK CARD)
        ZERO-MAINTENANCE DESIGN -- EXAMPLE PROBLEM -- 13-INCH SLAB
      (BLANK CARD)
13.00
10001000010000100001
10000000000000000000
      (BLANK CARD)
        ZERO-MAINTENANCE DESIGN -- EXAMPLE PROBLEM -- 15-INCH SLAB
      (BLANK CARD)
15.00
10001000010000100001
00000000000000000000
```

*A standard card form, IBM electro 888157, is available for punching statements from this form.

**Number of forms per pad may vary slightly

The following are JCP-1 program outputs for the 13-in. slab (excluding detailed fatigue analysis output for each month excepting October).

```
                 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
```

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

FOUNDATION SUPPORT
****

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

OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
240.	224.	224.	500.	500.	135.	178.	190.	240.	240.	240.	240.

ERODABILITY OF FOUNDATION AT BEGINNING OF DESIGN PERIOD (INS.) 0.0
ERODABILITY OF FOUNDATION AT END OF DESIGN PERIOD (INS.) 12.00

DESIGN MODULUS OF FOUNDATION SUPPORT (K) FOR
SERVICEABILITY/PERFORMANCE ANALYSIS - PCI 212.00

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

Detailed fatigue output for first month of October.

FATIGUE DAMAGE SUBTOTALS FOR YEAR # 1

MONTH	D/N	LOAD	STRL	STRC	R	STRT	F	N	NAAL	DAMAGE
1	1	3000.	2.37E 01	2.36E 01	1.1554	5.096E 01	5.999E 02	1.300E 15	8.717E 02	6.704E-07
1	1	7000.	5.52E 01	2.36E 01	1.1554	8.252E 01	5.999E 02	1.540E 14	1.949E 03	1.266E-05
1	1	8000.	6.31E 01	2.36E 01	1.1554	9.041E 01	5.999E 02	9.035E 13	9.280E 02	1.027E-05
1	1	12000.	9.47E 01	2.36E 01	1.1554	1.220E 02	5.999E 02	1.070E 13	1.797E 03	1.679E-04
1	1	16000.	1.26E 02	2.36E 01	1.1554	1.535E 02	5.999E 02	1.268E 12	5.688E 02	4.487E-04
1	1	18000.	1.42E 02	2.36E 01	1.1554	1.693E 02	5.999E 02	4.363E 11	2.323E 02	5.325E-04
1	1	20000.	1.58E 02	2.36E 01	1.1554	1.851E 02	5.999E 02	1.501E 11	1.581E 02	1.053E-03
1	1	22000.	1.74E 02	2.36E 01	1.1554	2.009E 02	5.999E 02	5.168E 10	1.221E 02	2.364E-03
1	1	24000.	1.89E 02	2.36E 01	1.1554	2.166E 02	5.999E 02	1.778E 10	5.029E 01	2.828E-03
1	1	26000.	2.05E 02	2.36E 01	1.1554	2.324E 02	5.999E 02	6.121E 09	1.676E 01	2.739E-03
1	1	28000.	2.21E 02	2.36E 01	1.1554	2.482E 02	5.999E 02	2.107E 09	7.184E 00	3.410E-03
1	1	30000.	2.37E 02	2.36E 01	1.1554	2.640E 02	5.999E 02	7.250E 08	2.395E 00	3.303E-03
1	1	32000.	2.52E 02	2.36E 01	1.1554	2.798E 02	5.999E 02	2.495E 08	1.197E 00	4.799E-03
1	1	34000.	2.68E 02	2.36E 01	1.1554	2.955E 02	5.999E 02	8.587E 07	1.197E 00	1.394E-02
1	1	6000.	2.07E 01	2.36E 01	1.1554	4.798E 01	5.999E 02	1.590E 15	8.861E 01	5.572E-08
1	1	12000.	4.14E 01	2.36E 01	1.1554	6.867E 01	5.999E 02	3.927E 14	2.337E 03	5.952E-06
1	1	18000.	6.21E 01	2.36E 01	1.1554	8.936E 01	5.999E 02	9.696E 13	1.044E 03	1.077E-05
1	1	24000.	8.28E 01	2.36E 01	1.1554	1.101E 02	5.999E 02	2.394E 13	1.360E 03	5.681E-05
1	1	30000.	1.03E 02	2.36E 01	1.1554	1.307E 02	5.999E 02	5.912E 12	2.136E 03	3.613E-04
1	1	32000.	1.10E 02	2.36E 01	1.1554	1.376E 02	5.999E 02	3.709E 12	1.173E 03	3.164E-04
1	1	34000.	1.17E 02	2.36E 01	1.1554	1.445E 02	5.999E 02	2.327E 12	1.030E 03	4.425E-04
1	1	36000.	1.24E 02	2.36E 01	1.1554	1.514E 02	5.999E 02	1.460E 12	8.142E 02	5.578E-04
1	1	38000.	1.31E 02	2.36E 01	1.1554	1.583E 02	5.999E 02	9.159E 11	3.353E 02	3.661E-04
1	1	40000.	1.38E 02	2.36E 01	1.1554	1.652E 02	5.999E 02	5.746E 11	1.150E 02	2.001E-04
1	1	42000.	1.45E 02	2.36E 01	1.1554	1.721E 02	5.999E 02	3.605E 11	4.550E 01	1.262E-04
1	1	44000.	1.52E 02	2.36E 01	1.1554	1.790E 02	5.999E 02	2.261E 11	1.916E 01	8.472E-05
1	1	46000.	1.59E 02	2.36E 01	1.1554	1.859E 02	5.999E 02	1.419E 11	1.437E 01	1.013E-04
1	1	48000.	1.66E 02	2.36E 01	1.1554	1.928E 02	5.999E 02	8.901E 10	7.184E 00	8.071E-05
1	1	50000.	1.72E 02	2.36E 01	1.1554	1.997E 02	5.999E 02	5.584E 10	4.790E 00	8.577E-05
1	1	52000.	1.79E 02	2.36E 01	1.1554	2.066E 02	5.999E 02	3.503E 10	4.790E 00	1.367E-04
1	1	54000.	1.86E 02	2.36E 01	1.1554	2.135E 02	5.999E 02	2.198E 10	2.395E 00	1.090E-04
1	1	56000.	1.93E 02	2.36E 01	1.1554	2.204E 02	5.999E 02	1.379E 10	2.395E 00	1.737E-04
1	2	3000.	2.37E 01	-2.83E 01	1.0692	-6.579E 00	5.999E 02	6.355E 16	5.811E 02	9.145E-09
1	2	7000.	5.52E 01	-2.83E 01	1.0692	2.498E 01	5.999E 02	7.527E 15	1.300E 03	1.726E-07
1	2	8000.	6.31E 01	-2.83E 01	1.0692	3.287E 01	5.999E 02	4.416E 15	6.187E 02	1.401E-07
1	2	12000.	9.47E 01	-2.83E 01	1.0692	6.443E 01	5.999E 02	5.231E 14	1.198E 03	2.291E-06
1	2	16000.	1.26E 02	-2.83E 01	1.0692	9.599E 01	5.999E 02	6.196E 13	3.792E 02	6.120E-06
1	2	18000.	1.42E 02	-2.83E 01	1.0692	1.118E 02	5.999E 02	2.132E 13	1.549E 02	7.263E-06
1	2	20000.	1.58E 02	-2.83E 01	1.0692	1.275E 02	5.999E 02	7.338E 12	1.054E 02	1.436E-05
1	2	22000.	1.74E 02	-2.83E 01	1.0692	1.433E 02	5.999E 02	2.526E 12	8.142E 01	3.224E-05
1	2	24000.	1.89E 02	-2.83E 01	1.0692	1.591E 02	5.999E 02	8.692E 11	3.353E 01	3.857E-05
1	2	26000.	2.05E 02	-2.83E 01	1.0692	1.749E 02	5.999E 02	2.991E 11	1.118E 01	3.736E-05
1	2	28000.	2.21E 02	-2.83E 01	1.0692	1.907E 02	5.999E 02	1.030E 11	4.790E 00	4.652E-05
1	2	30000.	2.37E 02	-2.83E 01	1.0692	2.064E 02	5.999E 02	3.543E 10	1.597E 00	4.506E-05
1	2	32000.	2.52E 02	-2.83E 01	1.0692	2.222E 02	5.999E 02	1.219E 10	7.983E-01	6.545E-05
1	2	34000.	2.68E 02	-2.83E 01	1.0692	2.380E 02	5.999E 02	4.197E 09	7.983E-01	1.902E-04
1	2	6000.	2.07E 01	-2.83E 01	1.0692	-9.557E 00	5.999E 02	7.772E 16	5.907E 01	7.601E-10
1	2	12000.	4.14E 01	-2.83E 01	1.0692	1.113E 01	5.999E 02	1.919E 16	1.558E 03	8.119E-08
1	2	18000.	6.21E 01	-2.83E 01	1.0692	3.183E 01	5.999E 02	4.739E 15	6.961E 02	1.469E-07
1	2	24000.	8.28E 01	-2.83E 01	1.0692	5.252E 01	5.999E 02	1.170E 15	9.068E 02	7.750E-07
1	2	30000.	1.03E 02	-2.83E 01	1.0692	7.321E 01	5.999E 02	2.889E 14	1.424E 03	4.929E-06
1	2	32000.	1.10E 02	-2.83E 01	1.0692	8.011E 01	5.999E 02	1.813E 14	7.823E 02	4.316E-06
1	2	34000.	1.17E 02	-2.83E 01	1.0692	8.700E 01	5.999E 02	1.137E 14	6.865E 02	6.036E-06
1	2	36000.	1.24E 02	-2.83E 01	1.0692	9.390E 01	5.999E 02	7.135E 13	5.428E 02	7.608E-06
1	2	38000.	1.31E 02	-2.83E 01	1.0692	1.008E 02	5.999E 02	4.476E 13	2.235E 02	4.993E-06
1	2	40000.	1.38E 02	-2.83E 01	1.0692	1.077E 02	5.999E 02	2.808E 13	7.663E 01	2.729E-06
1	2	42000.	1.45E 02	-2.83E 01	1.0692	1.146E 02	5.999E 02	1.762E 13	3.033E 01	1.722E-06

1	2	44000.	1.52E 02	-2.83E 01	1.0692	1.215E 02	5.999E 02	1.105E 13	1.277E 01	1.156E-06
1	2	46000.	1.59E 02	-2.83E 01	1.0692	1.284E 02	5.999E 02	6.934E 12	9.579E 00	1.381E-06
1	2	48000.	1.66E 02	-2.83E 01	1.0692	1.353E 02	5.999E 02	4.350E 12	4.790E 00	1.101E-06
1	2	50000.	1.72E 02	-2.83E 01	1.0692	1.422E 02	5.999E 02	2.729E 12	3.193E 00	1.170E-06
1	2	52000.	1.79E 02	-2.83E 01	1.0692	1.491E 02	5.999E 02	1.712E 12	3.193E 00	1.865E-06
1	2	54000.	1.86E 02	-2.83E 01	1.0692	1.560E 02	5.999E 02	1.074E 12	1.597E 00	1.486E-06
1	2	56000.	1.93E 02	-2.83E 01	1.0692	1.629E 02	5.999E 02	6.739E 11	1.597E 00	2.369E-06

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

PROBLEM # 3

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

****

FOR YEAR # 1

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

	DAY	NIGHT	TOTAL
OCT	3.883E-02	5.296E-04	3.936E-02
NOV	1.366E-02	3.379E-04	1.400E-02
DEC	9.218E-03	5.732E-04	9.791E-03
JAN	1.366E-03	2.781E-05	1.393E-03
FEB	8.026E-04	3.136E-05	8.339E-04
MAR	1.144E-02	3.831E-04	1.182E-02
APR	4.436E-02	4.281E-04	4.479E-02
MAY	2.847E-02	3.136E-04	2.878E-02
JUN	4.864E-02	1.615E-04	4.880E-02
JUL	1.495E-01	1.714E-04	1.496E-01
AUG	6.791E-02	1.241E-04	6.803E-02
SEP	1.311E-02	5.632E-05	1.317E-02

SUM OF FATIGUE DAMAGE FOR DAY LOADING IS 4.273E-01

SUM OF FATIGUE DAMAGE FOR NIGHT LOADING IS 3.138E-03

TOTAL FATIGUE DAMAGE FOR YEAR # 1 IS 4.304E-01

RESULTS - SERVICEABILITY/PERFORMANCE OF JCP DESIGN LANE
****

SERVICEABILITY INDEX AT END OF YEAR # 1 4.444E 00
NUMBER OF ACCUMULATED 18-KIP EQUIVALENT
SINGLE AXLE LOADS AT END OF YEAR # 1 1.332E 06

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

****

PROBLEM # 3

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

****

FOR YEAR # 5

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

	DAY	NIGHT	TOTAL
OCT	2.005E-03	5.761E-05	2.063E-03
NOV	1.441E-03	6.012E-05	1.501E-03
DEC	1.433E-03	1.240E-04	1.557E-03
JAN	3.634E-04	1.129E-05	3.746E-04
FEB	2.623E-04	1.399E-05	2.763E-04
MAR	2.841E-03	1.301E-04	2.971E-03
APR	1.121E-02	1.646E-04	1.137E-02
MAY	8.478E-03	1.363E-04	8.614E-03
JUN	1.526E-02	8.042E-05	1.534E-02
JUL	4.594E-02	8.970E-05	4.603E-02
AUG	2.399E-02	6.976E-05	2.406E-02
SEP	5.559E-03	3.456E-05	5.593E-03

SUM OF FATIGUE DAMAGE FOR DAY LOADING IS 1.188E-01

SUM OF FATIGUE DAMAGE FOR NIGHT LOADING IS 9.724E-04

TOTAL FATIGUE DAMAGE FOR YEAR # 5 IS 1.198E-01

RESULTS - SERVICEABILITY/PERFORMANCE OF JCP DESIGN LANE
****

SERVICEABILITY INDEX AT END OF YEAR # 5 4.175E 00
NUMBER OF ACCUMULATED 18-KIP EQUIVALENT
SINGLE AXLE LOADS AT END OF YEAR # 5 6.850E 06

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                    ZERO-MAINTENANCE PORTLAND CEMENT CONCRETE
                   PLAIN JOINTED PAVEMENT DESIGN PROGRAM   (JCP-1)
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 PROBLEM # 3
                 ZERO-MAINTENANCE DESIGN -- EXAMPLE PROBLEM -- 13 INCH SLAB

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FOR YEAR # 10

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

             DAY           NIGHT          TOTAL
OCT       1.726E-03      5.688E-05      1.783E-03
NOV       1.267E-03      5.960E-05      1.326E-03
DEC       1.266E-03      1.197E-04      1.386E-03
JAN       3.361E-04      1.179E-05      3.479E-04
FEB       2.469E-04      1.454E-05      2.614E-04
MAR       2.472E-03      1.274E-04      2.600E-03
APR       9.267E-03      1.605E-04      9.428E-03
MAY       7.160E-03      1.350E-04      7.295E-03
JUN       1.259E-02      8.130E-05      1.267E-02
JUL       3.635E-02      9.060E-05      3.644E-02
AUG       1.960E-02      7.144E-05      1.967E-02
SEP       4.827E-03      3.637E-05      4.863E-03

SUM OF FATIGUE DAMAGE FOR DAY LOADING IS        9.711E-02
SUM OF FATIGUE DAMAGE FOR NIGHT LOADING IS      9.651E-04
TOTAL FATIGUE DAMAGE FOR YEAR # 10 IS           9.808E-02

RESULTS - SERVICEABILITY/PERFORMANCE OF JCP DESIGN LANE
*******

SERVICEABILITY INDEX AT END OF YEAR # 10        3.850E 00
NUMBER OF ACCUMULATED 18-KIP EQUIVALENT
   SINGLE AXLE LOADS AT END OF YEAR # 10        1.417E 07
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ZERO-MAINTENANCE PORTLAND CEMENT CONCRETE
PLAIN JOINTED PAVEMENT DESIGN PROGRAM (JCP-1)
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PROBLEM # 3

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

****

FOR YEAR # 15

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

	DAY	NIGHT	TOTAL
OCT	1.750E-03	6.444E-05	1.815E-03
NOV	1.303E-03	6.766E-05	1.371E-03
DEC	1.305E-03	1.325E-04	1.437E-03
JAN	3.526E-04	1.365E-05	3.663E-04
FEB	2.619E-04	1.673E-05	2.786E-04
MAR	2.515E-03	1.430E-04	2.658E-03
APR	8.988E-03	1.781E-04	9.166E-03
MAY	7.033E-03	1.512E-04	7.184E-03
JUN	1.207E-02	9.204E-05	1.216E-02
JUL	3.363E-02	1.023E-04	3.373E-02
AUG	1.854E-02	8.142E-05	1.862E-02
SEP	4.779E-03	4.238E-05	4.822E-03

SUM OF FATIGUE DAMAGE FOR DAY LOADING IS 9.253E-02

SUM OF FATIGUE DAMAGE FOR NIGHT LOADING IS 1.085E-03

TOTAL FATIGUE DAMAGE FOR YEAR # 15 IS 9.362E-02

RESULTS - SERVICEABILITY/PERFORMANCE OF JCP DESIGN LANE
****

SERVICEABILITY INDEX AT END OF YEAR # 15 3.444E 00
NUMBER OF ACCUMULATED 18-KIP EQUIVALENT
SINGLE AXLE LOADS AT END OF YEAR # 15 2.197E 07

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

****

PROBLEM # 3

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

****

FOR YEAR # 20

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

	DAY	NIGHT	TOTAL
OCT	1.859E-03	7.598E-05	1.935E-03
NOV	1.403E-03	7.995E-05	1.483E-03
DEC	1.405E-03	1.527E-04	1.557E-03
JAN	3.836E-04	1.630E-05	3.999E-04
FEB	2.877E-04	1.984E-05	3.075E-04
MAR	2.679E-03	1.674E-04	2.847E-03
APR	9.141E-03	2.055E-04	9.346E-03
MAY	7.228E-03	1.759E-04	7.404E-03
JUN	1.210E-02	1.079E-04	1.221E-02
JUL	3.263E-02	1.195E-04	3.275E-02
AUG	1.835E-02	9.602E-05	1.845E-02
SEP	4.930E-03	5.105E-05	4.981E-03

SUM OF FATIGUE DAMAGE FOR DAY LOADING IS 9.240E-02

SUM OF FATIGUE DAMAGE FOR NIGHT LOADING IS 1.268E-03

TOTAL FATIGUE DAMAGE FOR YEAR # 20 IS 9.366E-02

RESULTS - SERVICEABILITY/PERFORMANCE OF JCP DESIGN LANE
****

SERVICEABILITY INDEX AT END OF YEAR # 20 3.119E 00
NUMBER OF ACCUMULATED 18-KIP EQUIVALENT
SINGLE AXLE LOADS AT END OF YEAR # 20 3.023E 07

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	7.619E-02	1.748E-03	7.794E-02
NOV	4.086E-02	1.612E-03	4.247E-02
DEC	3.625E-02	3.118E-03	3.937E-02
JAN	8.385E-03	2.751E-04	8.660E-03
FEB	5.937E-03	3.353E-04	6.272E-03
MAR	6.400E-02	3.088E-03	6.709E-02
APR	2.414E-01	3.809E-03	2.452E-01
MAY	1.794E-01	3.149E-03	1.825E-01
JUN	3.134E-01	1.862E-03	3.152E-01
JUL	9.175E-01	2.061E-03	9.196E-01
AUG	4.779E-01	1.614E-03	4.795E-01
SEP	1.129E-01	8.172E-04	1.138E-01

SUM OF FATIGUE DAMAGE FOR DAY LOADING IS 2.474E 00

SUM OF FATIGUE DAMAGE FOR NIGHT LOADING IS 2.349E-02

TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD IS 2.498E 00

RESULTS - SERVICEABILITY/PERFORMANCE OF JCP DESIGN LANE

SERVICEABILITY INDEX AT END OF YEAR # 20 3.119E 00
NUMBER OF ACCUMULATED 18-KIP EQUIVALENT
SINGLE AXLE LOADS AT END OF YEAR # 20 3.023E 07

Rigid Pavement Structure - a combination of subbase and surface course placed on a subgrade to support the traffic load and distribute it to the roadbed.

Rigid Pavement - a pavement structure which distributes loads to the subgrade, having as one course a Portland cement concrete slab of relatively high bending resistance.

Roadbed - the graded portion of a highway between top and side slopes, prepared as a foundation for the pavement structure and shoulder.

Subgrade - the top surface of a roadbed upon which the pavement structure and shoulders are constructed.

Roadbed Material - the material below the subgrade in cuts and embankments and in embankment foundations, extending to such depth as affects the support of the pavement structure.

Selected Material - a suitable native material obtained from a specified source such as a particular roadway cut or borrow area, of a suitable material having specified characteristics to be used for a specific purpose.

Subbase - the layer or layers of specified or selected material of designed thickness placed on a subgrade to support the portland cement concrete slab.

Axle Load - the total load transmitted by all wheels whose centers may be included between two parallel transverse vertical planes 40 inches apart, extending across the full width of the vehicle.

Serviceability - the ability at time of observation of a pavement to serve high-speed, high-volume automobile and truck traffic.

Present Serviceability Rating (PSR) - the mean value of the independent subjective ratings by members of a special Panel for the AASHO Road Test as to the serviceability of a section of highway. The members of the Panel included highway specialists representing many fields of interest and concern in highways.

Present Serviceability Index (SI) - a number derived by formula for estimating the serviceability rating from measurements of certain physical features of the pavement.

Pavement Performance - the trend of serviceability with load applications.

Climatic Regional Factor (RF) - a numerical factor that is used to adjust the slab thickness for climatic and environmental conditions.

Modulus of Subgrade Reaction (k) - Westergaard's elastic modulus of subgrade reaction for use in rigid pavement design (the load in pounds per square inch on a loaded area of the subgrade or subbase divided by the elastic deflection in inches of the subgrade or subbase, psi/in.).

Traffic Equivalence Factor (e) - a numerical factor that expresses the relationship of a given axle load to another axle load in terms of their effect on the serviceability of a pavement structure. In this guide all axle loads are equated in terms of the equivalent number of repetitions of an 18,000-pound single axle.

Pumping - the ejection of foundation material, either wet or dry, through joints or cracks, or along edges of rigid slabs resulting from vertical movements of the slab under traffic.

Slab Length - the distance between adjacent transverse joints.

Crack - a fissure or open seam not necessarily extending through the body of a material.

Expansion Joint - a joint located to provide for expansion of a rigid slab, without damage to itself, adjacent slabs, or structures.

Contraction Joint - a joint normally placed at recurrent intervals in a rigid slab to control transverse cracking.

Longitudinal Joint - a joint normally placed between traffic lanes in rigid pavements to control longitudinal cracking.

Construction Joint - a joint made necessary by a prolonged interruption in the placing of concrete.

Load Transfer Device - a mechanical means designed to carry loads across a joint in a rigid slab.

Dowel - a load transfer device in a rigid slab, consisting of a plain or corrosion proof round steel bar.

Tie Bar - a deformed steel bar or connector embedded across a joint in a rigid slab to prevent separation of abutting slabs.

Reinforcement - steel embedded in a rigid slab to resist tensile stresses and detrimental opening of cracks.

Deformed Bar - a reinforcing bar for rigid slabs conforming to "Requirements for Deformations," in AASHO Designations M31, M42, or M53.

Zero- Maintenance - refers only to the structural adequacy of the pavement travel lanes and shoulder system; and does not include activities, such as mowing, guard rail repair, striping, providing skid resistance, wear from studded tires, etc. Includes such activities as cracking repair or filling, slab replacement, patching, grinding, and overlay.

Axle Load Group - a range in axle weights for either single or tandem axles, such as 18,000 to 20,000 pounds.

FFICE: 1978 O— 621-629/271 REGION 3-1

FEDERALLY COORDINATED PROGRAM OF HIGHWAY RESEARCH AND DEVELOPMENT (FCP)

The Offices of Research and Development of the Federal Highway Administration are responsible for a broad program of research with resources including its own staff, contract programs, and a Federal-Aid program which is conducted by or through the State highway departments and which also finances the National Cooperative Highway Research Program managed by the Transportation Research Board. The Federally Coordinated Program of Highway Research and Development (FCP) is a carefully selected group of projects aimed at urgent, national problems, which concentrates these resources on these problems to obtain timely solutions. Virtually all of the available funds and staff resources are a part of the FCP, together with as much of the Federal-aid research funds of the States and the NCHRP resources as the States agree to devote to these projects.*

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems connected with the responsibilities of the Federal Highway Administration under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by keeping the demand-capacity relationship in better balance through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements which affect the quality of the human environment. The ultimate goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge of materials properties and technology to fully utilize available naturally occurring materials, to develop extender or substitute materials for materials in short supply, and to devise procedures for converting industrial and other wastes into useful highway products. These activities are all directed toward the common goals of lowering the cost of highway construction and extending the period of maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural designs, fabrication processes, and construction techniques, to provide safe, efficient highways at reasonable cost.

6. Prototype Development and Implementation of Research

This category is concerned with developing and transferring research and technology into practice, or, as it has been commonly identified, "technology transfer."

7. Improved Technology for Highway Maintenance

Maintenance R&D objectives include the development and application of new technology to improve management, to augment the utilization of resources, and to increase operational efficiency and safety in the maintenance of highway facilities.

* The complete 7-volume official statement of the FCP is available from the National Technical Information Service (NTIS), Springfield, Virginia 22161 (Order No. PB 242057, price $45 postpaid). Single copies of the introductory volume are obtainable without charge from Program Analysis (HRD-2), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.

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